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TETON DAM—FOUNDATION GROUT TESTING PROGRAM

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16. ABSTRACT

After failure of Teton Dam in Idaho on June 5, 1976, the Secretary of the Department of the Interior appointed the Interior Teton Dam Failure Review Group (IRG) to investigate the failure. The Grouting Task Group of the IRG requested that the Bureau of Reclamation initiate a program to test foundation grouts similar to those used during construction of Teton Dam. Grouts were to be (a) made with the same cement, sand, bentonite, and calcium chloride as were used during construction, (b) made using mix proportions representative of grouts used during construction, and (c) mixed and cured as congruently to field conditions as possible. Tests performed on grouts from 66 mixes included: time of setting, unconfined compressive strength, triaxial shear strength, drying shrinkage, erodibility, and permeability. Bleeding characteristics were also analyzed, and a detailed petrographic examination was performed. All grouts exhibited good hydration properties and good physical soundness, adequate strengths, no degradation due to calcium chloride, and low permeability. Areas of future research in neat-cement and sand-cement grouts are also listed.

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On November 6, 1979, the Bureau of Reclamation was renamed the Water and Power Resources Service in the U.S. Department of the Interior. The new name more closely identifies the agency with its principal functions — supplying water and power.

The text of this publication was prepared prior to adoption of the new name; all references to the Bureau of Reclamation or any derivative thereof are to be considered synonymous with the Water and Power Resources Service.

Note: The data reported in this document were measured in inch-pound units and converted to SI metric units.

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INTRODUCTION

In an internal memorandum dated September 3, 1976, to the Chairman of the Interior Teton Dam Failure Review Group, the Chairman of the Grouting Task Group recommended that a laboratory program be initiated to test foundation grouts similar to those used during construction of Teton Dam in Idaho. In November 1976, the Concrete and Structural Branch, Engineering and Research Center, USBR (Bureau of Reclamation) initiated the Teton Dam Foundation Grout Testing Program.

The main objective of the Grout Testing Program was to determine the effects of calcium chloride on physical properties of the grouts. Parameters included in this program were:

- Grout materials — cement, sand, bentonite, and calcium chloride — were to be as comparable as possible to those used at the Teton Dam construction site.
- Mix proportions of tested grouts were to be representative of grouts actually used during construction of the foundation grout curtain and grout blanket.
- Mixing operations and curing conditions were to parallel field conditions as closely as possible.

This report on the Grout Testing Program discusses the physical properties of the grout studied, test parameters, test procedures, test results, conclusions, and recommendations for future research.

SUMMARY

1. Inclusion of calcium chloride in grout mixes (a) accelerated hydration and reduced setting time, (b) generally increased strength at all grout temperatures, (c) greatly increased strengths at low grout temperatures [2 to 4 °C (35 to 40 °F)], (d) increased drying shrinkage of hardened grout, and (e) caused mixes to thicken appreciably at the end of the mixing period with calcium chloride dosages of 6 and 8 percent by weight of cement.

2. For sanded grouts, a maximum dosage of about 6 percent calcium chloride realized (a) the greatest reduction in time of setting when compared to a control mix containing no calcium chloride, and (b) the greatest increase in unconfined compressive strength of hardened grout when compared to a control mix. Sanded grouts also suffered more strength loss between 7 and 90 days when calcium chloride contents were 6 and 8 percent.

3. Increases in grout temperature (a) lowered strength, (b) decreased drying shrinkage slightly, and (c) caused mixes to thicken appreciably by the end of the mixing period. The time of setting was not affected by an increase in grout temperature. Grout temperature effects on bleeding are inconclusive.

4. All grouts demonstrated good strengths through an age of 90 days.

5. The two hardened grouts tested for permeability (a lean, neat-cement grout with a W:C ratio[1] of 5:1 and a rich, neat-cement grout with a W:C ratio of 0.8:1) had very low coefficients of permeability.

6. The grouts with high W:C ratios had very large amounts of bleeding.

7. In spite of irregularities in the appearance of the hardened grout which included white streaks, white crystals, spots of light gray, and flaking crust, no physical or chemical aberrations in grout quality could be found.

CONCLUSIONS

1. All mixes in the testing program produced grouts exhibiting good hydration properties and good physical soundness.

2. Inclusion of calcium chloride in grout mixes apparently did not cause formation of any compounds or substances which would be water soluble or erodible.

3. Future consideration should be given to specifying an upper limit of about 6 percent calcium chloride, by weight of cement, for sanded foundation grouts.

4. Variations in the grout temperature at the end of the mixing period did not have adverse effects on grout.

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[1] W:C = Water to cement ratio by volume.

5. Although grouts tested were not impermeable, their relative permeability is low enough to preclude significant waterflow.

6. Large amounts of bleeding, in grouts with high W:C and W:C:S ratios[2], seem relatively inconsequential. When foundation grouts are pumped under high pressures, much of this "bleeding" is forced to take place. The resultant in-place grout has a much lower W:C or W:C:S ratio.

PHYSICAL PROPERTIES

The seven physical properties investigated in this study were: (1) time of setting, (2) unconfined compressive strength, (3) triaxial shear strength, (4) drying shrinkage, (5) erodibility, (6) permeability, and (7) bleeding. A detailed petrographic examination was added to supplement the other seven properties. Reasons for the choices of these seven properties plus a petrographic examination are discussed in the following paragraphs.

A physical property of foundation grout, which is of special interest, is time of setting. The time it takes for grout to begin to set, as it is forced into cracks in foundation rock, affects the distance it will travel from the grout pump. This, in turn, affects quantities of grout required to complete a grout curtain. Increased quantities of grout, which are required due to long travel distances, mean increased costs to a project. Hence, it was desirable to study initial and final times of setting.

Strength is a good indicator of durability for mortar and concrete mixtures and should give a good idea of the physical adequacy of grouts. Unconfined compressive strength testing was, therefore, included in the Grout Testing Program. Also, in an effort to gain some understanding of strength characteristics of grout as it is confined in a rock mass, triaxial shear testing was undertaken.

Cementitious mixtures with high water contents, such as grouts, usually undergo shrinkage due to evaporation of water. This shrinkage, termed "drying shrinkage," could hinder the impermeability of a grout curtain. After crevices in foundation rock are sealed, drying shrinkage could possibly cause minute cracks where grout pulls away from rock surfaces. Drying shrinkage was then included in the study as an important physical property.

In foundation grouting state-of-the-art, it is assumed that grout completely fills and hardens in the voids. However, if grout only partially fills some crevices, flow of water could have adverse effects on grout integrity through erosion. Little information could be found in literature concerning erodibility of grouts such as those in this study. Weaker neat-cement grouts with a W:C ratio of 5:1 were subjected to the flow of water under pressure to determine if they were erodible.

When grout completely fills the voids in foundation rock, a grout curtain is formed which is practically impenetrable by waterflow. However, if hardened grout is permeable, it would allow water to seep through the grout curtain. Hardened grouts under high-pressure head were tested to evaluate their permeability.

In cementitious mixtures of high water content, bleeding is a concern. Bleeding is the rise of water to the top surfaces of grout due to the settling of solid particles. In grouting state-of-the-art, it is assumed that much of the water in a grout mixture is forced away during pressure pumping; hence, the quantity of water which is left to contribute to bleeding is not actually known. Laboratory specimens cast under atmospheric pressure theoretically would be much more susceptible to bleeding than grout pumped into foundation rock, so bleeding characteristics of laboratory specimens were only qualitatively determined.

Since calcium chloride is widely used in foundation grouting to accelerate the hydration process, and physical appearances of some laboratory grout specimens indicated that calcium chloride might have deleterious effects on the grouts, a thorough petrographic examination was performed to secure information about the chemical and physical composition of the hydrated grouts. The mechanism of the action of calcium chloride on the hydration of cement is very complex since it must take into account the reactions occurring with the different phases of the cement[1][3]. Nevertheless, the petrographic examination of grout specimens helped to clarify some of the hydration reactions and physical appearances of specimens.

[2] W:C:S = Water to cement to sand ratios by volume.

[3] Numbers in brackets refer to entries in the bibliography.

TEST PARAMETERS

The primary reference used in determining testing parameters was a paper by Peter Aberle [2], formerly Chief Inspector at Teton Dam. Additional sources of information were construction specifications No. DC-6766, Teton Dam Pilot Grouting, and No. DC-6910, Teton Dam and Power and Pumping Plant, and various geologic data obtained from the Teton Project Office and the Pacific Northwest Regional Office.

Materials

Except for batch water, all materials used to mix laboratory grouts were the same as, or equivalent to, those used at the construction site.

The Teton Project Office shipped sacks of cement (which had been in storage) and sand to the E&R (Engineering and Research) Center. The cement was a type I/II, low alkali, from Idaho Cement Company, Inkom, Idaho. Sand was subangular to angular in shape, composed primarily of basalt, quartzite, and glassy volcanics. It had a specific gravity of 2.49, an absorption of 1.2 percent, and was potentially alkali-reactive with high-alkali cement. Practically all of it passed a No. 8 screen. Sand used in time-of-set testing was screened to remove all grains larger than No. 8, since these larger particles can give faulty penetration readings if the vicat needle strikes them.

Bentonite used during construction was supplied by Wyoming Bentonite Products Company, Greybull, Wyo. For this study, the bentonite was purchased from their distributor in Denver, Colo. – Wyo-Ben Products, Inc.

Both Allied Chemical Corp. and Pittsburgh Plate Glass Industries supplied the calcium chloride used at the jobsite. All calcium chloride was anhydrous, 90 to 94 percent pure, and mostly flake-type; however, a small amount of the granular type was used. Calcium chloride used in the laboratory was obtained from Van Waters and Rogers, Denver, Colo., and was Dow Chemical brand, anhydrous, 94 to 97 percent pure, flake.

