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CONTROL OF REACTIVE CARBONATE ROCKS IN CONCRETE

by

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The effects of using reactive carbonate rocks as concrete aggregates were evaluated in a laboratory investigation. Three reactive carbonate rocks, each producing a different manifestation of the alkali-carbonate rock reaction in concrete, were each used at three dilution levels, one with low-alkali and two with high-alkali portland cements, to make concrete specimens that were tested for length changes for 3 yr in a moist environment, and for compressive and tensile strengths to 1 yr. Limited testing for compressive
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strength was extended to 3 yr. A carbonate rock and a granite gneiss were also used as coarse aggregates in other concrete mixtures to serve as controls. The same carbonate rock was used as fine aggregate in all the concrete mixtures except the three that contained gneiss coarse and fine aggregates. In addition, the expansion of samples of the reactive rocks was measured in 1 N sodium hydroxide solution. Petrographic examinations and examinations with a scanning electron microscope were made of rock and concrete samples. The detection procedure and control criteria of Appendix C of the Standard Practice for Concrete for potentially reactive carbonate rocks intended for use as concrete aggregates were considered for validity in view of the laboratory results. The laboratory findings were as follows: (a) Each reactive aggregate did create the intended reaction in the concretes containing them. (b) The negative rim-forming calcitic Pixley rock is not expansive in alkali solution, and its reaction in concrete does not result in any detectable effects on the volume or strength of concrete specimens. (c) The siliceous rim-forming dolomitic Rapid rock that was used is slowly expansive in alkali solution; normal-sized rock specimens require more than 6 months to show expansion, but larger specimens start expanding much sooner. Comparison shows that this Rapid rock is less reactive than the well known Rapid rock from the Glory Quarry. (1) There was no detectable effect of the reaction of the rock on the volume of concrete specimens. (2) Concrete specimens containing this rock failed to show a normal gain in compressive strength to an age of 1 yr. Efforts to determine whether this effect extended beyond 1 yr were not successful. There was no detectable effect on splitting tensile strength values. (3) Since the effect on compressive strength was not influenced by the alkali content of the cement, it is suggested that the strength effect may not be due to the reaction of the rock. The fact that the present test results are similar to those found by others for the more reactive rock from the Glory Quarry also suggests that differences in the reactivity of the rock do not influence the strength behavior of concrete. It is suggested that the high porosity of the rock may lower its strength so that it does not carry its proper load in concrete specimens during strength testing. (d) The reactive 1-8 rock was rapidly expansive in alkali solution, and its use in concrete did cause expansive volume change. There was no detectable effect of the reaction on the strength of concrete specimens. As expected, the amount of volume change of concrete specimens was directly related to the amount of 1-8 rock and the alkali content of the cement used. These results were consistent with other data. (e) There was a tentative indication that the amount of concrete expansion was also related to the amount of C_3A that was in the cement used. (f) The expansions of rock specimens stored in alkali solution are 15-20 times the expansions of concrete specimens of the same ages that are stored moist. The test data indicate that the numerical values used in Appendix C are satisfacotory without change. It is recommended that Appendix C be modified to permit optional testing of potentially reactive rocks in concrete when this seems desirable.

PREFACE

The authority for the work described herein was provided by first indorsement dated 31 May 1967 from the Office, Chief of Engineers, to a letter from the U. S. Army Engineer Waterways Experiment Station (WES) dated 15 March 1967, subject: Project Plan for Research on Alkali-Carbonate Rock Reaction in Concrete (ES 603.4). The work was started in 1968 as item 4 of ES 603, Cement-Aggregate Reaction; redesignated as item 7 of ES 630, Cement-Aggregate Reaction; and is now part of Work Unit 31329, Cement-Aggregate Reaction. All work was done by personnel of the Concrete Laboratory (CL) (formerly Concrete Division) of WES, under the supervision of Mr. Bryant Mather, Chief of the CL, Messrs. Leonard Pepper and R. V. Tye, Jr., Chief and former Chief, respectively, of the Engineering Sciences Division, and Mrs. Katharine Mather, Chief of the Petrography and X-ray Branch. Mr. A. D. Buck was Project Leader and prepared this report. The statistical evaluation of the data was performed with the help of Mr. Pepper.

The assistance furnished by the following persons is gratefully acknowledged:

- a. Messrs. T. L. Welp, formerly of the Iowa State Highway Commission, and J. D. Myers of the Commission for their help in obtaining the supply of reactive Iowa rock that was used.
- b. Professor John Lemish of Iowa State University for furnishing the hand sample of reactive rock from the Glory Quarry and for the evaluation of the other Iowa rock.
- c. Mr. H. H. Newlon, Jr., of the Virginia Highway Research Council for supplying the samples of reactive Virginia rock.

Directors of WES during the conduct of this study and the preparation and publication of this report were COL J. R. Oswalt, Jr., CE, COL L. A. Brown, CE, BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Directors were Mr. J. B. Tiffany and Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
inches	25.4	millimetres
cubic feet	0.028317	cubic metres
pounds (mass)	0.4535924	kilograms
pounds (force) per square inch	0.00689476	megapascals
pounds (mass) per cubic yard	0.59327643	kilograms per cubic metre
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 Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

CONTROL OF REACTIVE CARBONATE ROCKS IN CONCRETE

PART I: INTRODUCTION

1. In 1964-65 the Concrete Division* and four other laboratories participated in a cooperative test program for the American Society for Testing and Materials (ASTM) Subcommittee II-b** of Committee C-9 on Concrete and Concrete Aggregates to determine the effectiveness of an existing ASTM method in evaluating the potential reactivity of carbonate rocks used as concrete aggregate in alkali-carbonate rock reaction. Seven carbonate rocks were tested according to ASTM Designation C 227, Standard Method of Test for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method).† Although this test is intended to detect siliceous rocks capable of deleterious alkali-silica reaction with the alkalies in portland cement, the intent of the interlaboratory testing was to determine whether Test Method C 227 would also serve to detect potentially reactive carbonate rocks. It was concluded that this test was not suitable for this purpose.

2. A procedure providing instructions for the use or avoidance of potentially reactive carbonate rock as concrete aggregate was prepared by the Concrete Laboratory (CL) in late 1966 for inclusion in the Corps of Engineers Standard Practice for Concrete.[2] The instructions were published as Appendix C in the 1 November 1971 edition of this document. In this appendix potentially reactive carbonate rock is defined as one that expands 0.1 percent or more during 84 days of testing by immersion in 1 N sodium hydroxide solution in accordance with CRD-C 146†† (ASTM Designation C 586-69). The criteria in Appendix C[2] were based on several sources of information:

> a. Information gained by the CL in testing carbonate rocks for length change using the procedures of CRD-C 146.

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* Now the Concrete Laboratory.

** Now C09.02.02.

† All ASTM test methods are given in Reference 1.

†† All CRD-C test methods are described in the Handbook for Concrete and Cement.[3]

b. The interlaboratory cooperative mortar-bar work conducted in accordance with ASTM Designation C 227.

c. The experience of other organizations in testing reactive carbonate rocks for length change in (1) sodium hydroxide solution, (2) mortar bars, and (3) concrete beams.

The criteria were actually based on limited amounts of data and principally on only one of several different possible manifestations of the alkali-carbonate rock reaction. The work described in this report was conducted to evaluate the detection criteria that had been established and to determine if those carbonate rocks that produce other manifestations of this reaction would be detected by these criteria.

3. Three portland cements selected to provide different levels of alkali and tricalcium aluminate (C_3A*) content, and three reactive carbonate rocks, each selected for a different manifestation of the reaction, were used in this investigation. In addition, each reactive rock was used in three different concentrations or levels of dilution, which were selected to provide data on the following:

a. Differences in degrees of reaction with different reactive rocks.

b. Effect of alkali content of cement on degree of reaction.

c. Effect of tricalcium aluminate (C_3A) content of cement on degree of reaction.

d. Effect of amount of reactive rock on degree of reaction.

e. Effect of the reaction on such physical properties of concrete as strength and volume.

f. The relation between expansions of different samples of a reactive rock in alkali solution and in concrete.

4. A general review of developments in recognizing and controlling the use of potentially reactive carbonate rocks as concrete aggregate was published in 1972.[4] This review was published while the investigation described herein was in progress and was based in part on the preliminary results of this investigation.

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* Usual cement notation: C = CaO, A = Al_2O_3, etc.

PART II: PROCEDURES

5. The reactivity of each of the reactive aggregates was verified using a combination of petrography, length change of rock specimens, and visual observation of the results obtained by embedment of rock samples in portland cement paste. Concrete mixtures containing different cements and different amounts of reactive and of control aggregates were made. Specimens from these concrete mixtures were tested for compressive and splitting tensile strengths and length change. These tests were conducted at intervals ranging from 1 day to over 3 yr.

Materials

Aggregates

6. Three reactive carbonate coarse aggregates, two control coarse aggregates (one carbonate, one siliceous), and two fine aggregates were used. Each is identified below:

a. CRD-G-35(A,B). This is a reactive calcitic dolomite from Pints' Quarry near Evansdale, Iowa, which produces rim silicification. The A portion was 43 bags (about 3000 lb*) of No. 4 to 3/4-in. aggregate; it represented beds 17A and 17B in the quarry. The B portion was six hand samples, nominally 6-in. aggregate, with piece 3 from bed 17B and pieces 4-6 from bed 17A; pieces 1 and 2 were from bed 17C, which was not represented in the A portion of this material. This rock came from the Rapid member of the Cedar Valley Formation of Devonian Age and will be referred to as the Rapid calcitic dolomite. A hand specimen of Rapid rock from the Glory Quarry was provided for comparison with rock from Pints' Quarry. Rock from both quarries had been tested and described previously.[5,6]

b. CRD-G-36, 36(A,B). This is a clayey calcitic dolomite which produces expansive dedolomitization. It comes from Virginia and has been designated in the literature[7,8] as 1-8. Samples G-36 and G-36(B) were 16 and 6 bags, respectively (about 2700 lb), of No. 4 to 3/4-in. aggregate received at different times from the same lot; G-36(A) was

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* A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

one hand sample. It is referred to as 1-8 rock.

c. KAN-4G-6(3,4). This is a limestone that produces negative reaction rims. It comes from the Pixley Mine at Independence, Missouri, and has been referred to as the Pixley limestone in the literature.[9] Sample G-6(3) consisted of hand samples while G-6(4) was 30 bags of aggregate from the 3/4- and 1/2-in. stockpiles.

d. CRD-G-31(11). This is the control dolomitic limestone which was used as coarse aggregate. It comes from the Hermitage Quarry near Nashville, Tennessee, and is referred to as Hermitage rock. Manufactured sand (CRD-MS-17(4)) from this source was used as fine aggregate in all concrete mixtures except the three made with the granite gneiss aggregate.

e. CRD-G-25. This rock is a granite gneiss from Fortson, Georgia, and was used as siliceous coarse aggregate. Sand (CRD-G-25(MS)) was processed from this rock and used as fine aggregate in the three mixtures that contained this rock as coarse aggregate.

Portland cements

7. The three portland cements used in the investigations are as follows:

a. RC-168. A low-alkali Type I cement.

b. RC-167. A high-alkali Type I cement.

c. RC-594. A high-alkali Type II cement.

Dilution

8. Each reactive carbonate rock was used as 100, 40, and 20 percent of the coarse aggregate in mixtures with each cement. The Hermitage carbonate rock was used to replace reactive rock on a solid volume basis when dilution was required.

Mixtures

9. The use of three reactive carbonate rocks with three cements at three dilution levels plus the use of two control rocks with each cement required a total of 33 concrete mixtures. Three rounds of each mixture were made, with the casting sequence randomized in rounds 2 and 3.

The mixtures were made according to the requirements of test method CRD-C 114; all aggregates were graded to pass a 3/4-in. sieve so that none of the pieces would be too large for the required bar dimensions. External vibration was used to consolidate all test specimens. Twelve 3- by 6-in. cylinders and three 2- by 2- by 11-1/4-in. bars were made from each mixture for each round. A total of 1188 cylinders and 297 bars was made.

Curing

10. All concrete specimens were cured continuously at 73 ± 2°F and about 100 percent relative humidity.

Tests

Rock

11. Portions of each reactive aggregate were placed in small covered plastic containers in pastes of each high-alkali cement and stored at 100°F to accelerate the reaction and to verify that the desired reaction would occur. Slices were later cut from these specimens and examined for signs of visible reaction rims before and after etching in dilute hydrochloric acid (HCl).

12. The specific gravity and the absorption of each aggregate were determined. The results are shown in Table 1.

13. A composite sample of each reactive aggregate was ground to pass a No. 325 sieve and then examined by X-ray diffraction (XRD) to determine mineralogical composition. Dilute HCl was used to determine the amount of acid-insoluble residue in each of the three reactive rocks, and the insoluble residue was identified by XRD. In addition, the dolomitic reactive aggregates, Rapid and 1-8 rocks, were examined by the XRD method of Tennant and Berger[10] to determine the dolomite-to-calcite ratio. Chemical analyses for MgO and CaO content of the Rapid and 1-8 samples were also conducted; this test was repeated for the 1-8 rock. Results are shown in Table 2.

14. Each hand sample of reactive rock was approximately the size of a 4- to 6-in. piece of aggregate. The total number of hand samples was seven large pieces of Rapid rock, one large piece of 1-8 rock, and three large pieces of Pixley limestone. Two small rock cores, approximately 1/4 by 1-1/4 in., were taken side by side from each hand sample of the reactive rocks. Two were also taken from the piece of rock from the Glory Quarry. A single larger core, about 1/2 by 2 in., was taken from the same area as were the smaller cores in pieces 3, 4, and 6 of the Rapid rock to evaluate size effect. All cores were tested for length change by CRD-C 146. Test results are indicated in Table 3. A slice about 1 in. thick was cut from each of the hand samples normal to bedding and etched in acid. A powdered portion of each hand sample was examined by XRD. Thin sections wére made from the hand samples of the Rapid rock, including the Glory sample and the 1-8 rock, and examined with a polarizing microscope. Care was taken to obtain the XRD samples and the thin sections from the same parts of the pieces from which the cores were taken in order to minimize sampling differences. No thin sections were made of the Pixley limestone since it had already been examined for other work.[9] The acid-insoluble residue of the piece of Rapid rock from the Glory Quarry was determined, and its composition was determined by XRD. These results are reported in Table 2.

15. Buck[9] had shown in work with the Pixley limestone that XRD examination of the surface of a slice of rock before and after it had been in contact with portland cement paste was a promising technique for the study of the mechanism of alkali-carbonate rock reaction. Therefore, the following specimens, each about 1 by 1 by 1/4 in., were prepared for a similar study:

<u>Rapid rock</u>

<u>Piece 3</u>

Slab 1 in sodium hydroxide solution

Slab 2 in RC-168 paste

Slab 3 in RC-167 paste

Slab 4 in RC-594 paste

Piece 4

Slab 1 in sodium hydroxide solution

Piece 6

Slab 1 in sodium hydroxide solution

Slab 3 in RC-168 paste

Slab 4 in RC-167 paste

Slab 5 in RC-594 paste

1-8 rock

Slab 1 in RC-168 paste

Slab 2 in RC-167 paste

Slab 3 in sodium hydroxide solution

Slab 4 in RC-594 paste

Each slab was taken from the same area in the hand samples as were the length-change cores.

16. All X-ray work was done with an X-ray diffractometer using nickel-filtered copper radiation.

Portland cements

17. The chemical composition and physical properties of the portland cements were determined in accordance with CRD-C 200 (Table 4). All three cements were examined by X-ray diffraction.

Concrete

18. The size of the concrete batches was 1.2 cu ft so that a minimum of coarse aggregate would be needed. It was believed that there would be less likelihood of variation in smaller batches of reactive rocks. Consequently the size and number of test specimens were limited.

19. The disposition of the test specimens is described below:

a. A 3- by 6-in. cylinder from each round of each mixture was broken at 7, 14, 28, 90, 180, and 360 days to determine compressive strength according to CRD-C 14.

b. A 3- by 6-in. cylinder from each round of each mixture was broken at 7, 14, 28, 90, 180, and 360 days to determine splitting tensile strength according to CRD-C 77.

c. Three 2- by 2- by 11-1/4-in. bars from each round of each mixture were measured at 1, 7, 14, 28, 56, 90, 180, and 360 days to determine length change. Measurements were continued at 6-month intervals thereafter to 3 yr for all bars except as noted below. In addition, selected bars were examined for cracks after testing was completed.

20. Since the compressive strength of the concrete mixtures containing the Rapid rock as coarse aggregate became of special interest, cubes were cut from six selected length-change bars and broken at different intervals to determine compressive strengths between 1 and 3 yr. Three of the bars contained Rapid rock as coarse aggregate and three contained Hermitage aggregate as a control. In addition, a bar containing 1-8 aggregate and a bar containing Hermitage were examined with a scanning electron microscope (SEM) to determine whether the effects of the expansive reaction of reactive carbonate rock produced recognizable and meaningful changes.

PART III: RESULTS AND DISCUSSION

21. Each of the reactive carbonate rocks in combination with hydrated portland cement did manifest the reaction it had been selected to show. However, only those concrete specimens containing the reactive 1-8 coarse aggregate showed expansion above that normal for specimens stored in the moist room, and only those specimens containing the Rapid rock as all of the coarse aggregate had unusual compressive strengths. These points are considered in detail in later paragraphs.

Rocks

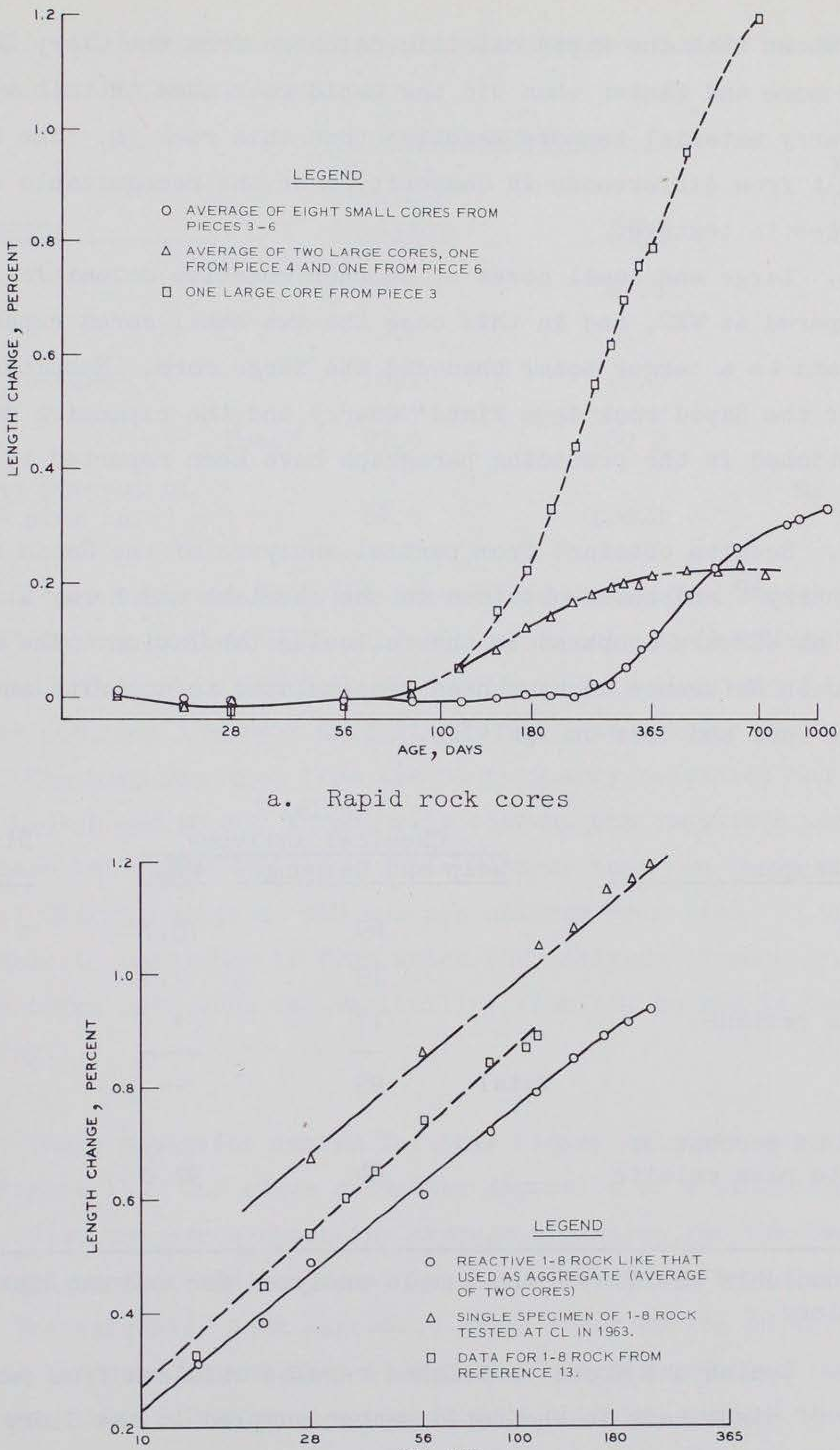
22. The specific gravity and absorptions of five coarse aggregates and two fine aggregates are shown in Table 1. Note the low specific gravity and high absorption of the Rapid rock as compared with those of the other aggregates. Note also that the specific gravities for the Hermitage dolomitic limestone and the reactive 1-8 rock are similar enough that the solid volume replacements in the concrete mixtures did not result in significant differences in bulk volumes.

23. Composition data for the reactive aggregates and the hand samples of these rocks are shown in Table 2 with some chemical data for the aggregate samples of the Rapid rock and the 1-8 rock. Petrographic data for the hand samples of the Rapid rock from the Glory Quarry are also shown.

24. Individual and average length-change data for small cores stored in 1 N sodium hydroxide solution are given for ages to 3 yr in Table 3.

Rapid calcitic dolomite

25. The average expansion of eight small cores from pieces 3-6 that represent the composition of the aggregate used in concrete is shown in Figure 1a; the expansion curves for the three larger cores from pieces 3, 4, and 6 of the calcitic dolomite are also shown. The larger cores, 0.531 by 2 in., expanded earlier than did the smaller cores, which were about 0.35 in. in diameter and 1.25 in. long. In either case, this Rapid rock expanded later than did the 1-8 rock (see Figure 1b).



a. Rapid rock cores

b. Small 1-8 rock cores

Figure 1. Length change of cores stored in 1 N NaOH solution (CRD-C 146)

Table 3 shows that the Rapid calcitic dolomite from the Glory Quarry expanded more and faster than did the Rapid rock used in this work; the Glory Quarry material is more reactive than this rock is. The difference may result from differences in composition or the recognizable slight differences in texture.

26. Large and small cores of another reactive dolomitic limestone were compared at WES, and in this case the two small cores expanded more rapidly and to a larger total than did the large core. Results like those for the Rapid rock from Pints' Quarry and the expansive dolomitic rock mentioned in the preceding paragraph have been reported by Dolar-Mantuani.[12]

27. Results obtained from partial analyses of the Rapid rock from Pints' Quarry[13] and those obtained in the chemical and X-ray diffraction analyses at WES are compared in the following tabulation. The results published in Reference 13 have been recalculated to dolomite and calcite from MgO, CaO, and loss on ignition.

Sample		Partial Chemical Analyses: Welp and DeYoung[12]	Partial Chemical Analyses: WES	X-ray Diffraction WES
Dolomite		69	78.7	76
Calcite		13	7.8	8
Insoluble residue		17	*	16
	Total	99	--	100
Dolomite as percent of dolomite plus calcite		84	91.0	90

* The insoluble residue of the sample analyzed for CaO and MgO was not determined.

