TIME EFFECT OF ALKALI-AGGREGATE REACTION ON PERFORMANCE OF CONCRETE

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ABSTRACT: This paper presents a continuation of the findings of a long-time study of the performance of cements varying in their chemical and physical characteristics. Most of the cements were provided by the Portland Cement Association, and others were obtained form a local manufacturer. The study was initiated in 1940 by the Portland Cement Association in collaboration with the U.S. Bureau of Reclamation. The 28 cement types studied varied in chemical and physical characteristics and were used in the construction of the parapet wall located at Green Mountain Dam. Each of the 28 cements was used in 3 or 4 of the 104 panels of the parapet wall. The Green Mountain Dam is located on the Blue River, a tributary of the Colorado River, 21 km southeast of Kremmling, Colo. The dam itself is an earth-fill structure, 94 m high, with a crest length of 350 m. Some of the cements used were high-alkali cements, and the aggregates contained reactive silica. This paper investigates the development of alkali-aggregate reaction during the past 53 years on the parapet wall and its impact on strength and durability of concrete. Specifically, the results of a visual inspection and compressive strength are presented as a function of the amount of equivalent alkalis present in these different cements for the years 1943, 1946, and 1997.

INTRODUCTION

Studying the time effect of deterioration on the performance of structures is important because much of the nation's essential infrastructure is aging (Rens 1994; Rens et al. 1997). Some of the production standards of cements used in the construction of many of these existing infrastructures were different from today's cement manufacturing standards. For example, present day cements are produced generally with higher degrees of fineness. However, all the cements investigated in this paper meet the current ASTM general and optional requirements as specified in C 150-96 (ASTM 1996). Studying the performance characteristics of these cement types is essential because they were used in structures that are still in service. The adequacy of structural performance of these infrastructures needs to be assessed in the light of the current properties of their concrete. Many parameters need to be investigated to assess the quality and current condition of the concrete of an aging infrastructure. These parameters include, but are not limited to, chemical constituents, degree of cement hydration, aggregate type, and environmental conditions. The alkali-aggregate reaction phenomenon discussed in this paper is the cause of considerable damage to concrete structures built during the late 1920s to early 1940s. The damage was the result of cracking throughout the concrete, manifested at the surface as extensive map cracking or pattern cracking or surface popouts and spalling. Such problems were confined mostly to certain regions of the country.

BACKGROUND OF STUDY

The effect of variation in physical and chemical characteristics of cements with respect to early compressive strength was discussed in Mohamed et al. (2000). In this paper, the variation of compressive strength of parapet wall panels in the first 2 years and the current 50-year-old compressive strengths are related to the amounts of equivalent alkalis. The wall panels were built with 28 different cements. These cements belonged to one (or more) of the five ASTM cement types shown in Appendix I.

Construction, Inspection, and Testing History

The parapet wall, which was constructed in the 1940s, consists of 104 panels. Fig. 1 shows a general view of the parapet wall. Each panel is approximately 2.74 m long $\times$ 1.22 m tall $\times$ 0.41 m thick (1 m = 3.28 ft). Data presented in this paper were obtained from testing of the cement, aggregate, and concrete used in the construction of the parapet wall at the Green

FIG. 1. Overall View of Wall Panels (Facing South)

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Note. Associate Editor: David Lange. Discussion open until September 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on February 10, 1998; revised September 27, 1999. This paper is part of the ***Journal of Materials in Civil Engineering***, Vol. 13, No. 2, March/April, 2001. ©ASCE, ISSN 0899-1561/01/0002-0143–0151/$8.00 + $.50 per page. Paper No. 17650.

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Mountain Dam, Colo., in the 1940s. Concrete materials used in the construction of the parapet wall were tested prior to the construction to determine their physical and chemical characteristics. Test results are included in the Materials Laboratory Report No. C-345 of the U.S. Bureau of Reclamation (USBR) (Douglass et al. 1947). The wall was visually inspected in October 1943, May and September 1944, June 1945, and June 1946. Several other tests were performed on test cylinders and on different sizes of reinforcing bars at the USBR between May 1943 and June 1946. No additional documented inspections were made until June 1997 when the wall was more comprehensively inspected. The 1997 investigation included visual inspection, destructive testing of cores obtained from the wall, ultrasonic nondestructive testing of both the wall and the cores, and petrographic examinations.

Testing

The objective of this paper is to investigate the development and long-term effect of alkali-aggregate reaction and its impact on concrete compressive strength. This paper also discusses some suspected aggregate constituents with regard to their contribution to alkali-aggregate reaction. The conclusions derived reflect the current condition of the concrete after >50 years. The following sections briefly introduce some of the tests conducted in 1943, 1946, and 1997.

Visual Inspection

Visual inspection is one of the most important and cost-effective methods to observe signs of distress (Pepper 1979). The wall was visually inspected several times between 1943 and 1946. The results of visual inspection in the first 3 years of the construction show pattern cracking in panels (e.g., 43-1) that can be attributed to alkali-aggregate reaction. Most panels remained in good condition.

ANALYSIS OF TEST RESULTS

The following sections provide details of the petrographic examination, visual inspection, and compressive strength test results.