Mixes

There were three variables for each grout mix: (1) Water to cement ratio or water to cement to sand ratio, (2) calcium chloride dosage, and (3) grout temperature. Values selected for these variables were:

1. Water to cement ratio (by volume)

   a. 0.8:1
   b. 5:1
   c. 8:1

   Water to cement to sand ratio (by volume)

   a. 1:1:1
   b. 1:1:1.4
   c. 1:1:1.8

2. Calcium chloride dosage (percent by weight of cement)

   a. 0 percent
   b. 2 percent
   c. 5 and/or 6 percent
   d. 8 percent

3. Grout temperature (at end of 8-minute mixing period)

   a. 2 to 4 °C (35 to 40 °F)
   b. 13 to 21 °C (55 to 70 °F)
   c. 27 to 32 °C (80 to 90 °F)

Specific mixes tested for each physical property are indicated in table 1 and in the TEST PROCEDURES section.

Neat-cement grout mix proportions used in construction ranged from 0.8:1 to 8:1. Therefore, neat-cement grouts selected for testing had W:C ratios of 0.8:1, 5:1, and 8:1. Construction W:C:S ratios ranged from 1:1:1.2 to 1:1:1.6. In this study, a wider range was chosen and the W:C:S ratios tested included: 1:1:1, 1:1:1.4, 1:1:1.8. Two percent bentonite (by weight of cement) was used in all sanded grouts during construction and, therefore, was provided for in this study.

At the jobsite, as much as 6-1/2 percent calcium chloride was routinely added to grout mixes to accelerate hydration of grouts to limit distances of grout travel. However, as noted in conversations with Mr. Aberle, the use of as much as 8 percent calcium chloride was attempted. Calcium chloride was added mainly to rich, neat-cement grouts, and occasionally to sanded grouts. Calcium chloride was not used in lean, neat-cement grouts. Dosages of calcium chloride to be used in this study were initially set at 0, 2, 5, and 8 percent. However, it was felt that a 6-percent calcium chloride dosage was used in a sufficient number of mixes during construction to represent a specific data point for this study. With two exceptions, standard calcium

Table 1.-*Summary of grout mixes tested*

Calcium chloride content,* %	W:C or W:C:S ratio	Physical property test											
		Time of setting			Unconfined compressive strength			Triaxial shear strength			Drying shrinkage		
		Grout temperature, °C (°F)**											
		2-4 (35-40)	13-21 (55-70)	27-32 (80-90)	2-4 (35-40)	13-21 (55-70)	27-32 (80-90)	2-4 (35-40)	13-21 (55-70)	27-32 (80-90)	2-4 (35-40)	13-21 (55-70)	27-32 (80-90)
0	0.8:1	x		x	x	x	x	x	x	x	x	x	***0
0	5:1				x	x	x						
0	8:1				x	x							
0	1:1:1	x		x	x	x	x	x	x	x	***0	***0	0
0	1:1:1.4	x		x	x	x	x	x	x	x	0	0	0
0	1:1:1.8	x			x	x	x		x	x	x	0	0
2	0.8:1	x	x	x	x	x	x	x	x	x	x	x	x
2	1:1:1	x	x	x	x	x	x				x	x	x
2	1:1:1.4	x	x	x	x	x	x				0	x	x
2	1:1:1.8	x	x	x	x	x	x				0	x	0
5	0.8:1	x	x	x							0	x	x
5	1:1:1	x	x	x							x	x	0
5	1:1:1.4	x	x	x							x	x	x
5	1:1:1.8	x	x	x							x	x	x
6	0.8:1	x	x	x	x	x	x	x	x	x			
6	1:1:1	x	x	x	x	x	x						
6	1:1:1.4	x	x	x	x	x	x						
6	1:1:1.8	x	x	x	x	x	x						
8	0.8:1	x	x	x	x	x	x	x	x	x	0	0	x
8	1:1:1	x	x	x	x	x	x				0	x	x
8	1:1:1.4	x	x	x	x	x	x				0	x	x
8	1:1:1.8	x	x	x	x	x	x				0	x	x

* By weight of cement.
** Determined at end of 8-minute mixing period.
*** Testing was attempted, but data were not obtained due to cracking and breaking of specimens as explained in TEST RESULTS — Drying shrinkage.

chloride dosages in the program were 0, 2, 6, and 8 percent. Drying shrinkage testing had essentially been completed utilizing the initial midrange dosage of 5 percent. No additional drying shrinkage tests were performed at a 6-percent calcium chloride dosage. Time-of-set tests involved grouts with 0, 2, 5, 6, and 8 percent calcium chloride, so both intermediate percentages (5 and 6 percent) were included.

Mr. Aberle noted that the temperature of a grout mix was a good indicator of its pumpability. Grout temperature was taken at the holding tank immediately before grout was pumped into the drill hole. Grouts with best pumpability had temperatures of 21 to 32 °C (70 to 90 °F). For a complete range of temperatures, colder grouts were studied, as well as those in the 21 to 32 °C (70 to 90 °F) range. Therefore, low-, medium-, and high-temperature ranges of 2 to 4 °C (35 to 40 °F), 13 to 21 °C (55 to 70 °F), and 27 to 32 °C (80 to 90 °F) were considered. By adjusting the mix water temperature, and using ice as part of the mix water when necessary, grout temperatures were forced to fall in one of these temperature ranges.

In order to draw some conclusions on the relationship of grout properties with respect to time, compressive strength and triaxial strength tests were performed at grout ages of 7, 28, and 90 days.

Mixing and Curing

The grouting subcontractor at Teton Dam employed a unique system to batch, mix, and handle grout. His six-step system, which normally required from 6 to 8 minutes to complete, involved the following:

1. Dry materials — cement, sand, bentonite, and calcium chloride — were batched via an electronic control panel.

2. Batched materials were conveyed by belt to one of three mixers.

3. Grout was circulated within mixers by high-velocity pumps.

4. As grout was circulated, a three-way valve diverted it into 50-mm (2-in) delivery lines. These delivery lines transported grout to holding tanks located at the drill holes.

5. At the holding tanks, grout was continually agitated and its temperature was monitored.

6. Grout was then pumped into drill holes.

The laboratory mixing procedure was adapted to attempt to simulate these field operations. Dry materials were weighed together in a pan and then added to batch water in the mixer bowl during the first 30 seconds of an 8-minute mix period. A slow speed setting was used while adding the ingredients to the mix bowl. Grout was then mixed at medium speed for the remaining 7-1/2 minutes. Hobart laboratory mixers with 4.75-L (5-qt) bowls were used. When large batch volumes were required, a Hobart mixer with a 19.0-L (20-qt) bowl was used. The larger mixer was also operated for an 8-minute mix period and at speed settings comparable to those used with the 4.75-L (5-qt) mixer.

To establish laboratory ambient curing conditions, information was obtained from Mr. Aberle and from the Pacific Northwest Regional Geologist. Data from drill holes indicate average rock mass temperatures at Teton Dam site to be between 10 and 15 °C (50 and 60 °F), and relative humidity in most tunnels was roughly 50 percent. During grouting many things can alter rock moisture conditions; for example, drill holes are pressure tested with water before grouting is begun, and water is forced out of the rock/grout mass during pressure grouting. Also, in the laboratory, there were some physical limitations as to how a large quantity of specimens could be cured. A calorimeter room provided the ambient curing atmosphere for grout specimens. It provided a large volume of constant-temperature air to dissipate heat from grout specimens. An average temperature of 13 °C (55 °F) and a relative humidity of about 40 percent were maintained in the room.

An exception to the standard curing procedure was the method used to cure 150- by 300-mm (6- by 12-in) cylinders for permeability testing; i.e., 23.0 $\pm$ 1.7 °C (73.4 $\pm$ 3 °F) and 100 percent relative humidity. This was done to eliminate cracking and is discussed further in TEST PROCEDURES — Permeability.

TEST PROCEDURES

Tests included in this study were time of setting, unconfined compressive strength, triaxial shear strength, drying shrinkage, erodibility, permeability, plus a petrographic examination which involved megascopic and microscopic analyses, differential thermal analysis, and X-ray diffraction. These physical property tests were essentially performed according to standard ASTM (American Society for Testing and Materials), Corps of Engineers, or USBR test methods. In attempting to simulate certain field conditions, some modifications to these standard methods were necessary. However, in accordance with all test methods, observations of physical characteristics such as cracks, deformations, and discolorations were recorded for all specimens. Mixes and their various combinations of W:C or W:C:S ratios, calcium chloride content, and grout temperature are listed in table 1 for four tests: time of setting, unconfined compressive strength, triaxial shear strength, and drying shrinkage. Mixes used in erodibility, permeability, and petrographic testing are specified under the appropriate test procedure paragraph.

Time of Setting

Time-of-set testing was performed according to Method of Test for Time of Setting of Grout Mixtures, Corps of Engineers CRD-C 82-76.

Some slight changes made in test procedures were:

1. An 8-minute mixing period was used as standard for all grout batches in the test program, instead of a 3- to 3-1/4-minute mixing period.

2. All time-of-set specimens were cured and tested in standard ambient conditions of 13 °C (55 °F) and 40 percent relative humidity. These were the closest approximations of field conditions available in the laboratory and, therefore, specimens were not stored in a moist closet as the standard test procedure specifies.

Data on time-of-set specimens represent 55 grout mixes (table 1).

Unconfined Compressive Strength

Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM designation C 39-72, was followed for unconfined compression tests with these additional specific procedures:

1. Specimens were cast in 50- by 100-mm (2- by 4-in) cylindrical plastic molds (fig. 1).

2. All cylinders were capped and then tested in a 534-kN (120 000-lbf) universal testing machine. Cylinders were loaded at a rate of 26.7 kN/min (6000 lbf/min) [(approximately 13.8 MPa/min (2000 lbf/in^2/min)].

Fifty-three grout mixes were tested for compressive strength (table 1).