28. Lemish and Moore[5] published results obtained from partial analyses of eight beds in the Rapid member sampled in the Glory Quarry. Of these eight beds, bed 10 was selected as the one most similar to the hand specimen of Rapid rock examined at WES, and the results of the analysis of this bed and the results of X-ray diffraction and

determination of insoluble residue of the specimen examined at WES are compared in the following tabulation.

Sample		Lemish and Moore[5] Partial Chemical Analyses	Lemish and Moore[5] XRD	WES XRD and Insoluble Residue
Dolomite		68.9	84.0	70
Calcite		12.9	--	18
Insoluble residue		16.1	16.2	12
	Total	97.9	100.2	100
Dolomite as percent of dolomite plus calcite		84.0	100.0	80

29. It is apparent from the preceding tabulations that the rock from Pints' Quarry used at WES as coarse aggregate and the Pints' Quarry samples examined by Welp and DeYoung[13] contained similar amounts of insoluble residue, but the rock used at WES had less calcite and more dolomite. The hand specimen from the Glory Quarry resembled bed 10 as tested by Lemish and Moore[5] in dolomite content but contained more calcite and less insoluble residue. Table 2 shows that the Rapid rock from Pints' Quarry tested at WES was not uniform from piece to piece, and the table in Reference 12 from which the analysis of rock from bed 10 was taken indicates the variability from bed to bed in the Glory Quarry.

1-8 rock

30. Three expansion curves for this clayey calcitic dolomite are shown in Figure 1b. One curve shows the expansion of a single specimen tested in 1963; one curve shows the average expansion for the two cores from the hand sample; and the remaining curve was taken from Reference 13. The generally good agreement among these curves shows that the rock is homogeneous and that it expanded quickly and to a large total in this test. It always expanded more than 0.1 percent during the first week of testing. Compositions of samples of this rock reported by Newlon and Sherwood[7,8] and the composition as determined at WES are compared in the following tabulation.

Sample	Newlon and Sherwood: HRB Bulletin 355	Newlon and Sherwood: HR Record No. 45	WES: XRD	WES: Partial Chemical Analysis
Dolomite	45	45	48	43
Calcite	29	27	24	33
Insoluble residue	26	28	28	*
Total	100	100	100	
Dolomite as percent of total carbonate	61	63	67	

* Not determined.

In all three cases dolomite and calcite were determined by the method of Tennant and Berger[10] and insoluble residue by treatment with excess HCl.

Pixley limestone

31. This limestone shows slight shrinkage of about 0.03 percent during length-change testing for 3 yr (Table 3). The compositions of a sample reported by Buck and Dolch[15] and the sample tested at WES are compared below:

Sample	Buck and Dolch	WES*	
Dolomite	**	5	0
Calcite	97	90	95
Insoluble residue	3	5	5
Total	100	100	100
Dolomite as percent of total carbonate	0	5	0

* Two samples.
** Not detectable.

Hermitage dolomitic limestone

32. Length-change data are not reported. Fourteen small cores were tested in 1 N NaOH solution. Twelve of these either showed negligible expansion or shrank during 3 yr of testing. Two of the 14 cores

expanded more than 0.1 percent in 84 days of testing. This rock is only slightly reactive. In this respect the Hermitage limestone resembles expansive rocks from Indiana with satisfactory physical properties as tested by Hadley.[16]

Portland Cements

33. Table 4 shows chemical and physical data for the cements used. The cements were also examined by X-ray diffraction. RC-168 contained fairly high belite, rather low alite, periclase (MgO), high C_3A, and an aluminoferrite of essentially the alumina to alumina plus iron oxide ratio of C_4AF, i.e. 0.50. RC-167 contained more C_3A than did RC-168, high alite, rather low belite, periclase, and an aluminoferrite between C_6AF_2 and C_4AF, with the ratio of alumina to alumina plus iron oxide of 0.41. RC-594 contained less C_3A than did the other two, less alite than RC-168, more belite than RC-167 but less than RC-168, periclase, and an aluminoferrite between C_6AF_2 and C_4AF, with the ratio of alumina to alumina plus iron oxide of 0.44. The difference in fineness among the three cements was considerable.

Concrete

34. Identifying data and test data on slump, air content, and cement factors are shown in Table 5 for all 33 of the concrete mixtures. The water-cement ratio for all mixtures was 0.49.

Compressive strength

35. Table 6 shows strengths of individual cylinders and averages at 7, 14, 28, 90, 180, and 365 days. An analysis of variance (ANOVA) was made with this data. The variables were (a) coarse aggregates at 11 levels (3 reactive aggregates at each of 3 dilutions and 2 control aggregates), (b) cements at 3 levels, (c) ages at 6 levels, and (d) rounds at 3 levels. Several significant results were obtained, some of which were highly significant. At all ages the strengths of round 3 were found to be significantly lower than those of rounds 1 and 2. However,

there was no physical basis for eliminating the third round. Therefore, the data were averaged for all three rounds (Table 6) since the same conclusions are reached by examining either overall averages or individual round averages.

36. Figure 2 shows strength development of concrete containing

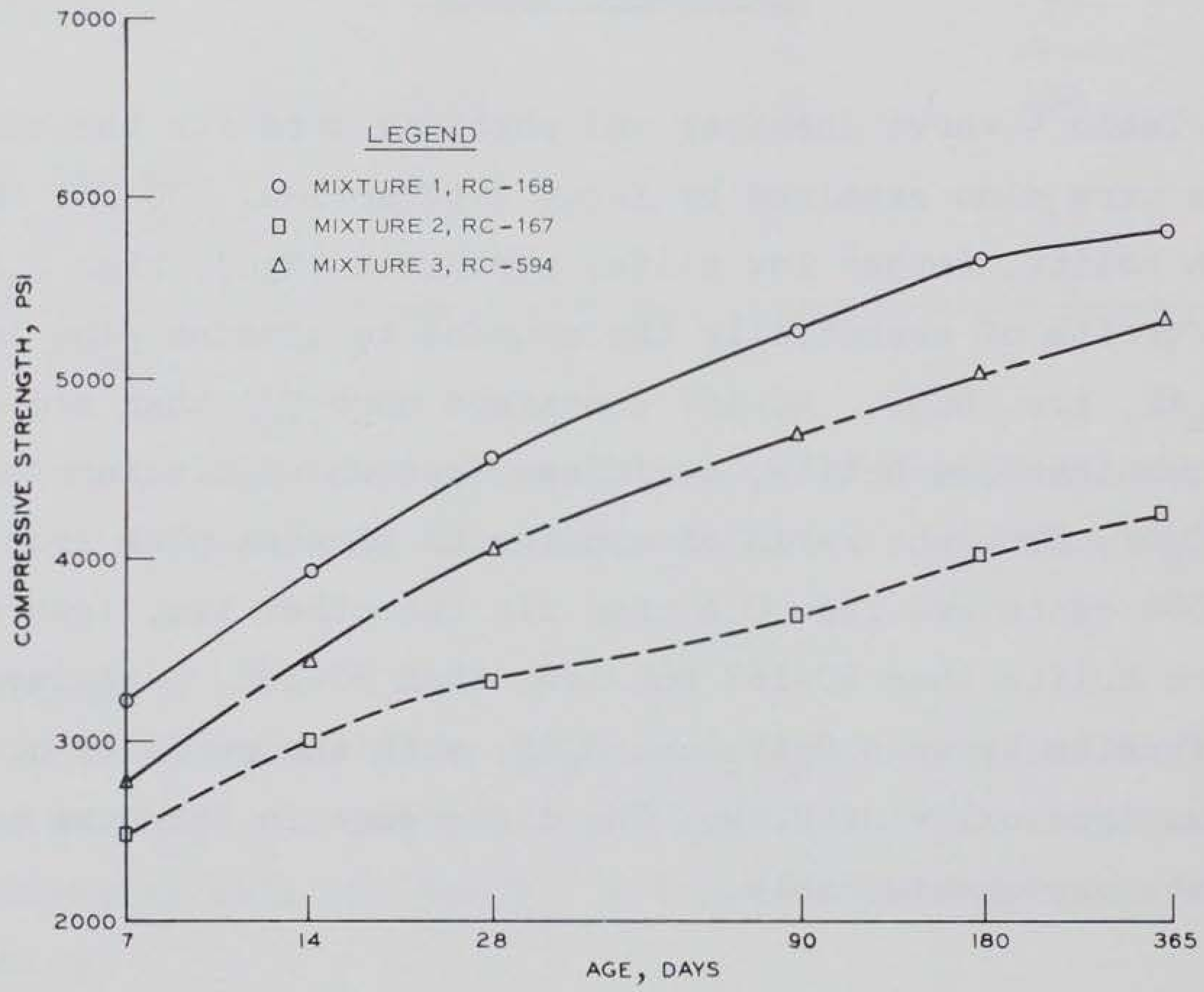


Figure 2. Compressive strengths of concrete cylinders made with gneiss and different cements (3 rounds)

the granite gneiss with each cement. The concrete strengths arrange themselves in order of alkali content, with the low alkali cement stronger than either high-alkali cement and with the coarsest cement producing the lowest strengths. The ANOVA indicated that with each cement there was no significant difference between compressive strengths of mixtures which contained 20 and 40 percent Rapid calcitic dolomite; therefore, the curves for these two mixtures are combined in Figures 3-5, which show the compressive strengths to 1 yr of concretes containing the Rapid coarse aggregate with each cement. The control mixtures containing Hermitage dolomitic limestone are shown for comparison. The ANOVA also indicated that for each cement there were no significant

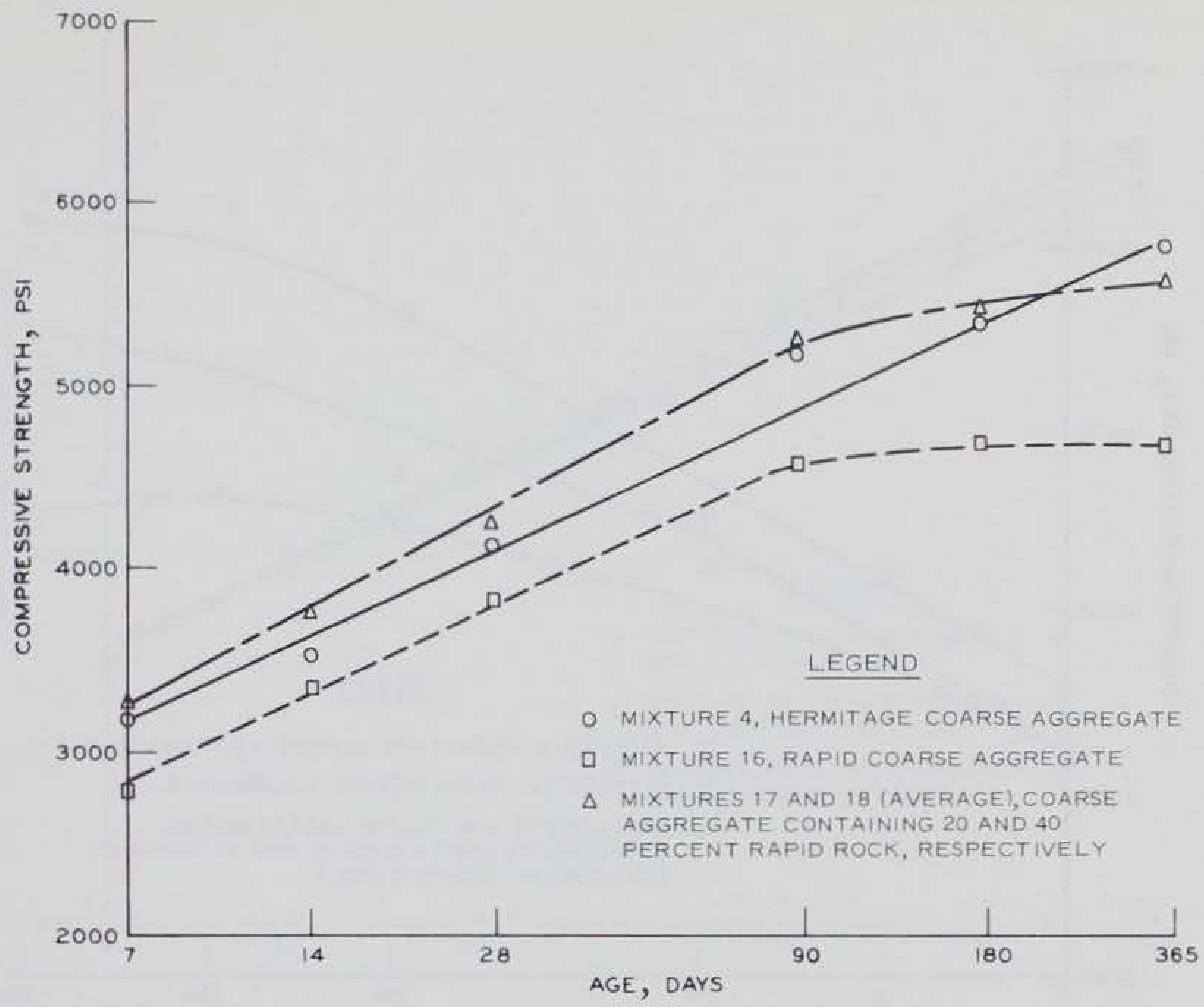


Figure 3. Comparison of compressive strengths of concrete cylinders made with RC-168 and different coarse aggregates (3 rounds)

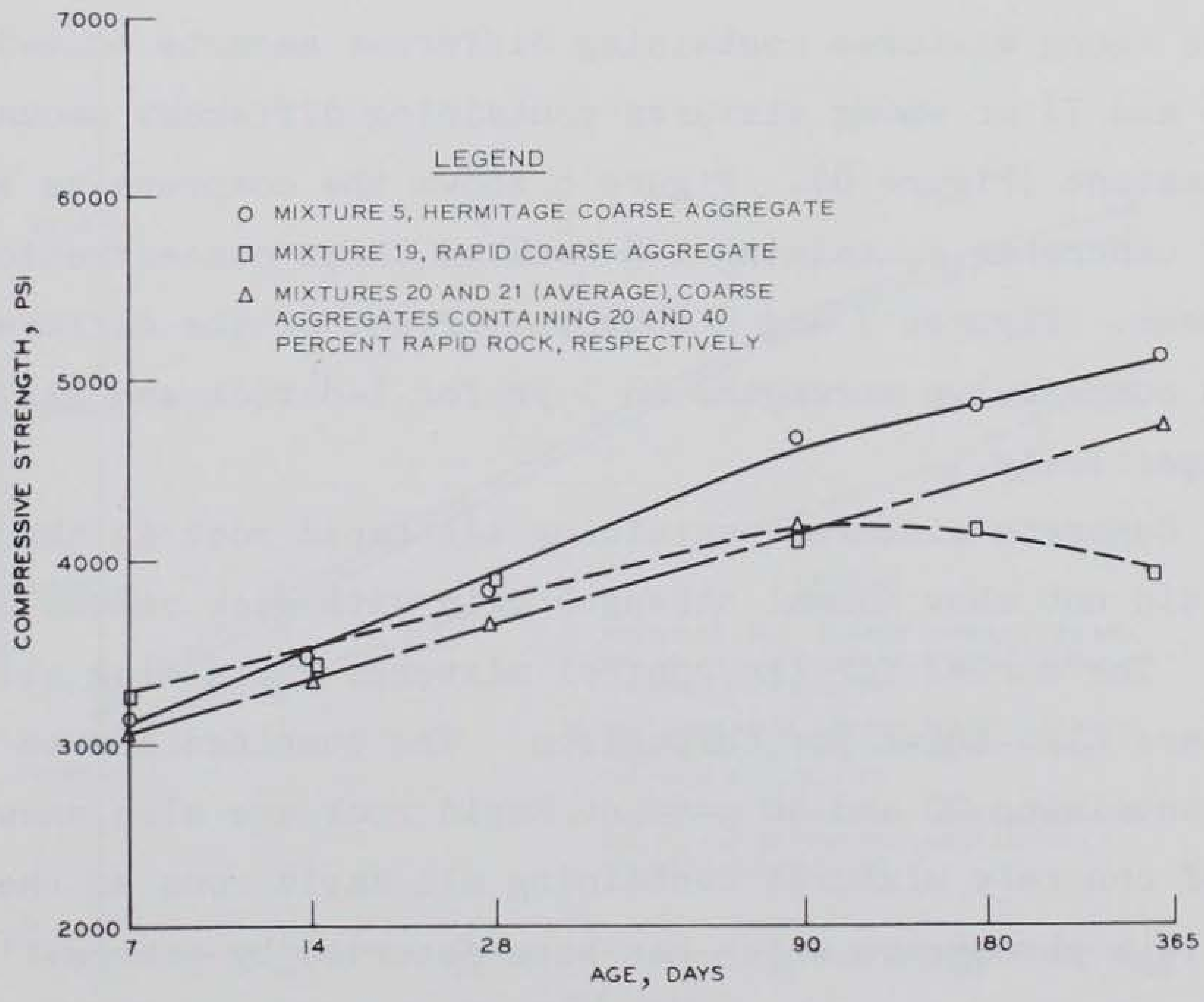


Figure 4. Comparison of compressive strengths of concrete cylinders made with RC-167 and different coarse aggregates (3 rounds)

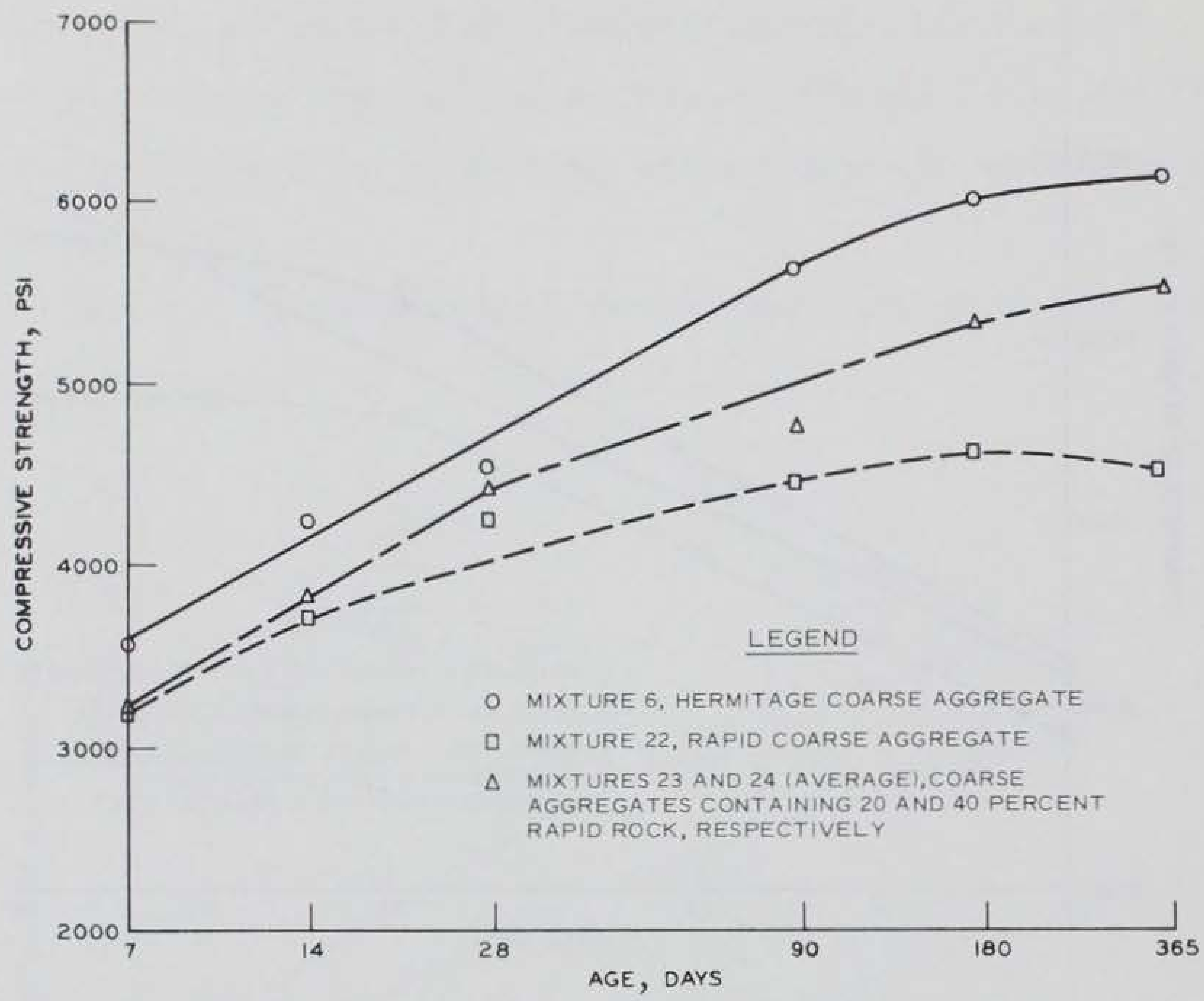


Figure 5. Comparison of compressive strengths of concrete cylinders made with RC-594 and different coarse aggregates (3 rounds)

differences among mixtures containing different amounts of 1-8 rock (Figures 6 and 7) or among mixtures containing different amounts of Pixley limestone (Figure 8). Figure 6 shows the compressive strengths of 1 yr of concretes containing 1-8 rock at three concentrations with RC-594 cement. Figures 7 and 8 show the effect of the different cements on compressive strengths to 1 yr for 1-8 rock and Pixley limestone, respectively.

