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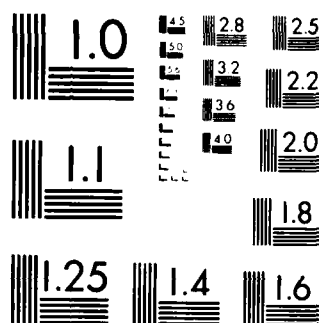
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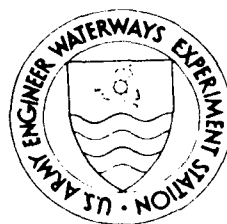
CEMENT COMPOSITION AND CONCRETE DURABILITY IN SEA WATER

by

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Structures Laboratory

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The effects of cement composition on durability of concrete in sea water were investigated. The separate and combined effects of alkali-silica reaction and sulfate attack were evaluated both in the laboratory and using concrete specimens from 16 mixtures exposed in warm sea water at St. Augustine, Florida. Three mixtures were made that were susceptible to both alkali-silica reaction and sulfate attack, three that should not manifest either reaction, (Continued)		

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20. ABSTRACT (Continued).

three susceptible to alkali-silica reaction only, and seven susceptible to sulfate attack only. Performance of specimens in the field plus some laboratory tests indicated these intents were generally successful. A major finding from this work was that the combined effects of both reactions caused quicker and more complete destruction of concrete and mortar than either reaction alone. While one would intuitively guess this would be the case, this work provided proof of this for the first time, so far as is known. Another result was to confirm that the mitigating effects of a pozzolan are optimized when the proper amount of pozzolan is used. This work also showed more alkali-silica reaction due to high potassium levels than to high sodium levels.

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PREFACE

The work described in this report was authorized in 1954 and started in 1955; it involved laboratory work and exposure of concrete specimens at St. Augustine, Florida; it was part of Engineering Study Item 603.1. Mr. Fred Anderson (DAEN-CWE-DC) was the OCE Technical Monitor when this report was prepared.

Many people were involved in this project over this span of time. Mr. Cecil Willetts was the original Project Leader and Mr. Alan D. Buck was the last Project Leader. All of the laboratory work was done in the Structures Laboratory (SL). Original overall supervision was under Mr. T. B. Kennedy; final supervision was under Mr. John M. Scanlon, Chief, Concrete Technology Division, and Mr. Bryant Mather, Chief, SL. The report was prepared by Mr. Buck.

Commanders and Directors of the USAE Waterways Experiment Station (WES) during preparation and issuance of this report were COL Tilford C. Creel, CE, and COL Robert C. Lee, CE. Mr. F. R. Brown was Technical Director at this time.

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Contents

	<u>Page</u>
Preface	1
Conversion Factors, Non-SI to SI (Metric) Units of Measurement	3
Background	4
Materials, Mixtures, and Tests	5
Materials	5
Mixtures and tests	6
Results	7
Sea water	7
Project materials	7
Mortars	8
Concretes	9
Discussion	10
Conclusions	11
References	13
Figures 1 and 2	
Tables 1-9	
Six Inclosures (Petrographic Reports)	

Conversion Factors, Non-SI to SI (Metric)

Units of Measurement

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

<u>Multiply</u>	<u>by</u>	<u>To obtain</u>
inches	25.4	millimetres
angstroms	0.1	nanometres
pounds (force) per square inch (psi)	6.894757	kilopascals
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvins (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

CEMENT COMPOSITION AND CONCRETE DURABILITY IN SEA WATER

Background

1. A study to determine if sulfate attack of concrete would have any effect on the degree of alkali-silica reaction that developed in the same concrete was conceived and executed. Laboratory tests were used to characterize the materials used and to evaluate their potential for expansive reaction or reactions when they were used in various combinations. Field exposure and testing were used to evaluate 16 different concrete mixtures. Concrete specimens were made in the laboratory and most of them were transported to the warm sea water exposure station at St. Augustine, Florida; the balance of the concrete specimens were stored out of doors at the moderate weathering exposure station near Jackson, Mississippi. The concrete specimens were monitored periodically by determination of pulse velocity and by visual inspections for about 10 years.¹ When specimens failed, some of these were returned to the laboratory for petrographic examination. The results of this testing have had only limited publication.^{1,2} The intent of this work was to provide opportunity for alkali-silica reaction or sulfate attack or both to occur in a favorable environment (warm sea water) and to monitor the results.

2. Specimens representing these 16 concrete mixtures were installed at the mean-tide level at St. Augustine, Florida, in 1955-56. The mixtures involved combinations of four portland cements, two granulated iron blast-furnace slags, three aggregates, and two types of pozzolan (fly ash and ground calcined shale). The four portland cements included examples with high- and low-alkali contents and high- and low-tricalcium aluminate contents. The aggregates included reactive and nonreactive types. Three of the mixtures with high-alkali, high- C_3A cement, and reactive aggregate were expected to experience both alkali-aggregate reaction and sulfate attack; three others with high-alkali, low- C_3A cement, and reactive aggregate were expected to experience only alkali-aggregate reaction; seven with nonreactive aggregate but high- C_3A cement were expected to experience sulfate attack only; the remaining three were not expected to experience either kind of attack. Since two of the mixtures were made twice, there was a total of 18 mixtures with 16 of them being different.

3. A description of this project and discussion of results to that time were presented at the 1959 American Concrete Institute (ACI) Convention.⁶

Materials, Mixtures, and Tests

Materials

4. The four portland cements used are shown below:

<u>RC No.</u>	<u>Alkali</u>	<u>Tricalcium Aluminate (C₃A*)</u>
331	High	Low
332	High	High
333	Low	Low
334	Low	High

* Usual cement notation, $C_3A = 3CaO \cdot Al_2O_3$

5. The two pozzolans and the two ground granulated iron blast-furnace slags that were used are shown below:

<u>Serial No.</u>	<u>Type of Material</u>	<u>Portland Cement Replacements by Solid Volume, %</u>
AD-3(3)	Fly Ash	20
AD-5(3)	Calcined Shale	30
RC-216(4)	Granulated Blast- Furnace Slag	40
RC-296	Granulated Blast- Furnace Slag	40

6. The aggregates that were used included:

<u>CL Serial No.</u>	<u>Kind of Aggregate and Material</u>	<u>Relative Alkali- Silica Reactivity</u>
VICKS-3 G-1(20)	Coarse Crushed	None
VICKS-3 MS-10	Fine Dolomitic Limestone	
WES-1 G-5(3)	Coarse Natural	Moderate
WES-1 S-8(3)	Fine Siliceous	
	Gravel and Sand	

<u>CL Serial No.</u>	<u>Kind of Aggregate and Material</u>	<u>Relative Alkali- Silica Reactivity</u>
OM-2G-2(9)	Coarse Quartzite	Highly
CRD-G-22(2)	Fine Pyrex Glass	Highly

7. The quartzite was reactive because it contained an opal matrix; the quartzite was used to replace 5 percent of the natural gravel in some mixtures. When the natural gravel was crushed for use in mortar bars, the quartzite replacement was 1, 3, and 1 percent of the 600- μ m, 300- μ m, and 150- μ m (No. 30, 50, and 100) sizes, respectively. When the replacement of natural gravel was in concrete, the replacement with quartzite was by solid volume of the total gravel with approximately 35 percent in the 19.0-mm to 37.5-mm (3/4- to 1-1/2-in.) size when used and the balance in the 4.75-mm to 19.0-mm (No. 4 to 3/4-in.) size material.

8. The limestone, natural sand and gravel, and the quartzite, in different combinations, were used in the concrete. The Pyrex glass was used only in two of the laboratory mortar mixtures. These Pyrex mixtures were repeated for a total of four mixtures.

Mixtures and tests

9. Various physical and chemical tests and petrographic examinations were used to characterize the materials and some of the mortar mixtures that were made. This included petrographic examination of some concrete specimens from storage at St. Augustine. Specimens stored out of doors at Jackson were inspected as well as being tested in conjunction with testing of the St. Augustine specimens.

10. Concretes. In 1955, three rounds of 12 mixtures were made. Three concrete beams, each 6 by 6 by 30 in., and nine 6- by 12-in. cylinders were made from each round for a total of 108 beams and 324 cylinders. Six beams from each mixture were placed on the exposure rack at St. Augustine, Florida, in August 1955, and the remaining beams were placed outdoors at the CL in September 1955.

11. In 1956, three rounds of six more concrete mixtures were made as before. Six beams from each mixture were placed at St. Augustine and the remaining three from each mixture were placed outdoors at the CL, all in August 1956. Two of these were repeats of the earlier mixtures but with 19.0-mm (3/4-in.) instead of 37.5-mm (1-1/2-in.) nominal maximum aggregate size.

12. The pulse velocity and dynamic Young's modulus of elasticity (E) of the beams kept at St. Augustine and outdoors in Mississippi were determined biennially until 1970. In mid-1971, one concrete beam from each of the 15 sets that had not failed at St. Augustine was returned to the laboratory and given a final reading. These included beams 1833, 1842, 1863, 1868, 1878, 1889, 1901, 1905, 1917, 2542, 2545, 2554, 2565, 2571, and 2587. No readings of the specimens kept outdoors in Mississippi were made after the 1970 reading.

13. The cylinders were tested for static E at 28 and 90 days and for compressive strength at 7, 28, and 90 days.

14. All of the 18 concrete mixtures had a water-cement ratio of 0.5, slump of $2\frac{1}{2} \pm \frac{1}{2}$ in., and air content of $5 \pm \frac{1}{2}$ percent.

15. Mortar. A total of 16 mixtures were made and the bars were tested for length change by CRD C 123-48³ (ASTM: C 227). Fourteen of the mixtures were different combinations of materials and two mixtures were repeats.

16. Ten mortar mixtures were made and specimens were measured for length change by the Lerch test (CRD-232)³ (ASTM: C 452) and six other mixtures by the Lean Mortar Bar Test* to evaluate the sulfate resistance of the four project cements and of the two high C₃A ones (RC-332, 334) when combined with granulated blast-furnace slag.

Results

Sea water

17. A chemical analysis of a sample of sea water from St. Augustine was made in 1958; the data are shown in Table 1. The temperature of the sea water was 82° F when this sample was taken.

Project Materials

18. Tables 2, 3, and 4 contain data for the four cements, two ground slags, two pozzolans, and five aggregates, respectively. The most notable features of the cements are their range in C₃A and total alkali contents and distribution of alkalies. These are:

* Done as described in Appendix A to the 1952 report of ASTM Committee C-1, ASTM Proceedings, Vol 52.

Cement RC-	Calculated C_3A	Total Alkali as Na_2O	Alkali as	
			K_2O	Na_2O
331	5	0.94	0.23	0.79
332	14.3	1.00	0.95	0.37
333	3	0.33	0.20	0.20
334	13.5	0.24	0.16	0.13

19. Inclosure 1 is a 1955 petrographic report about the five aggregates (three types) that were used in the concrete mixtures. It points out that the Klufa quartzite contained about 14 percent opal. Since the quartzite was used at the 5 percent level when it was used, there should have been about 0.7 percent opal in the total aggregate. This is a probable pessimum which was confirmed by field behavior of appropriate beams (Table 9).

20. Inclosure 2 is a petrographic report, largely X-ray diffraction (XRD), of cements RC-332 and 334 and of two slags from the same sources as the two project slags. It points out that while both cements are high C_3A by calculation, based on the chemical analyses, RC-334 has about half as much crystalline C_3A by XRD. The difference in these two cements and their sulfate resistance was discussed extensively in a 1965 report.⁴ At that time it was concluded that since they were similar in calculated C_3A content but differed significantly in amount of crystalline C_3A by XRD, the difference was that some of the C_3A was glassy and that this explained their differing behavior to sulfate attack. The slags are shown to be largely glassy with small amounts of crystalline quartz, calcite, and melilite (RC-216(4) only).

21. Mortars. Table 5 shows expansion data through 1 year for the 16 mortar mixtures. No bars were made with the low-alkali and high- C_3A cement RC-334. The chert gravel and opaline quartzite combination with high-alkali cement RC-331 was repeated with substantially more expansion the second time. Since this testing was done when there was difficulty in obtaining the nearly 100 percent relative humidity within a container that is required for this test, the presumption is that the humidity was lower in the initial test. The same aggregate combination with the other high-alkali cement (RC-332) was also repeated, both sets of results were similar so humidity was not a problem. Note that expansion with high-alkali and high C_3A RC-332 was approximately twice what it was with high-alkali and low C_3A cement RC-331.

22. Inclosure 3 is a petrographic report about examination of 12 of the 16 mortar bar sets (Table 5) after testing was stopped after 1 year. This

Compressive Strength and Static Modulus Data for 18 Concrete Mixtures

Designation (a)	Mixture Data		Compressive Strength, psi (b)			Static Modulus, $\times 10^6$ (b)	
	Materials		7 Day	28 Day	90 Day	28 Day	90 Day
Low-Alkali, Low- C_3A Cement RC-333							
3	Limestone aggregate		2790	3910	5210	4.90	5.44
2	Natural + 5 percent quartzite		2380	3420	4590	5.24	5.78
High-Alkali, Low- C_3A Cement RC-331							
7	Natural aggregate		2740	3850	4760	5.48	5.42
1	Natural + 5 percent quartzite		2700	3860	4450	5.35	6.22
10	Natural + 5 percent quartzite, 20 percent fly ash (AD-3(3))		2360	3520	4360	5.50	5.92
9	Natural + 5 percent quartzite, 30 percent calcined shale (AD-5(3))		1970	3360	4450	4.88	5.22
Low-Alkali, High- C_3A Cement RC-334							
6	Limestone aggregate		2950	4070	5010	5.18	5.35
B	Limestone aggregate		3190	4690	5460	5.20	5.65
E	Limestone aggregate, 40 percent RC-296 slag		2360	3870	4990	5.52	5.91
F	Limestone aggregate, 40 percent RC-216(4) slag		2300	4150	5100	5.35	5.61
High-Alkali, High- C_3A Cement RC-332							
5	Limestone aggregate		3630	4400	4870	5.05	5.14
A	Limestone aggregate		3750	4200	4690	5.46	5.56
8	Natural aggregate		2920	3800	4100	5.28	5.31
4	Natural aggregate + 5 percent quartzite		3080	3970	4300	5.56	5.33
12	Natural + 5 percent quartzite, 20 percent fly ash (AD-3(3))		2610	3650	4190	5.43	5.88

(Continued)

Table 7

Selected Length-Change Data for Six Mortar Mixtures by the
Lean Mortar-Bar Test (a)

Materials	Expansion, % (b)				
	14 Day	28 Day	84 Day	196 Day	364 Day
RC-332 (High alkali, high C ₃ A)	0.008	0.027	(Bars broke after 42-day reading)		
RC-332 plus 40 percent RC-216(4) slag	0.010	0.024	0.032	0.042	0.057
RC-332 plus 40 percent RC-296 slag	0.009	0.020	0.027	0.036	0.058
RC-334 (Low alkali, high C ₃ A)	0.013	0.051	0.160	1.235	(Bars broke after the 196-day reading)
RC-334 plus 40 percent RC-216(4) slag	0.009	0.022	0.028	0.036	0.068
RC-334 plus 40 percent RC-296 slag	0.008	0.019	0.024	0.031	0.070

(a) The method used was referenced as a footnote in the report.