Petrographic Examination and Alkali Reactivity of Aggregate

During the 1940s petrographic study, the aggregates used in the construction of the parapet wall were examined with hand lenses and segregated into consistent lithological groups. A detailed geologic description is included in the Douglass et al. report (1947) and is summarized in Table 1. Some of the groups were studied in detail by means of thin sections and a petrographic microscope, a device to observe the microstructure of the aggregate. The coarse sands were examined under a wide-field microscope, and the fine sands were studied in detail by means of grain mounts under the petrographic microscope. No segregation of the constituents of the sand was attempted by the petrographer. The results (given as percentage of rock type) of the petrographic analyses of different size ranges are shown in Table 1. The size ranges covered are typical of the size ranges of aggregate used in the construction of the wall. The segregations designated as diorites and diorite porphyries, andesites, thyolites, tuffs, and chalcedonic rocks are lithologically similar to rock types that previous field and laboratory experience has shown to be susceptible to attack by alkalis in cement (Douglass et al. 1947). Table 1 shows that tuffs and chalcedonic rocks comprise a very small proportion of the gravel but the other suspected rock types are significantly abundant. Therefore, the segregations made during the petrographic analyses could be crushed for use as aggregates in a mortar bar testing program with high-alkali and low-alkali cements. The segregation designated as andesites contain two types of andesites. One is closely related to the albitized diorite porphyries but contains a smaller proportion of phenocrysts and is considerably finer in grain. This type may be classified as andesite porphyries. The second type of andesite is gray to buff in color. To test alkali reactivity and the expansion potential of aggregates, segregations of andesites, diorites and diorite porphyries, and rhyolites were made during the examination of the coarse aggregate.

These minerals were crushed to make sand from which, together with crushed quartz, bars ($2.5 \times 2.5 \times 25$ cm) were fabricated with high-alkali (No. 2742) and low-alkali (No. 2735) cements. The segregations were used in various percentages with the crushed quartz to make sure that they were included in the ‘‘pessimum’’ quantity. The bars were cured at 55°C in sealed containers. As portrayed in Fig. 2, all these segregated materials expanded with high-alkali cement, in all percentages. A pessimum quantity was indicated with diorite and rhyolite. Rhyolite was not tested for reaction with low-alkali cement because there was a limited amount after it had been tested for reaction with high-alkali cements. However neither andesite nor diorite and diorite porphyries expanded with low-alkali cement.

Further testing for reactivity of the wall aggregate was performed on $5 \times 5 \times 25$ cm bars. Table 2 shows the expansion test results. Three different combinations wee used: (1) sand

TABLE 1. Petrographic Analyses of Aggregate (Douglass et al. 1947)

Rock type (1)	Percentage by Weight: 1-1/2 to 3/4 in. (2)	3/4 to 3/8 in. (3)	3/8 in. to No. 4 (4)	Description of rock types (5)
Granitic rock	36	36.8	28.4	Slightly to moderate weathered, fine to coarse grained granites
Gneisses and schists	39.4	42.6	48.7	Slightly to moderately weathered, fine to coarse grained, some quartzites
Diorites and diorite porphyries	10	6.8	13.7	Slightly to moderately weathered, fine grained to aphanitic massive to porphyritic
Rhylites	1.1	1.5	0.9	Slightly to moderately weathered, aphanitic, gray to buff, massive to porphyritic
Andesites	10.2	8	4.4	Slightly to moderately weathered, aphanitic, gray to buff, porphyritic
Basalts	2.1	2.7	1	Slightly to moderately weathered, aphanitic, black, dense to vesicular
Tuffs	0.3	0.2	0.3	Soft, porous, massive, light colored, acidic
Sandstones	0.8	1.2	1.6	Hard, quartzose, massive, fine to medium grained
Shales	—	—	0.8	Soft, platy, dark buff, silty shales
Coal	0.1	—	—	Soft, friable, black, massive
Chalcedonic rocks	—	0.2	0.2	Very hard, massive, silicified volcanics

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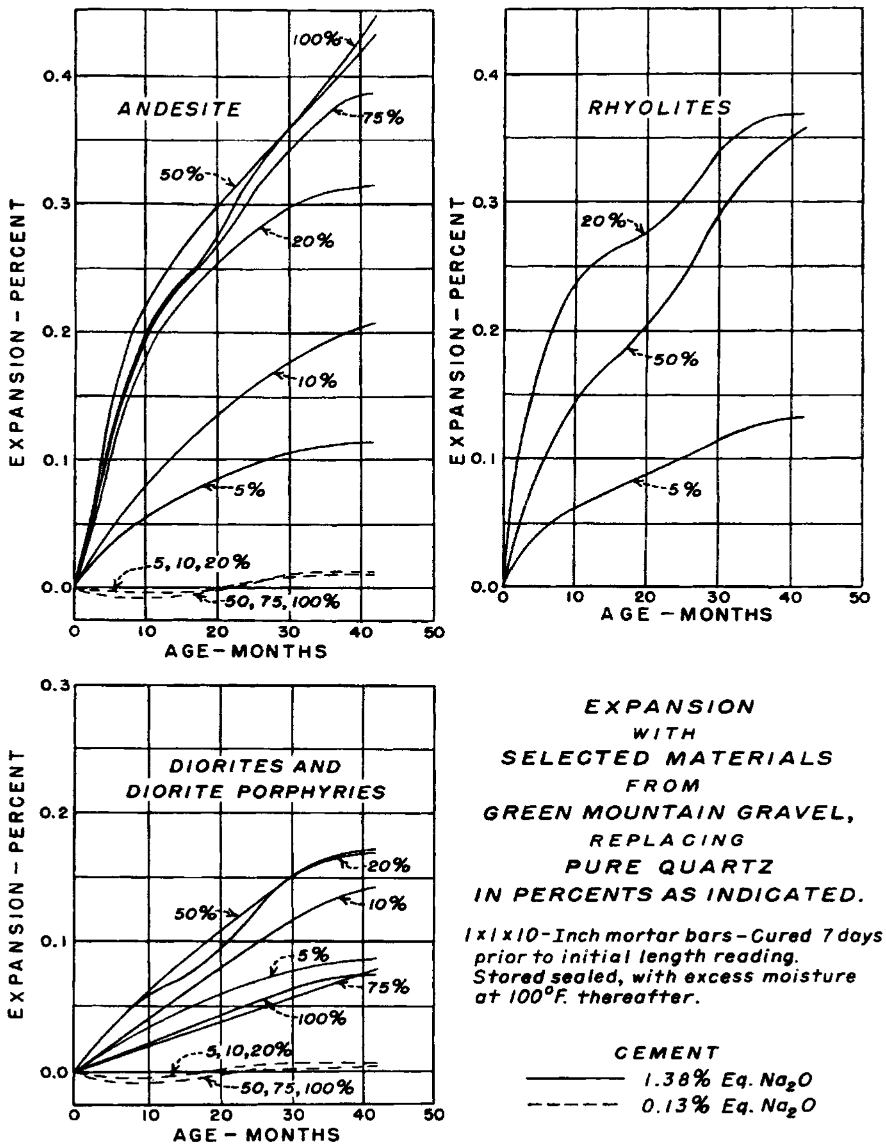