37. Concrete mixtures containing all Rapid rock as the coarse aggregate did not show normal strength gain with each cement (Figures 3-5). The curves for the control mixtures containing all Hermitage rock are also shown for comparison. The combined curves for the mixtures containing 20 and 40 percent Rapid rock are also shown. This behavior of concrete mixtures containing all Rapid rock as the coarse aggregate is a phenomenon which has been observed by others.[5,6] The compressive strength data shown in Table 7 for 2-in. cubes cut from selected length-change bars were obtained in an attempt to determine

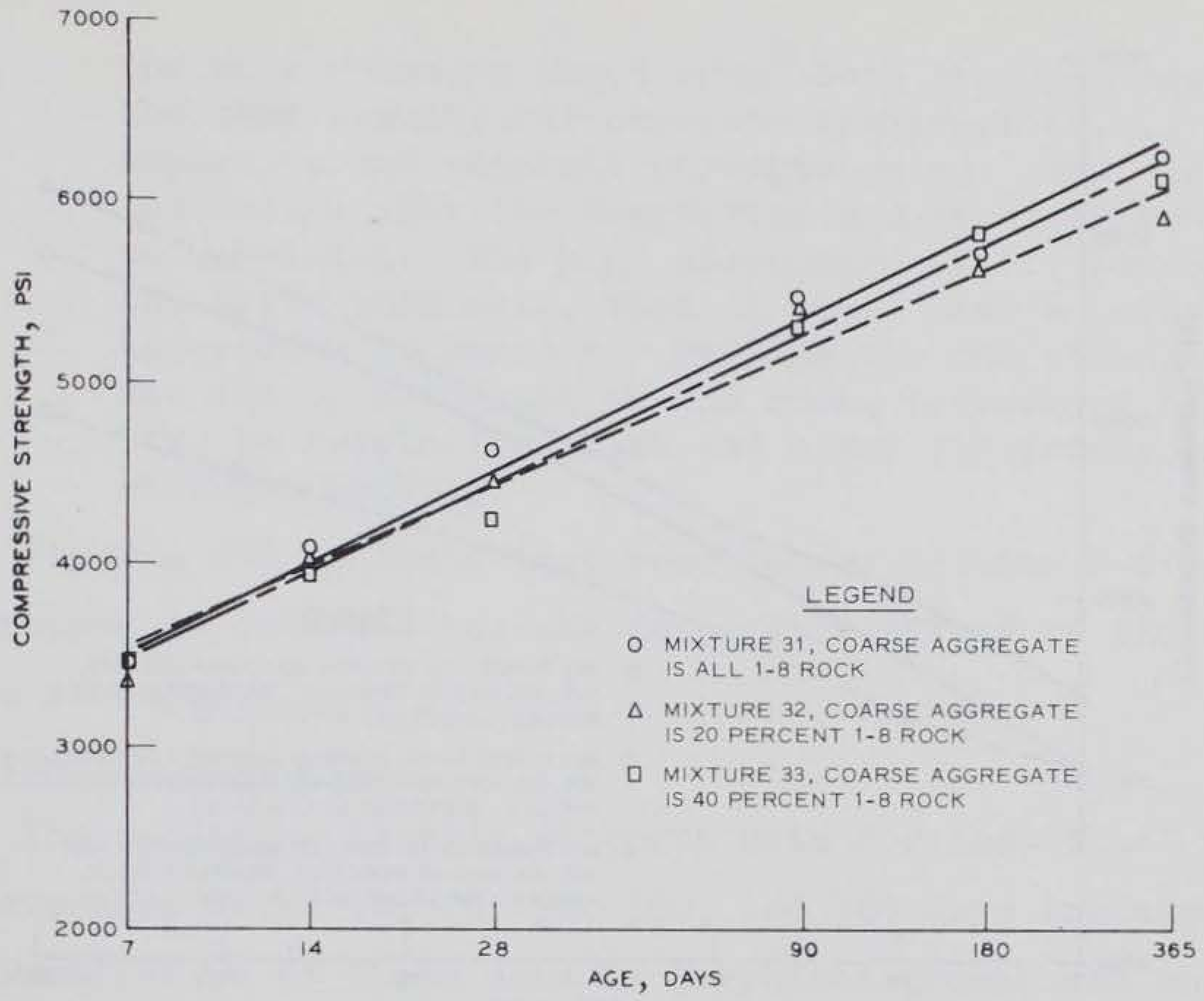


Figure 6. Compressive strengths of concrete cylinders made with 1-8 rock and RC-594 (3 rounds)

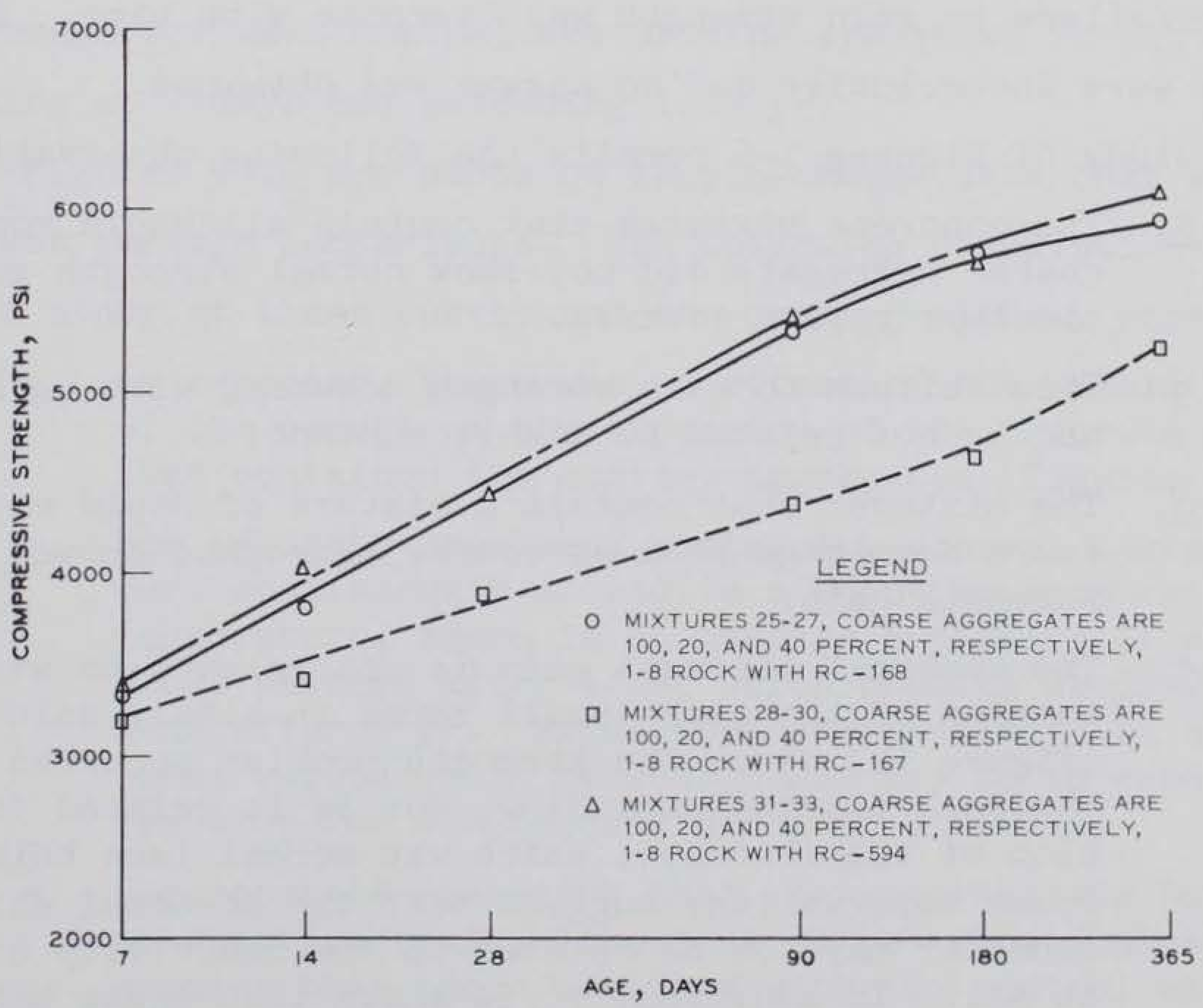


Figure 7. Compressive strengths of concrete cylinders made with 1-8 rock and different cements (3 rounds)

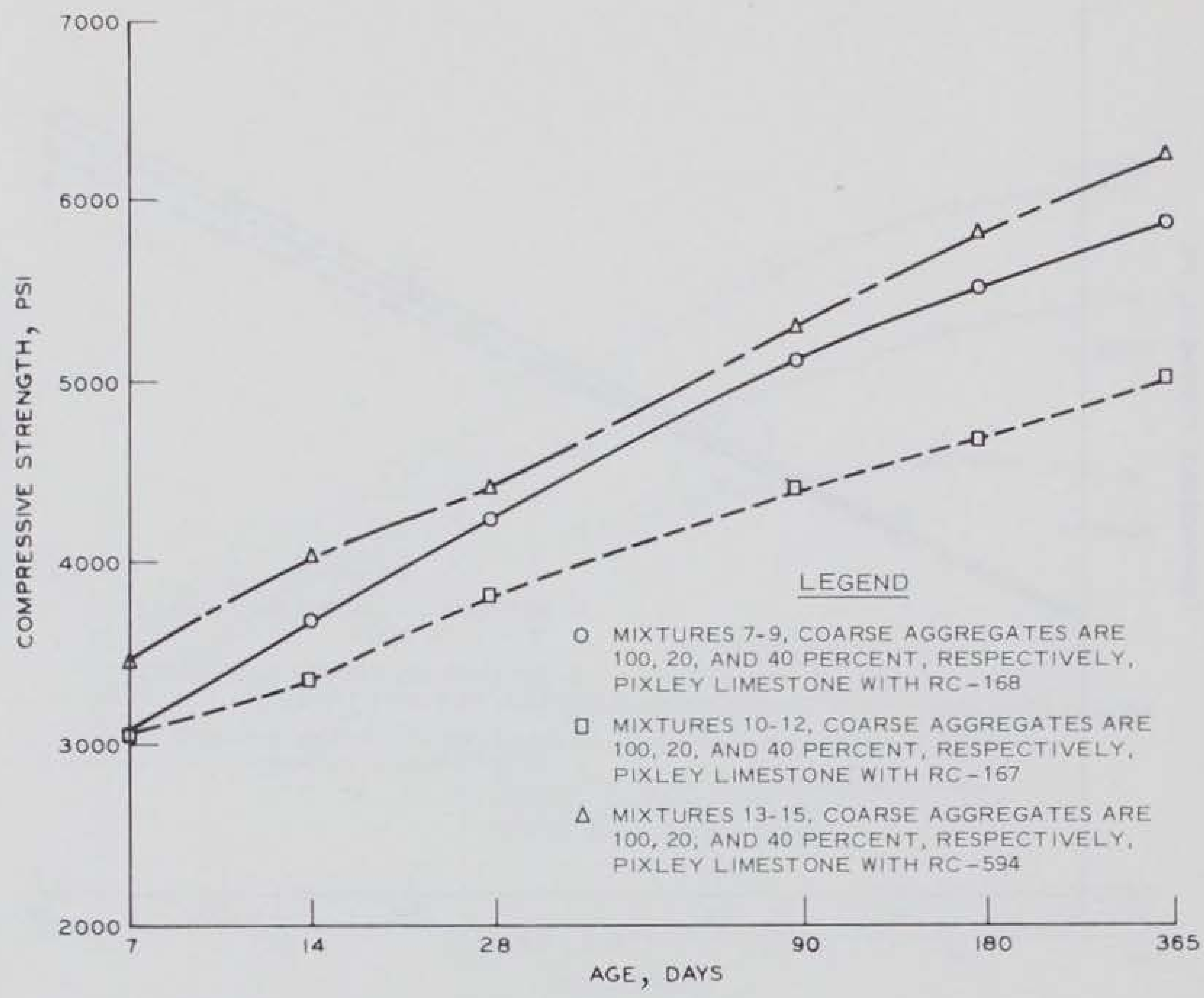


Figure 8. Compressive strengths of concrete cylinders made with Pixley limestone and different cements (3 rounds)

whether the failure to gain strength was overcome with time. However, the results were inconclusive and no answer was obtained.

38. Study of Figures 1-5 permits the following observations:

a. The concrete mixtures that contain all Rapid rock as coarse aggregate did not show normal strength gain over the 1-yr period covered.

b. This failure to gain strength occurred with each cement and is not related to alkali content.

c. The mixtures that contain a mixture of Rapid rock and inert Hermitage rock as coarse aggregate showed normal strength gain.

d. The abnormal strength gain is not related to average expansion of the eight small cores in alkali solution (Figure 1a) since the strength problem occurred before the rock started expanding, nor is it related to expansion of the concrete, which was normal (see below). These observations suggest that the abnormal strength behavior may not be related to the reactivity of the rock at all. In addition, it is known that tests with the less reactive Rapid rock used in this work and tests with the more reactive Rapid rock[6] both produced essentially the same results for concrete specimens (i.e., normal expansion and abnormal strength gain). This is another indication that the reactivity and strength behavior may be unrelated. The high absorption of 6.7 percent for the Rapid rock means that it would have a porosity that approaches 20 percent. Perhaps the odd strength behavior was due to a failure of the rock, because of high porosity, to retain its shape and carry its proper load during strength testing.

39. Figures 6-8 indicate that reaction of neither 1-8 rock nor Pixley limestone in concrete has any detectable effect on the concrete compressive strength.

Splitting tensile strength

40. The splitting tensile strength data for individual cylinders and their averages at 7, 14, 28, 90, 180, and 365 days are shown in Table 8. Examination of these data by graphical procedures showed that the test variation was too great to permit any useful analysis.

Length changes

41. Three concrete bars, each 2 by 2 by 11-1/4 in., were made from each round of each mixture. The length-change data for each bar and the average for each nominal set of nine are shown in Table 9 for ages starting at 7 days and extending to 3 yr.

42. Figures 9-14 are plots of length-change data that were selected to illustrate certain comparisons. The following observations may be made from a study of these curves and the data previously presented.

a. As expected, there was no effect of the alkali content of the cement on the expansion of the concrete specimens that contained the control aggregates (Figures 9 and 10).

b. For concrete specimens containing control aggregates that were continuously stored in a moist environment at room temperature, there is an average expansion of about 0.025 percent after 1 yr, which becomes about 0.030 percent after 3 yr. Expansions substantially in excess of these values would be considered due to an expansive reaction for the present group of mixtures.

c. The concrete specimens that contain reactive Rapid rock or reactive Pixley limestone do not show expansions greater than those obtained with the control aggregates (Figures 11 and 12).

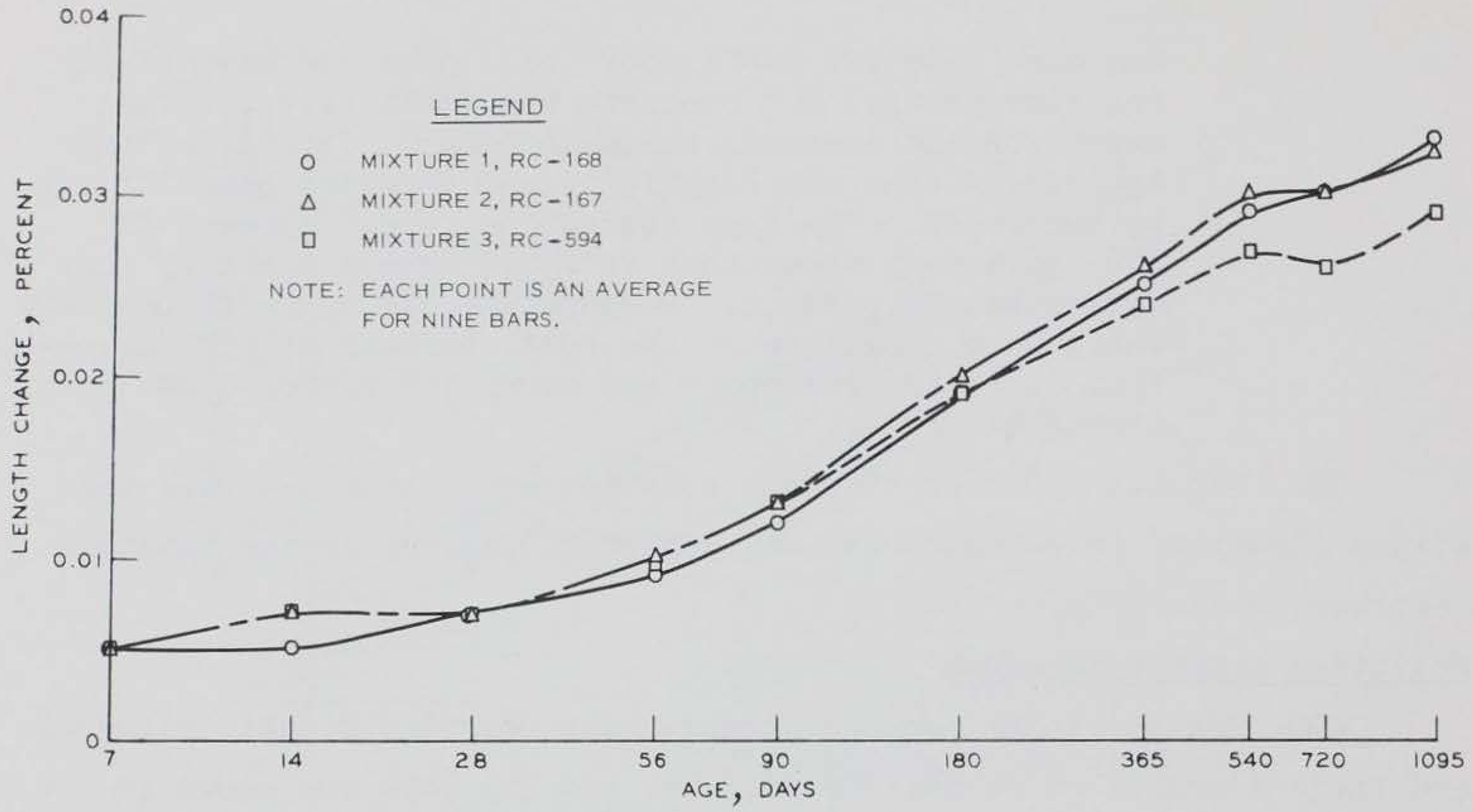


Figure 9. Length change of concrete bars made with granite gneiss and different cements

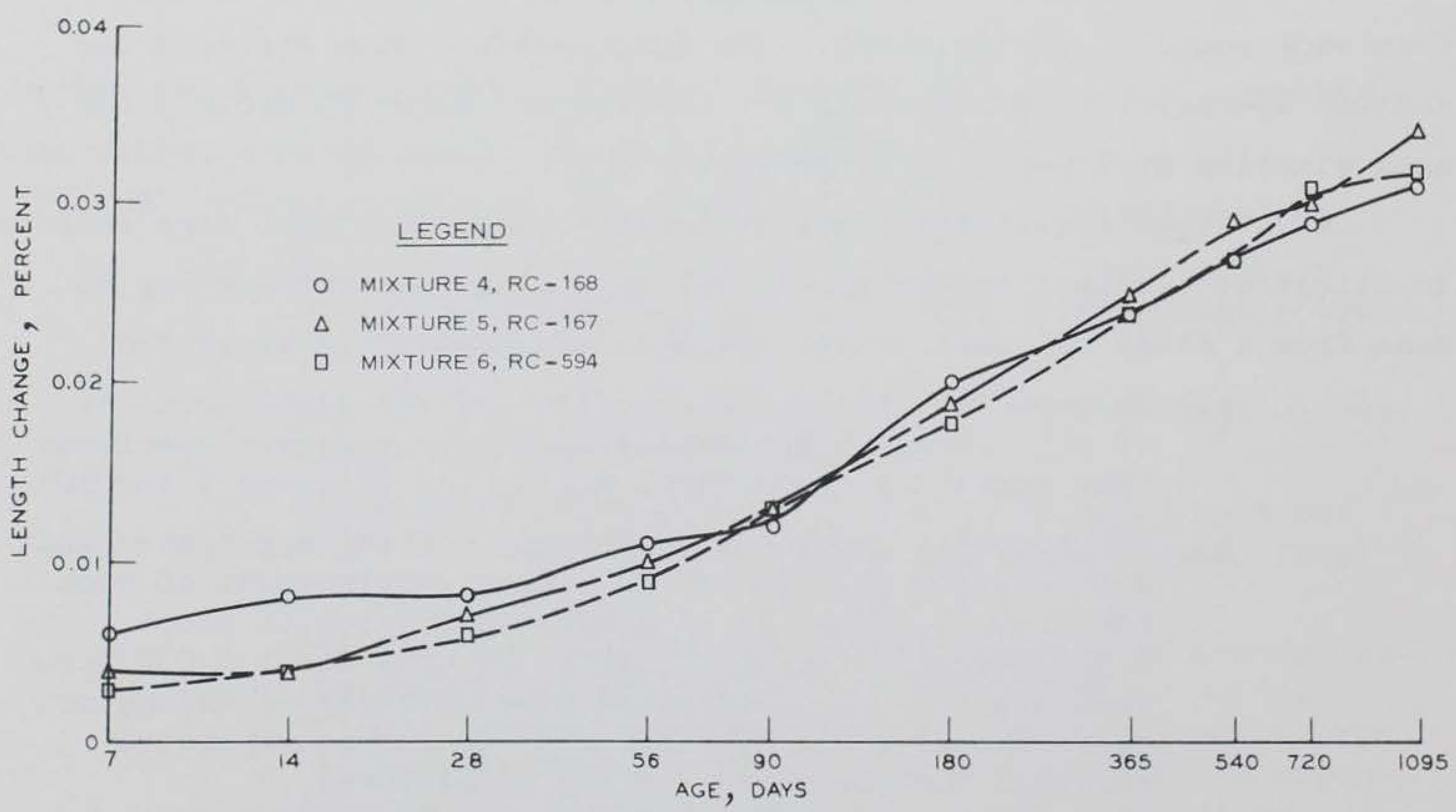


Figure 10. Length change of concrete bars made with Hermitage rock and different cements

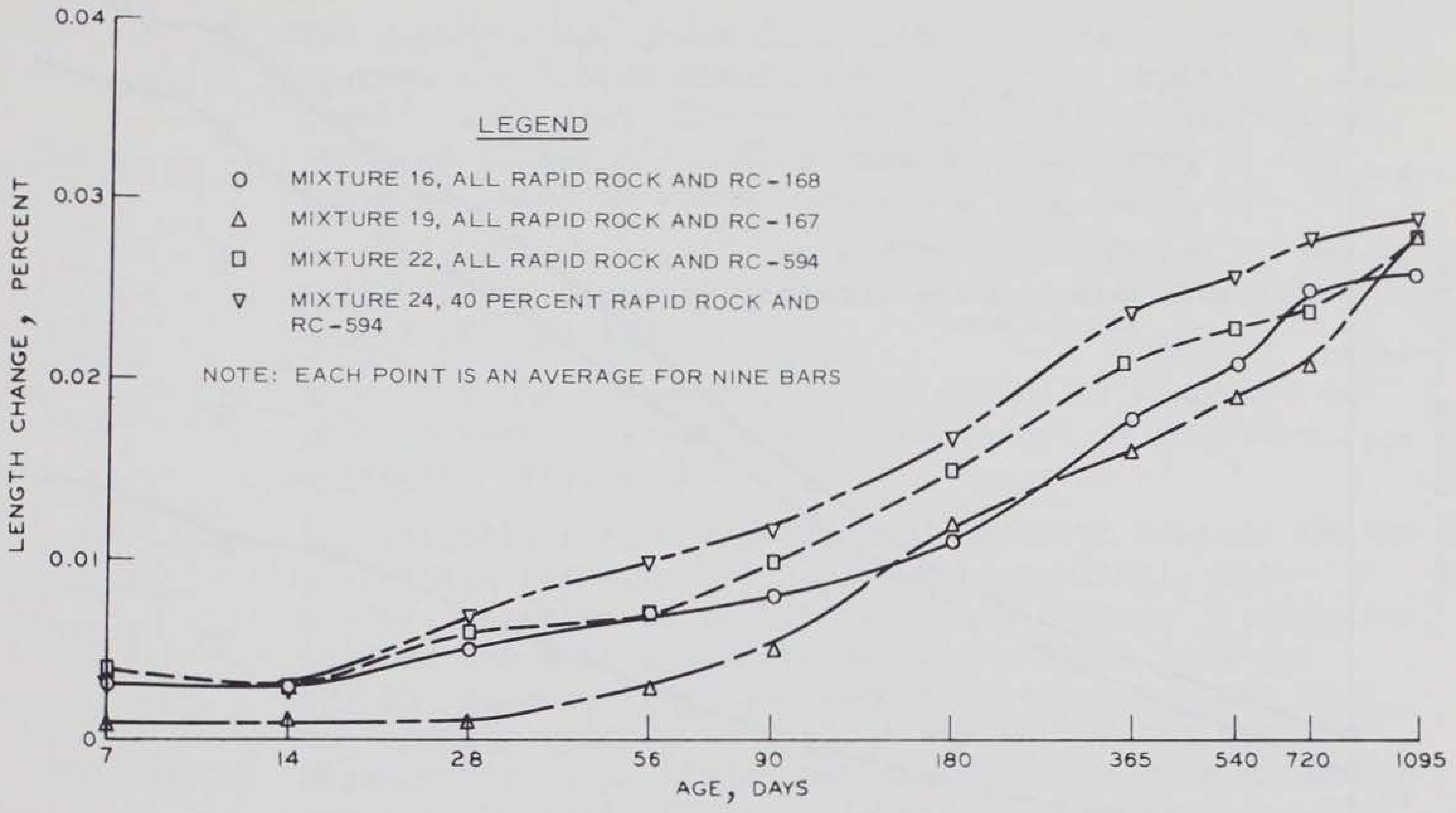


Figure 11. Length change of concrete bars made with 40 and 100 percent Rapid rock and different cements