(b) Each value is an average, usually of four bars.

Table 6

Selected Length-Change Data of 10 Mortar Mixtures by the
Lerch Added Sulfate Test (CRD-C 232) (a)

Materials	Expansion, % (b) (c)					
	7 Day	28 Day	84 Day	196 Day	364 Day	Day
RC-331, High alkali, low C ₃ A	0.024	0.047	0.073	0.094	0.108	
RC-332, High alkali, high C ₃ A	0.051	0.124	0.346	0.348	0.354	
Repeat of above mixture	0.040	0.105	0.268	0.269	0.272	
RC-332 plus 40 percent RC-296 slag	0.048	0.117	0.222	0.222	0.224	
RC-332 plus 40 percent RC-216(4) slag	0.049	0.133	0.155	0.158	0.157	
RC-333, Low alkali, low C ₃ A	0.013	0.025	0.036	0.044	0.056	
RC-334, Low alkali, high C ₃ A	0.054	0.142	0.354	1.762	1.772	
Repeat of above mixture	0.051	0.130	0.295	1.312	1.332	
RC-334 plus 40 percent RC-296 slag	0.057	0.115	0.228	0.331	0.333	
RC-334 plus 40 percent RC-216(4) slag	0.055	0.126	0.228	0.246	0.250	

(a) Reference 1.

(b) Each value is an average, usually of six bars.

(c) All values are positive.

Table 5

Selected Length-Change Data of Bars from 16 Mortar Mixtures in the
Alkali-Aggregate Test for Reactivity (CRD-C 123) (a)

Cement RC-	Aggregate	Pozzolans	Expansion, % (b) (c)					
			3 Day	28 Day	84 Day	196 Day	364 Day	
331	Limestone Sand	None	-0.005	-0.005	0.000	0.005	0.008	
331	Natural Sand	None	-0.004	-0.003	0.001	0.000	0.007	
High-Alkali								
Low C ₃ A								
331	Gravel	None	-0.001	-0.002	-0.001	-0.003	0.000	
331	Gravel + Quartzite	None	0.001	0.004	0.011	0.010	0.014	
	Repeat of Above Mixture		0.001	0.014	0.025	0.054	0.063	
331	Pyrex Glass	--	0.075	0.257	0.321	0.344	0.358	
331	Gravel + Quartzite	AD-5(3)	0.003	-0.003	-0.003	-0.002	0.004	
331	Gravel + Quartzite	AD-3(3)	0.002	0.003	0.010	0.013	0.020	
332	Gravel + Quartzite	None	0.012	0.022	0.069	0.120	0.130	
High-Alkali								
High C ₃ A								
332	Repeat of Above Mixture		0.010	0.028	0.070	0.105	0.109	
332	Pyrex Glass		0.161	0.288	0.298	0.311	0.320	
332	Gravel + Quartzite	AD-5(3)	0.005	0.003	0.003	0.003	0.009	
333	Gravel + Quartzite	None	0.001	-0.003	-0.002	-0.004	0.000	
333	Limestone Sand	None	-0.002	-0.006	-0.003	-0.003	0.000	
Low Alkali								
Low C ₃ A								
333	Natural Sand	None	-0.001	-0.004	0.001	0.000	0.002	
333	Gravel	None	0.001	-0.001	0.000	-0.008	-0.003	

- (a) Reference 1; the test method was deviated from fixed proportions so the water content of each mixture would give a flow of 110 ± 5 percent.
 (b) Each value is the average of nine bars.
 (c) All values are positive unless preceded by a minus sign.

Table 4

Physical Data for Coarse and Fine Aggregates

	WES-1 G-5(3)			VICKS-3 G-1(20)			OM-2 G-2(9)		
	Natural Gravel			Limestone			Quartzite		
Bulk Sp. Gr., Sat. Surf. Dry (a)	19.0 mm to 4.75 mm	19.0 mm to 4.75 mm	19.0 mm to 4.75 mm	19.0 mm to 4.75 mm	19.0 mm to 4.75 mm	19.0 mm to 4.75 mm	19.0 mm to 4.75 mm	19.0 mm to 4.75 mm	19.0 mm to 4.75 mm
Absorption, % (a)	37.5 mm (No. 4 to 3/4 in.)	37.5 mm (No. 4 to 3/4 in.)	37.5 mm (No. 4 to 3/4 in.)	37.5 mm (No. 4 to 3/4 in.)	37.5 mm (No. 4 to 3/4 in.)	37.5 mm (No. 4 to 3/4 in.)	37.5 mm (No. 4 to 3/4 in.)	37.5 mm (No. 4 to 3/4 in.)	37.5 mm (No. 4 to 3/4 in.)
Flat and Elongated, % (a)	1-1/2 in. to 3/4 in.	1-1/2 in. to 3/4 in.	1-1/2 in. to 3/4 in.	1-1/2 in. to 3/4 in.	1-1/2 in. to 3/4 in.	1-1/2 in. to 3/4 in.	1-1/2 in. to 3/4 in.	1-1/2 in. to 3/4 in.	1-1/2 in. to 3/4 in.
M ₂ SO ₄ Loss, % (Weighted Avg) (a)									
Abrasion Loss (L.A.), % (a)									
Grading (Cum. % Passing) (a)									
50 mm (2 in.)	2.56	2.50	2.62	2.70	2.71	2.66	2.37	2.36	2.36
37.5 mm (1-1/2 in.)	1.5	3.4	0.5	0.6	0.5	1.5	2.2	2.4	2.4
25.0 mm (1 in.)	1.1	2.2	--	7.6	10.7	--	4.0	15.4	15.4
19.0 mm (3/4 in.)	2.9	6.2	2.2	2.4	5.9	14.0	6.8	12.8	12.8
12.5 mm (1/2 in.)	21.7	24.5	--	27.1	25.4	--	30.8	30.0	30.0
9.5 mm (3/8 in.)									
4.75 mm (No. 4)	100						100		
2.36 mm (No. 8)	98						98		
1.18 mm (No. 16)	56	100					56	100	
600 μ m (No. 30)	10	96					10	96	
300 μ m (No. 50)	1	70					1	70	
150 μ m (No. 100)	0	48					0	48	
75 μ m (No. 200)	0	5	95				0	5	
Passing 75 μ m (No. 200)			81						
Fineness Modulus			70						
			54						
			17						
			6						
			3.2						
			2.7						
			2.76						

(a) Reference 1.

Table 3

Chemical and Physical Data for Four Admixtures

Chemical Data, %	AD-3(3) Fly Ash	AD-5(3) Calcedine Shale	RC-216		RC-198	
			Granulated Blast-Furnace Slag (a)	Granulated Blast-Furnace Slag (b)	Granulated Blast-Furnace Slag (a)	Granulated Blast-Furnace Slag (b)
SiO ₂	48.3	61.2	37.9		38.8	
Al ₂ O ₃	14.7	11.8	13.3		11.3	
Fe ₂ O ₃	18.9	4.9	1.0		0.5	
CaO	8.5	9.2	35.3		43.6	
MgO	2.1	2.9	10.2		2.0	
SO ₃	3.0	0.4	0.1		0.1	
Loss on Ignition	1.4	6.8	0.6		1.4	
Na ₂ O	2.5	0.2	0.2		0.2	
K ₂ O	2.0	0.4	1.0		1.2	
Total Sulfur	0.2	0.4	1.3		0.9	
Insoluble Residue	66.4	66.1	0.5		0.6	
Total Carbon	0.8	1.1	0.5		0.4	
Physical Data, %						
Air-permeability Fineness, cm ² /g (Blaine)	3580	12,930	3700		3600	
Amount Passing 45-μm (No. 325) sieve	94.4	97.7	97.2		90.2	
Specific Gravity	2.52	2.50	2.87		2.84	

(a) Data from ALES MP No. 6-123, Investigation of Cement-Replacement Materials, Report No. 1, Apr 1953.

(b) Same source as the RC-296 that was used in this work.

Table 2
Chemical and Physical Data for Four Portland Cements

Chemical Data, %	RC-331 High Alkali, Low C ₃ A	RC-332 High Alkali, High C ₃ A	RC-333 Low Alkali, Low C ₃ A	RC-334 Low Alkali, High C ₃ A
SiO ₂	22.2	19.6	24.5	21.6
Al ₂ O ₃	4.4	6.8	3.0	5.5
Fe ₂ O ₃	4.2	2.5	2.9	1.9
CaO	63.7	63.1	64.2	63.0
MgO	1.1	2.7	1.0	2.9
SO ₃	2.0	2.1	2.1	2.1
Loss on Ignition	1.0	1.4	0.9	1.4
Na ₂ O	0.79	0.37	0.20	0.13
K ₂ O	0.23	0.95	0.20	0.16
Total Alkalies as Na ₂ O	0.94	1.00	0.33	0.24
Insoluble Residue	0.3	0.3	0.2	0.3
Calculated Compounds, %				
C ₃ S	50	52	45	46
C ₂ S	26	17	36	27
C ₃ A	5	14.3	3	13.5
C ₄ AF	13	8	9	6
Physical Data				
Air-permeability Fineness, cm ² /g (Blaine)	3005	3290	3240	3550
Specific Gravity	3.15	3.14	3.16	3.10
Compressive Strength, psi				
3 days	2620	2510	1820	1700
7 days	3450	3740	2850	2840
28 days	5600	4600	4420	4840

Table 1
Analysis of Sea Water from St. Augustine Exposure
Station, Made by Chemistry Section, CD
Reported 9 September 1958

<u>Constituents</u>	<u>ppm</u>	<u>Equivalents</u>
Suspended Solids	160.0	--
Dissolved Solids	38,610	--
Dissolved SiO ₂	6.0	--
Dissolved R ₂ O ₃	7.0	--
Dissolved Ca	430.2	21.46
Dissolved Mg	1,340.0	110.2
Dissolved Na	11,130	484.1
Dissolved K	447	<u>11.43</u>
		627.19
Dissolved Cl	20,460	576.9
Dissolved SO ₄	2,780	<u>57.88</u>
		634.78

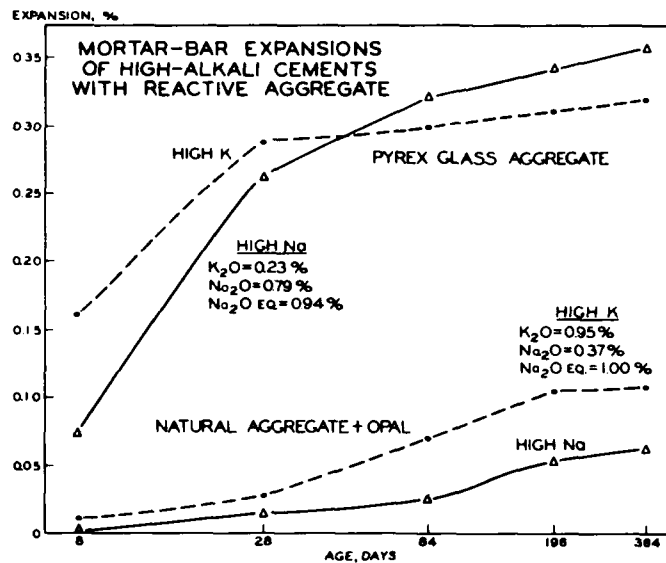


Figure 1. Mortar-bar expansions of high-alkali cements with reactive aggregate

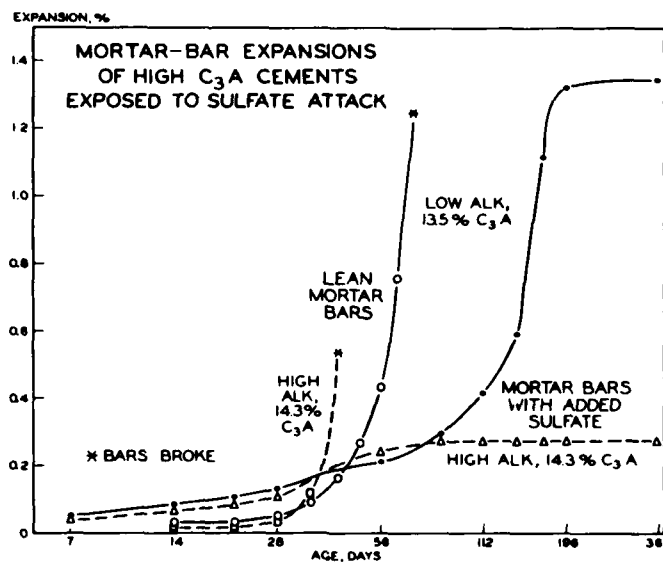


Figure 2. Mortar-bar expansions of high-C₃A cements exposed to sulfate attack

References

1. "Investigation of Performance of Concrete and Concreting Materials Exposed to Natural Weathering," Section 29 of Vol 1, Active Investigations, Vol 2, Completed Programs of Investigation, with periodic supplements, U. S. Army Engineer Waterways Experiment Station, CE, Technical Report No. 6-553, Vicksburg, Miss., Jun 1960.
2. Mather, Katharine, "Concrete Weathering at Treat Island, Maine," pp 101-111, ACI SP-65, Performance of Concrete in Marine Environment, 1980.
3. U. S. Army Engineer Waterways Experiment Station, CE, Handbook for Concrete and Cement, with quarterly supplements, Vicksburg, Miss., Aug 1949.
4. Mather, Bryant, "Investigation of Portland Blast-Furnace Slag Cements," Report 2, Supplementary Data, U. S. Army Engineer Waterways Experiment Station, Technical Report No. 6-445, Sep 1965, Vicksburg, Miss.
5. U. S. Army Engineer Waterways Experiment Station, Technical Report No. 6-481, "Effectiveness of Mineral Admixtures in Preventing Excessive Expansion of Concrete Due to Alkali-Aggregate Reaction," Jul 1958, Vicksburg, Miss.
6. Mather, Bryant, 1959, "Cement Composition and Durability in Sea Water," American Concrete Institute Convention, Feb 1959, presentation at off-the-record Research Session (not published).