Triaxial Shear Strength

The test method and apparatus for triaxial shear strength testing were those used by the USBR in testing small rock cores and are described in USBR report No. C-1134, Triaxial Shear Equipment for Small Rock Core Specimens. The specimens were 50- by 100-mm (2- by 4-in) cylinders (fig. 1).

A series of triaxial shear tests for any particular grout mix consisted of nine specimens, divided into three groups of three cylinders each. Tests were performed using a different confining pressure for each group. The first group was tested at zero confining pressure. From these results an unconfined compressive strength was calculated. The second and third confining pressures were then generally set at one-tenth and one-fifth of this unconfined compressive strength, respectively, and ranged from 1.0 and 2.1 MPa (150 and 300 lbf/in^2) to 5.2 and 10.3 MPa (750 and 1500 lbf/in^2).

In performing the triaxial test, each specimen of the second and third groups was placed in the text apparatus and the appropriate confining pressure was applied and held constant. The initial axial or contact load was recorded. Axial load was then increased at a rate of 26.7 kN/min (6000 lbf/min) [approximately 13.8 MPa/min (2000 lbf/in^2/min)] until the specimen failed.

Twenty mixes were selected as representative of grouts most often used during construction and only these were tested for triaxial shear strength (table 1).

Drying Shrinkage

Drying shrinkage testing was performed according to Standard Test Method for Length Change of Hardened Cement Mortar and Concrete, ASTM designation C 157-75, with the following exceptions.

1. Three-specimen molds were used without small end plates for holding gage studs (sec. 2.1).

2. A Brown temperature and humidity recorder was used in the calorimeter curing room (sec. 2.4.1).

Figure 1.-Cylinders, 50 by 100 mm (2 by 4 in), cast for unconfined compressive strength testing. W:C:S = 1:1:1, 0 percent calcium chloride 27 to 32 °C (80 to 90 °F). Note loss of bleed water and settling of solid particles. Some laitance can be seen as white spots on tops of specimens. Photograph C-8481-70.

3. Flow of grout mixes was not determined (sec. 4.3) because proportions were dictated by field mixes.

4. Most grout mixes were fluid enough to be poured into molds instead of being tamped in layers (sec. 5.1). After casting, and as grout began to set, nuts holding gage studs at ends of molds were loosened to reduce linear restraint on grout bars (fig. 2) (sec. 5.1).

5. Specimens were cured at 13 °C (55 °F) and approximately 40 percent relative humidity which was the curing atmosphere selected for all grout specimens in this study (sec. 6.1).

6. At an age of approximately 24 hours, specimens were removed from the molds. They were not placed in water for 15 minutes or longer as designated (sec. 6.2), nor were they cured in lime-saturated water until 28 days (sec. 6.3). These soaking and curing cycles would have hindered simulation of field conditions.

7. Rate of evaporation in the curing room was not determined (sec. 7.1.2).

Initial comparator readings were taken after specimens were removed from the molds. A second reading was taken 28 days after initial readings, and length changes of specimens were determined on the basis of these two readings.

Forty-eight mixes were tested in drying shrinkage (table 1).

Erodibility

The basic apparatus and method used for erodibility testing were developed at Oklahoma State University [3] for the USBR to test dispersive clays.

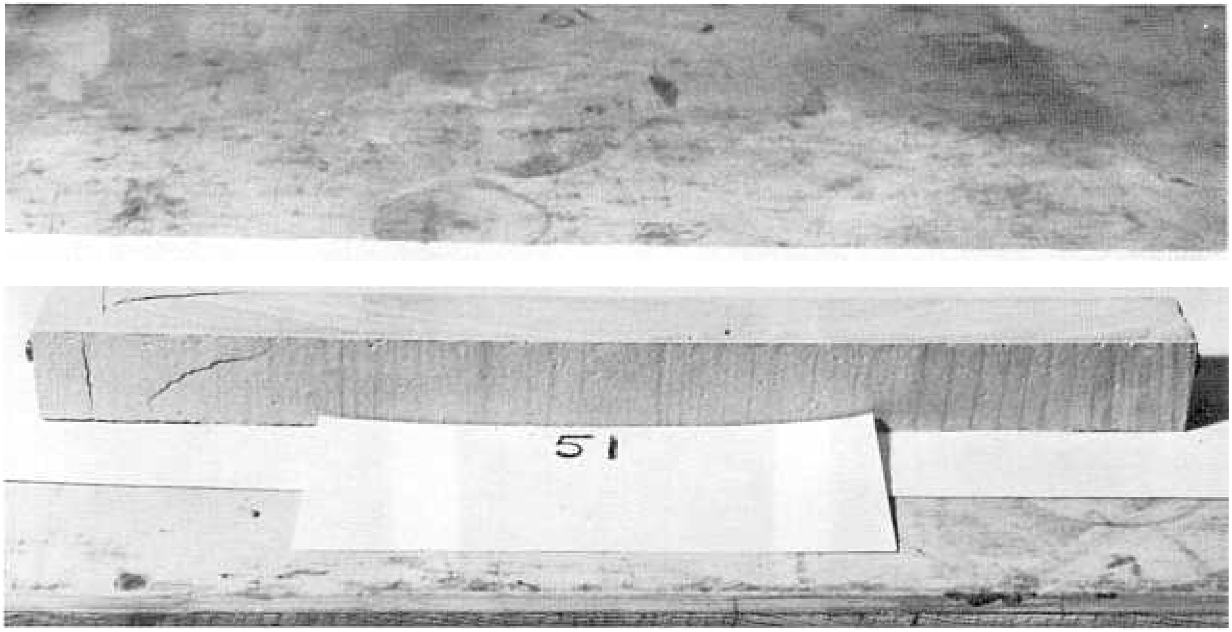


Figure 2.-Typical 25- by 25- by 285-mm (1- by 1- by 11¼-in) bar tested for drying shrinkage. W:C = 0.8:1, 8 percent calcium chloride, 27 to 32 °C (80 to 90 °F). Note transverse cracks at left end of bar. Gage studs are barely visible at either end of bar. Top surface as cast is on front side. Photograph C-8481-62.

Figure 3 is a sketch of physical erosion test apparatus. Test procedures were modified somewhat to test grouts and are summarized as follows:

1 Grout specimens were cast in 30-mm (1¼-in) diameter lucite cells of the standard type used to hold specimens during testing. One end of each cell was sealed with a waxed stopper before specimen casting (fig. 4).

2. Grout specimens were cured 90 days before testing.

3. At the end of the curing period, cells and grout cylinders were dried in an oven at 71 °C (160 °F) for 48 hours.

4. One 4.75-mm (3/16-in) hole was drilled through the axis of each cylinder using a drill press to ensure alinement (fig. 5).

5. Each hole was blown clean with compressed air. A cloth was used to remove any loose grout particles or laitance from specimens (figs. 5 and 6). Each cell and grout cylinder was weighed to the nearest 0.1 gram.

6. Each specimen was placed in physical erosion test apparatus and prepared for testing.

7. Manifold valves were opened to let the maximum available water pressure of 138 kPa (20 lbf/in²) reach each specimen.

8. Testing was begun by turning on the timer for each unit. Timers were set to open each solenoid valve at 1-minute intervals for a duration of 7 seconds. This provided a system to flush out any grout suspended in cylinder holes and cell.

9. Specimens were tested for an elapsed time of 80 minutes.

10. Specimens were removed from test apparatus and dried in an oven at 71 °C (160 °F) until there was no measurable weight loss. This drying period was determined to be approximately 48 hours. They were then weighed to the nearest 0.1 gram. Grout cylinders were removed from cells, and cells only were weighed.