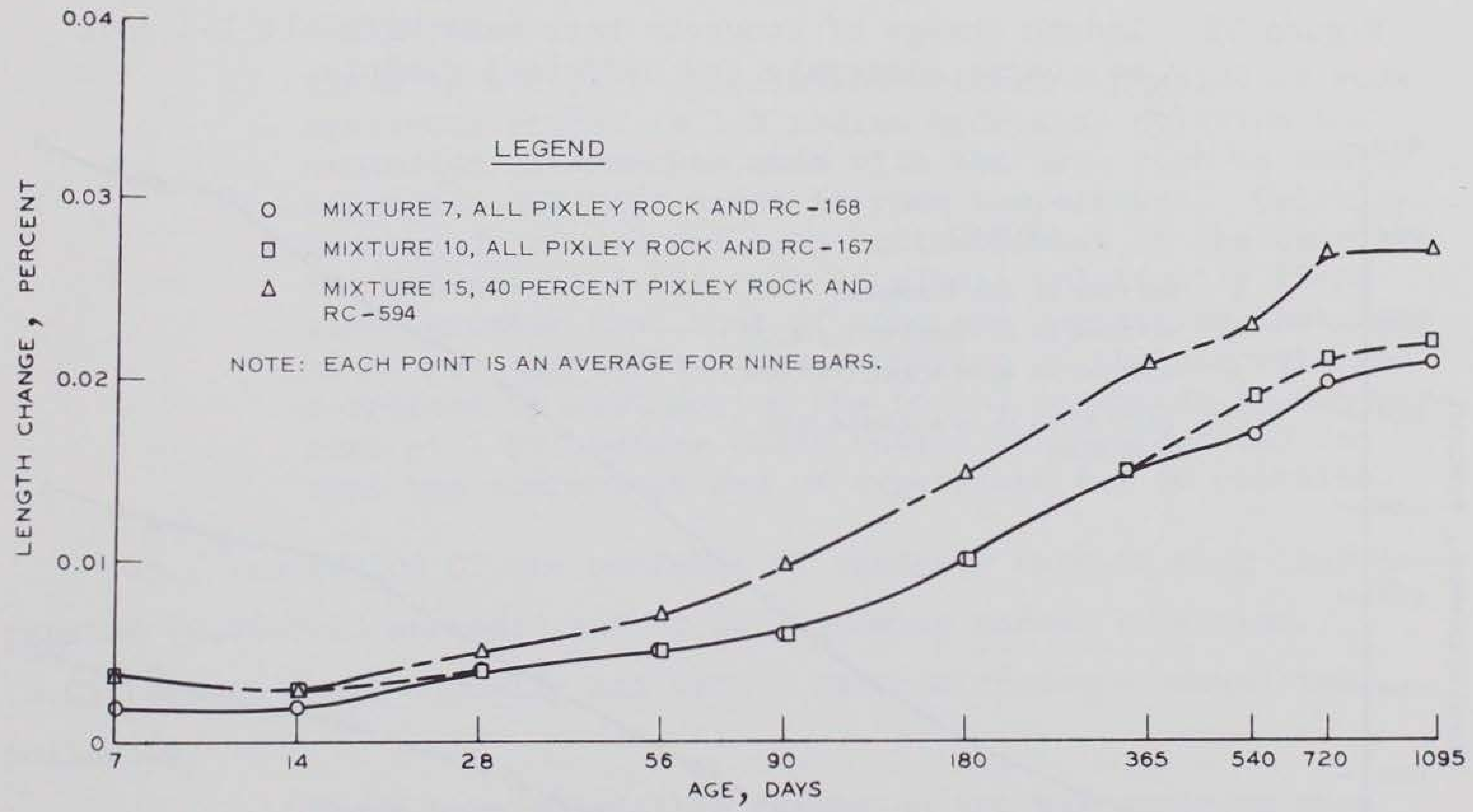


Figure 12. Length change of concrete bars made with 40 and 100 percent Pixley limestone and different cements

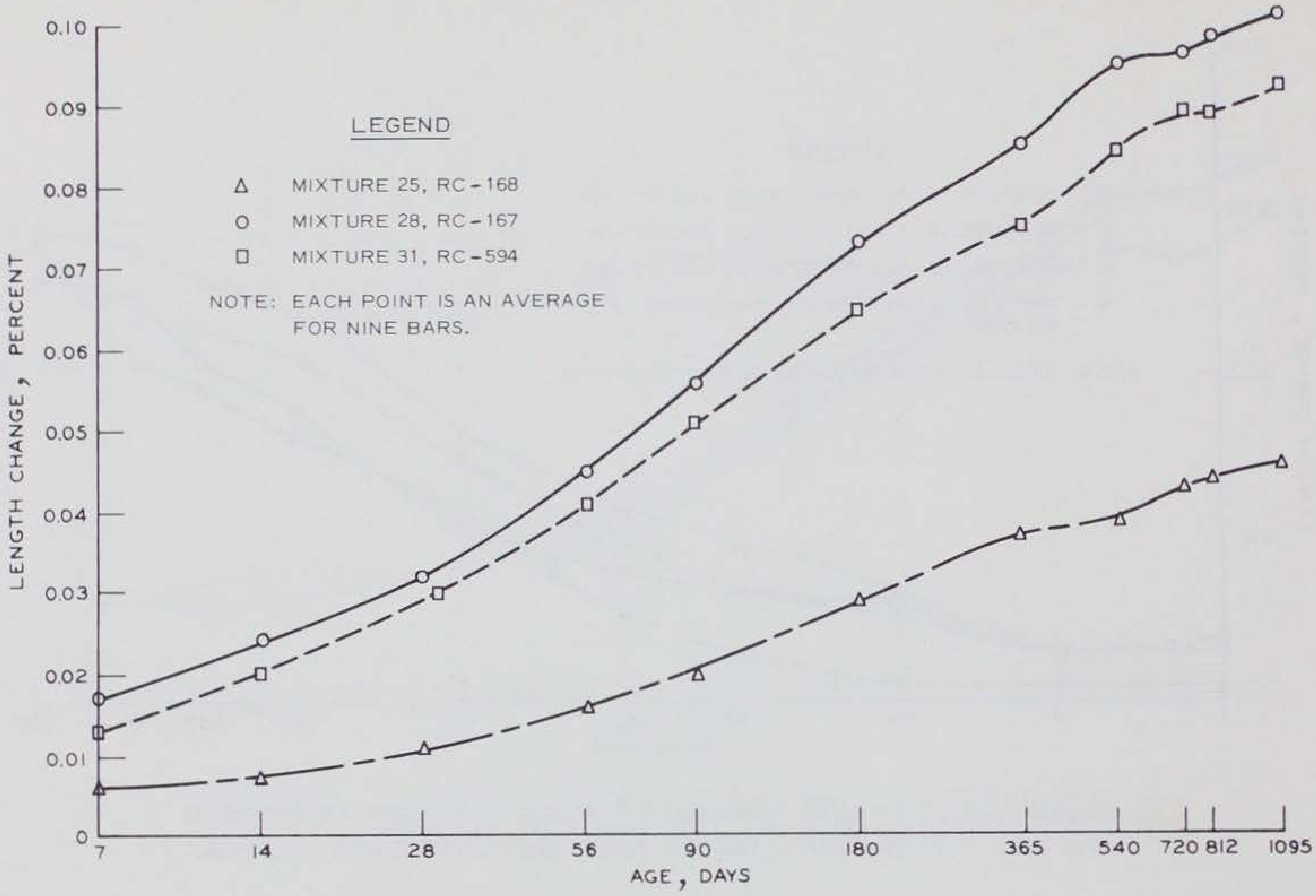


Figure 13. Length change of concrete bars made with all 1-8 rock as coarse aggregate and different cements

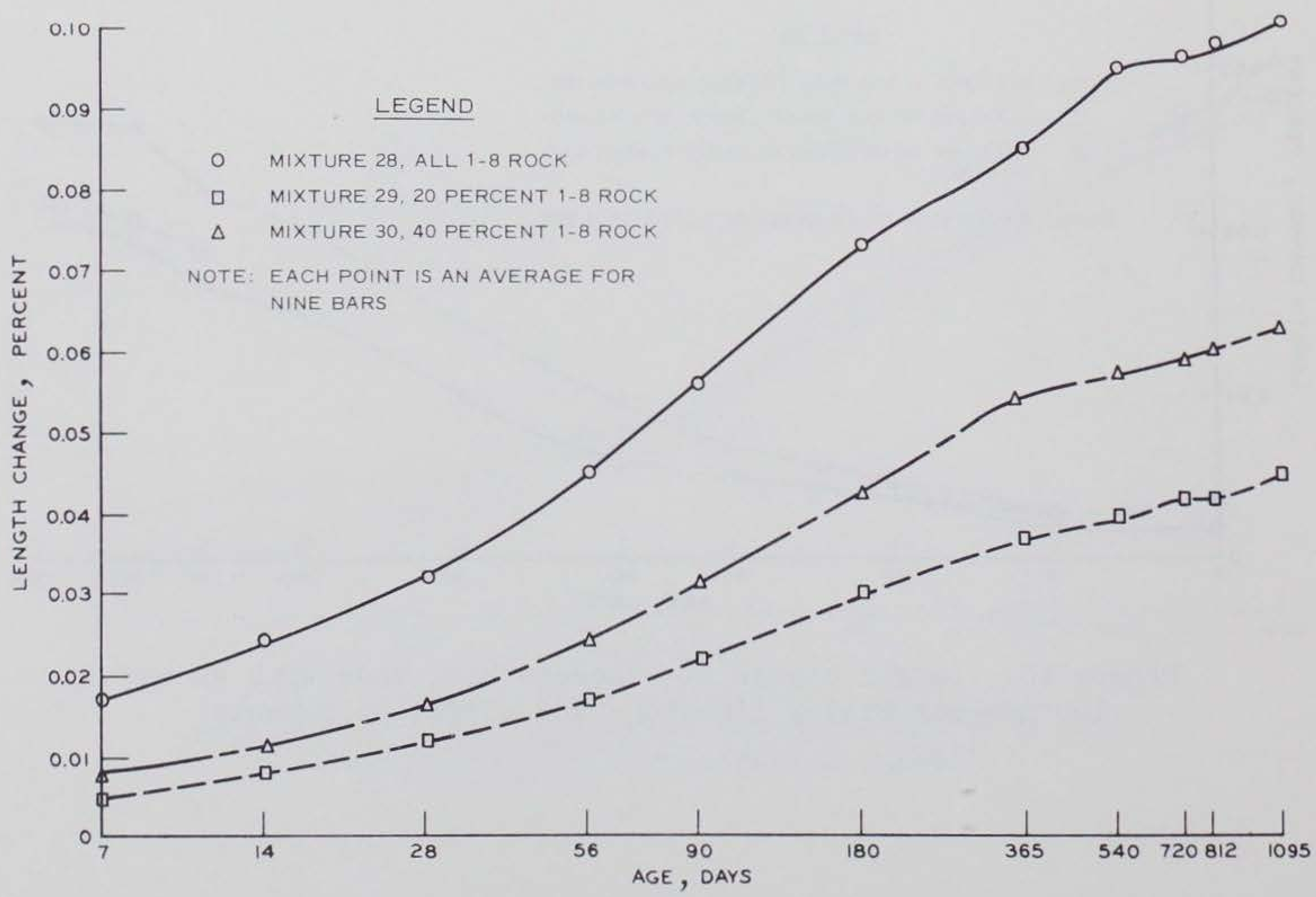


Figure 14. Length change of concrete bars made with RC-167 and different amounts of 1-8 rock as coarse aggregate

d. The concrete specimens made with 1-8 rock as coarse aggregate and high-alkali cement do show expansion greater than that obtained with the control aggregates (Figures 13 and 14). This expansion is three to four times as large as normal expansion at 1 yr of age.

e. As found elsewhere,[7,8] the amount of expansion of concrete varies directly with the alkali content of the cement (Figure 13).

f. Also as found elsewhere,[7,8] the amount of concrete expansion varies directly with the amount of reactive aggregate (Figure 14).

g. The slightly larger expansion of concrete mixture 28, containing reactive 1-8 rock and high-alkali, high-C_3A RC-167, relative to that of concrete mixture 31, containing the same aggregate and high-alkali, low-C_3A RC-594, suggests that the amount of expansion may also be directly related to the C_3A content of the cement. However, it is possible that the difference in expansion may be due solely to the slightly higher alkali content of RC-167 (Table 4).

h. The higher expansions had no detectable effect on either the compressive or the tensile strengths of the same mixtures.

i. There is a direct correlation between expansion of rock specimens stored in 1 N sodium hydroxide solution and expansion of concrete made with the same rock as coarse aggregate and kept moist at room temperature. Calculations made at several ages indicate that at the same age the expansion of the rock in alkali solution is 15-20 times greater than that of concrete containing that rock as coarse aggregate. The expansion of the concrete was corrected by subtracting the normal expansion (0.025 percent at 1 yr) before these ratios were calculated so that the comparison was of expansions due to reaction.

43. Inspection of the surfaces of concrete bars showing high expansion (0.08-0.10 percent) and of bars showing normal expansion (0.03 percent) both visually and with a stereomicroscope showed the following:

a. There were no visible cracks on the bar surfaces when examined without magnification.

b. Numerous cracks were visible on the surfaces of the high-expansion bars when examined at 10×.

c. No cracks were detected on the surfaces of the normal expansion bars when examined at 10× or higher magnification.

Evaluation of Appendix C[2] Criteria

44. Inspection of concrete bars showed that bar expansion of 0.08 to 0.10 percent produced cracking while 0.03 percent expansion did not cause cracking. Let us assume that 0.05 percent expansion is the maximum amount permissible for concrete and that an expansive rock in alkali solution expands 15 to 20 times more than does concrete containing that rock as coarse aggregate. Such a reactive rock will expand from 0.75 to 1.00 percent in the alkali solution. The reactive 1-8 rock in alkali solution exceeds 0.1 percent expansion by 7 days and has expanded about 0.8 percent by 84 days. The Appendix C[2] criteria of 0.1 percent expansion of rock in alkali solution by 84 days will detect the potentially reactive rock as intended. These criteria also include a desirable factor of safety. As shown in Figures 13 and 14, the use of low-alkali cement or dilution of reactive coarse aggregate to a value of 20 percent will restrict expansion of reactive concrete specimens kept continuously moist at room temperature for 3 yr to about 0.045 percent. This expansion would probably be less for specimens subjected to periods of drying. Therefore, the criteria of Appendix C,[2] which require the use of low-alkali cement dilution so that the maximum amount of reactive coarse or fine aggregate is 20 percent or the combined amount of reactive coarse and fine aggregate is 15 percent, and the use of the practical minimum aggregate size appear to be effective and not excessive. No data were obtained in this investigation on the effectiveness of aggregate size in controlling the expansive reaction. The combined use of several control measures, when individual ones are effective, provides a desirable factor of safety against damaging expansive reaction.

45. There is a substantial difference between Test Method CRD-C 146 (ASTM Designation C 586) and Appendix C of Reference 2. The test method states that the results obtained by storing rock specimens in alkali solution are not recommended for use for acceptance or rejection of aggregate sources; it favors the testing of potentially reactive aggregates in concrete as the basis for evaluating reactivity. Appendix C[2] directs that the test data of CRD-C 146 be used as the basis for

deciding if an aggregate is potentially reactive and specifies the controls to be used for materials classified as potentially reactive. When CRD-C 146 was written, the sampling problem (small rock specimens representing tons of material) and insufficient information regarding the relationship between expansion of a rock specimen in alkali solution and expansion of concrete containing the same rock as coarse aggregate were the main reasons for not using the test data to evaluate the potential reactivity of an aggregate. The sampling difficulty will always exist, but it should not prevent the use of CRD-C 146 test data for evaluation. The relationship between the expansion of concrete and rock specimens is now adequately known to permit the use of CRD-C 146 test data as they are used in Appendix C.[2]

Special Examinations

XRD

46. Selected surfaces of Rapid and 1-8 rock were examined by XRD before and after storage in alkali solution and also before and after embedment in pastes of high-alkali cements. The purpose of these examinations was to determine quantitative mineralogical changes. Quantitative data for the specimens stored in alkali solution for about 12-19 months are shown in Table 10 for the Rapid rock and Table 11 for the 1-8 rock. The results shown are similar to data reported in the literature.[17,18] Storage in alkali solution destroys some of the dolomite, which is replaced by calcite, brucite, and hydrotalcite or a hydrotalcite-like substance. The latter tends to be found on the original surface while brucite tends to be more common below the original rock surface. The presence or absence of visible reaction rims on the Rapid rock is also shown in Table 10.

47. It was not possible to extract the 1-8 rock from the cement pastes at a test age of 2 yr without damaging the selected surface. When this technique was used with the Pixley limestone,[9] the test period was only a few months. The increased paste age and the greater reactivity of the 1-8 rock developed a bond which was too strong to permit

separation at the interface between rock and cement paste. The nonquantitative XRD results obtained on the damaged 1-8 rock slabs after removal from cement paste are also shown in Table 11. The major point of interest here is that the 7.7-Å substance (hydrotalcite?) was definitely found at the reaction interface of rock and cement paste. Removal of the slabs of Rapid rock from cement paste was not attempted.

SEM

48. Eight micrographs are shown in Photos 1-3. They were chosen from about 100 micrographs of unreacted 1-8 rock, 1-8 rock after 19 months in sodium hydroxide solution, the 34-month-old interface areas of 1-8 rock in two high-alkali cement pastes, a 32-month-old concrete bar containing high-alkali cement RC-594 and 1-8 as coarse aggregate, and a 34-month-old concrete bar containing high-alkali cement RC-594 and the Hermitage rock as coarse aggregate. Examination of these pictures shows:

a. There is no striking difference in the appearance of fracture surfaces of the reactive 1-8 rock and the Hermitage rock (Photo 1).

b. There is a visible difference in the appearance of unreacted and reacted 1-8 rock in Photos 2a and 2b. This was interpreted as probably being due to a filling of void space by reaction products on the surface of the reacted rock.

c. The surface of the reacted 1-8 rock after storage in alkali solution (Photo 2c) is visibly different from the surface of the unreacted rock (Photo 2a). There appears to have been a removal of smaller material and rounding of the edges of the larger grains during the storage period. It is known from X-ray diffraction study of a surface of this slab that the amount of dolomite decreased, the amount of calcite increased, and new minerals (brucite, hydrotalcite (?)) appeared during its storage in the alkali solution. The fact that the new minerals are not recognizable on the reacted surface could mean that they are pseudomorphous after the old minerals or are too fine to be distinguishable.

d. The surface of RC-594 paste that was in contact with 1-8 slab 4 for 34 months appears more porous and finer grained than the surface of RC-167 paste after contact with 1-8 slab 2 for the same period (Photos 3a and 3b).

e. There is a difference in the appearance of the fracture surface of RC-167 paste where it was out of the reaction zone and the surface of the same paste where it was in contact with 1-8 slab 2 for 34 months (Photos 3b and 3c). There appears to be an absence of large crystals of calcium hydroxide in the reaction zone.

49. The photographs show that even when it is known from X-ray examinations that definite mineralogical changes have taken place or from length-change data that large expansions have occurred, the changes that can be seen by SEM are still quite subtle.

PART IV: CONCLUSIONS

50. This work was performed to evaluate the control parameters that were established in Appendix C of the Corps Standard Practice for Concrete.[2] The conclusions reached are indicated below:

a. It was established that each of the three reactive carbonate aggregates manifested its typical reaction in the laboratory concrete mixtures.

b. There was no detectable effect of the negative rim-forming nondolomitic Pixley limestone on the strength or volume of concrete mixtures, nor did the rock expand in alkali solution. In essence, the mixtures made with it were indistinguishable from the control mixtures.

c. Judged by expansion in alkali solution, the siliceous rim-forming dolomitic Rapid rock used was less reactive than the Rapid rock from the Glory Quarry that typified this reaction.[5,6] The difference in reactivity was believed to be due to differences in the amounts of dolomite, calcite, and acid-insoluble residue of this rock from two sources.

d. Previous results[5,6] of tests with the Rapid rock in concrete indicated that it retarded development of compressive strength to 1 yr and perhaps longer and that it did not cause expansion of concrete. This work produced the same results.

e. Since there does not appear to be any correlation between the reactivity of the Rapid rock and its effect on strength, it is suggested that the two are not related. Instead, it is proposed that its high porosity of 15-20 percent would cause the rock to fail to carry its load as expected during compressive strength testing of concrete specimens.

f. The behavior of the reactive 1-8 rock in alkali solution and of concrete containing it was consistent with expectations.[7,8,14,17] Concrete containing 1-8 rock as coarse aggregate was three to four times as expansive as mixtures that contained control aggregates; there was no detectable effect on the strength of concrete.

(1) The amount of concrete expansion is directly related to the alkali content of the cement used with 1-8 rock.

(2) The amount of concrete expansion is directly related to the amount of 1-8 rock that is in the mixture.

(3) There may be a relation between the amount of

concrete expansion and the C_3A content of the cement used; however, more data are needed to confirm this observation.

g. After reducing the amount of expansion of concrete mixtures containing 1-8 aggregate by the amount of normal expansion found in mixtures containing control aggregates, it was found that for equal ages 1-8 rock tested in alkali solution expands from 15 to 20 times as much as do concrete mixtures containing it.

51. In view of the results of this investigation, it is believed that the numerical values used in Appendix C[2] for detection of potentially reactive rocks and for control of the reaction in concrete are satisfactory without revisions.

PART V: RECOMMENDATIONS

52. Based on the findings of this work, interest should continue to be focused on carbonate rocks like 1-8 that cause undesirable expansion in concrete. Reactive rocks typified by the Pixley limestone and Rapid rock may be ignored since these reactions do not appear to produce significant damage to concrete.

53. The use of CRD-C 146 test results in Appendix C^2 to classify aggregate sources on the basis of reactivity should be continued. However, Appendix C^2 should be modified to permit testing of concrete as an aid in evaluating the aggregate if it seems desirable.

54. Additional testing should be conducted on other rocks to evaluate the finding that different sized specimens of Rapid rock expand at different rates. However, until such an evaluation is made, the specimen size specified in CRD-C 146 should continue to be used.

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Table 1

Specific Gravity and Absorption of Aggregates*

Serial No.	Description	Bulk Specific Gravity, Saturated Surface Dry	Absorption percent
CRD-G-25	Gneiss	2.67	0.7
CRD-G-25(MS)	Manufactured gneiss fine aggregate	2.67	0.6
CRD-G-31(11)	Hermitage limestone	2.71	0.6
CRD-MS-17(4)	Hermitage manufactured fine aggregate	2.67	1.4
CRD-G-36	1-8	2.73	1.0
CRD-G-35(A)	Rapid rock	2.50**	6.7
KAN-4 G-6(4)	Pixley limestone	2.64	1.7

* Single determinations made according to CRD-C 107 and 108 after aggregates were processed to meet the gradings required by CRD-C 114.