36. Two cements (RC-332, 334) with similar high amounts of calculated C_3A but different amounts of crystalline C_3A by XRD reacted differently to sulfate attack. The one with more glassy aluminates (RC-334) showed more and longer-term expansion as if the glassy phase was slower to react; perhaps because it was combined with other more slowly reactive phases.

that should show the effects of alkali-silica reaction only, and seven mixtures showing the effects of sulfate attack only. Armed with a knowledge of the materials used and consideration of the test results that have been described, it is apparent that this intent was generally successful. The mitigating effect of different pozzolans or slags on these reactions was recognizable. However, since they were not necessarily used at their optimum amounts, the effects were often limited in scope or duration.

31. Due to the fact that the two high-alkali cements (RC-331, 332) differed in type of major alkali, sodium or potassium, as well as being low or high in C_3A , comparisons between the effects of these cements was never definitely as simple as being due to C_3A or to type of alkali. However, comparison did indicate that the higher potassium cement (RC-332) did cause more and quicker expansion due to alkali-silica reaction than did the higher sodium cement (RC-331). This is shown graphically in Figure 1 which was used in the 1959 presentation at the ACI Convention.

32. The use of XRD to show that two high- C_3A cements (RC-332, 334) of presumably similar C_3A contents actually differed with RC-332 containing much more crystalline C_3A was considered significant. Each cement led to significant expansion due to sulfate attack (Tables 6, 7) with the one (RC-334) having the smaller amount of crystalline C_3A , and presumably more glassy aluminate, causing more longer-term expansion before any breakage of bars occurred. This suggests that liberation of incorporated aluminate by other phases took longer than the quicker reaction (i.e., <56 days) of crystalline C_3A . These results are shown in Figure 2, also from the 1959 ACI paper.

Conclusions

33. The effect of combined alkali-silica reaction and sulfate attack on concrete or mortar is faster and more destructive than the effect of either reaction by itself.

34. When slag or a pozzolan is to be used to mitigate the effect of alkali-silica reaction or of sulfate attack on mortar or concrete, it is preferable that enough advance experimentation be done with this material to determine the optimum amount of it to use for this purpose.

35. High potassium content in a cement caused more alkali-silica reaction than did high sodium content.

general, one can predict specimen behavior from a knowledge of materials combinations. For example, the combination of low-alkali and low- C_3A cement RC-333 with limestone or siliceous aggregate with 5 percent quartzite (Mixtures 3, 2) should be satisfactory, and it was through the 16 years of testing. On the other hand, the combination of high-alkali and high- C_3A cement RC-332 with siliceous aggregate and 5 percent quartzite (Mixture 4) should fail, and all of the beams had failed by 1960 after about 5 years of exposure to the marine environment.

27. Inclosure 4 is a 1958 petrographic report describing examination of two failed beams (1823, 1850) from the St. Augustine exposure and of the four project cements. Beam 1850 had obviously failed because of deleterious chemical reactions but Beam 1823 showed only negligible reaction and was probably broken by accident during handling. The report concluded that the much higher potassium content of cement RC-332 in Beam 1850 was probably the major explanation for the different behavior of the beams. It also speculated on possible interaction effect of one reaction (sulfate attack) on another (alkali-silica reaction).

28. Inclosure 5 is a 1957 petrographic report and memorandum about examination of three failed St. Augustine concrete specimens from a different test program. It is included because it is another example of extensive deterioration of concrete containing a high-alkali and high C_3A cement.

29. Inclosure 6 is another petrographic report, written in about 1966, of a failed beam that was returned from St. Augustine after about 9 years of exposure. It had the same high-alkali and high- C_3A cement (RC-332) and reactive aggregate combination as the earlier failed beam 1850, but this later beam also contained 20 percent fly ash. It appeared that the ultimate fate of this later beam was the same as Beam 1850, but this fate had been deferred but not prevented by the presence of the pozzolanic fly ash. This is not surprising since later work⁵ indicated that at least 40 percent of such ash would be required for maximum effectiveness.

Discussion

30. As indicated earlier, the intent was to make three concrete mixtures that would show maximum effect due to both types of reaction, to make three mixtures that should show no effect from either reaction, to make three mixtures

examination showed some evidence of alkali-silica reaction in most sets of bars, no sign of reaction in the low-alkali and low-C₃A cement RC-333 with chert gravel or this gravel with 5 percent quartzite, and most evidence of this reaction in the bars made with high-alkali and high-C₃A cement RC-332 with gravel and quartzite. There was no sign of sulfate attack in the form of recognizable ettringite.

23. Table 6 shows expansion data through 1 year for the 10 mortar mixtures tested in the Lerch test (CRD-C 232)³ (ASTM: C 452) using all 4 cements. The high-alkali and high-C₃A cement RC-332 mixture and the low-alkali and high-C₃A cement RC-334 mixture were both repeated. Reproducibility was probably satisfactory in both cases. The use of 40 percent of either slag with RC-332 was relatively ineffective. While they were more effective with cement RC-334, they still did not reduce expansion to a satisfactory level. The extreme expansion at 1 year of over 1 percent for the low-alkali and high-C₃A RC-334 was especially noticeable, particularly when compared to 1-year expansion of substantially less than 1 percent for the high-alkali and high-C₃A cement RC-332. As expected, expansion was lowest when alkali and C₃A contents were both low (RC-333).

24. Six mortar mixtures were tested in the Lean Mortar Bar Test (see footnote to Section 15). Expansion data for these through a maximum age of 609 days are shown in Table 7. These evaluate the high-C₃A cements (RC-332, 334) alone and with 40 percent of each slag. As with the other test for sulfate resistance, both cements lead to excessive expansion or breaking of bars with RC-334 bars expanding over 1 percent in less than 1 year. As before, the data indicate that each slag reduces expansion but probably not enough, especially at the longer ages.

25. Concretes. Table 8 shows the compressive strength data through 90 days and the static E results through 90 days that were obtained in the laboratory for the 18 concrete mixtures. Mixture B was a repeat of Mixture 6 with 3/4-in. instead of 1-1/2-in. limestone aggregate and cement RC-334. Mixture A was a repeat of Mixture 5 with 19.0-mm (3/4-in.) instead of 37.5-mm (1-1/2-in.) limestone aggregate and cement RC-332. The mixture designations are those used in the book that contained all of the field data.¹

26. Table 9 contains data from Reference 1 for the beams of these 18 concrete mixtures through the 1970 readings. In addition, the final readings that were made in the laboratory when 15 beams were returned are shown. In

Table 8 (Concluded)

Designation(a)	Mixture Data	Compressive Strength, psi(b)			Static Modulus, x 10 ⁶ (b)		
		7 Day	28 Day	90 Day	28 Day	90 Day	
	Materials	High-Alkali, High C ₃ A Cement RC-332					
11	Natural + 5 percent quartzite, 30 percent calcined shale (AD-5(3))	2260	3400	3870	4.71	5.07	
C	Limestone aggregate, 40 percent RC-296 slag	3210	4780	5430	5.79	6.24	
D	Limestone aggregate, 40 percent RC-216(4) slag	2880	4520	5340	5.51	5.84	

(a) The numbered mixtures contained 37.5-mm (1-1/2-in.) nominal maximum size aggregate; the other mixtures contained 19.0-mm (3/4-in.) nominal maximum size aggregate.

(b) Each value is the three-round average for nine cylinders (each 6 by 12 in.)

Table 9

Sonic Data for Concrete Beams Exposed at St. Augustine, Florida

Mixture Designation(e)	Replacement Material(a)	Fine Aggregate	Coarse(a) Aggregate	Pulse Veloc	1956	1958	1960	1962	1964	1966	1968	1970	1971(f)
No.	(Pozzolan)	Aggregate	Aggregate	%E f/s	%V ²	%E f/s	%V ²	%E f/s	%V ²	%E f/s	%V ²	%E f/s	%V ²
Low-Alkali, Low C ₃ A Cement RC-333													
3	1841	None	Limestone	100	14,880	100	109	112	120	115	119	121	
	1842			100	15,150	100	109	108	120	112	119	118	
	1844			100	14,975	100	112	112	124	116	117	119	
	1845			100	14,705	100	111	110	132	113	118	122	
	1847			100	14,535	100	114	111	146	114	119	122	
	1848			100	14,535	100	113	114	139	117	120	123	
2	1832	None	Natural sand	100	14,370	100	107	106	131	109	116	111	
	1833			100	14,370	100	109	109	132	109	112	111	
	1835			100	14,450	100	107	105	117	109	112	114	
	1836			100	15,060	100	107	102	120	102	115	108	
	1838			100	15,060	100	108	98	119	102	116	106	
	1839			100	14,880	100	108	101	120	102	115	108	
High-Alkali, Low C ₃ A Cement RC-331													
7	1877	None	Natural sand	100	15,060	100	104	99	125	101	110	104	
	1878			100	14,705	100	103	89	115	101	109	109	
	1880			100	14,795	100	103	100	119	100	108	105	
	1881			100	14,795	100	104	100	121	100	110	106	
	1883			100	14,970	100	107	98	121	98	108	105	
	1884			100	14,970	100	105	99	118	100	111	105	
1	1823	None	Natural sand	100	14,620	100	104	117	(b)				
	1824			100	14,970	100	103	99	115	96	64	98	
	1826			100	14,620	100	102	100	126	100	(d)		
	1827			100	14,535	100	104	104	121	102	92	92	
	1829			100	14,880	100	104	99	125	90	(d)		
	1830			100	15,060	100	103	98	131	97	106	93	

(Continued)

Table 9 (Continued)

Mixture Designation(e)	Beam No.	Replacement Material(a)	Fine Aggregate	Coarse(a) Aggregate	Pulse Veloc %E	1956 %V ²	1958 %E %V ²	1960 %E %V ²	1962 %E %V ²	1964 %E %V ²	1966 %E %V ²	1968 %E %V ²	1970 %E %V ²	1971(f) %E %V ²
10	1904	Flv ash	Natural	Natural	100	14,705	100	106	97	122	94	114	106	
	1905	20 percent	Natural sand	gravel	100	14,705	100	107	98	122	101	115	107	
	1907			+ quartzite (5 percent)	100	14,705	100	108	105	106	101	96	110	113 104
	1908				100	14,795	100	104	102	116	102	110	107	106 98
	1910				100	14,880	100	107	98	122	100	112	105	111 100
	1911				100	14,880	100	108	97	120	100	113	105	111 100
9	1895	Shale	Natural	Natural	100	13,735	100	115	102	131	112	107	109	104 110
	1896	30 percent	Natural sand	gravel	100	13,810	100	114	102	131	105	125	109	126 106
	1898			+ quartzite (5 percent)	100	14,125	100	109	99	122	102	119	110	113 103
	1899				100	14,370	100	110	98	123	101	121	107	113 111
	1901				100	13,890	100	113	99	129	110	133	110	125 113
	1902				100	14,125	100	110	99	127	102	121	106	115 112
Low-Alkali, High-C ₃ A Cement RC-334														
6	1868	None	Limestone sand	Limestone	100	14,705	100	108	114	125	117	107	116	103 122
	1869				100	14,205	100	110	115	130	118	119	120	114 129
	1871				100	14,620	100	110	113	126	116	116	120	112 128
	1872				100	14,880	100	110	113	128	115	117	118	111 131
	1874				100	14,970	100	108	109	127	112	118	116	114 126
	1875				100	14,880	100	108	109	131	112	117	115	112 125
b	2544	None	Limestone sand	Limestone	100	15,430	100	122	109	122	110	111	118	111 118
	2545				100	15,335	100	115	112	121	110	114	118	114 118
	2547				100	14,620	100	114	113	115	119	109	123	107 107
	2548				100	14,705	100	128	99	115	129	106	122	106 107
	2550				100	15,060	100	115	115	123	116	108	122	108 99
	2551				100	15,060	100	114	116	122	116	107	122	112 109

(Continued)

Table 9 (Continued)