FIG. 2. **Reaction of Suspected Aggregate Segregations with Low- and High-Alkali Cements (Douglass et al. 1947)**

with natural grading; (2) gravel crushed to sand sizes and used in straight grading; and (3) 37% sand with 63% crushed gravel mixture. All three aggregate combinations were used with five different cements, namely, high alkali (No. 2742), low alkali (No. 2735), medium-high alkali (No. 2754), sulfate-resisting type of high-alkali content, and reasonably low alkali (No. 4500). These chemical constituents of the cements used for the expansion tests are shown in Table 3.

Table 2 shows that the sand with high-alkali cement had expanded 0.121% at 6 months and the expansion reached 0.359% at 42 months and the length increase was continuing. The sand with medium-high–alkali cement expanded by 0.066% at 42 months and the expansion was also continuing. The other two aggregate combinations showed the same trend in expansion but were less significant than the sand.

The above tests on the wall aggregate, performed in 1947, led to the tentative conclusion that these aggregates were reactive. The impact of their reactivity was studied in conjunction with the visual inspection results as well as the time variation in compressive strength, as discussed in the following sections. Note that the above indications have resulted from accelerated tests only; i.e., when the specimens were cured at elevated temperature (100°F) under sealed moist storage. An additional experiment was performed with the 28 cements in which 7.5 × 7.5 × 38 cm bars were stored in moist cabinets held at 39°C for a period of 36 months. No significant expansions were registered with any of the 28 cements.

Visual Inspection

Table 4 shows three of the visual inspection results of the 11 selected panels. The panels were selected on the basis of the alkali content to cover three ranges, namely, low-alkali, medium-high–alkali, and high-alkali cements. Low-alkali cement contained equivalent alkalis <0.6%, as described in ASTM C 150-96. For the purpose of this study, cements that contained total equivalent alkalis greater than or equal to 0.6% and less than or equal to 1.0% were classified as medium-high–alkali cements. Cements containing equivalent alkalis >1.0% were considered high-alkali cements. For most panels, remarkable changes took place on the downstream face of the panel. Therefore, only changes in the downstream face of the wall are reported here.

The visual inspection results of selected panels are discussed in the following sections. The designations for these panels are shown in Appendix I. The definitions of the visual inspection terminology are presented in Appendix II.

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TABLE 2. Percent Expansion of Parapet Wall Aggregate with Various Cement Types (Douglass et al. 1947)

Aggregate (1)	Cement laboratory No. (2)	Na_2O + 0.658 K_2O (3)	AGE: Days 7 (4)	Months 1 (5)	2 (6)	3 (7)	4 (8)	5 (9)	6 (10)	8 (11)	12 (12)	18 (13)	24 (14)	30 (15)	36 (16)	42 (17)
Sand	2742	1.42	0	0.013	0.02	0.044	0.069	0.097	0.121	0.144	0.183	0.238	0.288	0.312	0.341	0.359
	2735	0.18	0	0	−0.003	−0.003	−0.001	0	0	−0.002	0.001	0.006	0.018	0.011	0.017	0.011
	2754	0.89	0	−0.003	0.004	0.005	0.007	0.012	0.014	0.014	0.025	0.046	0.038	0.061	0.059	0.066
	MS	0.92	0	−0.006	−0.002	−0.002	0.001	0.003	0.003	0.002	0.003	0.007	0.001	0.015	0.012	0.014
	4500	0.63	0	−0.006	−0.002	−0.001	0.002	0.003	0.003	0.002	0.002	0.004	0.001	0.011	0.01	0.011
Gravel 1-1/2″	2742	1.42	0	0.004	0.017	0.028	0.047	0.07	0.094	0.117	0.148	0.184	0.19	0.22	0.221	0.221
maximum	2735	0.18	0	−0.009	−0.011	−0.017	−0.006	−0.009	−0.006	−0.011	−0.037	−0.007	0.005	0.003	0.004	0.002
	2754	0.89	0	−0.01	−0.006	−0.014	0	0	0.004	−0.001	−0.028	0.008	0.023	0.028	0.042	0.048
	MS	0.92	0	−0.005	−0.009	−0.001	−0.003	−0.004	−0.004	−0.005	−0.006	−0.004	0.005	0.008	0.014	0.014
	4500	0.63	0	−0.007	−0.009	−0.002	−0.002	−0.005	−0.007	−0.008	−0.008	−0.005	0.009	0.013	0.018	0.015
37% sand +	2742	1.42	0	0.011	−0.008	0.022	0.033	0.048	0.065	0.077	0.119	0.172	0.197	0.242	0.276	0.279
63% gravel	2735	0.18	0	−0.008	−0.025	−0.006	−0.005	−0.006	−0.005	−0.007	−0.008	0.001	0.009	0.009	0.012	0.006
	2754	0.89	0	−0.001	0.004	0.005	0.01	0.009	0.012	0.014	0.01	0.021	0.032	0.031	0.038	0.041
	MS	0.92	0	−0.004	−0.002	−0.001	0.003	0.002	0.002	0.001	−0.004	0.007	0.008	0.002	0.007	0.01
	4500	0.63	0	0.001	0.004	0.005	0.008	0.006	0.006	0.005	0.001	0.012	0.02	0.013	0.017	0.014

Note: 5 × 5 × 25 cm bars, 1:2 mortar, sealed, moist cured at 100°F.