1 Initial and final dry weights of grout specimens were calculated and used to

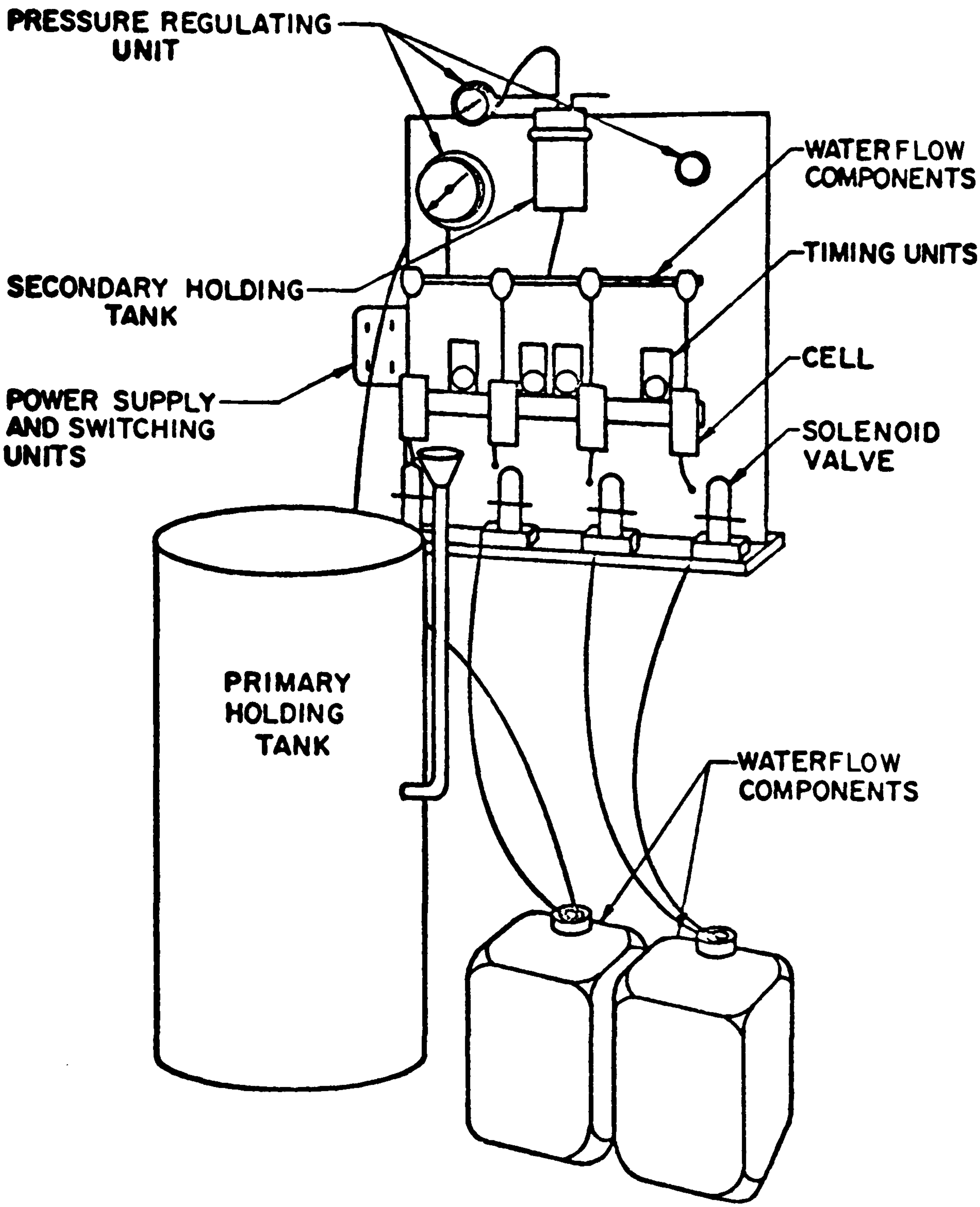


Figure 3.-Physical erosion test apparatus.

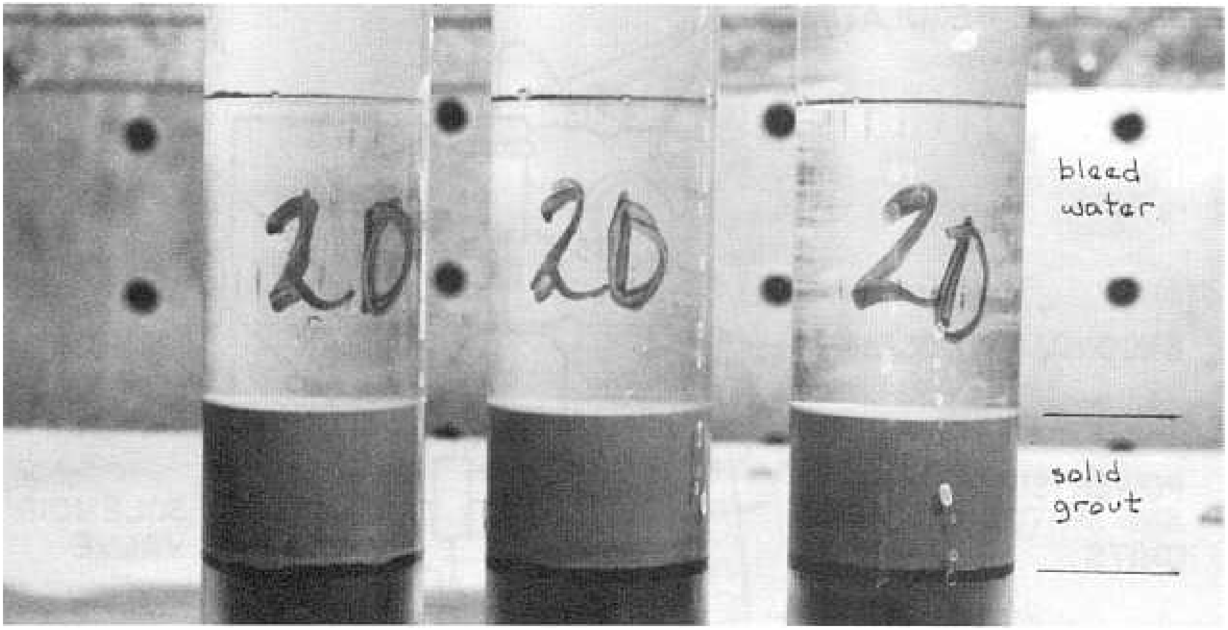


Figure 4.-Specimens cast for erodibility testing. W:C = 5:1, 0 percent calcium chloride, 13 to 21°C (55 to 70 °F). Lucite cells 135-mm (5¼-in) tall with stoppers in bottom enclose 30-mm (1¼-in) diameter grout cylinders. Specimens were cast approximately 3 hours prior to photographing. Photograph C-8481-126.

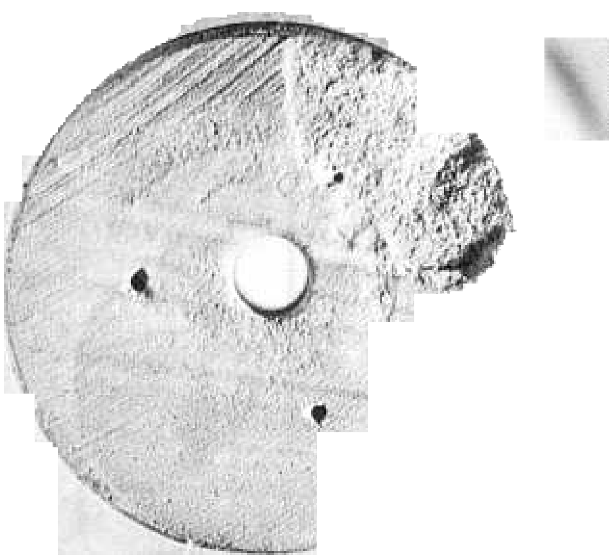


Figure 5.-Typical top view of 30-mm (1¼-in) diameter cylinder before erodibility testing. W:C = 5:1, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Chipped area caused by rubbing with cloth while removing laitance. Center hole is 4.75-mm (3/16-in) diameter. Photograph C-8481-158.

Figure 6.-Top of 30-mm (1¼-in) diameter cylinder cast for erodibility testing. W:C = 5:1, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Note laitance on surface. Photograph C-8481-155.

determine percent of erosion by the following formula:

$$E = \frac{I - F}{I}(100)$$

where:

E = percent erosion

I = initial dry weight of grout

F = final dry weight of grout

The physical erosion apparatus was designed to test soils at water pressures up to 138 kPa (20 lbf/in²), but water pressures higher than this would be needed to cause significant erosion of grout. Rather than attempt to modify this test equipment so higher pressures could be obtained, a weak grout [W:C of 5:1, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F)] was tested to see if it was erodible to any appreciable extent.

Permeability

The apparatus and test method were adapted from those used by the USBR in testing permeability of concrete. A schematic describing permeability equipment is shown on figure 7. Test procedures are summarized below.

1. Specimens were cast as 150- by 300-mm (6-by 12-in) cylinders. These cylinders were sawed to form 150- by 150-mm (6- by 6-in) specimens. Grouts with W:C ratios of 5:1 and 8:1 formed cylinders with heights much less than 300 mm (12 in) due to settling of cement particles (fig. 4 and TEST RESULTS — Bleeding), so it was not necessary to saw these specimens to heights of 150 mm (6 in). All specimens were sandblasted to expose rough grout surfaces.

2. Diameter and height of specimens were measured to the nearest 1.25 mm (0.05 in).

3. Specimens were sealed in containers, placing them in the same orientation as they were cast. Each container had a 125-mm (5-in) diameter hole in the bottom to allow outflow of water during testing. Grout specimens were seated on the bottom flange of containers with plaster of paris. Stearin pitch was then poured around specimens to seal the space between their outer surface and container walls (figs. 8 and 9).