** Average of two determinations.

Table 2

Mineralogical Data on Three Reactive Carbonate Rocks

Name	Sample No.	XRD Composition*	Reactive Texture**	Dolomite percent		Calcite percent	
				XRD†	Chem††	XRD†	Chem††
Rapid rock	Composite of CRD-G-35(A)	Calcitic dolomite; 16% acid-insoluble material (quartz, chert, plagioclase feldspar, marcasite,‡ and clay-mica)	‡‡	76	78.7	8	7.8
	Hand samples of CRD-G-35(B)						
	Pieces 1-3 and 5	Dolomite and minor quartz, feldspar, and clay-mica. Some kaolin clay in piece 5. No detectable calcite	1-3: No 5: Yes	‡‡	‡‡	‡‡	‡‡
	Piece 4	More dolomite and less non-carbonates than in pieces 1-3 and 5. Possible trace of calcite	No	‡‡	‡‡	‡‡	‡‡
	Piece 6	Dolomite with minor calcite, gypsum, quartz, feldspar, clay-mica, and kaolin	No	‡‡	‡‡	‡‡	‡‡

(Continued)

* Acid insoluble material based on treatment with dilute HCl.

** Using Hadley's criteria for dedolomitizing rock.[11]

† Using X-ray diffraction method of Tennant and Berger.[10]

†† Calculated from chemical analysis for CaO and MgO. MgO × 4.60 = dolomite; CaO - dolomite/3.3 × 1.8 = calcite.

‡ Not identified in pieces 1-6 but probably present in each.

‡‡ Not determined.

Table 2 (Concluded)

Name	Sample No.	XRD Composition	Reactive Texture	Dolomite percent XRD	Dolomite percent Chem	Calcite percent XRD	Calcite percent Chem
Rapid rock (con't)	Hand sample from Glory Quarry	Calcitic dolomite, 12% acid-insoluble material (quartz, feldspar, marcasite or pyrite, clay-mica, and a mixed-layer clay?)	Yes	70	‡‡	18	‡‡
1-8 rock	Composite of G-36	Calcitic dolomite, 28% acid-insoluble material (quartz, clay-mica, kaolin, chlorite)	‡‡	48	42.6	24	32.6
	Hand sample G-36(A)	‡‡	Yes	‡‡	‡‡	‡‡	‡‡
Pixley lime-stone	Composite of KAN-4G-6(4)	Dolomitic limestone, 5% acid-insoluble material (quartz, feldspar, clay-mica, kaolin, chlorite?)	‡‡	5	‡‡	90	‡‡
	Hand samples						
	Piece 1	Similar to the composite	No	‡‡	‡‡	‡‡	‡‡
	Piece 2	No dolomite detected; otherwise similar to piece 1	No	‡‡	‡‡	‡‡	‡‡
	Piece 3	Similar to piece 2	No	‡‡	‡‡	‡‡	‡‡

‡‡ Not determined.

Table 3

Length Change of Cores in 1 N NaOH Solution*

Sample	Length Change at Indicated Ages, percent									
	Days							Years (Approximate)		
	7	14	28	56	84	168	252	1	2	3
Rapid rock (CRD-G-35B)										
Bed 17C, not represented in aggregate										
Piece 1 core 1	-0.02	-0.02	-0.04	-0.01	-0.01	-0.01	-0.02	0.00	0.06	0.05
2	0.01	0.00	0.00	-0.01	0.01	0.00	0.03	0.01	0.05	0.05
Piece 2 core 1	0.01	0.00	-0.01	-0.01	-0.01	-0.01	0.00	0.02	0.15	0.16
2	0.00	-0.01	-0.02	-0.03	-0.02	-0.01	-0.04	0.01	0.13	0.14
Beds represented in aggregate										
Piece 3 core 1	-0.01	-0.01	-0.03	-0.03	-0.03	-0.01	0.02	0.14	0.42	0.48
2	0.01	0.02	0.01	0.00	0.00	0.01	0.06	0.18	0.49	0.54
large core 3	0.00	0.00	-0.03	-0.02	0.02	0.22	0.62	0.79	1.15	**
Piece 4 core 1	-0.01	0.00	-0.01	-0.01	-0.02	-0.03	0.02	0.09	0.19	0.19
2	-0.01	0.00	-0.03	-0.01	-0.02	-0.03	0.02	0.09	0.18	0.19
large core 3	0.00	0.00	0.00	0.00	0.00	0.15	0.18	0.21	0.20	**
Piece 5 core 1	0.01	0.01	0.01	0.00	0.02	0.06	0.10	0.14	0.21	0.24
2	0.01	0.01	0.01	0.01	0.02	0.06	0.10	0.14	0.24	0.28
Piece 6 core 1	-0.01	-0.01	-0.01	-0.01	0.00	-0.02	-0.01	0.07	0.34	0.37
2	-0.01	-0.01	-0.03	-0.02	-0.04	-0.04	-0.04	0.02	0.32	0.35
large core 3	0.00	0.00	0.01	-0.01	0.00	0.09	0.20	0.21	0.22	**
Average of cores 1 and 2 from pieces 3-6	0.00	0.00	-0.01	-0.01	-0.01	0.00	0.02	0.11	0.30	0.33

(Continued)

* Using Test Method CRD-C 146.

** Discontinued.

Table 3 (Concluded)

Sample	Length Change at Indicated Ages, percent									
	Days							Years (Approximate)		
	7	14	28	56	84	168	252	1	2	3
Hand sample from Glory Quarry										
Core 1	0.01	0.01	0.02	0.10	0.07	0.13	0.24	0.28	0.35	**
2	0.00	0.05	0.03	0.08	0.12	0.22	0.32	0.39	0.52	**
3	0.03	0.07	0.08	0.10	0.16	0.26	0.35	0.40	0.48	**
4	0.05	0.07	0.09	0.13	0.16	0.30	0.39	0.43	0.50	**
Average of Cores 1-4	0.02	0.05	0.05	0.10	0.13	0.23	0.32	0.37	0.47	--
1-8 hand sample (CRD-G-36(A))										
Core 1	0.17	0.32	0.58	0.70	0.83	1.01	1.08	1.10	1.10	**
2	0.17	0.29	0.40	0.51	0.61	0.78	0.82	0.84	0.84	**
Average of cores 1 and 2	0.17	0.31	0.49	0.61	0.72	0.89	0.95	0.97	0.97	--
Pixley limestone--hand samples of KAN-4G-6(3)										
Piece 1 core 1	0.01	0.01	0.00	0.01	-0.01	0.01	0.00	-0.01	-0.02	-0.02
2	0.00	-0.01	-0.01	0.00	-0.01	-0.01	-0.01	-0.02	-0.03	-0.03
Piece 2 core 1	0.01	-0.01	0.00	0.00	-0.01	-0.01	0.00	-0.01	-0.03	-0.02
2	0.00	0.01	0.01	0.00	0.00	0.00	-0.01	-0.01	-0.03	-0.02
Piece 3 core 1	0.01	0.00	0.00	0.01	-0.01	0.00	-0.01	-0.02	-0.04	-0.04
2	-0.01	-0.02	-0.02	-0.02	-0.04	-0.03	-0.02	-0.06	-0.08	-0.07
Average of 6 Pixley cores	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	-0.02	-0.04	-0.03

** Discontinued.

Table 4

Results of Chemical and Physical Tests of Three Cements*

Chemical Composition	RC-168	RC-167	RC-594
	Chemical Tests		
CaO, %	61.8	63.6	62.4
SiO_2, %	21.2	20.9	22.3
Al_2O_3, %	5.4	6.2	5.0
Fe_2O_3, %	2.9	2.7	3.2
MgO, %	3.6	2.9	3.2
SO_3, %	2.2	1.9	2.2
Loss on ignition, %	2.9	0.9	0.8
Na_2O, %	0.13	0.49	0.35
K_2O, %	0.41	0.78	0.90
Insoluble residue, %	0.7	0.2	0.2
Total alkalies as Na_2O, %	0.40	1.00	0.94
Calculated compounds, %			
C_3S	44	49	40
C_2S	27	23	33
C_3A	9.4	11.9	7.8
C_4AF	9	8	10
	Physical Tests		
Surface area, cm^2/g	2790	2445	3230
Compressive strength, psi			
3 days	1590	**	2175
7 days	2505	**	3015

* Tested according to CRD-C 200.

** Not determined.

Table 5

Concrete Mixtures

Mixture No.	Round No.	Materials Used* Portland Cement	Materials Used* Coarse Aggregate	Cement Content lb/yd^3	Air percent	Slump in.
1	1	RC-168	Granite gneiss	668.7	5.8	2.2
	2			667.4	6.0	2.8
	3			669.4	5.7	2.2
2	1	RC-167	Granite gneiss	656.0	6.3	2.2
	2			660.0	5.7	2.0
	3			656.0	6.3	2.2
3	1	RC-594	Granite gneiss	658.0	6.0	2.5
	2			658.0	6.0	2.8
	3			656.0	6.3	3.0
4	1	RC-168	Hermitage limestone (H)**	582.8	6.0	2.5
	2			581.1	6.3	2.5
	3			581.1	6.3	2.8
5	1	RC-167	H	575.1	5.7	2.8
	2			574.5	5.8	2.5
	3			572.3	6.2	2.8
6	1	RC-594	H	571.1	6.4	2.5
	2			573.4	6.0	2.8
	3			572.3	6.2	3.0
7	1	RC-168	Pixley rock (P)†	582.8	6.0	2.5
	2			581.1	6.3	2.5
	3			585.1	5.6	2.5
8	1	RC-168	20% P, 80% H	581.1	6.3	2.5
	2			584.5	5.7	2.5
	3			581.6	6.2	2.8
9	1	RC-168	40% P, 60% H	584.0	5.8	2.8
	2			581.1	6.3	2.8
	3			585.1	5.6	2.8

(Continued)

* The fine aggregate was made from the granite gneiss for mixtures 1-3; carbonate sand from the Hermitage source was used in the other mixtures.

** CRD-G-31(11).

† KAN-4G-6(4).

Mixture No.	Round No.	Materials Used: Portland Cement	Materials Used: Coarse Aggregate	Cement Content lb/yd^3	Air percent	Slump in.
10	1	RC-167	All P	575.1	5.7	2.8
	2			572.3	6.2	2.8
	3			572.8	6.1	3.0
11	1	RC-167	20% P, 80% H	573.4	6.0	2.8
	2			571.7	6.3	2.8
	3			574.0	5.9	3.0
12	1	RC-167	40% P, 60% H	575.1	5.7	2.5
	2			575.1	5.7	2.8
	3			572.8	6.1	2.8
13	1	RC-594	All P	572.3	6.2	2.5
	2			574.5	5.8	2.8
	3			573.4	6.0	3.0
14	1	RC-594	20% P, 80% H	573.4	6.0	2.8
	2			573.4	6.0	2.8
	3			574.5	5.8	2.5
15	1	RC-594	40% P, 60% H	573.4	6.0	2.8
	2			575.7	5.6	2.8
	3			572.3	6.2	2.8
16	1	RC-168	Rapid rock (R)††	582.8	6.0	2.5
	2			581.6	6.2	2.8
	3			584.0	5.8	2.2
17	1	RC-168	20% R, 80% H	585.1	5.6	2.8
	2			584.5	5.7	2.5
	3			585.1	5.6	2.8
18	1	RC-168	40% R, 60% H	582.8	6.0	2.5
	2			582.8	6.0	2.8
	3			584.5	5.7	2.8
19	1	RC-167	All R	575.1	5.7	2.5
	2			575.1	5.7	2.5
	3			576.3	5.5	2.8

(Continued)

†† CRD-G-35(A).

Mixture No.	Round No.	Materials Used: Portland Cement	Materials Used: Coarse Aggregate	Cement Content lb/yd3	Air percent	Slump in.
20	1	RC-167	20% R, 80% H	572.3	6.2	2.8
	2			575.1	5.7	2.5
	3			574.5	5.8	3.0
21	1	RC-167	40% R, 60% H	573.4	6.0	2.5
	2			575.1	5.7	2.8
	3			573.4	6.0	2.8
22	1	RC-594	All R	573.4	6.0	2.5
	2			574.5	5.8	2.5
	3			575.1	5.7	2.8
23	1	RC-594	20% R, 80% H	573.4	6.0	2.2
	2			576.3	5.5	2.8
	3			574.0	5.9	3.0
24	1	RC-594	40% R, 60% H	574.5	5.8	2.5
	2			573.4	6.0	2.8
	3			574.5	5.8	2.8
25	1	RC-168	Reactive 1-8 rock (V)‡	594.0	5.7	2.2
	2			594.6	5.6	2.5
	3			593.4	5.8	2.5
26	1	RC-168	20% V, 80% H	584.5	5.7	2.5
	2			584.5	5.7	2.5
	3			583.4	5.9	2.5
27	1	RC-168	40% V, 60% H	582.8	6.0	2.2
	2			582.2	6.1	2.5
	3			584.0	5.8	2.5
28	1	RC-167	All V	585.1	5.6	2.0
	2			584.0	5.8	2.2
	3			582.8	6.0	3.0
29	1	RC-167	20% V, 80% H	575.7	5.6	2.5
	2			574.0	5.9	2.5
	3			573.4	6.0	2.8

(Continued)

‡ CRD-G-36 and 36 (B).

Table 5 (Concluded)

Mixture No.	Round No.	Materials Used: Portland Cement	Materials Used: Coarse Aggregate	Cement Content lb/yd^3	Air percent	Slump in.
30	1	RC-167	40% V, 60% H	574.0	5.9	2.5
	2			571.7	6.3	2.8
	3			571.7	6.3	2.8
31	1	RC-594	All V	585.1	5.6	2.0
	2			583.4	5.9	2.2
	3			583.4	5.9	2.5
32	1	RC-594	20% V, 80% H	571.7	6.3	2.5
	2			575.1	5.7	2.5
	3			571.7	6.3	2.8
33	1	RC-594	40% V, 60% H	575.1	5.7	2.2
	2			573.4	6.0	2.8
	3			573.4	6.0	2.8

Table 6

Compressive Strengths of 33 Concrete Mixtures

Mixtures*	Round	Compressive Strength** of 3- by 6-in. Cylinder at Indicated Ages, psi 7 Days	14 Days	28 Days	90 Days	180 Days	365 Days
No. 1 (RC-168, all granite gneiss rock)	1	3480	4160	5130	5690	5980	5860
	2	2950	3780	4140	5120	5370	5940
	3	3220	3890†	4430	5060	5700	5660
	Average	3220	3940	4570	5290	5680	5820
No. 2 (RC-167, all granite gneiss rock)	1	2480	3350	3270	3970	4280	4340
	2	2480	2810	3680	3480	3900	4540
	3	2480	2840	3060	3650	3910	3960
	Average	2480	3000	3340	3700	4030	4280
No. 3 (RC-594, all granite gneiss rock)	1	2790	3680	4360	4750	5750	5700
	2	3000	3710	4150	4980	5040	5350
	3	2530	2970	3750	4380	4290	4940
	Average	2770	3450	4090	4700	5030	5330
No. 4 (RC-168, all H)	1	3240	3510	4240	5780	5260	6220
	2	3250	3610	4240	5150	5470	6030
	3	3060	3430	3900	4740	5430	5150
	Average	3180	3520	4130	5220	5390	5800
No. 5 (RC-167, all H)	1	3250	3710	3990	4780	5300	5020
	2	3150	3300	3770	4200	4540	5170
	3	2960	3310	3710	5060	4720	5150
	Average	3120	3440	3820	4680	4850	5110
No. 6 (RC-594, all H)	1	3970	4630	4900	5580	6550	6170
	2	3780	4370	4730	6080	6160	6580
	3	3030	3660	3920	5210	5280	5620
	Average	3590	4220	4520	5620	6000	6120

(Continued)

Note: H denotes Hermitage rock, P denotes Pixley rock, R denotes Rapid rock, and V denotes 1-8 rock.

* The fine aggregate in mixtures 4-33 was from the same source as was the Hermitage rock.

** Tested in accordance with CRD-C 14.

† Specimen was broken at 15 instead of 14 days.

(Sheet 1 of 5)

Table 6 (Continued)

Mixtures	Round	7 Days	14 Days	28 Days	90 Days	180 Days	365 Days
		Compressive Strength of 3- by 6-in. Cylinder at Indicated Ages, psi					
No. 7 (RC-168, all P)	1	3370	4160	4790	5700	5660	6220
	2	3420	4140	4160	5360	5540	6270
	3	2920	3690	4140	5040	5550	6000
	Average	3240	4000	4360	5370	5580	6160
No. 8 (RC-168, 80% H, 20% P)	1	3150	3950	4530	5350	5860	5760
	2	3040	3610	4020	5000	6050	6080
	3	2810	3480	4230	4840	5430	5280
	Average	3000	3680	4260	5060	5780	5710
No. 9 (RC-168, 60% H, 40% P)	1	3090	3470	4290	5250	5290	5690
	2	2550	3200	3560	4280	4880	5220
	3	3310	3590	4540	5150	5390	6510
	Average	2980	3420	4130	4890	5190	5810
No. 10 (RC-167, all P)	1	2940	3490	3800	4670	4560	5110
	2	3220	3570	3640	4140	4590	4980
	3	3320	3370	3960	4840	4880	3540
	Average	3160	3460	3800	4550	4680	4540
No. 11 (RC-167, 80% H, 20% P)	1	2870	3040	3540	4120	4260	4780
	2	3100	3440	4080	4490	4720	5570
	3	3250	3370	4000	4270	5210	4960
	Average	3070	3280	3870	4290	4730	5100
No. 12 (RC-167, 60% H, 40% P)	1	2190	3460	3780	4380	4770	5150
	2	3310	3480	3840	4750	4850	5850
	3	2720	3300	3760	4000	4380	5300
	Average	2980	3410	3790	4380	4670	5430
No. 13 (RC-594, all P)	1	3720	4410	4410	5780	5640	6380
	2	3780	4380	4660	5260	5880	5570
	3	3370	3830	4260	5120	5660	6120
	Average	3620	4210	4440	5390	5730	6020

(Continued)

Table 6 (Continued)

		Compressive Strength of 3- by 6-in. Cylinder at Indicated Ages, psi					
Mixtures	Round	7 Days	14 Days	28 Days	90 Days	180 Days	365 Days
No. 14 (RC-594, 80% H, 20% P)	1	3300	3750	4460	5200	5930	6080
	2	3590	4430	4550	5530	6220	6660
	3	3650	4080	4510	5420	5660	5760
	Average	3510	4090	4510	5380	5940	6170
No. 15 (RC-594, 60% H, 40% P)	1	3390	3880	3860	4950	5590	6270
	2	3750††	4160	4940	5970	6290	7070
	3	2890	3540	4210	4510	5620	6240
	Average	3340	3860	4340	5140	5830	6530
No. 16 (RC-168, all R)	1	2730	3150	3880	4780	4670	4430
	2	2660	3230	3590	4380	4950	4840
	3	2970	3620	4100	4610	4540	4840
	Average	2790	3330	3860	4590	4720	4700
No. 17 (RC-168, 80% H, 20% R)	1	3150	3800	4240	5080	5820	5950
	2	3460	4160	4670	6080	5770	5810
	3	3230	3790	4410	5370	5430	5950
	Average	3280	3920	4440	5510	5670	5900
No. 18 (RC-168, 60% H, 40% R)	1	3470	3770	4120	5110	5690	5430
	2	3270	3280	3920	4580	4780	5060
	3	3130	3820	4260	5230	5180	5370
	Average	3290	3620	4100	4970	5220	5290
No. 19 (RC-167, all R)	1	2940	3300	3950	3930	3850	3850
	2	3770	3440	3810	4070	4210	3680
	3	3510	3550	3910	4340	4460	4260
	Average	3240	3430	3890	4110	4140	3930
No. 20 (RC-167, 80% H, 20% R)	1	2590	3180	3440	3850	4050	4470
	2	3220	3510	3590	4190	4730	4310
	3	3180	3230	3730	4380	4480	5150
	Average	3000	3310	3590	4140	4420	4640

(Continued)

†† Specimen was broken at 8 instead of 7 days.

Table 6 (Continued)

Mixtures	Round	Compressive Strength of 3- by 6-in. Cylinder at Indicated Ages, psi					
		7 Days	14 Days	28 Days	90 Days	180 Days	365 Days
No. 21 (RC-167, 60% H, 40% R)	1	2960	3370	3560	4070	4440	4480
	2	3470	3630	4040	4570	4780	5130
	3	3130	3400	3680	4120	4290	4780
	Average	3190	3470	3760	4250	4500	4800
No. 22 (RC-594, all R)	1	2960	3680	4840	4440	4460	4380
	2	3540	3760	4160	4650	4670	4600
	3	3130	3750	3880	4290	4700	4580
	Average	3210	3730	4290	4460	4610	4520
No. 23 (RC-594, 80% H, 20% R)	1	3020	3720	4560	3490	5500	6130
	2	3440	4040	4220	4870	5450	5680
	3	3080	3510	3920	4820	5220	5500
	Average	3180	3760	4230	4390	5390	5770
No. 24 (RC-594, 60% H, 40% R)	1	2760	3740	4380	5260	5630	5370
	2	3640	4120	4880	5320	5300	5660
	3	3250	3760	4490	4950	4920	5400
	Average	3220	3870	4580	5180	5280	5480
No. 25 (RC-168, all V)	1	3390	3610	4870	5800	5250	4990
	2	3240††	3750	4530	5620	6050	6170
	3	3110	3790	4320	5160	5560	5540
	Average	3250	3720	4570	5530	5620	5570
No. 26 (RC-168, 80% H, 20% V)	1	3250	3820	4270	5190	6080	6410
	2	3620	4200	4830	5640	5960	6580
	3	2930	3560	4140	4500	5430	5910
	Average	3270	3860	4410	5110	5820	6300
No. 27 (RC-168, 60% H, 40% V)	1	3480	4360	4750	5970	6050	6290
	2	3780	3730	4260	5200	5910	6040
	3	3270	3590	4050	5150	5860	5790
	Average	3510	3890	4350	5440	5940	6040

(Continued)

†† Specimen was broken at 8 instead of 7 days.

Mixtures	Round	Compressive Strength of 3- by 6-in. Cylinder at Indicated Ages, psi 7 Days	14 Days	28 Days	90 Days	180 Days	365 Days
No. 28 (RC-167, all V)	1	3300	3620	4010	4550	5260	5600
	2	3710	4000	4460	4120	4890	5570
	3	3410	3350	3680	4270	4330	5040
	Average	3470	3660	4050	4310	4830	5400
No. 29 (RC-167, 80% H, 20% V)	1	3060	3300	4030	4440	4770	5390
	2	3030	3310	3960	4650	4400	5450
	3	3460	3830	4060	4820	4580	5400
	Average	3180	3480	4020	4640	4580	5410
No. 30 (RC-167, 60% H, 40% V)	1	3090	2610	3900	4460	4620	5150
	2	3010	3480†	3360	4090	4610	5290
	3	2790	3370	3650	4170	4310	4500
	Average	2960	3150	3640	4240	4510	4980
No. 31 (RC-594, all V)	1	3550	4170	4750	5590	5710	6450
	2	3390	4120	4620	5640	5690	6080
	3	3370	3960	4510	5250	5830	6290
	Average	3440	4080	4630	5490	5740	6270
No. 32 (RC-594, 80% H, 20% V)	1	3300	4060	4430	5360	5880	6020
	2	3900	4500	4910	5980	5780	6560
	3	2830	3620	4060	4980	5260	5210
	Average	3340	4060	4470	5440	5640	5930
No. 33 (RC-594, 60% H, 40% V)	1	3620	4180	4160	5800	6020	6170
	2	3550	4130†	4210	4770	5940	6350
	3	3110	3610	4440	5370	5620	5940
	Average	3430	3970	4270	5310	5860	6150

† Specimen was broken at 15 instead of 14 days.