Mixture Designation (c)	Replacem ^t Material (a) (Pozzol ^{an})	Beam No.	Fine Aggregate	Coarse (a) Aggregate	Pulse Veloc ² ZE ips %V ²	High-Alkali, High-C ₃ A Cement RC-332									
						1956 %E %V ²	1958 %E %V ²	1960 %E %V ²	1962 %E %V ²	1964 %E %V ²	1966 %E %V ²	1968 %E %V ²	1970 %E %V ²	1971 (t) %E %V ²	
v	RC 198 blast- furnace slag 40 percent	2571	Limestone	Limestone	100 15,530 100	127 103	132 111	117 115	114 103	114 103	114 114	112 106	110 104	116 97	
		2572	Limestone	Limestone	100 15,625 100	127 104	133 111	114 118	118 106	119 132	118 106	116 103	116 103	116 103	
		2573	Limestone	Limestone	100 15,150 100	128 105	117 110	111 119	111 103	111 123	117 123	121 110	121 105	121 105	
		2574	Limestone	Limestone	100 15,150 100	124 105	125 110	120 121	120 103	114 122	116 109	114 105	114 105	114 105	
		2575	Limestone	Limestone	100 15,245 100	128 105	122 110	117 119	117 102	117 119	124 107	122 102	122 102	122 102	
		2578	Limestone	Limestone	100 15,245 100	123 104	121 109	116 123	118 101	118 121	120 109	118 104	118 104	118 104	
f	RC 216 blast- furnace slag 40 percent	2580	Limestone	Limestone	100 15,245 100	127 104	121 110	115 124	131 105	112 119	116 110	116 105	116 105	116 105	
		2581	Limestone	Limestone	100 15,150 100	130 106	118 113	113 121	139 102	112 116	115 109	115 106	115 106	115 106	
		2582	Limestone	Limestone	100 15,150 100	130 106	123 110	114 119	112 106	117 121	115 109	113 102	113 102	113 102	
		2583	Limestone	Limestone	100 15,060 100	123 105	122 112	108 119	102 106	107 119	106 109	102 102	102 102	102 102	
		2586	Limestone	Limestone	100 15,150 100	130 105	116 113	110 113	110 103	114 142	113 110	109 98	109 98	109 98	
		2587	Limestone	Limestone	100 15,060 100	129 106	119 113	113 116	113 107	116 120	117 109	115 106	115 106	114 112	
b	None	1859	Limestone	Limestone	100 15,060 100	105 109	126 106	110 113	105 122	122 108	103 138	105 109	103 105	103 105	
		1860	Limestone	Limestone	100 14,880 100	105 109	120 117	110 115	99 124	107 112	103 126	101 113	101 109	101 109	
		1862	Limestone	Limestone	100 15,245 100	106 105	126 110	110 112	106 121	104 105	103 123	108 108	106 105	106 105	
		1863	Limestone	Limestone	100 14,795 100	105 109	124 113	112 113	108 122	108 112	106 122	108 112	108 110	106 109	
		1865	Limestone	Limestone	100 14,620 100	105 105	123 111	108 113	104 127	108 109	104 127	102 109	104 112	104 112	
		1866	Limestone	Limestone	100 14,620 100	105 109	124 109	119 120	114 132	115 111	114 131	119 122	119 117	119 117	
d	None	2535	Limestone	Limestone	100 15,245 100	113 109	115 115	109 116	107 106	105 112	107 109	108 103	108 103	108 103	
		2536	Limestone	Limestone	100 15,060 100	116 112	121 115	114 121	113 106	111 113	112 112	112 109	112 109	112 109	
		2538	Limestone	Limestone	100 14,795 100	111 106	117 114	110 117	106 105	104 110	115 106	117 108	117 108	117 108	
		2539	Limestone	Limestone	100 14,795 100	112 109	117 112	162 120	146 103	143 114	134 107	128 98	128 98	128 98	
		2541	Limestone	Limestone	100 14,970 100	111 109	113 115	104 126	104 110	102 111	106 111	107 107	107 107	107 107	
		2542	Limestone	Limestone	100 15,060 100	111 104	111 113	105 121	107 102	103 121	101 106	101 107	105 108	105 108	

(Continued)

Table 9 (Continued)

Mixture Designation (e)	Replacement Material (a)	Fine Aggregate	Coarse Aggregate	Pulse Veloc	1956	1958	1960	1962	1964	1966	1968	1970	1971 (f)
No.		Aggregate	Aggregate	% E fpc 2	% E 2	% E 2	% E 2	% E 2	% E 2	% E 2	% E 2	% E 2	% E 2
8	1886	Natural sand	Natural	100 14,285 100	105 97 115 109	107 105	103 106	105 100	105 111	103 106	105 100	105 100	
	1887	Gravel	Gravel	100 14,450 100	104 98 113 97	106 104	107 107	104 98	108 110	115 103	117 99	104 103	
	1889			100 14,370 100	103 98 112 100	111 106	107 110	109 100	105 113	109 105	111 99		
	1890			100 14,535 100	104 99 117 98	111 106	108 113	108 99	106 114	108 108	108 103		
	1892			100 14,880 100	104 98 114 97	107 101	103 105	106 95	104 111	102 99	102 101		
	1893			100 14,620 100	106 98 116 99	104 102	102 109	102 94	101 112	102 101	102 105		
9	1850	None	Natural	100 14,125 100	69 87 (b)								
	1851	Natural sand	Gravel	100 14,370 100	66 83 124 36	Failed							
	1853		+ quartzite (5 percent)	100 14,795 100	68 87 (c)								
	1854			100 14,620 100	86 89 110 39	Failed							
	1856			100 14,620 100	67 78 77 23	Failed							
	1857			100 14,620 100	56 79 73 26	Failed							
12	1922	Fly ash 20 percent	Natural	100 14,535 100	107 100 75 92	Failed 72							
	1923	Natural sand	Gravel	100 14,450 100	106 104 100 99	Failed 78							
	1925		+ quartzite (5 percent)	100 14,535 100	106 100 68 88	Failed 71							
	1926			100 14,535 100	107 101 120 102	112 105	66 89	43 58					
	1928			100 14,705 100	108 100 129 99	115 101	53 72	40 46	Failed				
	1929			100 14,970 100	107 100 115 96	69 85	Failed 70						
11	1913	Shale 30 percent	Natural	100 13,515 100	114 102 132 106	122 110	117 117	121 106	121 120	126 110	129 108		
	1914		Gravel	100 13,515 100	111 103 130 106	124 113	115 117	119 104	118 116	119 110	119 109		
	1916		+ quartzite (5 percent)	100 13,890 100	110 102 126 103	119 111	113 119	115 101	115 117	114 109	114 107		
	1917			100 13,890 100	113 103 124 105	118 110	113 115	113 101	113 115	115 106	115 106		116 114
	1919			100 14,125 100	111 102 127 106	116 106	110 111	111 99	113 114	115 103	111 97		
	1920			100 14,285 100	112 97 130 100	120 105	115 112	113 97	113 110	120 103	120 100		

(Cont inued)

Table 9 (Concluded)

Mixture Designation (e)	Beam No.	Replacement Material (a)	Fine Aggregate	Coarse Aggregate	Pulse Veloc		1956	1958	1960	1962	1964	1966	1968	1970	1971 (f)
					%E	fps	%E %V ²	%E %V ²	%E %V ²	%E %V ²	%E %V ²	%E %V ²	%E %V ²	%E %V ²	%E %V ²
c	2553	RC 198	Limestone	Limestone	100	15,925	100	111 108	122 108	109 119	114 106	112 143	112 108	112 103	
	2554	blast-furnace	sand		100	15,925	100	113 107	130 111	115 121	111 106	111 145	118 107	118 104	111 104
	2556	slag 40			100	15,530	100	115 109	128 111	109 120	114 106	113 144	114 105	116 101	
	2557	percent			100	15,625	100	111 108	124 111	111 117	109 105	109 144	109 107	109 100	
	2559				100	15,430	100	113 108	127 111	109 120	111 106	110 131	111 107	109 103	
d	2560				100	15,430	100	140 101	113 109	113 121	113 103	111 124	111 106	109 102	
	2562	RC 216	Limestone	Limestone	100	15,335	100	150 105	123 100	114 120	118 104	114 123	114 108	114 111	
	2563	blast-furnace	sand		100	15,335	100	147 105	114 103	114 121	110 104	114 123	112 108	112 110	
	2565	slag 40			100	15,335	100	113 109	130 105	112 117	108 106	109 119	108 107	106 104	111 96
	2568	percent			100	15,430	100	123 105	126 111	117 117	110 108	110 117	112 107	110 103	
	2569				100	15,060	100	114 108	127 113	109 118	109 107	111 125	113 111	111 108	
					100	14,970	100	119 108	128 115	112 122	112 109	113 121	116 111	114 109	

(a) Percentages given are by volume of material replaced.

(b) Returned to laboratory November 1957.

(c) Broken in handling 1958.

(d) Broken in handling 1960.

(e) Beams from the numbered mixtures were placed at St. Augustine in 1955; the others were placed there in 1956.

(f) Final reading made after return to laboratory.

CORPS OF ENGINEERS, U. S. ARMY WATERWAYS EXPERIMENT STATION		PETROGRAPHIC REPORT ☒ SUMMARY ☐ DETAILED		CONCRETE RESEARCH DIVISION P. O. DRAWER 2131 JACKSON, MISSISSIPPI	
SYMBOL: 6510		PROJECT: Effect of C3A on Alkali- Aggregate Reactivity		DATE REPORT SUBMITTED: 16 Sep '55	
INITIALS: ADB		SOURCES: WES-1 G-5(3) WES-1 S-8(3), VICKS-3 G-1(20), VICKS-3 MS-10 OM-2 G-2(9)			

1. Samples. Samples of five aggregates, for use in making concrete specimens for exposure at St. Augustine, Florida, were received for petrographic examination. These samples are:

<u>CD No.</u>	<u>Description</u>	<u>Source</u>
VICKS-3 G-1(20)	Danley Limestone	Near Nashville, Tenn.
VICKS-3 MS-10	Danley Limestone	Near Nashville, Tenn.
WES-1 G-5(3)	Natural Chert Gravel	Near Utica, Miss.
WES-1 S-8(3)	Natural Sand	Near Utica, Miss.
OM-2 G-2(9)	Klufa Quartzite	Near Pickstown, S. Dakota

2. Summary. The coarse and fine aggregates of the Danley limestone are composed largely of medium-dark grey, unweathered, dense, fine-grained limestone with lesser amounts of dolomitic limestone, medium-grained limestone, shaly limestone, chert, gypsum, and calcite (Table 1, 2); the particle shape is predominantly pyramidal. The fine aggregate is excessively dusty, almost every particle has a coating of loose limestone dust.

The natural chert gravel ranges from 99 per cent chert in the 1 1/2-in. - 3/4-in. sizes to 86 per cent chert in the 3/4-in. - No. 4 sizes (Table 3). The particle shape is blocky to tabular with rounded edges. Approximately three-fourths of the chert is dense with the remainder being either vugry or porous. A small amount* of the chert in this sample is chalcedonic. The natural sand is 83 per cent quartz and 16 per cent chert (Table 4); particle shape ranges from spherical to irregular with sharp or rounded edges. The color is yellowish grey.

The Klufa quartzite is about 70 per cent quartz, 14 per cent opal, and 13 per cent clay and feldspar (Table 5). The sample contains both weathered and unweathered rock; the weathered rock surfaces are partly covered with plants, probably lichens. The color on freshly broken surfaces is light olive grey. It is a very fine-grained, dense rock.

6 Incls

1. Detailed Report
- 2-6. Tables 1 - 5

* At least 0.2 percent, probably not over 1.0 percent.

CORPS OF ENGINEERS, U. S. ARMY WATERWAYS EXPERIMENT STATION		PETROGRAPHIC REPORT ☐ SUMMARY ☒ DETAILED		CONCRETE RESEARCH DIVISION P. O. DRAWER 2131 JACKSON, MISSISSIPPI	
SYMBOL: 6510		PROJECT: Effect of Alkali- Aggregate Reactivity		DATE REPORT SUBMITTED: 16 Sep 1955	
INITIALS: ADP		SOURCES: Attica, Miss. Near Nashville, Tenn. Pickstown, S. Dakota			
SERIAL NO. WES-1 G-5 (1) WES-1 S-4 (3), VICS-3 C-1 (20), VICS-3 S-10 6-1-2 6-2 (9)					

1. Test procedure. Representative portions of each sieve fraction of the Danley limestone and of the natural chert gravel and natural sand were examined and classified using either a stereoscopic or petrographic microscope. Acid and scratch tests were also used as an aid in classification. A number of chert particles were crushed and examined in immersion oil to determine the presence or absence of chalcedony by refractive indices. The fluka quartzite was examined using X-ray diffraction methods. In addition, several thin sections were made of typical quartzite rock; using a point-count technique with the petrographic microscope, fifteen hundred points were examined and classified on a thin section of weathered rock. This process was repeated on a thin section of unweathered rock. These data were used to calculate the composition of the rock.

2. Composition.

a. The coarse and fine aggregates of the Danley limestone are predominantly medium-dark grey, unweathered, dense, fine-grained limestone with lesser amounts of dolomitic limestone, medium-grained limestone, snaly limestone, chert, gypsum, and calcite. Most of the particles are pyramidal in shape; there is a general increase in amount of tabular particles with decreasing particle size. This sample is very similar to other samples of Danley limestone as described in petrographic reports dated 8 September 1950 and 2 August 1955. The only real difference being the coating of limestone dust carried on most of the sand particles of this sample.

b. The natural chert gravel is 99 per cent chert in the 1-1/2-in. - 3/4-in. sizes and 86 per cent chert in the 3/4-in. - No. 4 sizes. The balance of the smaller size range is largely quartz. The chert is of the dense, vuggy, and porous types with the dense chert making up the bulk of it. A small amount of the chert was found to be chalcedonic.

c. The natural sand is yellowish-grey in color and made up almost entirely of quartz, which is either spherical or irregular in shape.

d. The fluka quartzite is a dense, very fine-grained rock, which is made up of quartz and feldspar grains held together by a matrix of opal and clay. The sample contains both weathered and unweathered rock; some of the weathered rock surfaces are partially covered by plants, probably lichens. Two large, highly-fractured, brown calcite concretions were found on weathered surfaces of the rock. The composition of the weathered and unweathered rock, as determined by a point-count technique, is practically

identical. The color on freshly broken surfaces is light olive grey.

3. Description of constituents of the Danley limestone.

a. The fine-grained limestone particles are dark brown to dark grey with smooth surfaces. Tiny dolomite crystals are present in patches in the fine-grained rock or as layers adjacent to it at stylolite contacts in more than one-half of the particles. Stylolites are quite common in this rock.

b. The medium-grained limestone particles are tan to light brown in color, have smooth surfaces, and are largely free of dolomitic areas and stylolites. The rock consists of spherical oolites and angular fine-grained limestone fragments in a matrix of clear calcite. In the finer sand sizes this category was recorded as calcite and fine-grained limestone.

c. The dolomitic limestone was grouped with the fine-grained limestone category in the coarse aggregate. In the sand it was classified as a separate constituent. It ranges in color from light brown to yellowish green; the particle surfaces have a sugary texture.

d. The calcite was derived in part from the matrix of the medium-grained rock and in part from a few random pieces of calcite in the coarse aggregate. Most of the calcite is found as tiny, clear, crystalline rhombs.

e. The miscellaneous group includes chert, cherty limestone, shaly limestone, gypsum, and iron oxides. The chert is light grey in color and partly chalcedonic. The shaly limestone was derived largely from surfaces exposed by the parting of stylolite seams with crushing.