4. Lids were fastened on containers using a lead gasket. Assembled containers were connected to a testing unit.

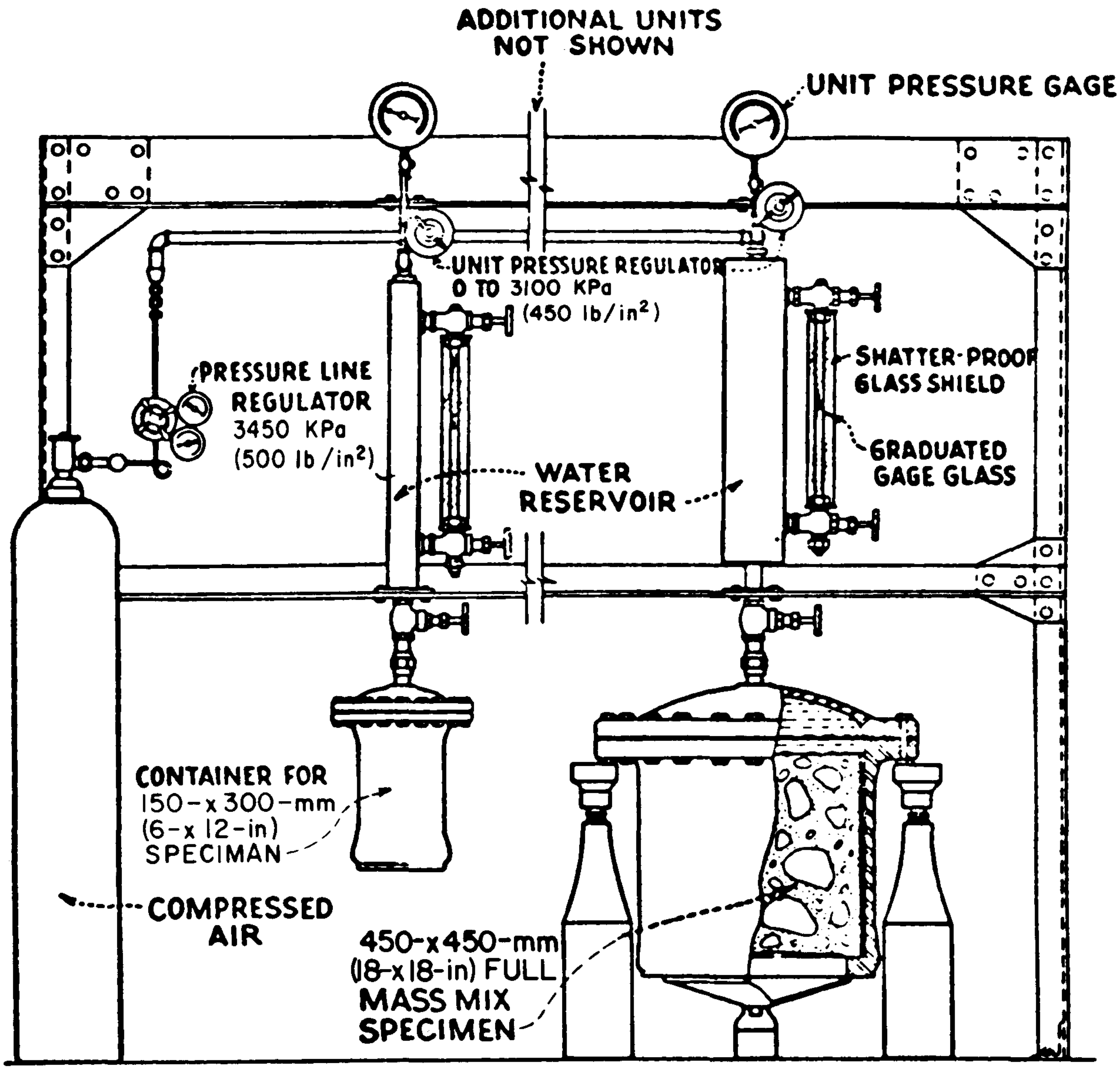


Figure 7.-Permeability test apparatus.

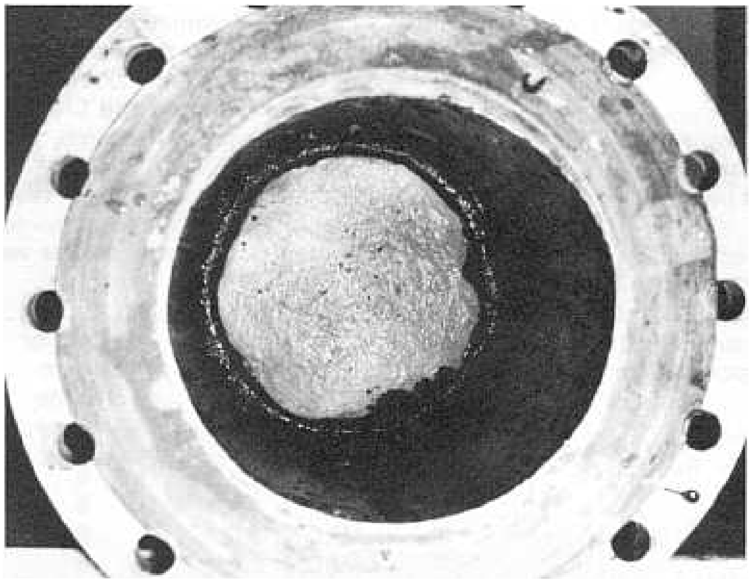


Figure 8.-Typical appearance of top of 150-mm (6-in) diameter specimen after permeability testing. W:C = 5:1, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Black stearin pitch around circumference provides seal between specimen and container. Photograph C-8481-163.

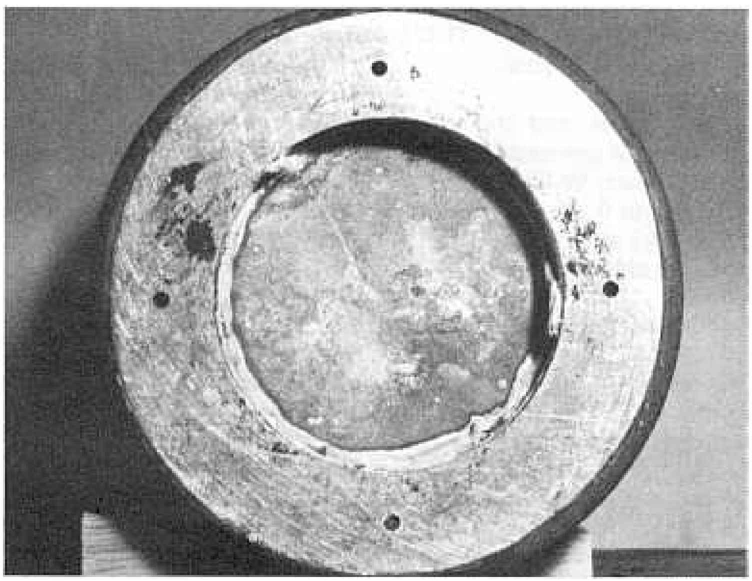


Figure 9.-Typical appearance of bottom of specimen and container after permeability testing. W:C = 0.8:1, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Hole in bottom of container is 125-mm (5-in) diameter. Plaster of paris around edge of hole seats 150-mm (6-in) diameter specimen to bottom flange of container. Photograph C-8481-164.

5. Water reservoirs were pressurized to 2760 kPa (400 lbf/in²) and this pressure was allowed to reach specimens by opening valves at tops of containers.

6. Inflow readings were taken from graduated gage glasses. Readings were taken every 24 hours over a test period of 670 hours.

7. Coefficient of permeability K is derived from Darcy's law for viscuous fluid flow through small connected voids. It states that, for constant physical conditions, the unit rate of discharge is proportional to the hydraulic gradient. That is:

$$Q = KA\left(\frac{H}{L}\right)$$

where:

K = coefficient of permeability in feet per year
Q = inflow in cubic feet per year
L = thickness of specimen in feet
A = cross-sectional area of specimen in square feet
H = water pressure head in feet

Permeability for concrete is defined as the volume of water which passes through a 0.09-m² (1-ft²) area at a unit hydraulic gradient in 1 year.

Two grouts, one relatively weak and the other relatively strong, were tested for permeability. Mix details for these two grouts were: W:C ratio of 5:1 at 13 to 21 °C (55 to 70°F) and 0 percent calcium chloride, and W:C ratio of 0.8:1 at 13 to 21 °C (55 to 70°F) and 0 percent calcium chloride.

The first permeability specimens were cured at standard conditions of 13°C (55°F) and 40 percent relative humidity; however, these specimens cracked due to drying and could not be tested. A second group of specimens was cured in a fog room at 23.0 ± 1.7°C (73.4 ± 3°F) and 100 percent relative humidity, and these were the specimens tested for permeability.

Petrographic Examination

In general, Proposed Standard Recommended Practice for Petrographic Examination of Hardened Concrete, ASTM designation C 856, was followed in petrographic examination of grout samples. As stated previously, specimens were examined megascopically, microscopically, by X-ray diffraction, and by differential thermal analysis. Megascopic and microscopic methods are set forth in ASTM designation C 856, while X-ray diffraction and differential thermal analysis studies were conducted according to standard practices of the Physical Sciences and Chemical Engineering Section, Division of Research, E&R Center, USBR.

Grouts from six mixes were examined petrographically. Their mix proportions, calcium chloride contents, and temperatures were as follows:

Mix proportions	Percent of calcium chloride	Temperature °C (°F)
W:C = 0.8:1	0	2 to 4 (35 to 40)
W:C = 0.8:1	6	2 to 4 (35 to 40)
W:C = 0.8:1	2	27 to 32 (80 to 90)
W:C = 0.8:1	8	27 to 32 (80 to 90)
W:C:S = 1:1:1.8	6	27 to 32 (80 to 90)
W:C:S = 1:1:1.8	8	27 to 32 (80 to 90)

TEST RESULTS

General

Practically all grout mixes could be poured from the mixing bowl to molds. Grouts with a W:C ratio of 5:1 and 8:1 were slightly thicker than water. For 0.8:1 (water to cement) and sanded grouts, consistencies ranged from that of milk to thick pancake batter. Sanded grouts were generally thicker than neat-cement grouts.

Some mixes became very thick in the bowl by the end of the mixing period, yet could still be poured, while some became so thick they lost their fluid nature and would not assume the shape of their container. Various combinations of increased calcium chloride content and increased grout temperature caused different degrees of thickening. A combination of high calcium chloride content (6 and 8 percent) and high temperature [27 to 32 °C (80 to 90 °F)] definitely brought about a thickening of the grout. Some mixes thickened appreciably at a temperature of 27 to 32 °C (80 to 90 °F) with no calcium chloride. Also, some mixes thickened at a medium temperature 13 to 21 °C (55 to 70 °F) with a moderate dosage of calcium chloride (5 percent). Grout temperatures seemed to have more effect on thickening of grout mixes than calcium chloride contents. Grouts that became very thick in the bowl were lightly compacted with a tamping rod while casting specimens. If this was not done, large voids were left in hardened specimens.

A scaly outer layer, or crust, was observed on some specimens (figs. 10 and 11, and as discussed in TEST RESULTS — Petrographic Examination). Grouts with and without calcium chloride displayed this crust. It was probably caused by a thin outer layer of grout partially adhering to plastic molds.

Laitance formed on the top surface of many specimens. Grouts with the highest water to cement ratios (5:1 and 8:1) showed the heaviest formation of laitance (fig. 6). Sanded grouts, which have a much lower water to solids ratio did not show as much laitance (fig. 1). Grouts with high calcium chloride contents generated even lesser amounts of laitance.

Figures 12 and 13 show moderate laitance before and after hardening of grout.