Table 7

Compressive Strength of Sawed Cubes from Six Concrete Mixtures*

Mixture	Round No.	Bar No.	Compressive Strengths of 2-in. Cubes** at Ages Indicated, psi: 24 Months	26-1/2 Months	30 Months	36 Months
No. 4 (RC-168,	2	4	--	6300	6550	6350
all H)	3	8	5300	--	5220	5250
No. 5 (RC-167,	2	5	--	5450	5400	5740
all H)	3	9	5780	--	5420	5000
No. 6 (RC-594,	2	6	--	7130	7000	6250
all H)	3	7	6620	--	6250	6080
No. 16 (RC-168,	2	5	--	4780	4820	4080
all R)	3	8	4600	--	4320	4450
No. 19 (RC-167,	2	4	--	4450	4540	3700
all R)	3	9	4700	--	4820	4900
No. 22 (RC-594,	2	4	--	5500	5200	5250
all R)	3	7	4900	--	4780	4850

Note: H denotes Hermitage rock; R denotes Rapid rock.

* Specimens were tested in general accordance with CRD-C 15.

** Successive 2-in. lengths were cut from the indicated 2- by 2- by 11-in. length-change bars to provide cubes for testing.

Table 8

Splitting Tensile Strengths of 33 Concrete Mixtures

Mixture*	Round	Tensile Strength of 3- by 6-in. Cylinder at Ages Indicated, psi** 7 Days	14 Days	28 Days	90 Days	180 Days	365 Days
No. 1 (RC-168, all granite gneiss rock)	1	230	440	455	485	530	700
	2	335	430	450	425	470	540
	3	375	325†	475	535	545	470
	Average	315	400	460	480	510	570
No. 2 (RC-167, all granite gneiss rock)	1	230	355	255	410	475	465
	2	280	320	410	425	360	415
	3	270	360	360	335	400	340
	Average	260	345	340	390	410	410
No. 3 (RC-594, all granite gneiss rock)	1	315	375	415	480	575	640
	2	345	415	410	425	540	555
	3	315	400	450	530	455	495
	Average	325	400	425	480	525	565
No. 4 (RC-168, all H)	1	320	410	435	430	690	710
	2	450	495	460	475	670	560
	3	280	355	490	540	400	510
	Average	350	420	460	480	585	595
No. 5 (RC-167, all H)	1	320	450	470	505	390	620
	2	370	345	455	440	500	595
	3	340	430	405	460	410	525
	Average	345	410	445	470	435	580
No. 6 (RC-594, all H)	1	350	370	470	500	530	575
	2	405	520	620	590	560	545
	3	370	515	500	530	515	520
	Average	375	470	530	540	535	545

(Continued)

Note: H denotes Hermitage rock. P denotes Pixley rock. R denotes Rapid rock. V denotes 1-8 rock.

* The fine aggregate in mixtures 4-33 was from the same source as was the Hermitage rock.

** Tested in accordance with CRD-C 77.

† Specimen was broken at 15 instead of 14 days.

Mixture	Round	7 Days	14 Days	28 Days	90 Days	180 Days	365 Days
		Tensile Strength of 3- by 6-in. Cylinder at Ages Indicated, psi					
No. 7 (RC-168, all P)	1	280	520	490	470	540	690
	2	345	460	520	605	580	615
	3	340	410	530	610	570	620
	Average	320	465	510	560	565	640
No. 8 (RC-168, 80% H, 20% P)	1	315	425	465	515	695	700
	2	405	360	495	510	425	710
	3	315	455	485	620	630	615
	Average	345	415	480	550	585	675
No. 9 (RC-168, 60% H, 40% P)	1	390	495	560	510	580	720
	2	360	280	380	515	500	590
	3	415	390	340	475	590	610
	Average	390	390	425	500	555	640
No. 10 (RC-167, all P)	1	325	420	400	500	420	610
	2	425	370	435	595	360	530
	3	350	310	460	500	485	485
	Average	365	365	430	530	420	540
No. 11 (RC-167, 80% H, 20% P)	1	350	410	400	480	575	470
	2	365	345	325	510	535	540
	3	395	350	435	405	455	530
	Average	370	370	385	465	520	515
No. 12 (RC-167, 60% H, 40% P)	1	265	395	385	525	335	630
	2	420	415	345	525	535	575
	3	355	315	420	470	455	600
	Average	345	375	385	505	440	600
No. 13 (RC-594, all P)	1	380	460	530	515	635	545
	2	425	555	465	610	520	690
	3	425	375	515	455	705	530
	Average	410	465	505	525	620	680
No. 14 (RC-594, 80% H, 20% P)	1	435	405	415	545	630	605
	2	465	525	555	625	695	680
	3	425	470	550	555	555	720
	Average	440	465	505	575	625	670

(Continued)

Mixture	Round	Tensile Strength of 3- by 6-in. Cylinder at Ages Indicated, psi: 7 Days	14 Days	28 Days	90 Days	180 Days	365 Days
No. 15 (RC-594, 60% H, 40% P)	1	445	390	585	665	545	615
	2	445††	440	545	670	585	560
	3	310	395	425	550	575	560
	Average	405	410	520	630	570	580
No. 16 (RC-168, all R)	1	170	330	425	475	455	440
	2	240	305	295	450	370	445
	3	320	405	430	470	490	550
	Average	245	345	385	465	440	480
No. 17 (RC-168, 80% H, 20% R)	1	430	400	420	535	595	590
	2	415	465	465	590	540	665
	3	410	485	485	455	710	590
	Average	420	450	455	525	615	615
No. 18 (RC-168, 60% H, 40% R)	1	280	280	365	510	565	590
	2	340	420	375	420	630	550
	3	320	435	365	700	610	550
	Average	315	380	370	545	600	565
No. 19 (RC-167, all R)	1	355	210	440	380	415	485
	2	280	410	375	425	450	440
	3	365	335	370	460	355	415
	Average	335	320	395	420	405	445
No. 20 (RC-167, 80% H, 20% R)	1	310	320	520	400	495	500
	2	360	350	400	405	515	530
	3	380	315	440	420	415	645
	Average	350	330	455	410	470	560
No. 21 (RC-167, 60% H, 40% R)	1	400	340	480	465	395	595
	2	425	355	350	435	545	495
	3	415	390	350	385	445	590
	Average	415	360	395	430	460	560

(Continued)

†† Specimen was broken at 8 instead of 7 days.

Table 9

Length Changes of 33 Concrete Mixtures

Mixture	Bar No.	Length Change of Bar at Indicated Ages, percent* 7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	365 Days	1-1/2 Years	2 Years	2-1/2 Years	3 Years
No. 1 (RC-168, all granite gneiss rock)	1	0.005	0.008	0.006	0.010	0.014	0.022	0.029	0.035	0.036	0.036	0.036
	2	0.003	0.006	0.004	0.007	0.009	0.019	0.027	0.032	0.033	0.035	0.035
	3	0.001	0.003	0.001	0.004	0.008	0.018	0.025	0.031	0.031	0.033	0.036
	4	0.007	0.005	0.007	0.008	0.010	0.018	0.025	0.029	0.030	0.030	0.031
	5	0.009	0.007	0.009	0.011	0.014	0.022	0.027	0.031	0.032	0.032	0.031
	6	0.002	0.006	0.009	0.012	0.015	0.024	0.026	0.032	0.032	0.032	0.032
	7	0.006	0.005	0.008	0.010	0.013	0.017	0.021	0.025	0.025	0.026	0.031
	8	0.006	0.005	0.010	0.011	0.014	0.018	0.023	0.026	0.026	0.028	0.033
	9	0.005	0.004	0.008	0.010	0.012	0.017	0.021	0.024	0.024	0.026	0.030
	Average	0.005	0.005	0.007	0.009	0.012	0.019	0.024	0.029	0.030	0.031	0.033
No. 2 (RC-167, all granite gneiss rock)	1	0.008	0.009	0.007	0.010	0.012	0.022	0.029	0.035	0.034	0.037	0.036
	2	0.008	0.010	0.009	0.012	0.015	0.023	0.030	0.037	0.035	0.040	0.038
	3	0.007	0.008	0.006	0.008	0.011	0.019	0.025	0.033	0.031	0.036	0.033
	4	0.003	0.005	0.008	0.010	0.012	0.016	0.024	0.026	0.028	0.029	0.031
	5	0.003	0.006	0.008	0.010	0.013	0.017	0.025	0.028	0.028	0.029	0.030
	6	0.002	0.007	0.008	0.011	0.013	0.017	0.028	0.028	0.027	0.029	0.030
	7	0.007	0.007	0.008	0.011	0.014	0.022	0.026	0.030	0.030	0.029	0.031
	8	0.005	0.006	0.006	0.010	0.013	0.020	0.024	0.026	0.031	0.028	**
	9	0.005	0.005	0.006	0.010	0.013	0.020	0.024	0.026	0.029	0.035	0.027
	Average	0.005	0.007	0.007	0.010	0.013	0.020	0.026	0.030	0.030	0.032	0.032
No. 3 (RC-594, all granite gneiss rock)	1	0.007	0.010	0.007	0.010	0.014	0.022	0.027	0.033	0.032	0.038	0.035
	2	0.005	0.008	0.007	0.009	0.012	0.020	0.027	0.032	0.033	0.036	0.035
	3	0.006	0.008	0.006	0.009	0.013	0.020	0.025	0.032	0.031	0.035	0.033
	4	0.006	0.005	0.007	0.010	0.013	0.017	0.023	0.028	0.026	0.026	0.027
	5	0.006	0.004	0.006	0.008	0.011	0.016	0.022	0.025	0.023	0.024	0.024
	6	0.007	0.005	0.007	0.009	0.013	0.018	0.023	0.027	0.026	0.026	0.027
	7	0.003	0.007	0.008	0.012	0.013	0.019	0.022	0.023	0.023	0.024	0.029
	8	0.002	0.007	0.007	0.011	0.012	0.018	0.021	0.022	0.022	0.022	0.027
	9	0.001	0.006	0.007	0.011	0.012	0.019	0.022	0.022	0.022	0.022	0.028
	Average	0.005	0.007	0.007	0.010	0.013	0.019	0.024	0.027	0.026	0.028	0.029
No. 4 (RC-168, all H)	1	0.008	0.010	0.008	0.010	0.013	0.024	0.030	0.033	0.032	0.036	0.033
	2	0.007	0.011	0.009	0.010	0.011	0.022	0.029	0.033	0.033	0.036	0.034
	3	0.008	0.010	0.008	0.011	0.014	0.022	0.029	0.034	0.034	0.038	0.036
	4	-0.001	0.003	0.001	0.006	0.006	0.014	0.014	0.019	0.021	†	--
	5	0.004	0.008	0.006	0.011	0.011	0.020	0.021	0.024	0.029	0.026	0.030
	6	0.003	0.006	0.004	0.010	0.010	0.017	0.019	0.019	0.028	0.021	0.026
	7	0.002	0.003	0.006	0.008	0.008	0.017	0.020	0.022	0.023	0.020	0.025
	8	0.002	0.003	0.006	0.008	0.008	0.014	0.017	0.021	0.022	†	--
	9	0.001	0.003	0.006	0.007	0.007	0.015	0.018	0.020	0.022	0.023	0.022
	Average	0.004	0.006	0.006	0.009	0.010	0.018	0.022	0.025	0.027	0.028	0.029
No. 5 (RC-167, all H)	1	0.004	0.005	0.006	0.008	0.011	0.015	0.024	0.028	0.031	0.032	0.032
	2	0.007	0.008	0.010	0.012	0.015	0.019	0.028	0.032	0.035	0.036	0.036
	3	0.001	0.002	0.004	0.007	0.009	0.013	0.023	0.027	0.030	0.031	0.031
	4	0.004	0.005	0.009	0.011	0.014	0.022	0.028	0.032	0.033	0.033	0.035
	5	0.003	0.004	0.008	0.010	0.013	0.019	0.026	0.029	0.032	†	--
	6	0.000	0.001	0.006	0.008	0.010	0.017	0.023	0.026	0.028	0.028	0.030
	7	0.002	0.002	0.003	0.008	0.012	0.020	0.021	0.022	0.028	0.027	0.029
	8	0.003	0.003	0.005	0.010	0.014	0.020	0.023	0.027	0.029	0.027	0.029
	9	0.004	0.004	0.006	0.010	0.015	0.020	0.022	0.022	0.029	†	--
	Average	0.003	0.004	0.006	0.009	0.013	0.018	0.024	0.027	0.031	0.031	0.032

(Continued)

Note: H denotes Hermitage rock. P denotes Pixley rock. R denotes Rapid rock. V denotes 1-8 rock.

* Values are positive unless a minus sign is shown.

** Bar was broken or failed to read it.

† Bar was used for compressive strength test.

Mixture	Bar No.	Length Change of Bar at Indicated Ages, percent										
		7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	365 Days	1-1/2 Years	2 Years	2-1/2 Years	3 Years
No. 6 (RC-594, all H)	1	0.004	0.005	0.007	0.009	0.012	0.017	0.028	0.032	0.035	0.037	0.039
	2	0.004	0.005	0.008	0.010	0.014	0.017	0.028	0.033	0.035	0.037	0.036
	3	0.002	0.003	0.005	0.008	0.010	0.013	0.024	0.029	0.030	0.033	0.031
	4	0.007	0.001	0.008	0.009	0.012	0.022	0.022	0.029	0.031	0.032	0.034
	5	0.005	-0.001	0.005	0.007	0.009	0.014	0.021	0.026	0.029	0.029	0.031
	6	0.005	0.000	0.008	0.009	0.011	0.019	0.021	0.028	0.031	†	--
	7	0.002	0.006	0.007	0.012	0.015	0.022	0.025	0.027	0.027	†	--
	8	0.003	0.008	0.010	0.015	0.018	0.025	0.029	0.030	0.030	0.031	††
	9	0.002	0.007	0.008	0.013	0.015	0.021	0.025	0.025	0.026	0.026	0.032
	Average	0.004	0.004	0.007	0.010	0.013	0.019	0.025	0.029	0.030	0.032	0.034
No. 7 (RC-168, all P)	1	0.005	0.004	0.005	0.005	0.006	0.008	0.018	0.022	0.024	0.025	0.024
	2	0.000	0.000	0.000	0.001	0.002	0.004	0.015	0.020	0.021	0.022	0.021
	3	0.002	0.002	0.001	0.001	0.003	0.005	0.016	0.019	0.021	0.022	0.021
	4	0.001	0.002	0.005	0.005	0.005	0.011	0.014	0.014	0.020	0.020	0.021
	5	0.002	0.003	0.006	0.006	0.006	0.013	0.011	0.015	0.021	0.021	0.024
	6	0.001	0.002	0.005	0.005	0.006	0.012	0.016	0.016	0.021	0.021	0.022
	7	0.003	0.004	0.005	0.007	0.009	0.012	0.016	0.016	0.019	0.018	0.021
	8	0.003	0.002	0.005	0.007	0.009	0.012	0.016	0.016	0.019	0.018	0.021
	9	0.002	0.002	0.003	0.008	0.010	0.010	0.013	0.013	0.017	0.016	0.018
	Average	0.002	0.002	0.004	0.005	0.006	0.010	0.015	0.017	0.020	0.020	0.021
No. 8 (RC-168, 80% H, 20% P)	1	0.004	0.003	0.005	0.006	0.007	0.010	0.020	0.023	0.026	0.028	0.027
	2	0.002	-0.001	0.001	0.002	0.004	0.007	0.017	0.019	0.020	0.023	0.022
	3	0.004	0.004	0.005	0.006	0.008	0.012	0.021	0.023	0.025	0.029	0.027
	4	0.002	0.001	0.003	0.005	0.009	0.012	0.016	0.017	0.021	0.020	0.022
	5	0.002	0.002	0.004	0.007	0.010	0.014	0.018	0.019	0.023	0.023	0.025
	6	0.002	0.002	0.003	0.006	0.009	0.012	0.017	0.018	0.023	0.021	0.023
	7	0.005	0.008	0.006	0.009	0.012	0.013	0.018	0.019	0.020	0.020	0.025
	8	0.003	0.005	0.005	0.008	0.010	0.011	0.015	0.018	0.019	0.020	0.025
	9	0.004	0.007	0.005	0.008	0.011	0.012	0.017	0.014	0.014	0.015	0.020
	Average	0.003	0.003	0.004	0.006	0.009	0.011	0.018	0.019	0.021	0.022	0.024
No. 9 (RC-168, 60% H, 40% P)	1	0.010	0.008	0.009	0.011	0.013	0.014	0.023	0.029	0.029	0.032	0.030
	2	**	--	--	--	--	--	--	--	--	--	--
	3	**	--	--	--	--	--	--	--	--	--	--
	4	0.003	0.004	0.004	0.005	0.008	0.013	0.015	0.017	0.020	0.018	0.019
	5	0.003	0.004	0.005	0.007	0.009	0.014	0.016	0.016	0.020	0.018	0.021
	6	0.002	0.003	0.003	0.006	0.010	0.013	0.014	0.018	0.020	0.018	0.019
	7	0.004	0.004	0.002	0.007	0.007	0.015	0.018	0.020	0.022	0.021	0.023
	8	0.004	0.003	0.003	0.006	0.006	0.014	0.017	0.020	0.021	0.021	0.022
	9	0.003	0.004	0.003	0.007	0.007	0.015	0.018	0.021	0.022	0.021	0.021
	Average	0.004	0.004	0.004	0.007	0.009	0.014	0.017	0.020	0.022	0.021	0.022
No. 10 (RC-167, all P)	1	0.006	0.005	0.007	0.007	0.007	0.010	0.016	0.022	0.023	0.025	0.024
	2	0.007	0.005	0.007	0.008	0.009	0.010	0.018	0.023	0.024	0.026	0.026
	3	0.005	0.004	0.004	0.005	0.007	0.009	0.015	0.020	0.021	0.023	0.026
	4	0.002	0.002	0.005	0.005	0.007	0.011	0.016	0.020	0.021	0.021	0.022
	5	0.002	0.002	0.004	0.004	0.006	0.010	0.015	0.018	0.020	0.019	0.021
	6	0.000	0.000	0.002	0.002	0.003	0.007	0.012	0.017	0.017	0.016	0.019
	7	0.004	0.003	0.002	0.005	0.005	0.012	0.015	0.018	0.019	0.018	0.019
	8	0.003	0.002	0.002	0.005	0.006	0.013	0.015	0.018	0.020	0.018	0.020
	9	0.004	0.003	0.002	0.006	0.005	0.012	0.015	0.017	0.020	0.018	0.021
	Average	0.004	0.003	0.004	0.005	0.006	0.010	0.015	0.019	0.021	0.020	0.022

(Continued)

** Bar was broken or failed to read it.
† Bar was used for compressive strength test.
†† Bar was used for SEM examination.

Mixture	Bar No.	Length Change of Bar at Indicated Ages, percent										
		7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	365 Days	1-1/2 Years	2 Years	2-1/2 Years	3 Years
No. 11 (RC-167, 80% H, 20% P)	1	0.007	0.007	0.010	0.012	0.014	0.018	0.026	0.032	0.033	0.036	0.034
	2	0.009	0.007	0.009	0.012	0.014	0.018	0.027	0.031	0.034	0.036	0.035
	3	0.008	0.009	0.011	0.013	0.016	0.020	0.027	0.032	0.035	0.037	0.036
	4	0.003	0.005	0.008	0.010	0.012	0.018	0.028	0.025	0.026	0.027	0.029
	5	0.002	0.004	0.005	0.007	0.010	0.017	0.026	0.025	0.027	0.026	0.029
	6	0.003	0.006	0.007	0.009	0.012	0.017	0.025	0.024	0.025	0.026	0.028
	7	0.001	0.000	0.005	0.008	0.011	0.015	0.020	0.023	0.024	0.023	0.025
	8	0.000	0.000	0.005	0.008	0.013	0.017	0.023	0.024	0.027	0.026	0.027
	9	0.000	0.000	0.005	0.009	0.014	0.018	0.024	0.025	0.027	0.026	0.028
	Average	0.004	0.004	0.007	0.010	0.013	0.018	0.025	0.027	0.029	0.029	0.030
No. 12 (RC-167, 60% H, 40% P)	1	0.009	0.009	0.010	0.012	0.014	0.018	0.025	0.030	0.033	0.035	0.034
	2	0.010	0.010	0.011	0.013	0.016	0.019	0.027	0.031	0.035	0.036	0.035
	3	0.009	0.009	0.010	0.012	0.015	0.018	0.026	0.031	0.033	0.034	0.033
	4	0.001	0.007	0.003	0.007	0.012	0.018	0.024	0.026	0.029	0.029	0.030
	5	0.001	0.007	0.002	0.006	0.011	0.016	0.022	0.024	0.027	0.026	0.028
	6	0.000	0.007	0.002	0.006	0.010	0.015	0.022	0.024	0.026	0.026	0.028
	7	0.001	0.004	0.003	0.008	0.011	0.018	0.020	0.024	0.025	0.022	0.024
	8	0.002	0.005	0.004	0.009	0.013	0.018	0.019	0.023	0.026	0.023	0.026
	9	0.002	0.004	0.004	0.009	0.013	0.018	0.018	0.023	0.025	0.024	0.025
	Average	0.004	0.007	0.005	0.009	0.013	0.018	0.023	0.026	0.029	0.028	0.029
No. 13 (RC-594, all P)	1	-0.011	-0.011	-0.008	-0.007	-0.006	-0.001	0.004	0.009	0.012	0.012	0.012
	2	-0.004	-0.005	-0.002	-0.001	0.000	0.004	0.010	0.015	0.019	0.019	0.019
	3	-0.003	-0.004	-0.001	-0.001	0.000	0.004	0.012	0.017	0.018	0.019	0.019
	4	0.002	0.002	0.006	0.007	0.008	0.012	0.016	0.019	0.019	0.019	0.019
	5	0.004	0.003	0.007	0.008	0.010	0.015	0.019	0.022	0.021	0.022	0.023
	6	0.003	0.002	0.007	0.007	0.008	0.013	0.017	0.019	0.020	0.021	0.021
	7	0.001	0.002	0.003	0.005	0.005	0.009	0.013	0.011	0.015	0.014	0.018
	8	0.004	0.004	0.005	0.009	0.008	0.013	0.015	0.013	0.018	0.017	0.021
	9	0.003	0.003	0.004	0.011	0.011	0.014	0.016	0.013	0.017	0.016	0.020
	Average	0.004	0.004	0.005	0.006	0.006	0.009	0.014	0.015	0.018	0.018	0.019
No. 14 (RC-594, 80% H, 20% P)	1	0.004	0.003	0.007	0.009	0.011	0.019	0.023	0.028	0.031	0.032	0.032
	2	0.004	0.005	0.008	0.010	0.012	0.017	0.026	0.028	0.032	0.033	0.033
	3	0.003	0.003	0.007	0.009	0.010	0.016	0.027	0.029	0.032	0.032	0.032
	4	0.003	0.002	0.005	0.010	0.015	0.018	0.024	0.027	0.031	0.031	0.031
	5	0.003	0.001	0.005	0.010	0.015	0.018	0.024	0.033	0.031	0.030	0.031
	6	0.004	0.002	0.006	0.012	0.018	0.019	0.026	0.026	0.033	0.033	0.031
	7	0.003	0.003	0.008	0.012	0.013	0.011	0.024	0.029	0.027	0.027	0.029
	8	0.003	0.004	0.007	0.012	0.014	0.011	0.023	0.029	0.031	0.027	0.030
	9	0.003	0.003	0.007	0.011	0.013	0.011	0.023	0.029	0.029	0.028	0.030
	Average	0.003	0.003	0.007	0.011	0.013	0.016	0.024	0.029	0.031	0.030	0.031
No. 15 (RC-594, 60% H, 40% P)	1	0.003	0.004	0.007	0.008	0.010	0.014	0.022	0.023	0.027	0.030	0.030
	2	0.003	0.003	0.006	0.008	0.010	0.014	0.022	0.023	0.029	0.031	0.030
	3	0.002	0.001	0.004	0.006	0.008	0.012	0.018	0.019	0.026	0.027	0.027
	4	0.007	0.005	0.005	0.007	0.010	0.017	0.025	0.026	0.031	0.029	0.032
	5	0.008	0.006	0.006	0.008	0.010	0.016	0.025	0.026	0.030	0.028	0.029
	6	0.008	0.005	0.006	0.007	0.009	0.016	0.025	0.026	0.030	0.028	0.031
	7	-0.001	0.001	0.004	0.009	0.013	0.017	0.020	0.024	0.025	0.024	0.026
	8	0.001	0.001	0.002	0.006	0.012	0.016	0.018	0.022	0.024	0.023	0.025
	9	0.002	0.001	0.001	0.006	0.010	0.014	0.016	0.020	0.021	0.018	0.020
	Average	0.004	0.003	0.005	0.005	0.010	0.015	0.021	0.023	0.027	0.026	0.027