4. Description of constituents of the natural chert gravel and sand.

a. About three-fourths of all the chert is the dense variety. Color is usually some shade of brown; the particle surfaces are smooth; particle shape is blocky to tabular with rounded edges. A small amount of this chert is chalcedonic.*

b. The vuggy chert is brownish in color. The particle surfaces are pitted with depressions of varying sizes, and the particle shape is blocky with rounded edges. Many of these particles are oolitic.

c. The porous chert is usually light in color, tabular in shape, and highly to moderately absorptive.

d. The quartz of the gravel is spherical in shape with a wide range of colors; that of the sand is spherical or irregular in shape, and most of it is the clear type of quartz.

* All 300+ particles in the 3/4- to 1-in. size were inspected; 12 were selected as possibly chalcedonic. A second inspection was made; 6 more were selected. Five of the 12 and 1 of the 6 (total 6 out of 18) showed chalcedony to the extent of 10 percent on the average of the particle. Thus, $6/300 \times 1/10 = 0.2$ percent of the sample has been shown to be chalcedony.

Petrographic Report (concl'd)

e. The miscellaneous group includes feldspar, iron oxides, and various accessory minerals.

5. Description of constituents of the Klufa quartzite.

a. The quartz occurs as clear, spherical grains.

b. The opal is present in the rock as a clear material which binds all the grains of the rock together. Opal is known to contribute to undesirable reactions in concrete which is made with it. Opal composes 14 per cent of both the weathered and unweathered rock.

c. The feldspar is largely plagioclase. The grains are rounded and unaltered.

d. The chert is present as dense, rounded grains.

e. The miscellaneous category includes clay, altered feldspar, clay covered quartz grains, and various accessory detrital minerals. The clay is of the illitic (non-swelling) type; it is the main constituent of this category and is found thoroughly disseminated throughout the rock. In addition, scattered throughout the rock are cavities up to one-half in. in diameter which are partially filled with a pale green, hard, waxlike material. X-ray analysis proves this material to have the same constituents as the host rock. The clay content of this material is much higher than the clay content of the host rock. The feldspar of this category is partially altered to sericitic mica and will eventually become illitic clay.

Table 1

COMPOSITION OF VICKS-3 G-1(20) - DANLEY LIMESTONE

Constituents	In Fractions Retained on Sieves Shown Below(a)					Composition by Size Ranges, Per Cent		
	Per Cent					1-1/2-in. - 3/4-in. 3/4-in. - No. 4		
	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4	1-1/2-in. - 3/4-in.	3/4-in. - No. 4	
Fine-grained Limestone, in Part Dolomitic	79	77	83	89	89	78	87	
Medium-grained Lime- stone	11	15	8	6	7	13	7	
Miscellaneous (b)	10	8	9	5	4	9	6	
Total	100	100	100	100	100	100	100	

Grading of Samples - As Individual Percentages Retained on Sieves Shown Below							
Size Range	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4	Passing No. 4(c)	Total
1-1/2-in. - 3/4-in.	48.5	45.4	3.6	0.7	0.6	1.2	100.0
3/4-in. - No. 4	-	2.2	30.7	26.6	32.3	8.2	100.0

(a) Based on a count of at least 300 particles per sieve fraction.

(b) Made up of chert, cherty limestone, shaly limestone, calcite, and gypsum.

(c) Composition similar to No. 4. Included with No. 4 in calculation of weighted average composition.

Table 2

COMPOSITION OF VICKS-3 MS-10 - DANLEY LIMESTONE

Constituents	In Fractions Retained on Sieves Shown Below(a), Per Cent						In Whole Sample, Per Cent
	No. 8	No. 16	No. 30	No. 50	No. 100	Passing No. 200(b)	
Fine-grained Limestone	56	62	73	76	71	51	37
Dolomitic Limestone	30	21	16	14	24	18	13
Medium-grained Limestone	10	13	9	5	-	-	-
Calcite	-	-	-	-	4	28	50
Miscellaneous(c)	4	4	2	5	1	3	-
Total	100	100	100	100	100	100	100

Grading of Sample - As Individual Percentages Retained on Sieves Shown Below

No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Passing No. 200	Total
6.6	33.6	23.9	15.4	10.5	3.9	6.1	100.0

(a) Based on count of at least 300 particles in each sieve fraction retained on No. 200.

(b) Estimated after examination.

(c) Made up of chert, quartz, shaly limestone, and iron oxides.

Table 3

COMPOSITION OF WES-1G-5(3) - NATURAL CHERT GRAVEL

Constituents	In Fractions Retained on Sieves Shown Below(a)						Composition by Size Ranges, Per Cent			
	Per Cent						1-1/2-in. - 3/4-in. 3/4-in. - No. 4			
	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4		1-1/2-in. - 3/4-in.	3/4-in. - No. 4		
Chert - Dense	73	78	78	75	62		75	68		
Chert - Vuggy	22	16	11	10	3		19	7		
Chert - Porous	4	5	10	13	13		5	11		
Quartz	-	-	-	-	22		-	13		
Miscellaneous	1	1	1	2	-		1	1		
Total	100	100	100	100	100		100	100		

Grading of Samples - As Individual Percentages Retained on Sieves Shown Below									
Size Range	1-1/2-in.	1-in.	3/4-in.	1/2-in.	3/8-in.	No. 4	Passing No. 4(c)	Total	
1-1/2-in. - 3/4-in. 2.0 ^(b)	42.3	45.4	9.5	0.4	0.2	0.2	100.0		
3/4-in. - No. 4	-	3.7	26.1	22.4	43.1	4.7	100.0		

(a) Based on a count of at least 300 particles per sieve fraction.

(b) Included with 1-in. material for calculation of weighted average composition.

(c) Composition assumed to be like that of sand. Included with No. 4 in calculation of weighted average composition.

Table 4

COMPOSITION OF WES-1S-8(3) - NATURAL SAND

Constituents	In Fractions Retained on Sieves Shown Below(a), Per Cent							In Whole Sample, Per Cent
	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	Passing No. 200(b)	
Quartz	22	54	74	93	97	96	90	83
Chert	78	46	26	6	2	3	5	16
Miscellaneous(c)	-	-	-	1	1	1	4	1
Total	100	100	100	100	100	100	100	100

Grading of Sample - As Individual Percentages Retained on Sieves Shown Below

No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Passing No. 200	Total
5.7	14.6	10.8	17.0	36.4	13.3	1.3	0.9	100.0

(a) Based on count of at least 300 particles in each sieve fraction retained on No. 200.

(b) Estimated after examination.

(c) Made up of feldspar, iron oxides, and various accessory detrital minerals.

abundant signs of alkali-aggregate reaction in fairly equal amounts. In addition, it would be expected that the set represented by Beam 1850 would show much more signs of sulfate attack than the set represented by Beam 1823. This examination has shown that the sulfate attack was about as expected, but the amount of attack by alkali-aggregate reaction and the overall condition of the beams were not as expected. The deleterious effects of the reactions that beset Beam 1850 were sufficient to cause its failure after an extremely short exposure time. Beam 1823 showed no deleterious effects from the slight alkali-aggregate reaction seen after identical exposure. The concrete of Beam 1823 appears to be in the same excellent condition at the time of this writing as it was when originally placed at St. Augustine.

17. As previously stated, the only difference in the two beams before their exposure at St. Augustine was that they were made with different cements. The cement used in Beam 1850 is high C_3A while that used in Beam 1823 is low C_3A (Table 4). The individual alkali content of the two varies in the following manner:

	RC-331 (Beam 1823)	RC-332 (Beam 1850)
K_2O	0.23%	0.95%
Na_2O	0.79%	0.37%
Total as Na_2O	0.94%	1.00%

The difference in C_3A content could mean that there is a relationship between sulfate attack and attack by alkali-aggregate reaction; one reaction may act as a catalyst or accelerator to intensify the effects of the other when both are present. The difference in K_2O and Na_2O contents could mean that potash is a much more active alkali in promoting destructive alkali-aggregate reaction.

18. A recent paper by C. E. S. Davis,* writing on the comparison of the effect of soda and potash on expansion in cement-aggregate reaction, states that in general, K_2O caused more rapid reaction and expansion initially, less reaction later, and less total expansion than Na_2O . Table 3 contains some of the results of the mortar bar tests that were made as part of this program. A petrographic examination was made of the original group of alkali mortar bars shown in Table 3. Two of the sets were made with the same combinations of cements and aggregates as the two beams returned from St. Augustine. The results are given in a report dated 5 September 1956. The bars of both sets showed signs of alkali-aggregate reaction. Those made with the materials used in Beam 1850 were in poor condition and showed more evidence of reaction than those of the other set. The latter was in good condition. There was no formation of sulfoaluminate in either set of mortar bars. It should be noted that the condition of the mortar bars and of the beams is strikingly similar. The difference between the two sets of mortar bars was due entirely to alkali-aggregate reaction in the absence of sulfate attack. The majority of the evidence that has been presented, while not conclusive, seems to support the difference in potash and soda contents of the cements as being the proper explanation for the condition of Beams 1850 and 1823.

* Davis, C. E. S., "Studies in cement-aggregate reaction: XXVI, Comparison of the effect of soda and potash on expansion." *Australian Journal of Applied Science*, Vol 9, No. 1, pp 52-62 (1958). An abstract of this paper was carried in the Ceramic Abstracts portion of the *Journal of the American Ceramic Society*, Vol 41, No. 6, p 140 (June 1958).

adhered to the sides of and filled the outer portions of cracks. Tan colloform calcite coated the areas within the tiny circles. The colloform calcite was made up of wedge-shaped crystals in spherulitic arrangement. The calcite-gel mixture formed white, translucent coatings.

Beam 1823

12. This beam, which was made with a high-alkali and low-C₃A cement, was in good physical condition (Photographs 3, 4). There were signs of slight alkali-aggregate reaction but no indication that it has been detrimental to the concrete.

13. Exterior surfaces. The outer surfaces were covered with marine shells. The excellent condition of the concrete was indicated by the following observations:

- a. No disintegration, such as edge or corner rounding, pop-outs or surface pits, was visible.
- b. There was no surface cracking.
- c. The color of the mortar was light gray.
- d. The beam gave a clear ring when struck with a hammer.
- e. The beam was extremely difficult to break into pieces, even when a sledge hammer was used.

14. Interior surfaces.

a. Alkali-aggregate reaction. The evidence of reaction was the presence of a little gel in one void and on the surface of one aggregate particle and the condition of the Klufa quartzite particles. The opaline matrix of a few particles had partially vanished leaving groups of loosely bonded sand grains behind. It was possible to scratch, very slightly, the surfaces of most quartzite particles with a steel needle. Fresh Klufa quartzite, as received in the laboratory, cannot be scratched in this manner.

b. Sulfate attack. The absence of sulfoaluminate crystals indicates that there has been no sulfate attack on this beam.

Portland Cements

15. The results of the XRD examination of the four portland cements are contained in tables 4 and 5. Table 6 contains the results obtained by examination of each cement as a powder immersion mount with a petrographic microscope.

Discussion

16. Consideration of the materials used in these beams and the type of exposure they had would lead one to predict that both sets would show

to its length, and examined with a stereoscopic microscope. Special attention was devoted to the presence of cracks that could be attributed to alkali-aggregate reaction.

5. XRD patterns were made of each of the four cements, using the XRD-30 diffractometer with nickel-filtered copper radiation, 4-degree target angle, 49 KVP, and 16 milliamperes at slow scanning speed. The relative amounts of crystalline C₃A were determined by scaling the 2.70-Å peak of each cement. The apex of the peak was tuned in manually and scaled three times, at each of two locations on each sample surface, and the six values were averaged. The reverter was checked for 95 percent acceptance before and after these peak height determinations; it was adjusted for 93.5 percent acceptance for the background determinations. Background was determined by plotting a straight line through the chart background from 20 to 40 degrees two-theta, and taking the position of the line under the apex of the 2.70-Å peak as the background count.

6. Powder immersion mounts of each cement were examined with a petrographic microscope.

7. Several photographs were made.

Results

Beam 1850

8. This beam, made with a high-alkali and high-C₃A cement, was in poor physical condition. An unusually large and pure sample of alkali-aggregate reaction gel, about 1/2 in. in diameter and 1/8 in. thick, was found on the outer surface of the beam. Table 1 shows results of XRD, chemical analysis, and microscope examination of the gel.

9. The outer surfaces were overgrown with marine shells. Cracks were seen on the surfaces (Photograph 1); the mortar was chalky white rather than gray. Striking the beam with a hammer produced a drummy sound, and the beam was easily broken with a hammer.

10. Table 2 summarizes the evidence on alkali-silica reaction in Beam 1850. Photograph 2 shows interior cracking. Ettringite was very abundant on the surface of many chert particles, lining old cracks, and in many air voids. It did not completely fill the voids as it sometimes does when it is this plentiful. The sulfoaluminate and gel are what produce the white color of the mortar. During the examination of thin sections, one microcrack in the mortar was noted in which sulfoaluminate had plainly been deposited before the accompanying gel. Sulfate attack may have commenced in this volume at least before alkali-aggregate reaction. Most of the microcracks were empty or the sequence of secondary deposition was not clear.