Time of Setting

Data obtained from time-of-set tests are contained in table 2. Time-of-set data were not taken on grout mixes with W:C ratios of 5:1 and 8:1 (table 1). In these mixes, cement particles settled, leaving a specimen too short to test properly. Testing of grout mixes with 13 to 21 °C (55 to 70 °F) temperatures and 0 percent calcium chloride (table 2) was attempted, but no data were obtained since their setting times were much longer than one working shift. The grout with a 1:1:1.8 W:C:S ratio, 0 percent calcium chloride, and 27 to 32°C (80 to 90°F) temperature (table 2) was not tested. Figures 12 and 13 show a time-of-set specimen before and after final set. The addition of calcium chloride definitely accelerated setting of both 0.8:1 and sanded grouts in all temperature ranges (figs. 14, 15, and 16). If the setting time of a 0.8:1 grout with calcium chloride is compared to the setting time of a 0.8:1 control, a reduction in setting time can be

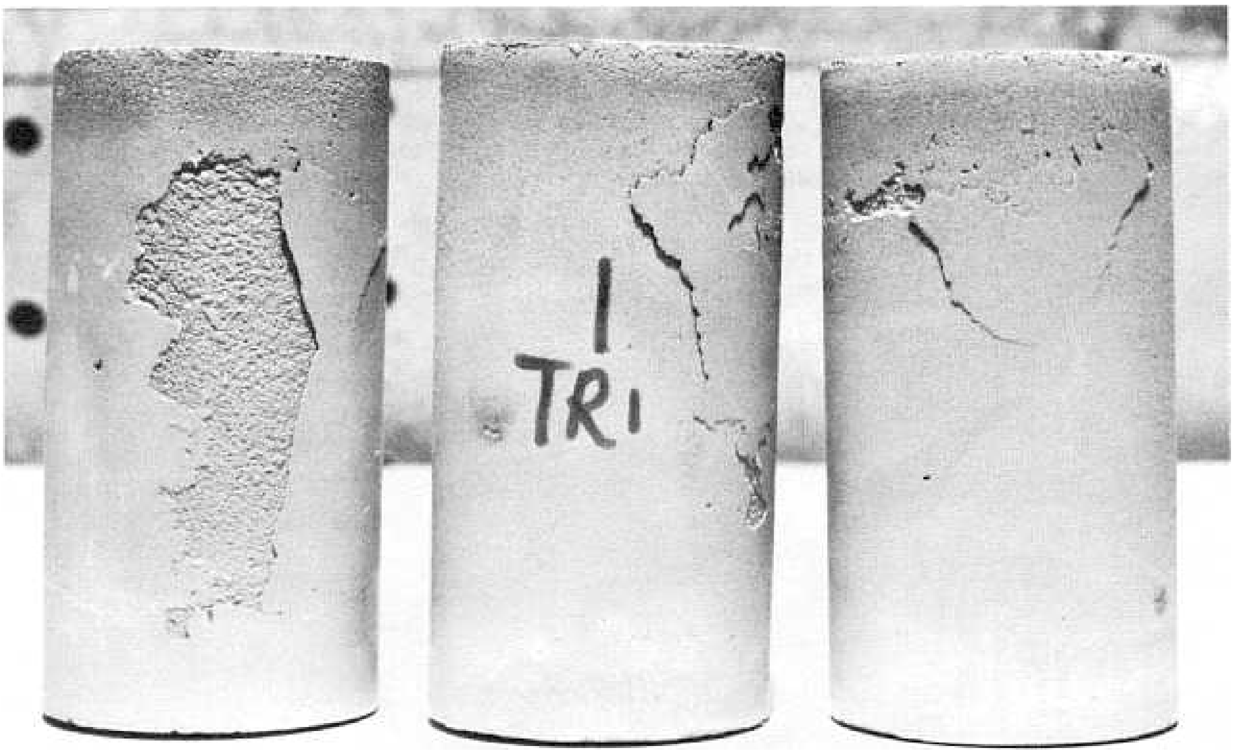


Figure 10.-Cylinders, 50 by 100 mm (2 by 4 in), cast for triaxial shear testing. W:C = 0.8:1, 0 percent calcium chloride, 2 to 4 °C (35 to 40 °F). Note outer layer, or crust, which has separated. Photograph C-8481-124.

Figure 11.-Cylinders, 50 by 100 mm (2 by 4 in), cast for triaxial shear testing. W:C = 0.8:1, 6 percent calcium chloride, 27 to 32 °C (80 to 90 °F). Portions of outer layer, or crust, have separated from cylinders 1 and 2 (above arrows). Note white crystals. Small voids on cylinder 2 caused by crystals adhering to plastic mold. Photograph C-8481-142.

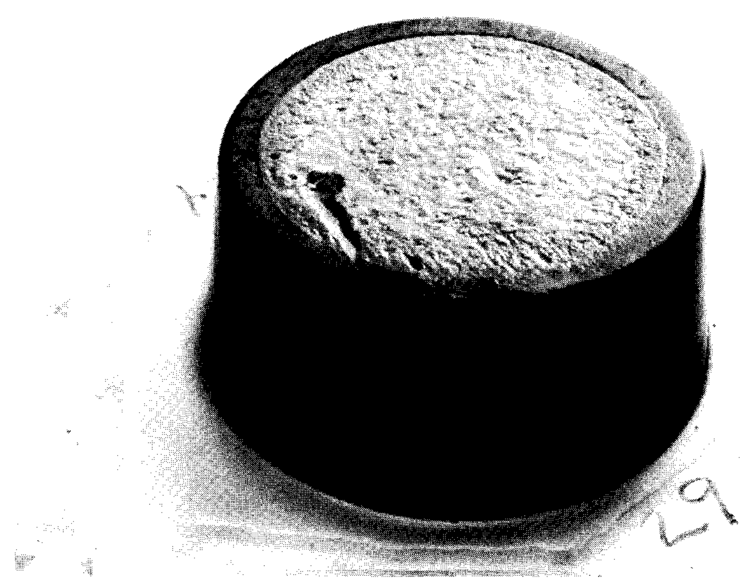


Figure 12.-Typical time of setting specimen cast 2-1/2 hours prior to photographing and had not reached initial set. W:C = 0.8:1, 5 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Note bleeding and laitance forming on top. Photograph C-8481-64.

Figure 13.-Typical time of setting specimen cast 7 hours prior to photographing and had reached final set. W:C = 0.8:1, 5 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Note laitance on top. Photograph C-8481-74.

Table 2.-*Initial and final time of setting**

W:C or W:C:S ratio	Calcium chloride content (percent by weight of cement)									
	0		2		5		6		8	
	Time of setting									
	Initial	Final	Initial	Final	Initial	Final	Initial	Final	Initial	Final
	h min	h min	h min	h min	h min	h min	h min	h min	h min	h min
	2 to 4 °C (35 to 40 °F) grouts**									
0.8:1	12 10	15 45	6 20	8 30	5 30	7 20	5 30	6 45	4 40	6 25
1:1:1	11 45	14 25	6 55	9 00	5 40	8 05	5 25	6 40	6 45	8 00
1:1:1.4	11 00	12 50	5 20	7 15	4 55	6 45	4 30	5 40	5 25	6 50
1:1:1.8	8 30	11 30	4 55	7 15	4 30	6 25	3 55	4 50	3 45	6 10
	13 to 21 °C (55 to 70 °F) grouts									
0.8:1			5 25	8 00	3 55	5 45	9 25	<21	2 10	3 30
1:1:1			4 45	8 25	3 35	6 45	4 30	6 20	5 30	7 10
1:1:1.4			4 40	7 00	3 05	4 40	3 50	6 40	6 00	7 35
1:1:1.8			4 45	6 55	2 45	4 00	2 35	4 45	5 40	7 40
	27 to 32 °C (80 to 90 °F) grouts									
0.8:1	12 20	16 50	5 35	8 50	5 15	7 20	4 25	7 15	3 15	5 00
1:1:1	11 05	14 45	6 50	9 50	3 00	6 30	3 25	4 30	4 55	7 00
1:1:1.4	9 30	12 20	6 20	8 30	2 50	4 50	3 00	3 55	5 00	6 30
1:1:1.8			5 15	8 05	2 45	4 15	3 30	5 45	4 55	6 45

* Test method—Corps of Engineers CRD-C 82-76(C) with exceptions as noted in TEST PROCEDURES—Time of Setting.

** Grout temperature determined at end of 8-minute mixing period.

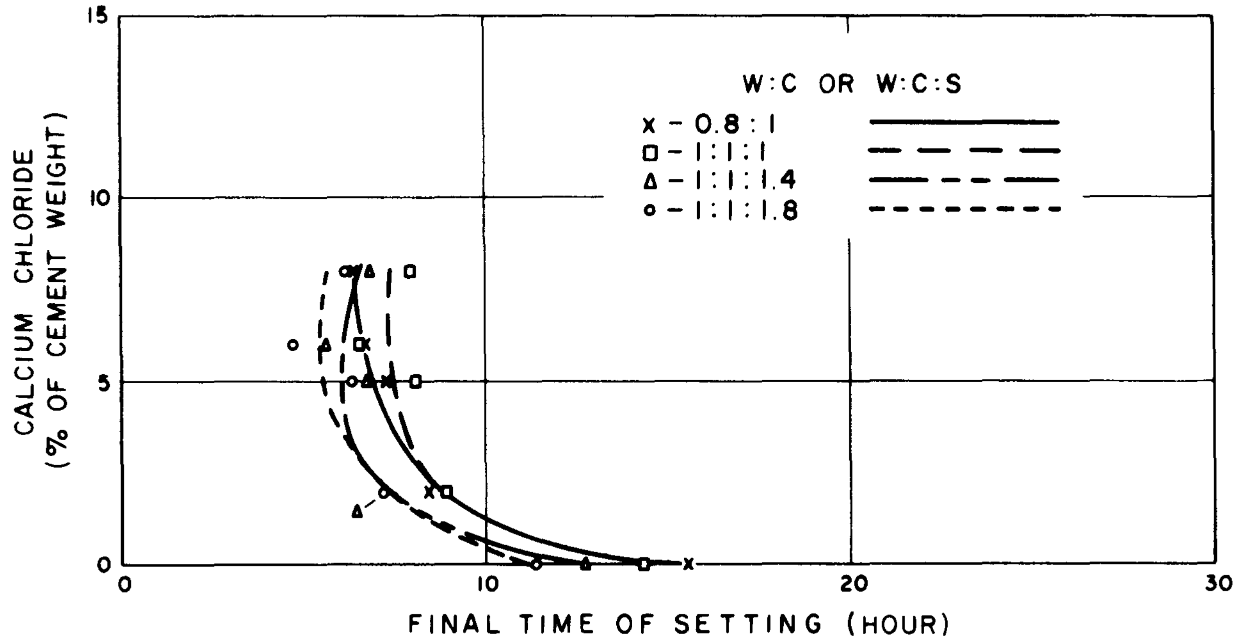


Figure 14.-Grouts at 2 to 4 °C (35 to 40 °F), calcium chloride content versus final time of setting.