(Continued)

Mixture	Bar No.	Length Change of Bar at Indicated Ages, percent										
		7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	365 Days	1-1/2 Years	2 Years	2-1/2 Years	3 Years
No. 16 (RC-168, all R)	1	0.003	0.003	0.004	0.005	0.006	0.011	0.019	0.020	0.026	0.028	0.027
	2	0.002	0.000	0.001	0.002	0.003	0.008	0.016	0.017	0.023	0.026	0.025
	3	-0.001	-0.001	0.000	0.001	0.003	0.009	0.016	0.017	0.023	0.025	0.025
	4	0.002	0.003	0.004	0.006	0.009	0.015	0.017	0.019	0.023	0.021	0.023
	5	0.002	0.003	0.005	0.007	0.010	0.015	0.016	0.019	0.024	†	--
	6	0.003	0.004	0.005	0.007	0.011	0.018	0.018	0.020	0.025	0.023	0.027
	7	0.004	0.003	0.007	0.010	0.010	0.008	0.020	0.024	0.026	0.025	0.026
	8	0.005	0.005	0.008	0.011	0.012	0.010	0.022	0.025	0.026	†	--
	9	0.003	0.003	0.007	0.010	0.010	0.008	0.020	0.025	0.025	0.024	0.027
	Average	0.003	0.003	0.005	0.007	0.008	0.011	0.018	0.021	0.025	0.019	0.026
No. 17 (RC-168, 80% H, 20% R)	1	0.001	0.001	0.008	0.008	0.007	0.010	0.018	0.020	0.024	0.026	0.026
	2	0.003	0.002	0.006	0.008	0.010	0.019	0.027	0.029	0.034	0.035	0.036
	3	0.001	0.002	0.003	0.005	0.007	0.010	0.017	0.020	0.024	0.027	0.026
	4	0.001	0.002	0.006	0.007	0.008	0.014	0.018	0.020	0.022	0.025	0.026
	5	0.002	0.002	0.006	0.007	0.008	0.014	0.018	0.020	0.021	0.024	0.026
	6	0.003	0.002	0.006	0.007	0.008	0.016	0.020	0.022	0.024	0.024	0.024
	7	0.002	0.001	0.007	0.007	0.009	0.012	0.018	0.020	0.020	0.020	0.024
	8	0.002	0.001	0.005	0.005	0.008	0.012	0.019	0.018	0.019	0.020	0.023
	9	0.003	0.001	0.005	0.005	0.008	0.011	0.018	0.016	0.018	0.019	0.023
	Average	0.002	0.002	0.006	0.007	0.008	0.013	0.017	0.018	0.023	0.024	0.026
No. 18 (RC-168, 60% H, 40% R)	1	0.002	0.003	0.004	0.005	0.007	0.010	0.020	0.022	0.027	0.027	0.027
	2	0.002	0.002	0.004	0.005	0.007	0.011	0.020	0.022	0.024	0.025	0.026
	3	0.002	0.003	0.004	0.005	0.006	0.010	0.020	0.022	0.025	0.026	0.026
	4	0.002	0.003	0.004	0.005	0.006	0.013	0.018	0.020	0.023	0.022	0.025
	5	0.001	0.001	0.003	0.004	0.005	0.011	0.015	0.018	0.022	0.019	0.021
	6	0.001	0.001	0.002	0.003	0.004	0.010	0.015	0.018	0.021	0.019	0.021
	7	0.003	0.003	0.003	0.007	0.008	0.011	0.015	0.015	0.021	0.022	0.025
	8	0.002	0.003	0.002	0.006	0.008	0.010	0.032	0.021	0.021	0.020	0.025
	9	0.003	0.005	0.003	0.007	0.009	0.012	0.016	0.016	0.020	0.020	0.025
	Average	0.002	0.003	0.003	0.005	0.007	0.011	0.019	0.019	0.023	0.022	0.025
No. 19 (RC-167, all R)	1	0.002	0.003	0.001	0.003	0.006	0.013	0.023	0.026	0.026	0.029	0.027
	2	0.000	0.000	-0.002	0.000	0.002	0.008	0.017	0.020	0.022	0.026	0.023
	3	0.000	0.001	-0.001	0.001	0.004	0.010	0.018	0.020	0.022	0.025	0.024
	4	-0.002	0.000	0.000	0.002	0.003	0.010	0.011	0.015	0.020	†	--
	5	-0.003	0.001	-0.002	0.000	0.001	0.005	0.007	0.010	0.014	0.014	0.014
	6	0.000	0.004	0.002	0.003	0.005	0.013	0.014	0.017	0.020	0.018	0.022
	7	0.004	0.002	0.003	0.005	0.008	0.016	0.018	0.020	0.023	0.022	0.025
	8	0.004	0.001	0.003	0.005	0.008	0.016	0.018	0.020	0.021	0.020	0.023
	9	0.003	0.001	0.003	0.005	0.008	0.014	0.018	0.020	0.022	†	--
	Average	0.001	0.001	0.001	0.003	0.004	0.012	0.017	0.019	0.021	0.022	0.023
No. 20 (RC-167, 80% H, 20% R)	1	0.002	0.002	0.002	0.005	0.008	0.017	0.025	0.030	0.031	0.031	0.031
	2	0.000	0.000	0.001	0.005	0.009	0.014	0.023	0.027	0.029	0.028	0.028
	3	0.001	0.001	0.002	0.005	0.009	0.016	0.024	0.029	0.030	0.029	0.029
	4	0.005	0.004	0.007	0.008	0.010	0.015	0.019	0.023	0.026	0.024	0.027
	5	0.002	0.002	0.006	0.007	0.009	0.015	0.019	0.024	0.026	0.023	0.027
	6	0.003	0.003	0.006	0.008	0.010	0.017	0.021	0.024	0.027	0.025	0.027
	7	-0.001	0.001	0.000	0.005	0.006	0.015	0.017	0.022	0.023	0.021	0.024
	8	0.003	0.005	0.003	0.009	0.010	0.020	0.021	0.027	0.029	0.027	0.030
	9	0.004	0.004	0.004	0.008	**	--	--	--	--	--	--
	Average	0.002	0.002	0.003	0.007	0.009	0.014	0.021	0.023	0.028	0.028	0.028

(Continued)

** Bar was broken or failed to read it.

† Bar was used for compressive strength test.

Table 9 (Continued)

Mixture	Bar No.	7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	365 Days	1-1/2 Years	2 Years	2-1/2 Years	3 Years
		Length Change of Bar at Indicated Ages, percent										
No. 21 (RC-167, 60% H, 40% R)	1	0.002	0.002	0.003	0.006	0.009	0.016	0.024	0.027	0.028	0.029	0.029
	2	0.001	0.001	0.002	0.004	0.008	0.014	0.023	0.026	0.028	0.029	0.029
	3	0.001	0.001	0.002	0.004	0.007	0.015	0.023	0.026	0.028	0.028	0.028
	4	0.005	0.000	0.004	0.004	0.005	0.013	0.015	0.021	0.025	0.025	0.027
	5	0.006	-0.001	0.006	0.007	0.008	0.015	0.015	0.022	0.027	0.026	0.028
	6	0.005	0.000	0.005	0.006	0.007	0.015	0.016	0.022	0.026	0.026	0.028
	7	0.005	0.002	0.005	0.008	0.011	0.016	0.021	0.025	0.025	0.025	0.027
	8	0.005	0.002	0.006	0.009	0.012	0.018	0.022	0.026	0.027	0.026	0.028
	9	0.005	0.005	0.005	0.008	0.011	0.018	0.022	0.025	0.026	0.026	0.027
	Average	0.004	0.001	0.004	0.006	0.009	0.016	0.020	0.024	0.027	0.027	0.028
No. 22 (RC-594, all R)	1	0.000	0.000	0.000	0.003	0.006	0.012	0.021	0.023	0.025	0.026	0.026
	2	0.000	0.000	0.000	0.002	0.005	0.011	0.021	0.022	0.024	0.026	0.025
	3	-0.003	-0.003	-0.004	-0.001	-0.001	0.008	0.016	0.018	0.020	0.021	0.021
	4	0.010	0.010	0.013	0.015	0.016	0.020	0.023	0.032	0.031	†	--
	5	0.010	0.010	0.013	0.015	0.016	0.022	0.026	0.029	0.031	0.032	0.035
	6	0.009	0.009	0.012	0.013	0.015	0.020	0.025	0.030	0.029	0.030	0.033
	7	0.004	0.002	0.006	0.006	0.010	0.013	0.019	0.018	0.019	†	--
	8	0.004	0.001	0.005	0.006	0.009	0.012	0.018	0.019	0.020	0.021	0.027
	9	0.004	0.002	0.006	0.006	0.010	0.013	0.013	0.019	0.020	0.021	0.027
	Average	0.004	0.003	0.006	0.007	0.010	0.015	0.021	0.023	0.024	0.026	0.028
No. 23 (RC-594, 80% H, 20% R)	1	0.000	0.004	0.004	0.007	0.012	0.015	0.023	0.027	0.026	0.029	0.029
	2	0.005	0.009	0.009	0.013	0.017	0.022	0.030	0.033	0.034	0.036	0.036
	3	0.003	0.006	0.007	0.012	0.015	0.018	0.032	0.032	0.030	0.033	0.033
	4	0.007	0.010	0.011	0.014	0.017	0.024	0.027	0.031	0.034	0.032	0.037
	5	0.000	0.002	0.002	0.005	0.009	0.017	0.018	0.021	0.025	0.023	0.028
	6	0.001	0.004	0.004	0.007	0.011	0.019	0.020	0.026	0.030	0.025	0.029
	7	0.003	0.004	0.006	0.009	0.014	0.020	0.023	0.026	0.027	0.028	0.029
	8	0.004	0.007	0.006	0.008	0.014	0.020	0.024	0.025	0.027	0.028	0.029
	9	0.004	0.003	0.005	0.007	0.012	0.018	0.023	0.027	0.026	0.027	0.028
	Average	0.003	0.005	0.006	0.009	0.013	0.019	0.024	0.028	0.029	0.029	0.031
No. 24 (RC-594, 60% H, 40% R)	1	0.004	0.007	0.008	0.012	0.016	0.019	0.028	0.030	0.032	0.034	0.034
	2	0.002	0.005	0.006	0.009	0.012	0.016	0.029	0.028	0.027	0.030	0.030
	3	0.005	0.008	0.009	0.013	0.017	0.020	0.029	0.031	0.033	0.034	0.034
	4	0.001	-0.001	0.006	0.008	0.009	0.014	0.020	0.022	0.022	0.207	0.028
	5	0.001	-0.001	0.008	0.010	0.013	0.018	0.022	0.025	0.031	0.029	0.031
	6	0.002	-0.001	0.008	0.012	0.014	0.017	0.022	0.024	0.029	0.028	0.029
	7	0.005	0.004	0.005	0.008	0.011	0.017	0.022	0.024	0.027	0.025	0.027
	8	0.005	0.003	0.004	0.006	0.008	0.016	0.021	0.024	0.026	0.022	0.024
	9	0.005	0.004	0.006	0.008	0.010	0.018	0.024	0.027	0.028	0.025	0.028
	Average	0.003	0.003	0.007	0.010	0.012	0.017	0.024	0.026	0.028	0.028	0.029
No. 25 (RC-168, all V)	1	0.002	0.002	0.012	0.016	0.018	0.027	0.035	0.041	0.042	0.044	0.044
	2	0.002	0.002	0.013	0.015	0.018	0.027	**	--	--	--	--
	3	0.008	0.009	0.009	0.015	0.021	0.032	0.038	0.044	0.046	0.048	0.049
	4	0.010	0.010	0.012	0.016	0.021	0.031	0.042	0.044	0.049	0.049	0.052
	5	0.009	0.008	0.009	0.014	0.019	0.029	0.039	0.040	0.044	0.044	0.048
	6	0.008	0.009	0.010	0.015	0.020	0.030	0.041	0.043	0.046	0.047	0.049
	7	0.006	0.010	0.013	0.019	0.022	0.029	0.034	0.035	0.041	0.041	0.043
	8	0.006	0.009	0.013	0.017	0.020	0.027	0.032	0.033	0.040	0.039	0.040
	9	0.004	0.006	0.012	0.018	0.020	0.027	0.032	0.033	0.038	0.038	0.039
	Average	0.006	0.007	0.011	0.016	0.020	0.029	0.037	0.039	0.043	0.044	0.046

(Continued)

** Bar was broken or failed to read it.
† Bar was used for compressive strength test.

Mixture	Bar No.	Length Change of Bar at Indicated Ages, percent: 7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	365 Days	1-1/2 Years	2 Years	2-1/2 Years	3 Years
No. 26 (RC-168, 80% H, 20% V)	1	0.003	0.003	0.008	0.009	0.011	0.022	0.034	0.029	0.029	0.031	0.031
	2	0.000	0.001	0.006	0.007	0.009	0.016	0.023	0.028	0.028	0.029	0.029
	3	0.005	0.006	0.012	0.013	0.014	0.021	0.037	0.032	0.032	0.034	0.035
	4	0.000	0.007	0.005	0.009	0.013	0.020	0.028	0.030	0.038	0.033	0.035
	5	0.000	0.006	0.004	0.008	0.013	0.019	0.027	0.029	0.033	0.032	0.034
	6	0.001	0.008	0.005	0.009	0.013	0.020	0.027	0.027	0.032	0.032	0.032
	7	0.005	0.005	0.005	0.009	0.014	0.019	0.024	0.027	0.031	0.029	0.032
	8	0.005	0.004	0.009	0.012	0.015	0.020	0.026	0.029	0.033	0.030	0.033
	9	0.004	0.004	0.007	0.013	0.014	0.019	0.026	0.028	0.031	0.029	0.031
	Average	0.003	0.005	0.007	0.010	0.013	0.020	0.028	0.029	0.032	0.031	0.032
No. 27 (RC-168, 60% H, 40% V)	1	0.000	0.002	0.007	0.008	0.011	0.019	0.026	0.031	0.031	0.034	0.034
	2	0.001	0.003	0.005	0.009	0.013	0.020	0.028	0.033	0.034	0.038	0.037
	3	0.002	0.004	0.010	0.012	0.013	0.020	0.026	0.032	0.033	0.035	0.035
	4	0.002	0.003	0.006	0.008	0.011	0.018	0.023	0.028	0.032	0.031	0.034
	5	0.003	0.004	0.007	0.010	0.013	0.021	0.028	0.030	0.033	0.033	0.036
	6	0.003	0.004	0.007	0.009	0.011	0.019	0.025	0.030	0.033	0.031	0.035
	7	0.005	0.005	0.006	0.012	0.015	0.024	0.030	0.035	0.034	0.035	0.038
	8	0.009	0.009	0.009	0.012	0.015	0.024	0.031	0.036	0.035	0.035	0.036
	9	0.005	0.006	0.006	0.012	0.016	0.024	0.030	0.034	0.034	0.035	0.036
	Average	0.003	0.004	0.007	0.010	0.013	0.021	0.028	0.032	0.033	0.034	0.036
No. 28 (RC-167, all V)	1	0.019	0.019	0.030	0.041	0.052	0.070	0.086	0.091	0.096	0.098	0.101
	2	0.013	0.019	0.029	0.038	0.048	0.065	0.078	0.084	0.088	0.090	0.092
	3	0.011	0.018	0.027	0.038	0.049	0.066	0.081	0.086	0.089	0.092	0.094
	4	0.020	0.035	0.035	0.047	0.060	0.075	0.088	0.097	0.100	0.101	0.104
	5	0.021	0.026	0.037	0.050	0.063	0.077	0.089	0.097	0.100	0.101	0.103
	6	0.022	0.027	0.038	0.051	0.064	0.080	0.093	**	0.106	0.106	0.110
	7	0.017	0.025	0.031	0.047	0.058	0.078	0.089	0.097	0.101	0.103	0.103
	8	0.015	0.023	0.028	0.044	0.052	0.070	0.080	0.089	0.092	0.093	0.104
	9	0.015	0.024	0.030	0.047	0.056	0.075	0.081	0.090	0.094	0.095	0.096
	Average	0.017	0.024	0.032	0.045	0.056	0.073	0.085	0.091	0.096	0.098	0.101
No. 29 (RC-167, 80% H, 20% V)	1	0.005	0.008	0.011	0.019	0.028	0.026	0.035	0.036	0.038	0.040	0.040
	2	0.005	0.008	0.012	0.016	0.018	0.027	0.032	0.038	0.040	0.041	0.041
	3	0.005	0.005	0.010	0.013	0.017	0.029	0.039	0.039	0.040	0.042	0.042
	4	0.005	0.008	0.011	0.015	0.020	0.027	0.038	0.036	0.040	0.039	0.042
	5	0.006	0.010	0.014	0.019	0.025	0.034	0.044	0.043	0.046	0.046	0.049
	6	0.009	0.012	0.015	0.020	0.026	0.034	0.045	0.045	0.049	0.047	0.050
	7	0.002	0.007	0.011	0.018	0.023	0.032	0.034	0.039	0.042	0.042	**
	8	0.002	0.007	0.010	0.017	0.020	0.028	0.031	0.035	0.037	0.038	0.048
	9	0.004	0.010	0.013	0.019	0.024	0.032	0.036	0.040	0.043	0.043	0.044
	Average	0.005	0.008	0.012	0.017	0.022	0.030	0.037	0.039	0.042	0.042	0.045
No. 30 (RC-167, 60% H, 40% V)	1	0.010	0.013	0.017	0.025	0.033	0.047	0.060	0.062	0.065	0.068	0.069
	2	0.005	0.010	0.013	0.019	0.025	0.034	0.057	0.046	0.048	0.050	0.051
	3	0.005	0.010	0.013	0.019	0.026	0.035	0.043	0.047	0.050	0.052	0.053
	4	0.008	0.011	0.014	0.022	0.031	0.046	0.052	0.057	0.059	0.060	0.064
	5	0.008	0.012	0.015	0.023	0.032	0.046	0.052	0.060	0.059	0.060	0.063
	6	0.009	0.013	0.016	0.024	0.033	0.053	0.057	0.065	0.065	0.065	0.069
	7	0.010	0.013	0.022	0.030	0.037	0.044	0.061	0.065	0.066	0.065	0.068
	8	0.007	0.009	0.012	0.024	0.031	0.033	**	--	--	--	--
	9	0.007	0.010	0.018	0.026	0.032	0.037	0.052	0.056	0.060	0.059	0.063
	Average	0.008	0.011	0.016	0.024	0.031	0.042	0.054	0.057	0.059	0.060	0.063

(Continued)

** Bar was broken or failed to read it.

Mixture	Bar No.	Length Change of Bar at Indicated Ages, percent: 7 Days	14 Days	28 Days	56 Days	90 Days	180 Days	365 Days	1-1/2 Years	2 Years	2-1/2 Years	3 Years
No. 31 (RC-594, all V)	1	0.012	0.020	0.027	0.035	0.042	0.056	0.063	0.075	0.087	0.080	0.081
	2	0.013	0.020	0.028	0.036	0.045	0.059	0.066	0.078	0.082	0.084	0.086
	3	0.013	0.020	0.028	0.036	0.044	0.059	0.067	0.080	0.082	0.084	0.085
	4	0.015	0.023	0.034	0.045	0.056	0.070	0.081	0.090	0.094	0.096	0.100
	5	0.013	0.021	0.031	0.042	0.053	0.068	0.079	0.086	0.091	0.091	0.097
	6	0.014	0.023	0.032	0.043	0.055	0.072	0.084	0.088	0.094	0.094	0.099
	7	0.013	0.017	0.030	0.044	0.054	0.067	0.079	0.084	0.088	0.090	††
	8	0.013	0.018	0.032	0.046	0.056	0.072	0.084	0.095	0.100	0.101	0.103
	9	0.012	0.017	0.029	0.041	0.051	0.064	0.074	0.082	0.083	0.085	0.088
	Average	0.013	0.020	0.030	0.041	0.051	0.065	0.075	0.084	0.089	0.089	0.092
No. 32 (RC-594, 80% H, 20% V)	1	0.004	0.007	0.009	0.012	0.016	0.025	0.028	0.037	0.039	0.037	0.038
	2	0.004	0.008	0.011	0.014	0.018	0.026	0.029	0.039	0.039	0.040	0.040
	3	0.006	0.009	0.013	0.016	0.020	0.028	0.032	0.042	0.043	0.044	0.045
	4	0.004	0.005	0.014	0.017	0.021	0.028	0.035	0.038	0.042	0.042	0.042
	5	0.003	0.004	0.012	0.021	0.019	0.025	0.033	0.036	0.043	0.041	0.042
	6	0.004	0.005	0.014	0.028	0.022	0.031	0.039	0.042	0.047	0.046	0.047
	7	0.003	0.008	0.012	0.028	0.028	0.031	0.036	0.036	0.040	0.041	0.043
	8	0.003	0.008	0.013	0.018	0.023	0.031	0.035	0.036	0.041	0.043	0.043
	9	0.004	0.009	0.012	0.016	0.020	0.028	0.032	0.032	0.036	0.038	0.040
	Average	0.004	0.007	0.012	0.019	0.021	0.028	0.033	0.038	0.041	0.041	0.042
No. 33 (RC-594, 60% H, 40% V)	1	0.009	0.015	0.014	0.021	0.029	0.036	0.045	0.050	0.054	0.054	0.056
	2	0.008	0.013	0.014	0.021	0.029	0.036	0.045	0.051	0.054	0.056	0.057
	3	0.009	0.015	0.015	0.022	0.030	0.037	0.047	0.053	0.056	0.057	0.058
	4	0.008	0.013	0.015	0.023	0.031	0.046	0.051	0.059	0.061	0.060	0.064
	5	0.007	0.011	0.012	0.019	0.027	0.039	0.044	0.052	0.053	0.051	0.054
	6	0.008	0.016	0.015	0.023	0.032	0.047	0.051	0.058	0.062	0.056	0.060
	7	0.006	0.010	0.015	0.025	0.035	0.040	0.049	0.056	0.057	0.059	0.061
	8	0.005	0.012	0.017	0.023	0.032	0.043	0.047	0.053	0.055	0.056	0.059
	9	0.006	0.010	0.010	0.023	0.033	0.041	0.046	0.050	0.052	0.050	0.054
	Average	0.007	0.013	0.014	0.022	0.031	0.041	0.047	0.054	0.056	0.055	0.059

†† Bar was used for SEM examination.