11. Crack sealing materials. Some of the surface cracks were healed (Photograph 1), most commonly by calcite, or by a mixture of gel and calcite. Some of the calcite was light brown or tan and formed as adjoining circles (<1-mm diameter) with tiny vertical walls (<1 mm high). The calcite

Corps of Engineers, USAE	Petrographic Report	P. O. Box 631 Vicksburg, Mississippi															
Project Sea-Water Exposure Tests, Alkali-Aggregate Reactivity		Date June 1958 ADB															
Symbol: 545-6510/71 Serial No.: RC-331, RC-332, RC-333, RC-334, Beam 1850, Beam 1823																	
<u>Samples</u>																	
1. A large group of 6- by 6- by 30-in. concrete beams was installed at the St. Augustine Exposure Station during the Fall of 1955. Two of these beams were returned to the Concrete Division (CD) in November 1957, and stored in the moist room until examination was started in March 1958. Beam No. 1850 (RC-332) was one of a group of six which had shown distress by the time of their first inspection in August 1956. Beam No. 1823 (RC-331) was one of a group of six which showed no distress at that time. 2. The beams were made with the same mixture proportions, using a natural sand (WES-1 S-8(3)) and chert gravel (WES-1 G-5(3)); 5 percent by volume of the gravel was replaced by reactive Klufa quartzite (OM-2 G-2(9)). The two beams differed only in cement as far as intentional variables are concerned. 3. The four portland cements used in this program were examined by X-ray diffraction (XRD) with particular emphasis on crystalline tricalcium aluminate content. Two of the cements (RC-332, RC-334) had previously been examined and the results reported 21 August 1956 in accordance with Memorandum for All Concerned No. 662-D. Sources and serial numbers of the cements are shown below: <table border="1"> <thead> <tr> <th>CD Serial No.</th> <th></th> <th>Type</th> </tr> </thead> <tbody> <tr> <td>RC-331</td> <td>Lone Star Cement Corp., Norfolk, Virginia</td> <td>II</td> </tr> <tr> <td>RC-332</td> <td>Glens Falls Cement Co., Glens Falls, New York</td> <td>I</td> </tr> <tr> <td>RC-333</td> <td>Permanente Cement Corp., Permanente, California</td> <td>II</td> </tr> <tr> <td>RC-334</td> <td>Universal Atlas, Buffington, Indiana</td> <td>I</td> </tr> </tbody> </table>			CD Serial No.		Type	RC-331	Lone Star Cement Corp., Norfolk, Virginia	II	RC-332	Glens Falls Cement Co., Glens Falls, New York	I	RC-333	Permanente Cement Corp., Permanente, California	II	RC-334	Universal Atlas, Buffington, Indiana	I
CD Serial No.		Type															
RC-331	Lone Star Cement Corp., Norfolk, Virginia	II															
RC-332	Glens Falls Cement Co., Glens Falls, New York	I															
RC-333	Permanente Cement Corp., Permanente, California	II															
RC-334	Universal Atlas, Buffington, Indiana	I															
<u>Test Procedure</u>																	
4. Megascopic examination of the beams began immediately after they were removed from the moist room. The exterior appearance and condition of each was noted; the surfaces were examined for cracks, and each beam was struck several times with a hammer to determine its general physical condition. Portions of each beam were broken into pieces and examined with a stereoscopic microscope. Samples of secondary reaction products from the interior and exterior surfaces of Beam 1850 were examined with a petrographic microscope. A large pure sample of alkali-aggregate reaction gel from the surface of Beam 1850 was examined by XRD and a chemical analysis of it was made. Several thin sections were made from each beam and were examined with a petrographic microscope. A sawed surface was cut from each beam, normal																	

Table 2 (Continued)

Cement	RC-331 H1 Alk-Low C3A	RC-332 H1 Alk-H1 C3A	RC-333 Lo Alk-Lo C3A	RC-331 (H1 Alkali - Low C3A) + AD-5(3)	RC-332 (H1 Alk - H1 C3A + AD-5(3))
Aggregate	Natural Gravel + Klufa Quartzite				
Fracture	Bar breaks across most gravel aggre- gate - around most quartzite grains	Bar breaks around most aggregate. Bar easily broken in hand	Bar breaks across larger chert aggre- gate; around smaller aggre- gate.	Bar breaks through and around aggre- gate - pink color due to calcined Monterey shale	Bar breaks through and around aggregate. Pink color due to calcined Monterey shale
Optical Properties of Gel	Not tested	n is between 1.414 - 1.446; amorphous	-	Not tested	Not tested

Table 2

Examinations of Mortar Bars after Tests - Combinations Made With
Reactive Aggregates and Reactive Aggregates and Pozzolans

Cement	RC-331		RC-332		RC-333		RC-331 (H1 Alkali - Low C ₃ A) + AD-5(3)		RC-332 (H1 Alk - H1 C ₃ A + AD-5(3))	
	H1 Alk-Low C ₃ A	H1 Alk-H1 C ₃ A	H1 Alk-H1 C ₃ A	Lo Alk-Lo C ₃ A	Lo Alk-Lo C ₃ A	Lo Alk-Lo C ₃ A	Lo Alk-Lo C ₃ A	+ AD-5(3)	+ AD-5(3)	H1 C ₃ A + AD-5(3)
Aggregate	Natural Gravel + Klufa Quartzite									
Mixture No.	4	7	9	5	6	8				
Expansion at 1 yr, per cent	+0.014	+0.130	Zero	+0.004	+0.020	+0.009				
Warping	None	Minor (1 mm)	None	None	Minor (1 mm)	None				
Cracking	Scattered Micro-cracks	Fine, short, mostly micro- scopic cracks	None	None	None	None				
Surface Condition	A few incipi- ent popouts	Some incipi- ent popouts	As cast	As cast w/few incipi- ent popouts	As cast	As cast				
Sulfoaluminate	None	None	None	None	None	None				
Exterior Gel	Surfaces heavily spotted due to gel liquid - all dry; mostly clear; some white, opaque	Surfaces very heavily spotted due to gel liquid - all dry; mostly clear; some white, opaque	No surface gel present (no reaction)	Surfaces very slightly spotted w/gel	Surfaces heavily spotted with clear and some white gel	Surfaces slightly spotted due to dried gel liquid				
Interior Gel	Some voids partially lined with white gel. Few voids almost filled w/white gel	Many voids lined and partially filled w/white gel	No interior gel present (No reaction)	No interior gel present	Many voids lined and filled w/gel (partially)	Some voids have slight amount of gel lining them				

Job 6510
WIL
31 Aug. 1956

Table
Examinations of Mortar Bars after Test - Combinations Made With
Unreactive and Mildly Reactive Aggregates

Cement	RC-331 (High Alkali - Low C ₃ A)			RC-333 (Low Alkali - Low C ₃ A)		
	Manufactured	Natural	Crushed	Manufactured	Natural	Crushed
Aggregate	Limestone Sand	Quartz-Chert Sand	Chert Gravel	Limestone Sand	Quartz-Chert Sand	Chert Gravel
Mixture No.	1	2	3	10	11	12
Expansion at 1 yr. per cent	+0.008	+0.007	Zero	Zero	+0.002	+0.03
Warping	None	None	None (Bar 5 slight)	None	None	None
Cracking	None	None	None	None	None	None
Surface Condition	As Cast	As Cast	As Cast	As Cast	As Cast	As Cast
Sulfoaluminate	None	None	None	None	None	None
Exterior Gel	Scattered gel spots; both clear, watery liquid and opaque white gel	Scattered gel spots; both clear, watery liquid and opaque white gel. More numerous than in Mixture 1	Few spots of white gel on some (not all) bars	Two gel spots found on bar 6; rest are clean	No surface gel present	No surface gel present
Interior Gel	Gel filled void in Bar 6 next to chert that may not belong to this aggregate. None other found in six bars examined.	Very few voids are partially filled with clear liquid and opaque white gel. Liquid dries to white material.	No interior gel present	Very few voids have thin gel lining	Very few voids have gel lining	No interior gel present
Fracture	Bar breaks through aggregate mostly.	Bar breaks through aggregate mostly.	Bar breaks through aggregate mostly.	Bar breaks through aggregate.	Bar breaks through larger aggregate and around smaller rounded quartz grains.	Bar breaks across most chert pebbles.

SUBJECT: Report of Petrographic Examination of Mortar Bars

was clear, if liquid, and white or clear, if dried. The interior-void gel was always dry and usually a combination of clear and white with the clear material usually in contact with the sides of the voids. The gel from combination 7 is amorphous; its refractive index is between 1.414 - 1.446.

8. The following remarks apply only to the set of bars from combination 7 (high-alkali, high C_3A cement with reactive aggregate):

- a. There was a great deal of alkali-aggregate reaction.
- b. Fine cracks were visible on the surfaces of the bars.
- c. The bars were physically weak and could be broken easily by hand.
- d. Expansion after one year was greater than one-tenth of one per cent.

9. The bars of all combinations except those of No. 7 were essentially in good condition.

2 Incl
Tables 1, 2

CORPS OF ENGINEERS, U. S. ARMY
OFFICE OF THE DIRECTOR
WATERWAYS EXPERIMENT STATION
VICKSBURG, MISSISSIPPI

ADDRESS REPLY TO:
DIRECTOR
WATERWAYS EXPERIMENT STATION
CORPS OF ENGINEERS, U. S. ARMY
VICKSBURG, MISSISSIPPI

REFER TO SYMBOL **WESCI**

5 September 1956

SUBJECT: Report of Petrographic Examination of Mortar Bars

PROJECT: Exposure of Specimens at St. Augustine
(Job 6510, Memo: 662-A)

FROM: A. D. Buck through K. Mather and B. Mather

TO: C. H. Willetts

1. Twelve sets of mortar bars containing the combinations exposed at St. Augustine to determine the effect on alkali-aggregate reactivity of C_3A content have been examined and the results are shown on Tables 1, 2.
2. Six combinations (1, 2, 3, 10, 11, 12) contained aggregates believed to be unreactive or slightly reactive. Table 1 indicates that the high-alkali cement combinations developed a little more reaction than the low-alkali cement combinations.
3. Three combinations (4, 7, 9) contained reactive aggregates, two with high-alkali cements (4, 7) and one with low-alkali cement. The two with high-alkali cement both reacted. The one with low-alkali cement reacted less than any other combination except 12.
4. Three combinations (5, 6, 8) contained reactive aggregate and pozzolan. All three showed some signs of reaction; the two combinations with Monterey shale showed less reaction than the one with fly ash.
5. There was no formation of sulfoaluminate in these bars.
6. Evidence of alkali-aggregate reaction was found in all bars except those of combinations 9 and 12 (low-alkali, low- C_3A cement). The reaction was extremely slight in the bars of the two sets made with low-alkali cement which did react.
7. The evidence for alkali-aggregate reaction was in the form of gel in combinations 1, 2, 3, 10, 11, 6, and 8 and in the form of gel, cracks, and incipient popouts in combinations 4, 5, and 7. The gel was found on the bar surfaces and lining or filling interior voids or both. The surface gel

Table 2

Samples	Methods of Identification				Composition of Sample
	X-ray Diffraction	Petrographic Microscope	Acid Test	Phase Diagram	
RC-216(4)	-	Glass	-	-	Glass > 90%
	Melilite	Melilite	-	Melilite	Melilite
	Calcite	Calcite	Calcite	-	Calcite(a)
	Quartz	Quartz	-	-	Quartz(b)
RC-296	-	Glass	-	-	Glass > 90%
	Calcite	Calcite	Calcite	-	Calcite(a) - Major
	Quartz	Quartz	-	-	Quartz(b) - Minor

(a) Calcite is a common surface alteration product of finely ground quenched slags.

(b) Quartz is a common contaminant of slags.

Table 1

Samples	X-ray Diffraction, Counts per Second	Crystalline C_3A Determined by:	
		Calculation from Chemical Analysis Per Cent	
		Standard Method ^(a)	Swayze's Method ^(b)
RC-332	195	14	9.9
RC-334	100	13	10.2
RC-336(C)	No peak	2.2	2.2
RC-337(C)	125	16.6	5.2
RC-338(C)	150	11.6	10.9
RC-339(C)	130	8.7	8.7
RC-340(C)	215	13.3	12.1
RC-341(C)	190	12.4	8.9
RC-342(C)	200	10.5	4.5
RC-345(C)	130	12.3	7.4

(a) Note 2, Table I, Fed. Spec. SS-C-192a (CRD-C 200-54).

(b) Swayze's Method: $1.276 (\text{Wt of Fe}_2\text{O}_3) = \text{Wt of Al}_2\text{O}_3 \text{ in } C_6A_2F$.
 Total Al_2O_3 - Al_2O_3 in C_6A_2F = residual Al_2O_3 .
 $2.65 (\text{Al}_2\text{O}_3 \text{ residual}) = C_3A$. (Am. Jour. Sci., 244, 1946, p 34).

Petrographic Report (Cont'd) Symbol: 6510 Serial No. RC-332,334,
(CW 603) RC-216(4), RC-296

Date: 21 August 1956

b. Blast-furnace slags. Examination of these two slags (Table 2) indicated that each is essentially identical to previous samples from the same sources. Therefore, there is every reason to expect behavior similar to that of their counterparts in the blended cement and portland blast-furnace slag cement programs. Neither of these slags contains any crystalline C_3A ; no blast-furnace slag made under normal conditions should contain any crystalline C_3A . RC-296 was more efficiently quenched than RC-216(4).

CORPS OF ENGINEERS, U. S. ARMY WATERWAYS EXPERIMENT STATION		PETROGRAPHIC REPORT		CONCRETE RESEARCH DIVISION P. O. DRAWER 2131 JACKSON, MISSISSIPPI	
SYMBOL: 6510 (CW 603)		PROJECT: Sea-water Exposure Tests		DATE REPORT SUBMITTED: 21 AUGUST 1956	
INITIALS: ADB					
SERIAL NO: RC-332, 334; RC-216(4), RC-296		SOURCE: RC-332 - Glens Falls Cement Co.; RC-334 - Univ. Atlas, Buffington, Ind.; RC-216(4) - Birmingham Slag Co.; RC-296 - Southern Cement Co.			

1. Samples. The samples described below have been examined:

Serial No.	Class of Material
RC-332	Type I, high-alkali, high C_3A , portland cement.
RC-334	Type I, low-alkali, high C_3A , portland cement.
RC-216(4)	Water-quenched blast-furnace slag.
RC-296	Water-quenched blast-furnace slag.