Panel No. 14-1

This panel was constructed using cement Type 14, which can be classified as ASTM Type I cement. Cement Type 14 contained medium-high equivalent alkalis (0.96%). The development of alkali-aggregate reaction is well demonstrated with this cement type. The wall was first inspected in October 1943 (i.e., 5 months after the construction of the wall was completed). There was no visible sign of alkali-aggregate reaction, and this panel was in excellent condition. In 1946, signs of distress were first observed but the overall condition of the wall was relatively good. In 1997, the reaction caused significant expansion manifested with conspicuous (see Appendix II) pattern cracking covering most areas.

Panel No. 16-4

This panel was constructed using cement Type 16, which can be classified as ASTM Type I cement. Cement Type 16 contained low equivalent alkalis (0.57%). No significant distress was observed in the three inspections shown in Table 1.

Panel No. 18-1

This panel was constructed using cement Type 18, which can be classified as ASTM Type I cement. The cement contained low equivalent alkalis (0.28%). As anticipated for a low-alkali cement, no signs of distress in the first 3 years of the age of the concrete were observed. In 1997, the amount of distress was still minimal and could probably be due to other causes of distress such as freeze-thaw or other environmental conditions. No pattern cracking was observed in any of the three inspections documented in Table 4.

Panel No. 21-1

This panel was constructed with cement Type 21, which can be classified as ASTM Type II cement. Cement Type 21 contained a low equivalent alkalis amount of 0.58%. Although some signs of distress had been documented over the prior 53 years, no pattern cracking or discoloration has been reported, as shown in Table 1.

Panel No. 24-4

This panel was constructed using cement Type 24, which can be classified as ASTM Type II cement. Cement Type 24 contained a medium-high equivalent alkalis amount of 0.94%. No significant signs of distress were observed within the first 3 years of the wall. In 1997, this panel became one of the worst in overall condition. Significant amounts of silica gel were produced by the reaction and caused serious cracking that exceeded 15 mm. Pattern cracking, discoloration, and efflorescence represent the most apparent signs of distress, as shown in Fig. 3. Although the amount of equivalent alkalis in this cement type was slightly less than that present in Type 14-1, Panel 24-4 was much more distressed than Panel 14-1.

Panel No. 34-4

This panel was constructed using Type 34 cement, which can be classified as ASTM Type 3 cement. Cement Type 34 contained a low amount of equivalent alkalis (0.52%). The cement type showed minimal signs of distress within the first 3 years of the age of the concrete. Although the overall condition of this panel was much better than Panels 14-1 and 24-4, this panel was distressed in the form of pattern cracking and some discoloration. The reason for distress is probably alkali-aggregate reaction. If the cause of distress is truly alkali-aggregate reaction, then it could be inferred that even with low-alkali cements the likelihood for distress due to alkali-aggregate reaction exists. The variation in conditions of ex-

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TABLE 3. Chemical Analysis of Cements (Douglass et al. 1947)

Laboratory No. (1)	Cement type (2)	Percent							
		SiO_2 (3)	Al_2O_3 (4)	Fe_2O_3 (5)	CaO (6)	MgO (7)	Na_2O (8)	K_2O (9)	Equivalent alkalis (10)
2742	II	21.62	4.86	4.75	62.71	1.58	1.3	0.12	1.38
2735	II	22	4.52	3.81	64.78	1.3	0.04	0.14	0.13
2754	II	20.86	6.47	5.39	63.21	1.28	0.22	0.67	0.66
MS	v	21.84	4.42	4.41	63.65	1	0.28	0.64	0.7
4500	II	21.65	5.12	5.05	64.24	0.75	0.13	0.5	0.43

Note: Alkali reactivity of wall aggregates. Cement types used to examine reaction of aggregate segregations.

TABLE 4. Visual Inspection of Selected Panels [1943 and 1946 Inspections from Douglass et al. (1947)]