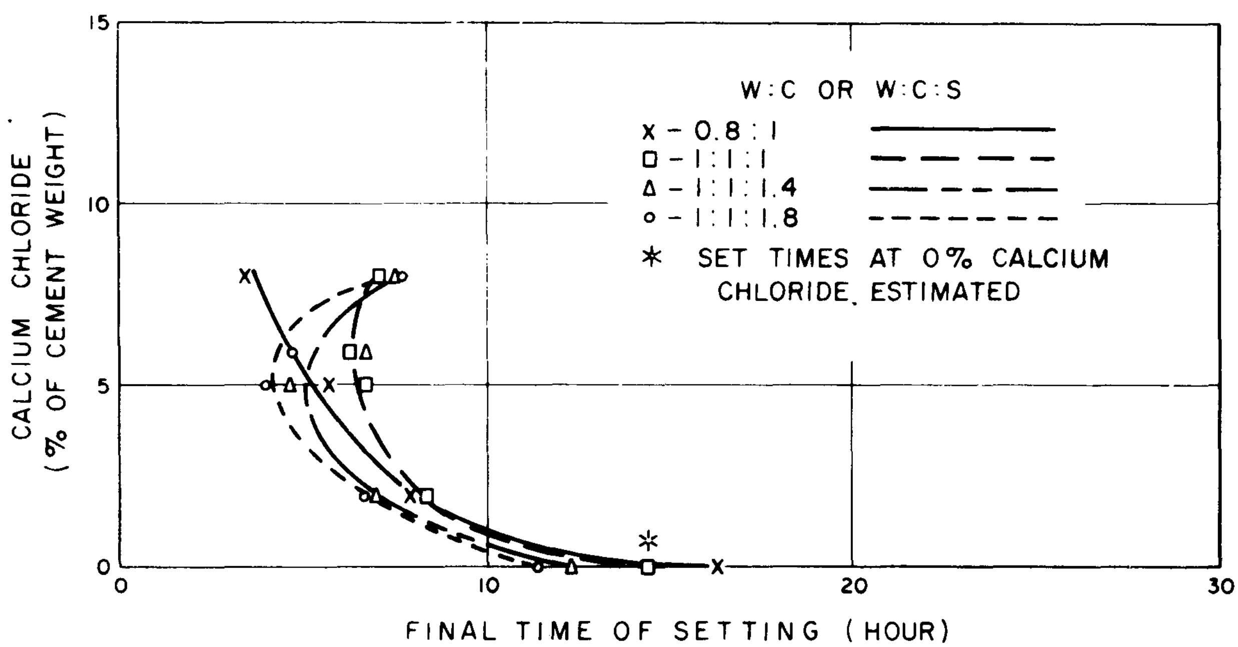


Figure 15.-Grouts at 13 to 21 °C (55 to 70 °F), calcium chloride content versus final time of setting.

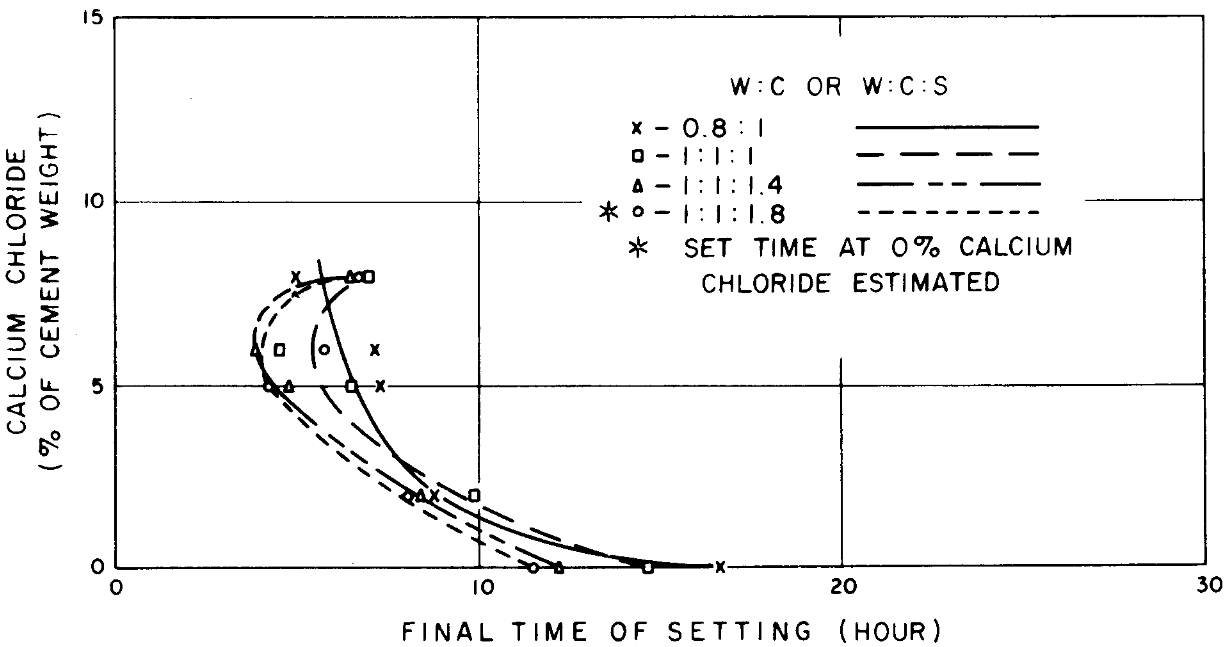


Figure 16.-Grouts at 27 to 32 °C (80 to 90 °F), calcium chloride content versus final time of setting.

calculated as a percent of the control setting time. Largest percentage reductions in times of setting over control grouts were as follows:

- *2 to 4 °C (35 to 40 °F)* — a 59-percent reduction for a 0.8:1 grout and 8 percent calcium chloride, and an average 56-percent reduction for sanded grouts with 6 percent calcium chloride.
- *13 to 21 °C (55 to 70 °F)* — a 79-percent reduction for a 0.8:1 grout and 8 percent calcium chloride, and an average 60-percent reduction for sanded grouts with 5 percent calcium chloride.
- *27 to 32 °C (80 to 90 °F)* — a 70-percent reduction for a 0.8:1 grout and 8 percent calcium chloride, and an average 62-percent reduction for sanded grouts with 6 percent calcium chloride.

There seemed to be an optimum calcium chloride content of approximately 6 percent where times of setting for sanded grouts were lowest. Figures 14, 15, and 16 each show a difference in the effect that higher dosages of calcium chloride had on the 0.8:1 grout versus the sanded grouts. Curves for neat-cement and sanded grouts in each temperature range have relatively the same slope between 0 and 2 percent calcium chloride. Above 2 percent calcium chloride, curves of neat-cement grouts diverge from those of sanded grouts, mainly in the 13 to 21 °C (55 to 70 °F) and 27 to 32 °C (80 to 90 °F) temperature ranges (figs. 15 and 16). That is, for neat-cement grouts, times of setting continue to decrease as calcium chloride contents increase. However, for sanded grouts, times of setting continue to decrease with calcium chloride contents up to about 6 percent; then times of setting begin to increase.

Some erratic test results were obtained with grouts containing 6 and 8 percent calcium chloride. For instance, the first test for a mix of 1:1:1.8 with 6 percent calcium chloride had a final setting time between 8 and 24 hours (the mix did not reach final set by the end of the working shift and was completely set by the start of work the following day). Upon testing this mix again, a final setting time of 4 hours 45 minutes was found (the value in table 3), which correlated with other test results. At least one test from each of eight grout mixes [at 13 to 21 °C (55 to 70 °F) or 27 to 32 °C (80 to 90 °F) with 6 or 8 percent calcium chloride] exhibited a prolonged setting time as described above. Also, two mixes, each with a W:C:S ratio of 1:1:1.8 and 27 to 32°C (80 to 90°F), had one test each in which the final set times were much less than expected. In general, tests indicated that relative times of setting were longer for mixes containing 6 percent calcium chloride or more, and that all mixes reached final set within 24 hours. Grout temperature had no significant effect on the time of setting, overall. However, the consistency of grout mixes was affected by temperatures (also discussed under TEST RESULTS — General). Higher temperatures caused grouts to become thicker and less fluid by the end of the mixing period. Grout temperature seemed to have more of an effect on thickening of grout mixes than did calcium chloride content.

Unconfined Compressive Strength

Table 1 lists grout mixes tested for unconfined compressive strength. Data for 0.8:1 grouts are presented on figures 17, 18, and 19. Strengths of grouts with a 1:1:1.4 W:C:S ratio were representative of all sanded grouts, and graphs depicting these data are shown on figures 20, 21, and 22. Figure 23 depicts strengths for 5:1 grouts.