2. Test procedure. X-ray diffraction patterns were made of each sample, using the XRD-3D diffractometer with nickel-filtered copper radiation, 4-deg target angle, at 49 Kvp, 16 ma, slow scanning speed. The relative amounts of C_3A in each cement were determined by scaling the 2.70- $\text{\AA}$ peak. The apex of the peak was tuned in manually and scaled three times, at each of three locations on each sample surface, and the nine values averaged. Background was determined by plotting a straight line through the chart background from 20deg to 40 deg 2-theta, and taking the position of the line under the apex of the 2.70- $\text{\AA}$ peak as the background count. The clinkers of the cements in the portland blast-furnace slag cement program were re-examined by this procedure. Values reported in Table 1 are average peak heights minus background. The slag patterns were compared with patterns of slags from the same sources examined previously. In addition, the slags were examined with a petrographic microscope; tests for magnetic materials and for reactions in dilute hydrochloric acid were made. The major oxides, CaO , Al_2O_3 , SiO_2 , and MgO were recomputed to 100 per cent from the chemical analyses, and the recalculated compositions plotted on the appropriate phase diagrams to compare the constituents identified with those expected(1).

3. Results.

a. Portland cements. Table 1 compares crystalline C_3A in these cements and in the PBFSC clinkers, as estimated by diffraction and by calculation from chemical analyses. The difference in amount of crystalline C_3A in RC-332 and RC-334 as determined by the X-ray method is regarded as significant, and it is expected that the behavior of these cements should reflect this difference whenever the crystalline C_3A content is a primary factor in affecting behavior.

(1) E. P. Osborn et al., "Optimum Composition of Blast-Furnace Slag as Deduced from Liquidus Data for the Quaternary System $CaO-MgO-Al_2O_3-SiO_2$," Journal of Metals, pp 3-15, 1954.

Table 5

COMPOSITION OF OM-2G-2(9) - KLUFA QUARTZITE

<u>Constituents</u>	<u>Weathered Rock Per Cent(a)</u>	<u>Unweathered Rock Per Cent(a)</u>
Quartz	70	67
Opal	14	14
Feldspar	7	5
Miscellaneous ^(b)	6	11
Chert	<u>3</u>	<u>3</u>
Total	100	100

(a) Determined by counting 1500 points on a thin section of typical rock using a point-count technique and a petrographic microscope.

(b) Consists of illitic clay, altered feldspar, clay covered quartz, and various accessory detrital minerals.

Table 1

Composition of Alkali-Aggregate Reaction Gel from the Surface of Beam 1850 (a)

Chemical Analysis		Methods of Examination	
	percent	X-Ray Diffraction	Microscope
Moisture loss at 105° C	5.22	Sample was 95 to 98 percent amorphous with a trace of calcite and quartz	Gel was completely amorphous with R.I. between 1.440-1.480. The majority was close to 1.460. A small amount of calcite was identified.
Additional moisture loss at 200° C	3.09		
Additional moisture loss at 300° C	None		
Total moisture loss	8.31		
SiO ₂	85.91		
Na ₂ O	2.41		
K ₂ O	0.60		
CaO	1.25		
Total	98.48		

(a) This was one patch of white, porcelainous to powdery gel of unusual size and purity. The spot was about 1/2 in. in diameter and 1/8 in. thick. The sample was further purified by hand picking under a stereoscopic microscope before the X-ray examination and chemical analysis were made.

Table 2

Results of Examination of Beam 1850

Exterior Cracks	Interior Cracks	Reacted Aggregate	Reaction Rims on Aggregate	Type of Fracture	Reaction Gel	Color of Mortar	Secondary Deposits on Aggregate Particles
Visible cracking seen on top, bottom, and one side of beam. The outer 1/8 to 1/4 in. of these cracks are often healed with a mixture of cal-cite and gel which may contain small amounts of Ca(OH)_2 . The cracks range up to 1 mm in width.	Cracking seen on the outer surfaces continued inside the beam. Minor cracking in some chert particles. No cracks seen that were continuous from mortar to aggregate or vice versa.	No evidence of reaction by fine aggregate or gravel. Much of Klufa quartzite reacted; opaline matrix dissolved leaving a residue of unconsolidated sand grains.	Not observed	Beam broke through the Klufa quartzite but around almost all of the chert particles.	White and porcelainous or clear. Found on beam surfaces and in voids on chert aggregate surfaces, saturating cement paste, and sealing surface cracks. Two types of interior gel distinguished with a petrographic microscope, one clear and amorphous with R.I. between 1.480-1.500; the other very slightly crystalline, has low birefringence and sweeping extinction with R.I. between 1.460-1.544, light tan in plane light.	No color gradation adjacent to cracks, the entire surface is white showing extensive reaction.	Ca(OH)_2 , sulfoaluminate crystals, and gel on surfaces of many chert particles.

Table 3

Partial Results of the Mortar Bar Test for Potential Alkali-Aggregate Reactivity

Cement	Aggregate (a)	Average Set Expansion, percent				
		8 day	28 day	84 day	196 day	364 day
RC-332, Hi Alk, Hi C ₃ A	Natural gravel + Klufa quartzite	0.012	0.022	0.069	0.120	0.130
RC-331, Hi Alk, Lo C ₃ A	Natural gravel + Klufa quartzite	0.001	0.004	0.011	0.010	0.014
RC-333, Lo Alk, Lo C ₃ A	Natural gravel + Klufa quartzite	0.001	-0.003	-0.002	-0.004	0.000
Additional Test Data Developed Due to Results Shown Above by RC-332 + RC-331						
RC-332	Same as above	0.010	0.028	0.070	0.105	0.109
RC-331	Same as above	0.001	0.014	0.025	0.054	0.063
RC-332	Pyrex glass	0.161	0.288	0.298	0.311	0.320
RC-331	Pyrex glass	0.075	0.257	0.321	0.344	0.358
Partial Results of the Lerch Mortar Bar Test for Potential Sulfate Resistance						
RC-334, Lo Alk, Hi C ₃ A	Standard Ottawa sand	0.054	0.142	0.354	1.762	1.772
RC-332, Hi Alk, Hi C ₃ A	Standard Ottawa sand	0.051	0.124	0.346	0.348	0.354
RC-331, Hi Alk, Lo C ₃ A	Standard Ottawa sand	0.024	0.047	0.073	0.094	0.108
RC-333, Lo Alk, Lo C ₃ A	Standard Ottawa sand	0.013	0.025	0.036	0.044	0.056

(a) Five percent of the gravel, by weight, was replaced by quartzite.

Table 4
C₃A in Four Portland Cements

CD Serial No.	C ₃ A Calculated from Chemical Analysis	X-Ray Intensity, counts/second on 2.70-A Peak	Peak Location, in Angstrom Units
RC-332	14.2%	310 ^(a)	2.704
RC-331	5.4%	235	2.710 ^(b)
RC-334	13.4%	205 ^(a)	2.699
RC-333	4.4%	Not detected	

- (a) The ratio of 310/205 is about 3:2. The values given in the previous report were 195/100, or about 4:2. The change in intensity values is due largely to changes made in the equipment during the interim. The agreement between the two ratios is considered quite satisfactory.
- (b) This is two peaks, one at 2.704 due to C₃A, one at 2.720 is a substituted calcium silicate. The 2.704 peak is stronger than the 2.699 peak of RC-334.

Table 5

Calcium Sulfates in Four Portland Cements

CD Serial No.	SO ₃ Content, by Chemical Analysis	Calcium Sulfates by X-Ray Diffraction		
		Gypsum (a) (CaSO ₄ · 2H ₂ O)	Hemihydrate of Gypsum (b) (CaSO ₄ · 0.5H ₂ O)	Anhydrite (a) (CaSO ₄)
RC-331	1.95%	Not detectable	Not detectable	Not detectable
RC-332	2.11%	Not detectable	Not detectable	Not detectable
RC-333	2.13%	Not detectable	Not detectable	Definitely identified
RC-334	2.14%	Not detectable	Not detectable	May be present

(a) Experience has indicated that these materials may be identified when they are present in amounts as small as 1 to 2 percent.

(b) A larger amount of this material is necessary for recognition than for either of the other two. It has not been definitely identified in any portland cements examined by this laboratory.

Table 6

Data on Calcium Silicates Obtained by Microscope Examination of Four Portland Cements

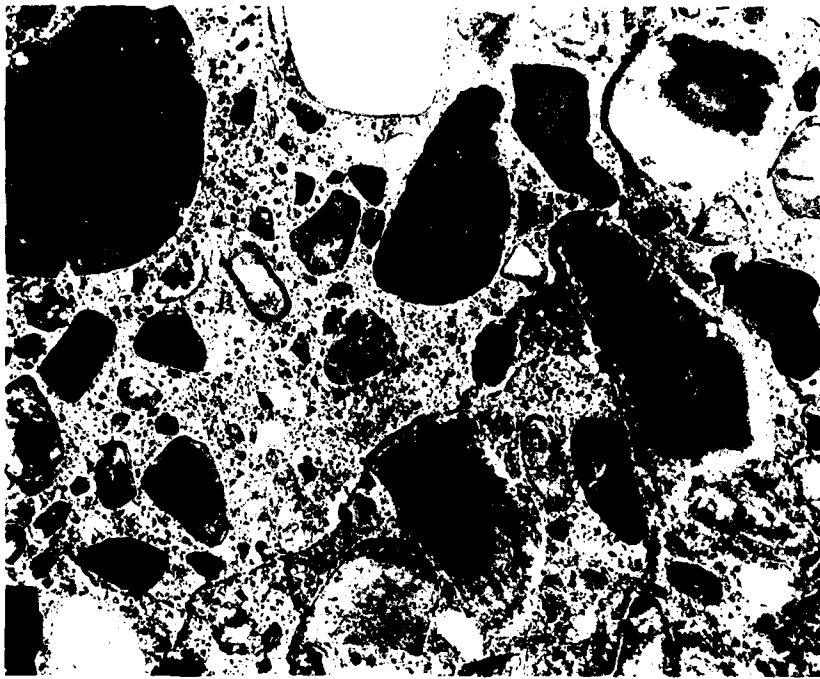
Cement	Belite Phase		Estimated Ranking of Cements by C ₂ S Content	Alite Phase	
	Average Crystal Size, Longest Diameter (a)	Maximum Crystal Size, Longest Diameter		Average Crystal Size, Longest Diameter (a)	Maximum Crystal Size, Longest Diameter
RC-331	40 microns	40 microns	First	20 microns	52 microns
RC-332	Not determined	50 microns	Fourth	40 microns	62 microns
RC-333	40 microns	50 microns	First	20 microns	70 microns
RC-334	<20 microns	20 microns	Third	20 microns	46 microns

(a) Value was estimated after several grains had been measured.



Outer surface of Beam 1850 (X1.5) showing cracks and marine shells. Some of the healed cracks are shown by the inked lines.

Photograph 1



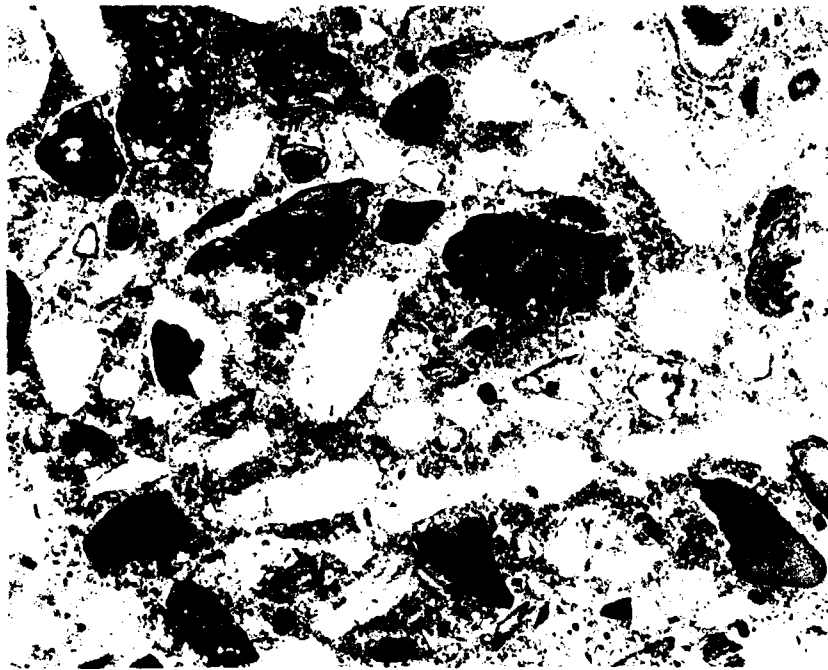
Sawed surface of Beam 1850 (X1.5) showing internal cracks.

Photograph 2



Outer surface of Beam 1823 (X1.5) showing marine shells. Note absence of cracks.

Photograph 3



Sawed surface of Beam 1823 (X1.5). Note absence of internal cracking.

Photograph 4

CORPS OF ENGINEERS, U. S. ARMY
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REFER TO SYMBOL WESCI

14 May 1957

MEMORANDUM FOR THE FILES:

SUBJECT: E-Series Columns, St. Augustine, Florida

1. Attached is a petrographic report dated 10 May 1957 giving data on and results of examination of three columns as follows:

Column	Year "Failed"	Cement		Concrete	
		Na ₂ O Eq., %	Calculated C ₃ A, %	Color of Mortar	Evidence of Deterioration
E-6-H	1950	0.60	4.6	Gray	None
E-9-H	1950	0.53	4.6	Gray	None
E-32-H	1948	1.02	13.6	Yellowish	Large amount of sulfoaluminate, abundant alkali- reaction gel

2. The significance of these findings is:

a. Only the concrete made with the high-alkali, high-C₃A cement shows evidence of deteriorative processes that led to failure; the other two "failed" specimens may represent breakage due to handling.

b. The examination of E-32-H provides one of the first examples of distinct alkali-aggregate reaction involving the natural aggregate from Long Island, New York; and also is an example of concurrent alkali-aggregate reaction and sulfate attack deterioration.