Panel no. (1)	1943 inspection (2)	1946 inspection (3)	1997 inspection (4)
14-1	Nothing to report	Horizontal crack 20 cm long at conduit level,[a] north end; considerable tight branch cracking; rather coarse spacing	Noticeable pattern cracking covering most of area, which decreases in width and intensity from top to bottom; crack at conduit level now extends full panel width; maximum measured crack width is 0.229 mm located at south end of crack at conduit level
16-4	Entire area thinly covered with white granular deposit	Horizontal crack at conduit over full length except south quarter; maximum opening 0.051 mm; moderate amount of tight branch cracking	Some barely visible cracks appeared in upper half of panel; maximum crack width is 0.076 mm; horizontal crack at conduit level runs across full width
18-1	Nothing to report	No change	Some efflorescence on upper half at limited locations; some delamination has started at limited locations
21-1	Scar or spall 25.4 mm diameter, 25.4 cm from north end; slight raveling at edges of blockout in pilaster; no corner cracks.	Horizontal crack 30.5 cm long at conduit on south end; blockout has short crack from bottom south corner and a horizontal crack 15.24 cm from top extending through chamfer; rather severe raveling at top and bottom of blockout	Minor crazing at limited locations; horizontal crack at conduit level is barely visible (1.07 m long); slight, barely visible cracks at limited locations
24-4	Nothing to report except very small deposit of carbonate just below corner crack	Horizontal crack at conduit over north two-thirds of panel; maximum opening 0.051 mm mm; carbonate deposit has disappeared	Extensive wide pattern cracking covers entire area, maximum crack width has exceeded 15.2 mm; panel is fully covered with orange discoloration, and many cracks are covered with efflorescence
34-4	Nothing to report	Slight branch cracking barely visible	Visible map cracks over most of area accompanied with discoloration or exudation or both
41-1	Nothing to report	Very small amount of branch cracking	No change except for conspicuous pattern cracks at left triangular zone; maximum crack width is 0.178 mm
42-1	Numerous small spots and streaks of light-colored deposit showing no grain structure at 30× magnification	Branch cracking in top 15.2 cm over entire area; light-colored deposit still evident; small spall at top near south end	Same as previous inspection; cracking in top 15.2 cm is barely visible
43-1	Nothing to report	Coarse pattern conspicuous over entire area; average spacing about 15.2 cm, maximum opening 0.076 mm; horizontal crack at conduit full length, maximum 0.076 mm	Extensive coarse pattern cracking over entire area, maximum measured crack width increased to 15.2 mm; horizontal crack extends along full length of panel; extensive orange discoloration over entire area; some efflorescence visible along cracks
43A-1	Appearance is mottled by large light and dark areas; no visible deposit	Horizontal crack at conduit 20.32 cm long, north end	Horizontal crack at conduit level is now 8.89 cm long with light exudation along crack; some crazing in upper left triangular zone with maximum crack width of 0.229 mm
51-4	Faintly mottled by lighter spots about 25.4 mm diameter	No change	No change except appearance of horizontal crack at conduit level, approximately 1.22 m long; maximum crack width is 1.016 mm

[a]Electrical conduit that provides power to wall for lighting and runs horizontally across wall panels—located approximately 0.6 m from top of wall.

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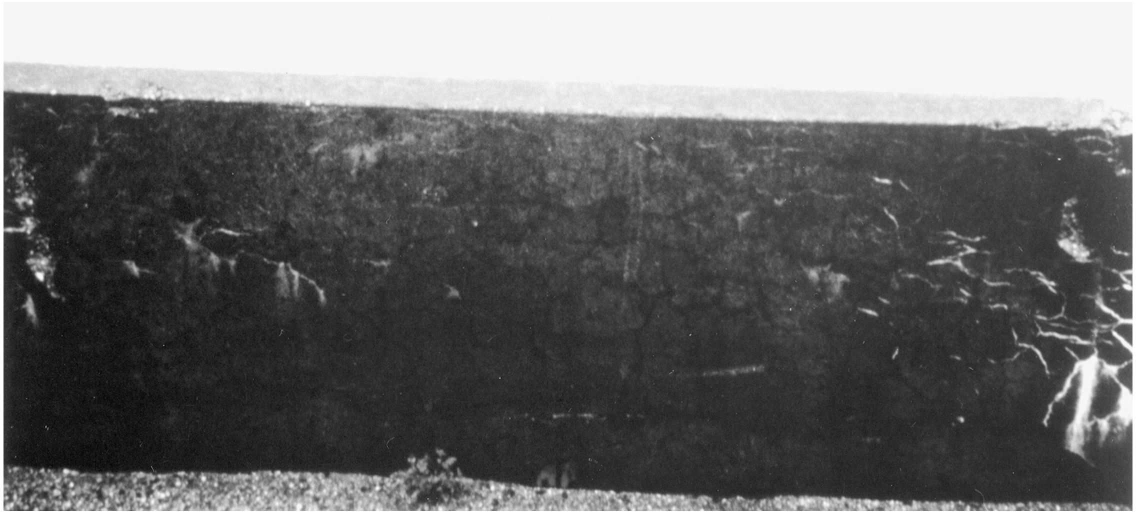

FIG. 3. Panel No. 24-4 (Notice Efflorescence, Pattern Cracking and Change of Color)

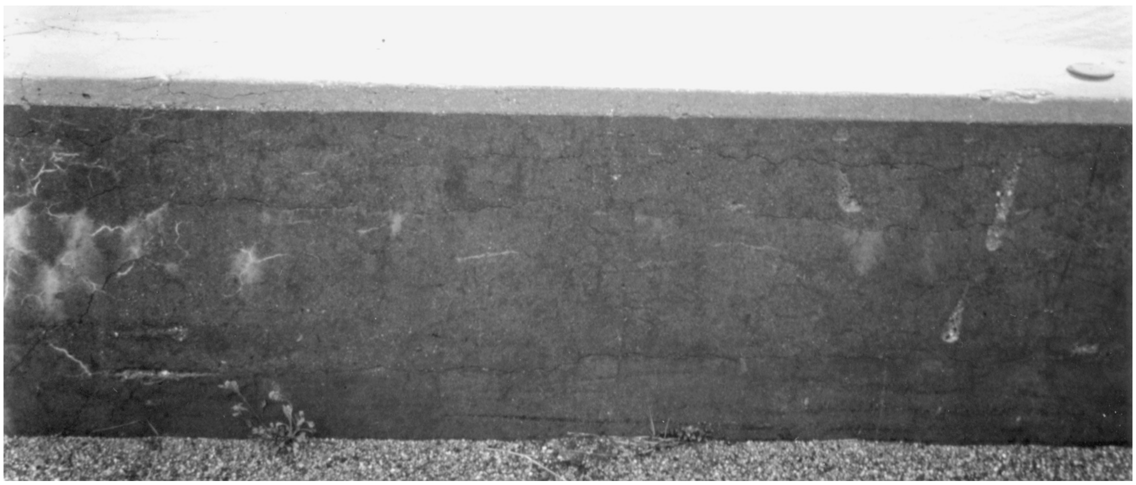

FIG. 4. Panel No. 43-3 (Notice Efflorescence, Pattern Cracking, and Change of Color)

posure to environmental conditions greatly affects the reaction—for example, sun exposure. The relative orientation of the panels results in variation in the duration and intensity of exposure to different environmental factors. The stoichiometry of the reaction is greatly affected by these variations (e.g., variation in temperature from one panel to another).