Table 10

Results of XRD Examination of Reactive Rapid Rock Before and After Storage in 1 N NaOH Solution*

Name of Mineral	XRD Spacing Å	Original Surface	Intensity of Selected XRD Spacings of Slab 1 of Piece 3 of CRD G-35(B), counts per second — After Storage in Alkali Solution--Surface Ground to Indicated Depths, Before XRD Examination: No Removal	0.016 in.	0.069 in.	0.166 in.
Dolomite	2.88	1341	1337	1409	1192	734
Change			-4	+68	-149	-607
Calcite	3.04	**	**	59	292	446
Brucite	4.77	**	**	**	28	74
Hydrotal-cite†	7.69	**	20	**	trace	**
Quartz	3.34	247	214	190	190	185
Change			-33	-57	-57	-62
Clay-mica	10.0	15	trace	**	trace	**
	Reaction rims	no	no	no	yes	yes

* Kept in solution for 1 yr and 18 days under conditions stated in CRD-C 146.
** Not detected.
† Tentative identification.

Table 11

Results of XRD Examination of Reactive 1-8 Rock Before and After Storage in 1 N NaOH Solution or Portland Cement

		Intensity of Selected XRD Spacings of Slab 3, counts per second					XRD Determination of New Phases During Storage in Portland Cement Paste as Indicated Below**		
			After Storage in Alkali Solution*-- Surface Ground to Indicated Depths Before XRD Examination, in.						
Name of Crystalline Phase	XRD Spacing Å	Original Surface	No Removal	0.018	0.072	0.123	Slab 1 in RC-168, 1 yr at 100°F and 205 days at Room Temperature	Slab 2 in RC-167, 1 yr at 100°F and 2 yr at Room Temperature	Slab 4 in RC-594, 1 yr at 100°F and 2 yr at Room Temperature
Dolomite	2.88	406	185	40	51	118			
Change			-221	-366	-355	-288			
Calcite	3.04	530	655	842	895	851			
Change			+125	+312	+365	+321			
Brucite	4.77	†	82	94	89	88			
Hydrotalcite††	7.69	†	72	24	11	7	Present	†	Present
Quartz	3.34	47	41	31	32	36			
Change			-6	-16	-15	-11			
Calcium hydroxide	4.90	†	†	†	†	†	Present	†	Present

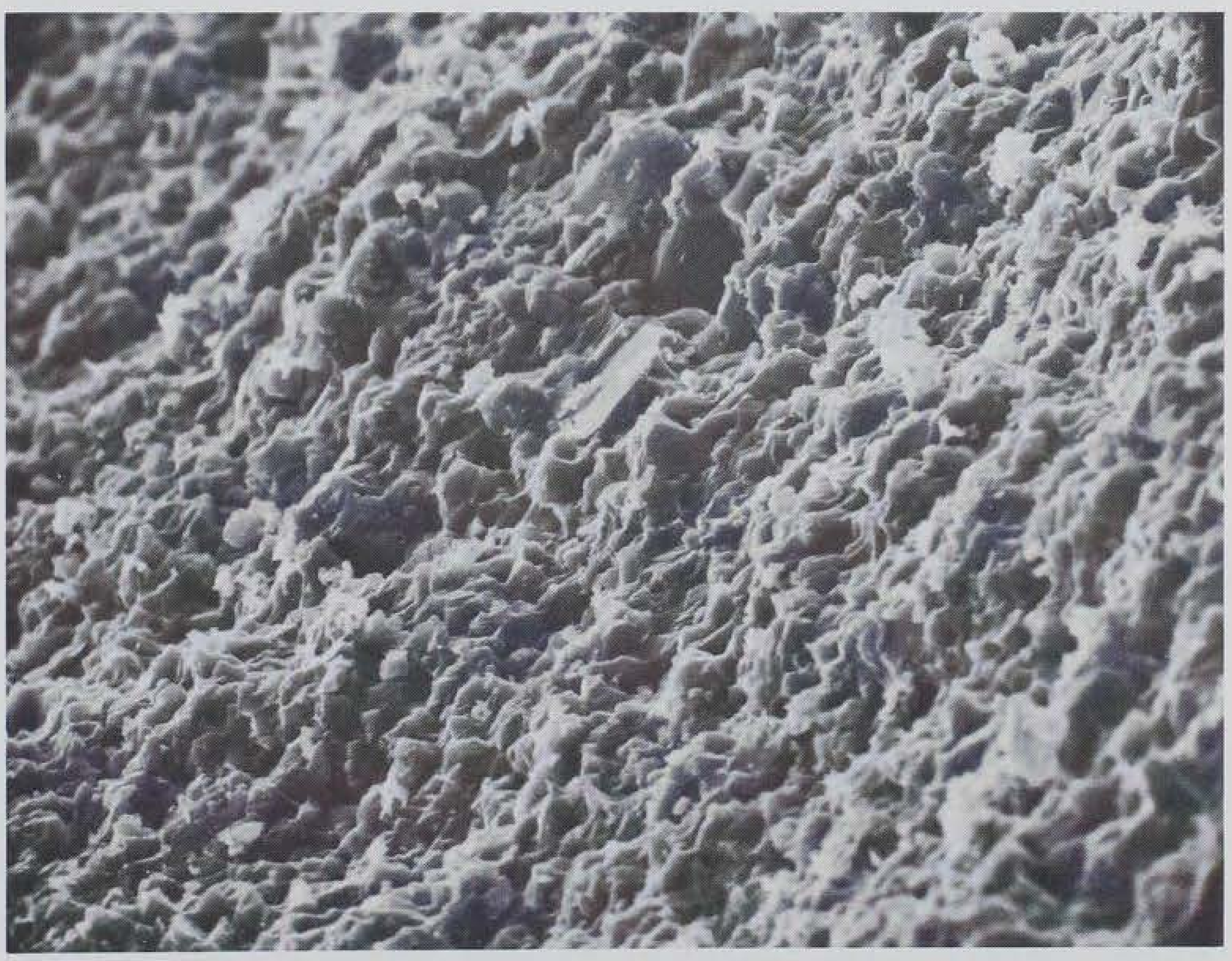
* Kept in solution for 18-3/4 months under conditions stated in CRD-C 146.

** Breakage of slabs during extraction from paste made quantitative measurements impossible; original surface of slab 2 lost during extraction.

† Not detected.

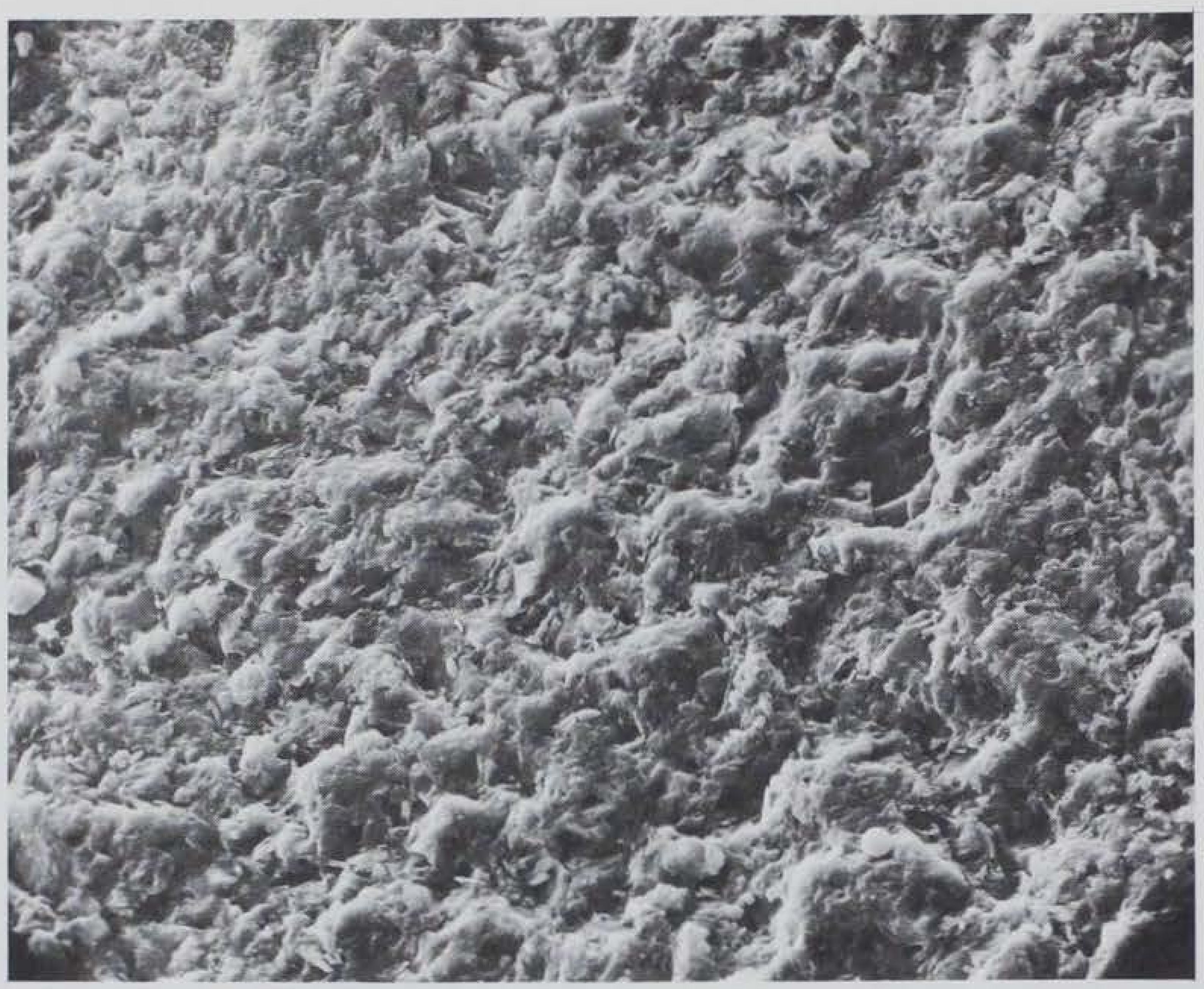
†† Tentative identification.

a. Unreacted 1-8 rock, ×1000 (010472-5)

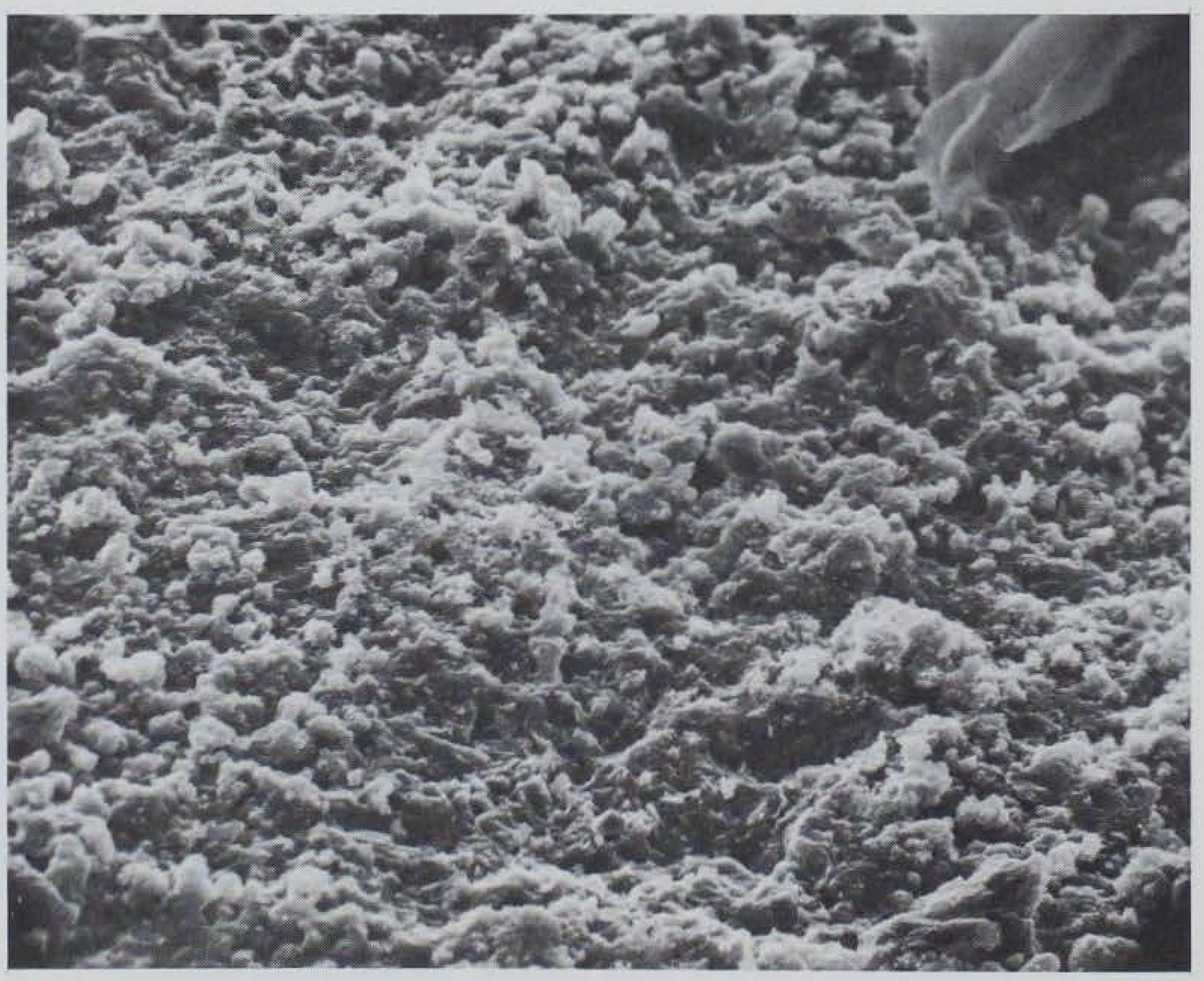


b. Hermitage rock from 34-month-old concrete bar 6-8, ×1000 (010472-11)

Photo 1. Fresh fracture surfaces of reactive 1-8 rock and Hermitage rock



a. Unreacted 1-8 rock, ×1000 (010472-8)

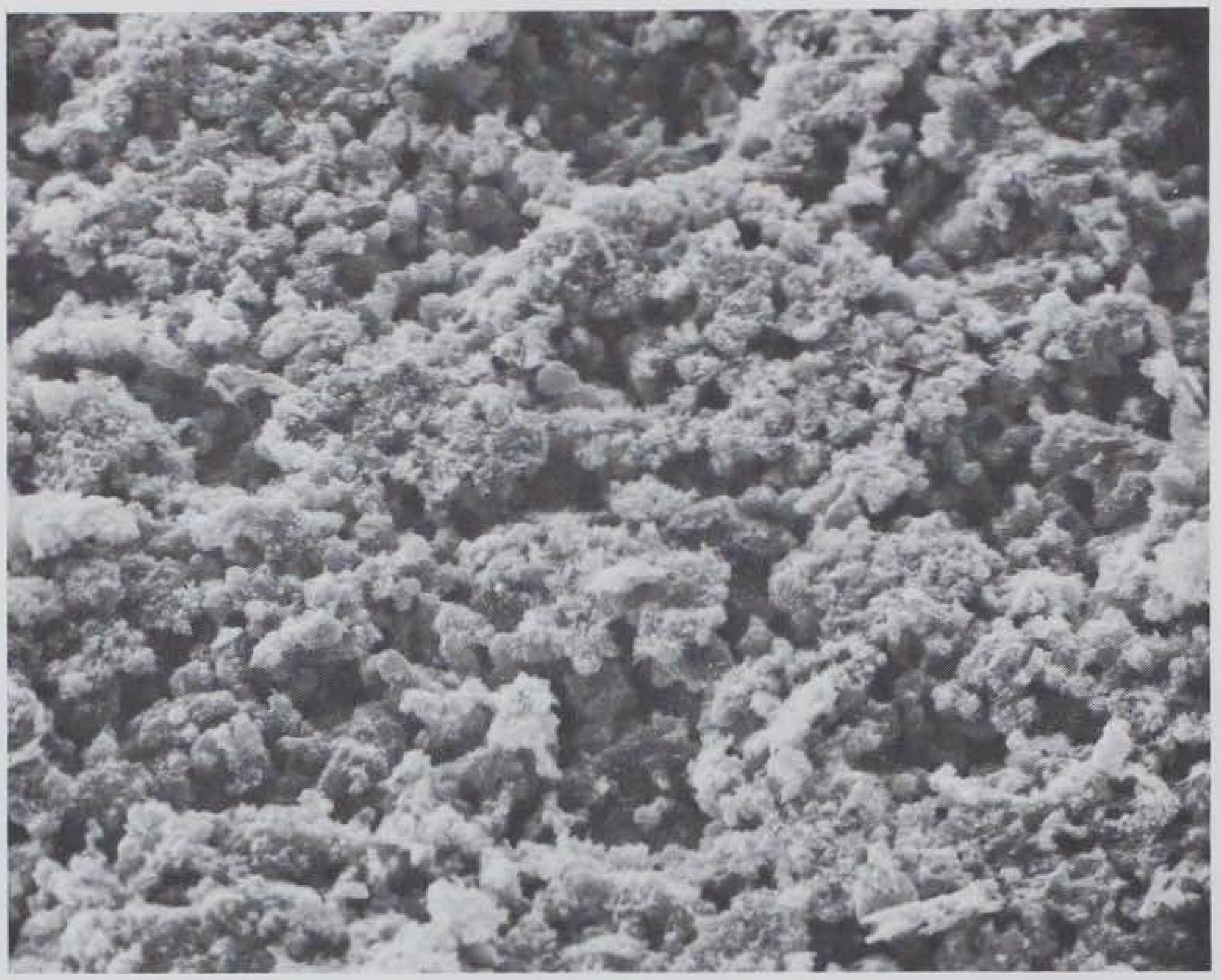


b. Reacted 1-8 slab 4 after 34 months in contact with RC-594 cement paste, ×1000 (010572-5)

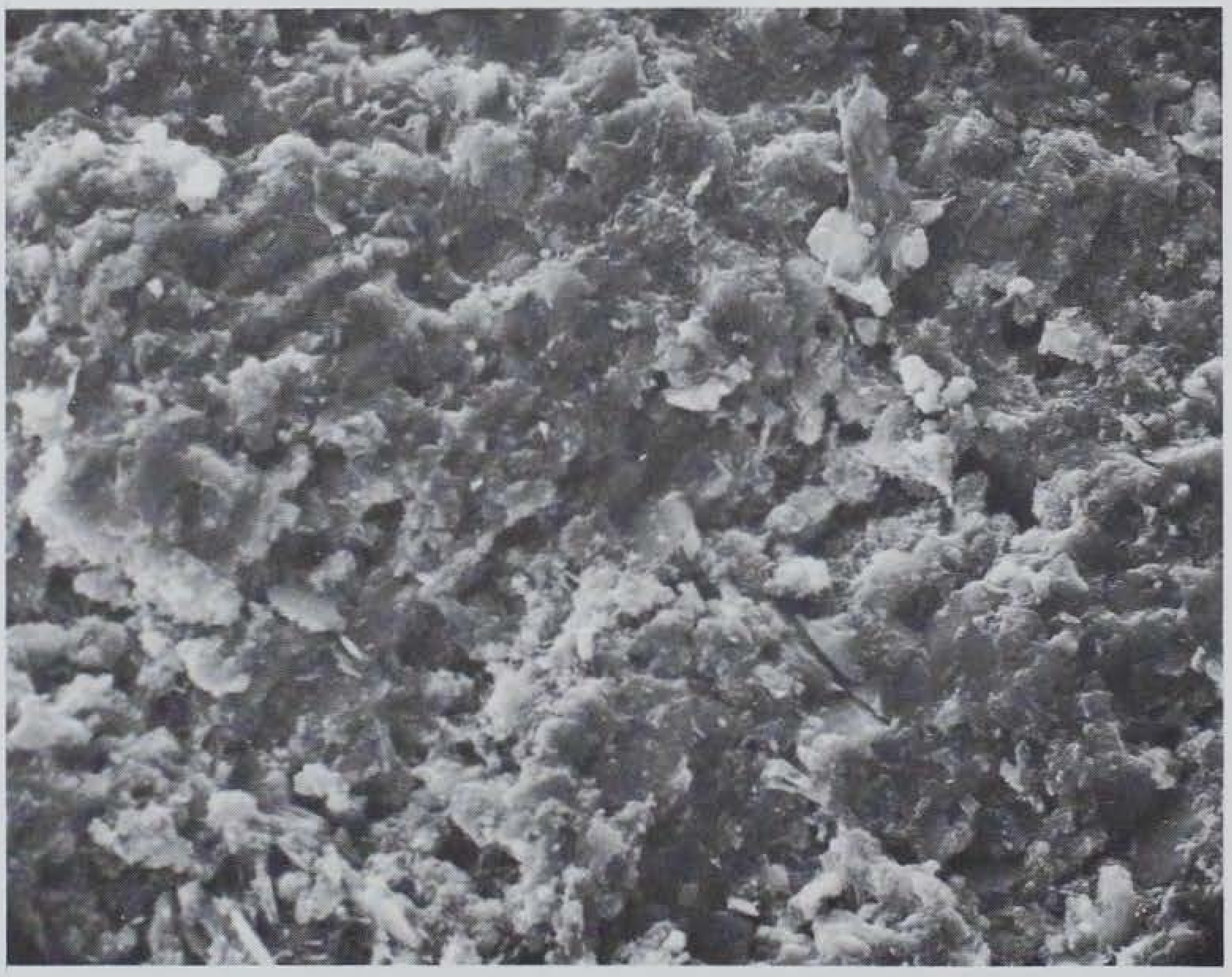
Photo 2. Ground surfaces of unreacted and reacted 1-8 rock (sheet 1 of 2)

c. Reacted 1-8 slab 3 after 19 months in 1 N NaOH solution, ×1000 (010472-23)

Photo 2 (sheet 2 of 2)



a. Surface of reacted paste of RC-594 after 34 months in contact with slab 4 of 1-8 rock, ×1000 (010572-8)



b. Fresh fracture surface of 34-month-old RC-167 cement paste in contact with 1-8 slab 2, ×1000. This is reaction zone (010472-26)

Photo 3. Surfaces of cement pastes (sheet 1 of 2)

c. Fresh fracture surface of 34-month-old RC-167 cement paste about 1 in. away from surface of 1-8 slab 2, ×1000. Should be out of reaction zone (010572-11)

Photo 3 (sheet 2 of 2)

In accordance with ER 70-2-3, paragraph 6c(1)(b), dated 15 February 1973, a facsimile catalog card in Library of Congress format is reproduced below.

Buck, Alan D
Control of reactive carbonate rocks in concrete, by Alan D. Buck. Vicksburg, U. S. Army Engineer Waterways Experiment Station, 1975.
1 v. (various pagings) illus. 27 cm. (U. S. Waterways Experiment Station. Technical report C-75-3)
Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C.
Includes bibliography.

1. Aggregates. 2. Alkali aggregate reactions. 3. Carbonate rocks. 4. Concrete aggregates. 5. Concrete strength. 6. Concrete test specimens. I. U. S. Army. Corps of Engineers. (Series: U. S. Waterways Experiment Station, Vicksburg, Miss. Technical report C-75-3)
TA7.W34 no.C-75-3