3. It is recommended that these findings be cited in:

a. The next general report on natural weathering in the series of which TM 6-226 (Report No. 5), May 1954, is the latest.

b. In the report of the investigation now in progress, "Exposure of Specimens at St. Augustine, Florida" (Memo. No. 662).

Incl
Form 557

Bryant Mather

BRYANT MATHER, Chief
Special Investigations Branch
Concrete Division

Incl 5

CORPS OF ENGINEERS, U. S. ARMY WATERWAYS EXPERIMENT STATION		PETROGRAPHIC REPORT		CONCRETE RESEARCH DIVISION P. O. DRAWER 2131 JACKSON, MISSISSIPPI	
SYMBOL: 6510		PROJECT: Sea-water Exposure Tests		DATE REPORT SUBMITTED: 10 May 1957	
INITIALS: ADB, WIL					
SERIAL NO: E-6-H, E-9-H, E-32-H		SOURCE: E-Series Columns St. Augustine, Florida			

1. Samples. Three 6-in. by 6-in. by 48-in. concrete columns from the series made as part of the Cement Durability Program,⁽¹⁾ which had failed during sea-water exposure tests at St. Augustine, Florida, were returned to the laboratory in August of 1956 for examination. The examination was conducted to determine, if possible, why the columns had failed, and any unusual features which might be noted. The columns were identified as E-6-H, E-9-H, and E-32-H. Each column contained a different cement; each cement was represented at the exposure station by a set of three columns. The same mixture proportions, and coarse and fine aggregate from one source, were used in all the concrete, so that the only variable under test was the cement. The mixture proportions used in making these specimens were as follows:

Cement	Proportions by Wt			w/c gal/ bag	C. P. bag, cu yd	Nominal Slump, in.
	Fine Aggregate	Coarse Aggregate 1 2-in. - No. 4	1-in. - 1/2-in.			
1	2.53	1.80	2.71	6.0	5.1	2

The specimens were made during the summer of 1940 and placed at the exposure station in early October of that year. The following table gives a summary of the durability factors for the sets concerned during the years 1940-1956.⁽²⁾

Table 1

Column	DFE						
	Year						
	1942	1946	1948	1950	1952	1954	1956
E-6-E	114	119	120	121	115	118	116
*E-6-H	115	122	111	Failed	-	-	-
E-6-K	112	126	123	120	119	114	120
E-9-E	114	122	Broken in Handling	-	-	-	-
*E-9-H	117	131	105	Failed	-	-	-
E-9-K	113	121	127	118	117	114	112
E-32-E	124	125	Failed	-	-	-	-
*E-32-H	127	126	Failed	-	-	-	-
E-32-K	127	128	Failed	-	-	-	-

(1) First Interim Report, Cement Durability Program, June 1942.

(2) Taken from Table 3 of Report No. 5, Technical Memorandum 6-266 and from unpublished data.

10 May 1957

Serial No.: E-6-H

E-9-H,

E-32-H

Some data for the cements that were used is shown in the following table:

Table 2

Cement Serial No.	Clinker Serial No.	Type Based on Existing Federal Speci- fications in 1942	Total Alkali Content, Expressed as Na ₂ O, %	C ₃ A Content, %	
				Calculated from the Chemical Analysis	Determined by Micrometric Analysis of Clinker
E-6(RC-6)	E-6	II, plain	0.60	4.6	0.1
E-9(RC-9)	E-9	II, plain	0.53	4.6	0.3
E-32(RC-29) - (a)		I, air-entraining	1.62	13.6	-(a)

(a) No E-32 clinker was sampled.

2. Test Procedure. The condition and appearance of the specimens were observed. The ring produced by striking the concrete with a hammer was observed. The toughness of the concrete was checked by using a hammer to break up portions of each specimen. Since the outer surfaces were covered with shells, etc., from the sea, the detailed examination was made on concrete from the interior of each column. Fresh broken and saved surfaces of each specimen were examined using a stereoscopic microscope. A saw cut was made normal to the length of each column about six inches from the end; a series of adjoining thin sections were then made across the mid-portion of each surface from one side to the other. A petrographic microscope was used to examine these sections and to check reaction products found in the concrete. The companion surface to each of those from which the thin sections were made was examined at 45X and at 60X with a stereoscopic microscope for the presence of microcracks. A point-count technique with a 3/8-in. point spacing was used. A General Electric XRD-3 diffractometer employing nickel-filtered copper radiation at 49 kilovolts and 16 milliamperes was used to obtain diffraction patterns of the clinkers of E-6 and E-9 and of the mortar from column E-32-H.

3. Results.

a. General Statement. Examination of column E-32-H indicates that it is entirely reasonable and to be expected that it and the remainder of the set failed during test. The failure was due to the damage suffered through the mechanism of alkali-aggregate reaction and the formation of excessive amounts of calcium sulfoaluminate. On the other hand, examination of columns E-6-H and E-9-H has revealed no obvious reason or reasons for

10 May 1957

Serial No.: E-6-H,
E-9-H,
E-32-H

their failure. These columns would still be in Florida undergoing test were it not for the single break in each which was responsible for their return to the laboratory.

b. General Observations.

(1) The mortar of column E-6-H and of E-9-H is medium gray in color; there is no sign of alkali-aggregate reaction; some calcium sulfoaluminate is present in voids and also may be found occasionally where mortar and aggregate meet. The concrete appears to be in good condition.

(2) The mortar of column E-32-H is very, very light yellowish gray in color. This color is probably associated with secondary reactions, but it may be due to the color of the cement itself. There is a large amount of calcium sulfoaluminate in this specimen; it is found in voids and in aggregate sockets or on aggregate surfaces. Alkali-reaction gel is abundant in voids, on aggregate surfaces, and in mortar. The concrete of this specimen is not in as good condition as the concrete in E-6 and E-9.

(3) Examination of the thin sections gave results consistent with the observations made with the stereoscopic microscope. In addition, the sections showed that the depth of carbonation of the concrete surfaces was less than one-half inch.

(4) There are essentially no cracks, large or small, in the interiors of specimens E-6-H and E-9-H. The debris and shells on the outer surfaces made it impossible to examine them for cracking with any success.

(5) No unusual features were present in the X-ray patterns of clinkers E-6 and E-9. The amount of crystalline C_3A in each of these two clinkers appears to be below five per cent; this was determined by using the X-ray method reported in Miscellaneous Paper No. 6-201, March 1957. These results are in good agreement with those shown in Table 2 of this report. No sample of the cement or clinker of E-32 was available for study. The pattern of the mortar of E-32-H confirmed the findings which had been made by visual and microscopic examination of it.

Corps of Engineers, USAE Waterways Experiment Station	Petrographic Report	Concrete Division P. O. Drawer 2131 Jackson, Mississippi
Project Sea Water Exposure, Alkali-Aggregate Reactivity	Date About September 1966 AB, BA	
<u>Sample</u> 1. One 6- by 6- by 30-in. concrete beam described below was examined as directed by Memorandum for All Concerned No. 662. 2. The beam was installed at the St. Augustine Exposure Station during August 1955. It failed in 1964 and was received at the Concrete Division (CD) for examination in August 1966. The beam identification number was either 1926 or 1928, but positive identification was impossible due to the presence of numerous marine shells covering the entire surface of the beam. Beams 1926 and 1928 were two of a group of nine beams made to the same mixture proportions using high-alkali and high-C₃A cement (RC-332), natural sand (WES-1 S-8(3)), natural gravel (WES-1 G-5(3)) containing 5 percent Klufa quartzite (OM-2 G-2(9)) and 20 percent fly ash as a cement replacement material. The cement factor of this set was between 4.5 and 5.8 bags/ yd³, water/cement ratio was 0.5 by weight, air content was 5.0 ± 0.5 percent, and the slump was 2-1/2 ± 1/2 in. Six of the beams were sent to the St. Augustine Exposure Station and three stored out-of-doors at the CD. <u>Test Procedure</u> 3. The surface of the beam was examined for cracks and struck several times with a hammer. A photograph was taken to show the effects of reactions. The beam was broken and portions of it were examined with a stereomicroscope. 4. The beam was sawed normal to its length to expose a fresh surface and several thin sections were made from this surface. Special attention was devoted to cracks and possible alkali-aggregate reaction in selecting areas for thin sections. The thin sections were examined with a petrographic microscope on a comparative basis with sections already made from Beams 1850 and 1823. Beam 1850 had shown heavy alkali-aggregate reaction and sulfate attack while Beam 1823 had shown only slight alkali-aggregate reaction when examined in November 1957. Beam 1850 differed from Beam 1926 or 1928 in that it did not have fly ash as a cement replacement material. Beam 1823 was made with a different cement and contained no fly ash. 5. The beam, 1926 or 1928, was also compared with Beams 1924, 1927, and 1930 which have the same mixture proportions. These three beams were installed outdoors at the Concrete Laboratory during September 1955. The beams were compared by visual appearance and by determination of relative E. <u>Results</u> 6. This beam, made with a high-alkali and high-C₃A cement (RC-332), was in poor physical condition as a result of alkali-silica reaction and probable sulfate attack.		

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WES FORM No.
Rev Feb 1970 1115

7. The center of the beam was deeply and severely cracked around all four sides and had lesser cracks around all four sides at one end of the beam. The cracks perpendicular to the centerline of the beam were connected by lesser cracks running parallel to the length of the beam.

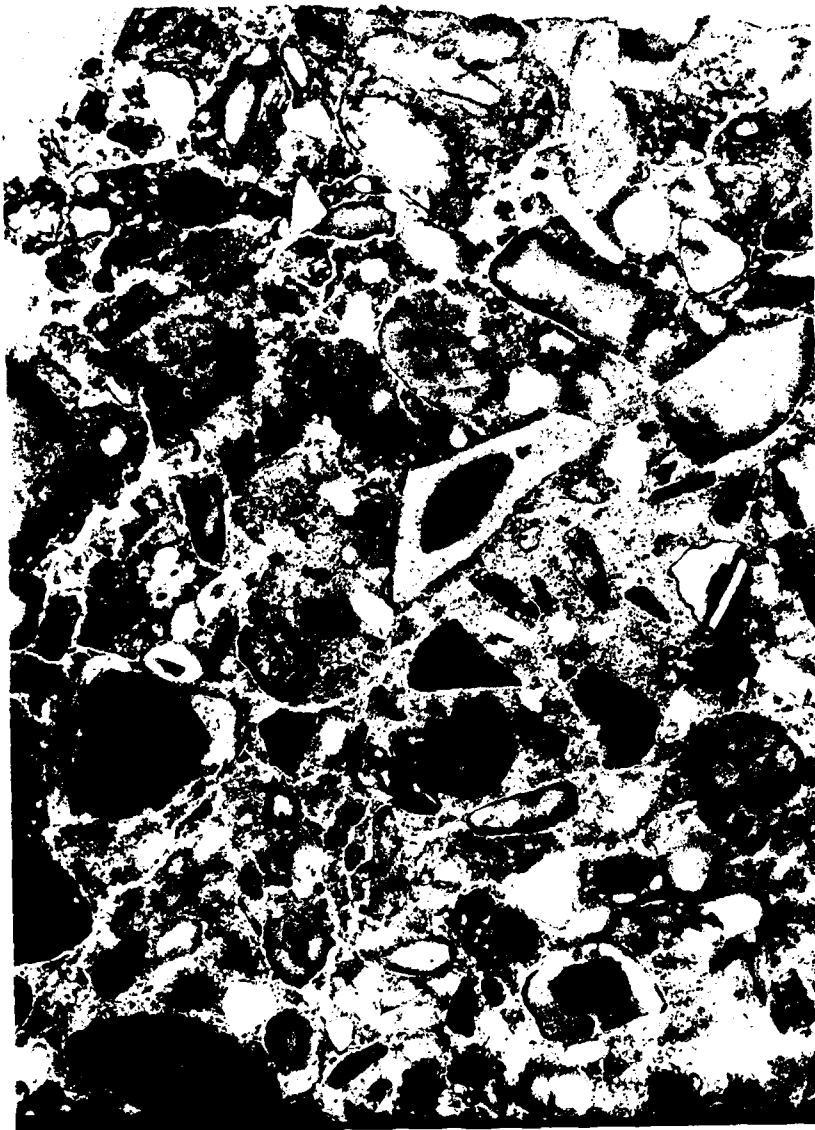
8. The beam was broken in the center where the most severe cracking had occurred. The beam had been penetrated nearly to its center by sea water and had a dark yellowish green color like the outer surface of the beam. A white and powdery reaction product was quite evident around the aggregate particles and in lesser amounts on the surface of the mortar. One reaction product and possibly two were confirmed under the stereomicroscope.

9. Freshly sawed surfaces of the beam revealed numerous fine cracks throughout the beam which generally propagated from aggregate particles which had been subjected to alkali-aggregate reaction. The reaction was especially noticeable in the reactive quartzite particles where the opal cementing agent had been dissolved leaving individual quartz particles loose or in a spongy mass. Photograph 1 shows three reacted quartzite particles where the core of the particles was unaffected. Other signs of reaction included the obvious expansion of the beam, gel found in cracks and other voids, and the reaction products on the surface of many chert particles.

Summary

10. Consideration of the materials used in this beam and of the type exposure it had been subjected to would lead one to predict that alkali-silica reaction was to be expected. It would also be expected that sulfate attack through the medium of sea water would occur.

11. The other three beams of this set, exposed outdoors at the Jackson, Mississippi, Suboffice showed no signs of distress except for a very fine crack on one end of Beam 1927. The crack obviously was so small that it did not affect its 1966 percent E reading which was 100, or else the cracking occurred after the reading had taken place. The crack in Beam 1927 may be the beginning of alkali-silica reaction proceeding slowly as would be expected without the aid of sulfate attack and with only occasional and limited amounts of water.



Sawed surface of Specimen 1926 or 1928, X1. Note the many cracks which are visible; many of these are filled with secondary deposits. Three reacted quartzite particles are marked with an X; these particles illustrate cases where the core of the particles was unaffected by the reaction

Photograph 1

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