Panel No. 41-1

This panel was constructed using cement Type 41, which can be classified as ASTM Type IV. This cement type contained medium-high equivalent alkalis (0.9%). This panel remained in generally good condition during all three inspections. The 1997 inspections showed conspicuous cracking limited to the upper left triangular zone. The overall appearance of this panel does not show substantial distress due to alkali-aggregate reaction. This medium-high–alkali cement behaved well compared to the other medium-high–alakli cements.

Panel No. 42-1

This panel was made with ASTM Type IV cement. This cement contained low equivalent alkalis (0.38%). Additional branch cracking had appeared between 1943 and 1946. The overall condition of the panel remained good and stable since the 1946 inspection.

Panel No. 43-1

This panel was constructed using cement Type 43, which can be classified as ASTM Type IV cement. This cement contained a high equivalent alkalis amount of 1.14%. The panel was in excellent condition according to the October 1943 inspection. Similar to the cement types containing different amounts of equivalent alkalis, the 5-month period was insufficient to produce any visible signs of distress externally (internal distress would probably start earlier than external distress). This is the only cement type in the selected panels that showed early signs of distress at the age of 3 years. Pattern cracking was visible over the entire area in the 1946 inspection. In 1997, this panel became one of the worst in overall condition, as shown in Fig. 4. Deterioration is manifested with extensive pattern cracking, orange discoloration, and efflorescence. The maximum measured crack width of 15 mm is also significant. Such a large amount of equivalent alkalis causes early distress of concrete.

Panel No. 43A-1

This panel was constructed using cement Type 43A, which can be classified as ASTM Type IV cement. Cement Type 43A contained low equivalent alkalis (0.44%). The general chemical and physical characteristics of this cement type are similar to Type 43. The main difference between Types 43 and 43A cements is the amount of equivalent alkalis. Type 43 cement is a

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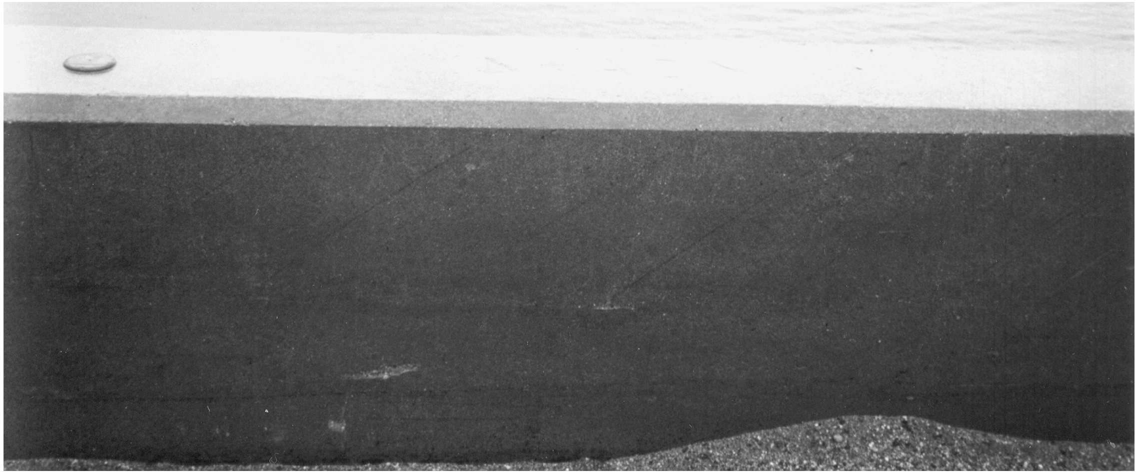

FIG. 5. Panel No. 43A-1 (No Visible Pattern Cracking, Discoloration, or Efflorescence)

TABLE 5. Compressive Strength of Concrete at Different Ages [7 Days to 2 Years; from Douglass et al. (1947)]

PCA cement type (1)	$Na_2 + 0.658\ K_2O$ (%) (2)	7 day (MPa) (3)	28 day (MPa) (4)	90 day (MPa) (5)	1 year (MPa) (6)	2 year (MPa) (7)	53 year (MPa) (8)
14	0.96	20.69	29.23	37.1	38.85	39.85	44.25
16	0.57	19.03	30.06	36.75	37.51	36.41	47.82
18	0.28	21.17	29.51	36.34	35.3	37.78	46.18
21	0.58	17.51	30.27	38.89	44.61	47.02	48.21
24	0.94	20.89	32.13	39.51	41.09	44.06	28.14
34	0.52	25.44	32.96	35.72	38.89	38.41	35.12
41	0.90	9.79	27.03	40.34	44.2	44.33	49.67
42	0.38	7.45	20.41	36.06	41.23	41.99	41.62
43	1.14	11.72	27.03	38.47	43.68	45.02	22.97
43A	0.44	10.69	26.06	38.54	45.64	44.27	44.09
51	0.26	16.48	28.48	36.34	42.2	44.13	42.21

Note: PCA = Portland Cement Association; 1 MPa (N/mm^2) = 145.03 psi.

high-alkali cement, whereas Type 43A cement is a low-alkali cement. Type 43A behaved much better than Type 43. Some distress was observed for Type 43A but the overall condition was good. No pattern cracking or discoloration was reported through the 53-year life span of the panel. One can see differences in the overall behavior by comparing Fig. 4 to Fig. 5.

Panel No. 51-4

This panel was constructed using cement Type 51, which can be classified as ASTM Type V cement. Cement Type 51 contained low equivalent alkalis (0.26%). This cement type behaved very well. There was no evidence of distress due to alkali-aggregate reaction, and the overall condition was good throughout the life of the wall.

Compressive Strength

In June 1997, cores were obtained from the 11 selected panels previously visually inspected. Five cores were obtained from most of the selected panels and three or four cores from other panels. The test types include uniaxial compression, cyclic loading, and splitting tension. In this paper, emphasis will be on the variation of compressive strength versus time and the effect of alkali-aggregate reaction on deterioration of compressive strength. The deterioration of compressive strength caused by alkali-aggregate reaction is believed to be due to cracking of aggregate and the surrounding mortar matrix.

The variation in compressive strength in the first 2 years of the wall was observed by test cylinders made and cured in the laboratory. Table 5 shows the variation in compressive strength of the 11 selected cement types. The variation in chemical and physical characteristics within each ASTM cement group is indicated by subclassifications within the group, as shown in Appendix I.

Cement Type I

Panel No. 14-1 was built with a medium-high–alkali cement. The exterior appearance was affected by alkali-aggregate reaction, as discussed in the visual inspection section. But the strength of this panel increased continuously with time, as shown in Table 5. The alkali-aggregate reaction did not result in internal disintegration sufficient to affect the long-time strength. All ASTM Type I cements (Types 14, 16, and 18) increased in strength continuously over the past 53 years. Cement Types 16 and 18 contained low equivalent alkalis. However, it is worthy of note that Panel 14-1 was the lowest in strength among panels constructed with Type I cements. This is probably due to some internal disintegration caused by alkali-aggregate reaction. Cement Type 16 contained equivalent alkalis very close to the ASTM C 150-96 limit for low equivalent alkalis of 0.6%. Cement Type 16 behaved very well as far as appearance and strength. Fig. 6 shows that for cement Type I all panels gained strength continuously since 1943 until the time of this study. Note that this gain of strength includes cement Type 14, which is medium-high–alkali cement according to the classification of this study. Cement Type 14 is a high-alkali cement based on the ASTM C 150-96 classification.

Cement Type II

Panel 24-4 gained strength continuously over the first 2 years. Because of alkali-aggregate reaction, this panel lost >36% of its compressive strength between 2 and 53 years. This is to be compared to Type 14 cement that contained approximately the same

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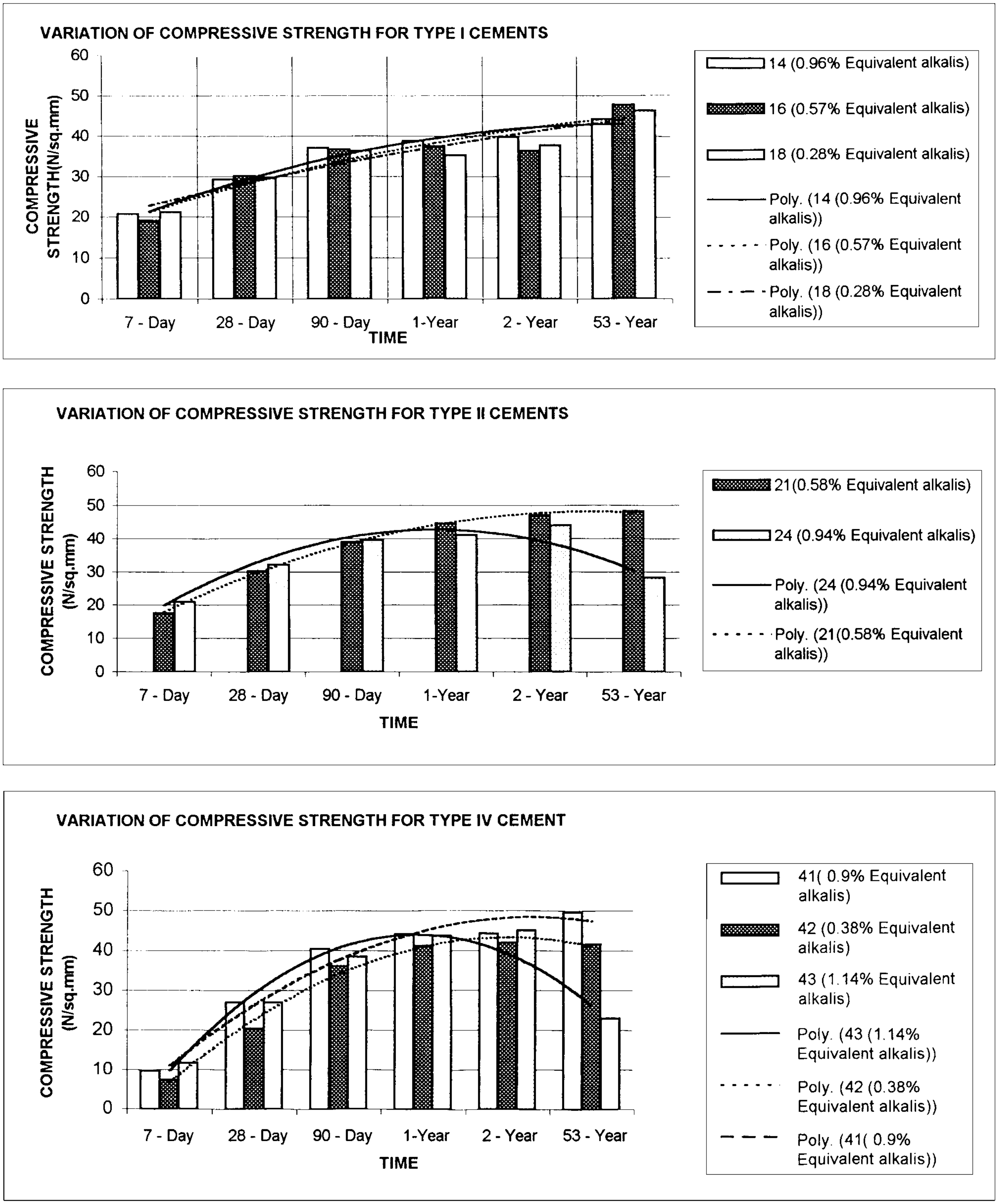

FIG. 6. Variation of Compressive Strength with Time for Cement Types I, II, and IV

amount of equivalent alkalis but was not significantly affected by alkali-aggregate reaction. Cement Type 21 contained equivalent alkalis of 0.58%, which is very close to the ASTM limit of 0.6%. This cement type behaved very well as far as strength gain. Fig. 6 shows the gain of strength for cement Type 21 and loss of strength for cement Type 24 at 53 years.

Cement Type III

Panel No. 34-4 gained strength in the first year and slightly dropped in strength between 2 and 53 years. Cement Type 34 contained low equivalent alkalis. The slight reduction in compressive strength (8.6%) between 2 and 53 years is expected for ASTM Type III cements (high early strength).

Cement Type IV

Panel No. 43-1 gained strength continuously over the first 2 years. Nonetheless, this panel suffered the greatest deterioration in compressive strength between 2 and 53 years. The reduction in strength was close to 50%. Cement Type 43 con-

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tained high equivalent alkalis (1.14%). The control to cement Type 43 is Type 43A, which is very similar to Type 43 in chemical composition except that cement Type 43A contained low equivalent alkalis (0.44%). Cement Type 43A gained strength through the first 2 years and maintained a reasonably high strength at 53 years. The other cement types that belong to ASTM Type IV (cement Types 41 and 42) either gained strength throughout the 53 years or remained close to the 2 years compressive strength. Cement Type 41 contained medium-high equivalent alkalis of 0.9%. Nonetheless, this cement type remained in good condition and gained high strength at 53 years. This is compared to Type 24, which also contained medium-high equivalent alkalis but was significantly distressed between 2 and 53 years. Fig. 6 shows the continuous gain of strength for cement Types 41 and 42 and the loss of strength for cement Type 43.

Cement Type V

Panel No. 51-4 gained strength continuously over the first 2 years and experienced a slight reduction in compressive strength at 53 years. Cement Type 51 contained low equivalent alkalis of 0.26% and therefore was not affected by alkali-aggregate reaction.

CONCLUSIONS

Outlined below are the main findings of this paper. These findings focus on the types of reactive minerals, the long-time effect on strength and appearance, and the reaction of the minerals with different alkali contents:

- Aggregate that contains ryholites, andesite, diorite, and diorite porphyries can react with cements that contain significant amounts of alkalis and cause significant loss of strength.
- A combination of reactive aggregates with high-alkali cements resulted in loss of strength up to 50% in a 50-year period. The long-term loss of strength was accompanied with visible signs of distress. No loss of strength occurred in the first 2 years, but signs of distress were visible.
- A combination of reactive aggregates with medium-high–alkali cements (0.6%–1.0% equivalent alkalis) produced a variety of results in this study. In 50 years, cement Type 24 (ASTM Type II) lost about 36% and showed significant visible distress whereas cement Types 14 (ASTM Type I) and 41 (ASTM Type IV) gained more strength and minor or no visible distress.

APPENDIX I. CEMENT TYPES

TABLE 6. Notations used for Cement Types[a]

ASTM group (1)	Cement types in group[b] (2)
Type 1	14, 16, 18
Type 2	21, 24
Type 3	34
Type 4	41, 42, 43, 43A[c]
Type 5	51

[a]Reflect variations in chemical constituents or physical characteristics or both between ASTM standard groups and within each group.
[b]Panel number.
[c]Letter A is used to differentiate between Type 43 (high-alkali cement) and Type 43A (low-alkali cement).

APPENDIX II. DEFINITIONS

General

Equivalent alkalis—sum $Na_2O + 0.685\ K_2O$ (%).
Pessimum quantity—amount of reactive silica present in the aggregates corresponding to the maximum expansion due to alkali-silica reaction.
Craze cracks—fine random cracks or fissures in a surface of plaster, cement paste, mortar, or concrete.
Pattern cracks—fine openings on concrete surfaces in the form of a pattern, resulting from a decrease in the volume of the material near the surface or increase in the volume of the material below the surface or both.
Efflorescence—deposit of salts, usually white, formed on a surface, the substance having emerged in solution form within either concrete or masonry and subsequently been precipitated by evaporation.
Exudation—liquid or viscous gel-like material discharged through a pore, crack, or opening in the surface of concrete.
Popout—breaking away of small portions of a concrete surface due to localized internal pressure, which leaves a shallow, typically conical, depression.
Spall—exfoliation usually in the shape of a flake, detached from a larger mass by a blow, the action of weather, pressure, or expansion within the large mass.

Specific

The following approximate terms were used to describe crazing in the 1943 and 1946 inspections and can be used in connection with Table 1 (Douglass et al. 1947).
Very fine pattern—average spacing of cracks is 25 mm or less.
Fine pattern—average spacing of cracks is 25–50 mm.
Coarse pattern—average spacing of cracks is 50–152 mm.
Barely visible—visible on close inspection only, frequently visible only when shaded from bright sunlight.
Easily visible but not conspicuous—visible from a distance of 0.6–3 mm.
Conspicuous—Visible from a distance of 3 m or more.

ACKNOWLEDGMENTS

The writers gratefully acknowledge the support of the National Science Foundation, Washington, D.C., for funding this study (Contract No. CMS-9705808). The USBR is also thanked for supporting this study in many ways and participating in cost share.

The opinions expressed in this article are solely those of the writers and do not reflect studies or conclusions of the USBR.

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