The resulting heights of grout specimens varied because of the different amounts of settling from mix to mix. Apparatus for casting 50-mm (2-in) diameter cylinders from grouts with W:C ratios of 5:1 and 8:1 is shown on figure 24. PVC "standpipes" had to extend 300 mm (12 in) above plastic molds to obtain a 100-mm (4-in) high specimen because of the settling of cement particles in these grouts as shown in figure 4. Since cylinder heights varied, all strengths were corrected for comparisons with standard cylinders with L/D (length/diameter) ratios of 2.0.

All grouts exhibited seemingly adequate compressive strengths. At an age of 28 days, 5:1 and 8:1 grouts had strengths of roughly 6900 kPa (1000 lbf/in^2), sanded grouts had strengths from 10.34 $\times$ 10^3 to 34.5 $\times$ 10^3 kPa (1500 to 5000 lbf/in^2),

Table 3.-*Average length change of hardened grout**
(Three bars averaged unless otherwise noted.)

W:C or W:C:S ratio	Calcium chloride content (percent by weight of cement)			
	0	2	5	8
	Average length change (shrinkage) in percent			
		2 to 4 °C (35 to 40 °F) grouts**		
0.8:1	0.313	1.067		
1:1:1		0.584	0.902	
1:1:1.4			0.902***	
1:1:1.8	0.461***		0.625	
		13 to 21 °C (55 to 70 °F) grouts		
0.8:1	0.420***	0.898	1.860	
1:1:1		0.520	0.821	1.259***
1:1:1.4		0.444	0.709	1.100****
1:1:1.8		0.385	0.584	0.868
		27 to 32 °C (80 to 90 °F) grouts		
0.8:1		0.930	1.580	2.300***
1:1:1		0.521***		1.059
1:1:1.4		0.431	0.553	0.846
1:1:1.8			0.488****	0.698

*Test method—ASTM designation C 157-75 with exceptions as noted in TEST PROCEDURES—Drying Shrinkage.
** Grout temperature determined at end of 8-minute mixing period.
*** Length change of one bar only.
**** Average length change of two bars.

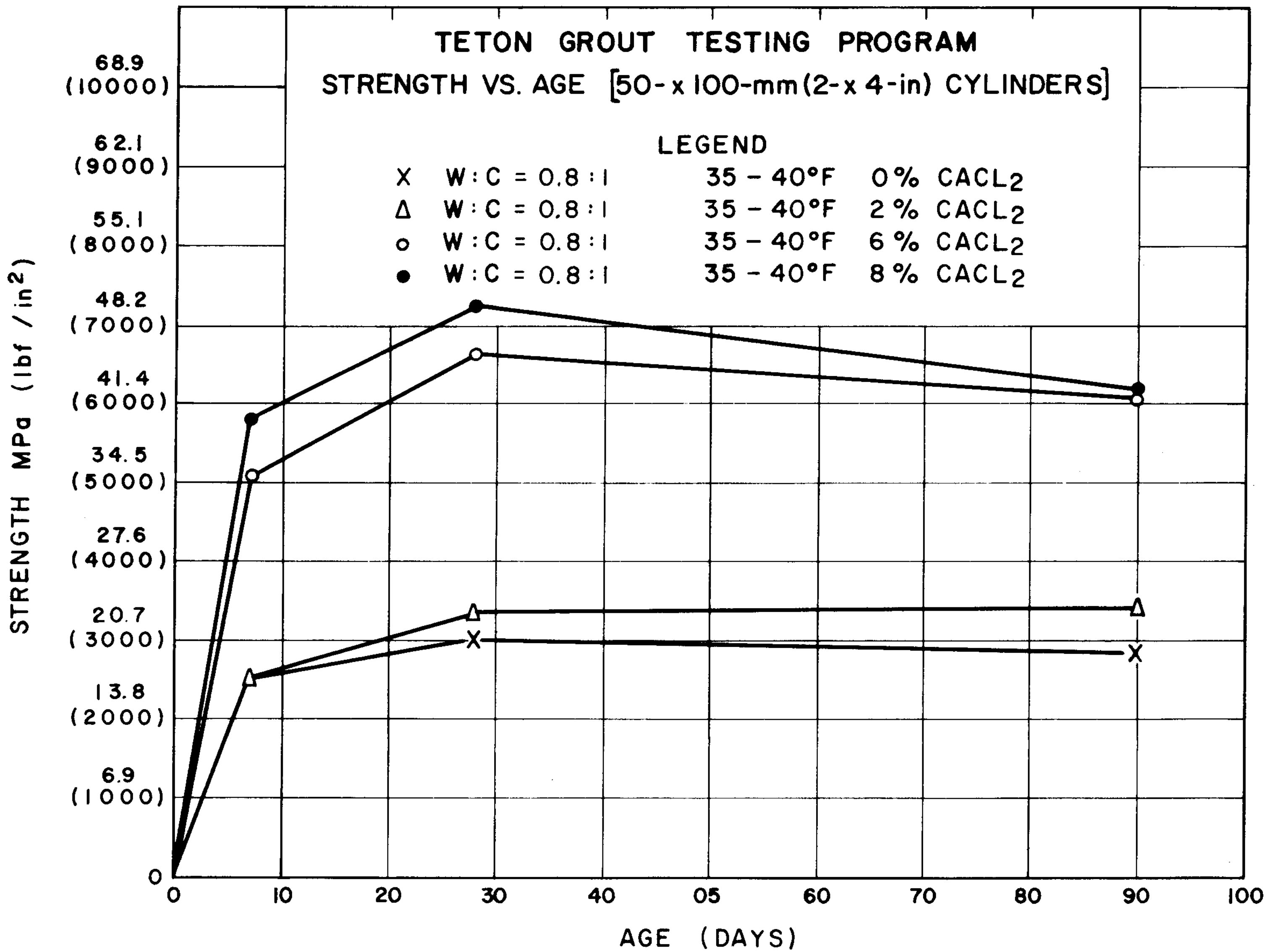


Figure 17.-Unconfined compressive strength, W:C = 0.8:1, 2 to 4 °C (35 to 40 °F).

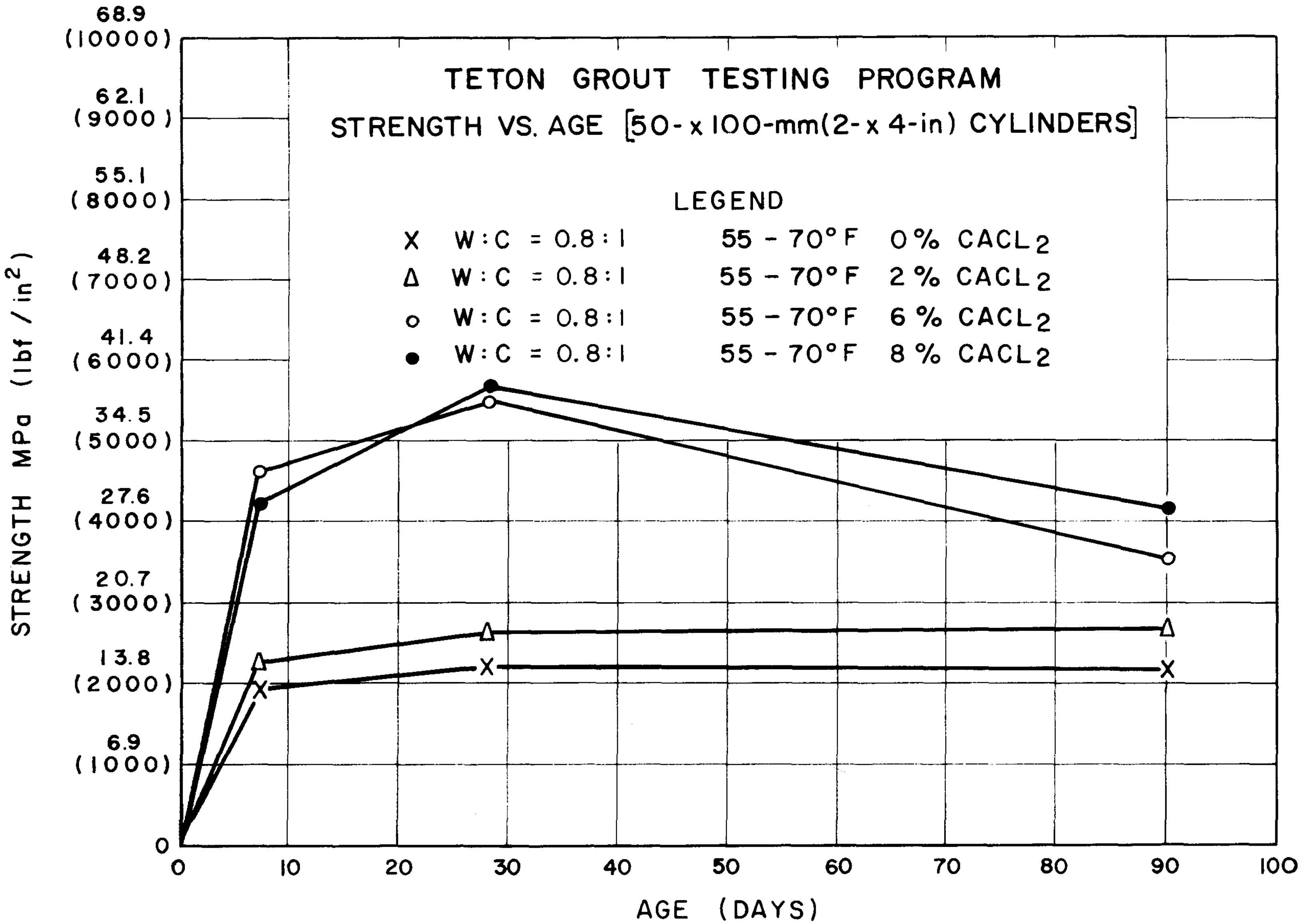


Figure 18.-Unconfined compressive strength, W:C = 0.8:1, 13 to 21 °C (55 to 70 °F).

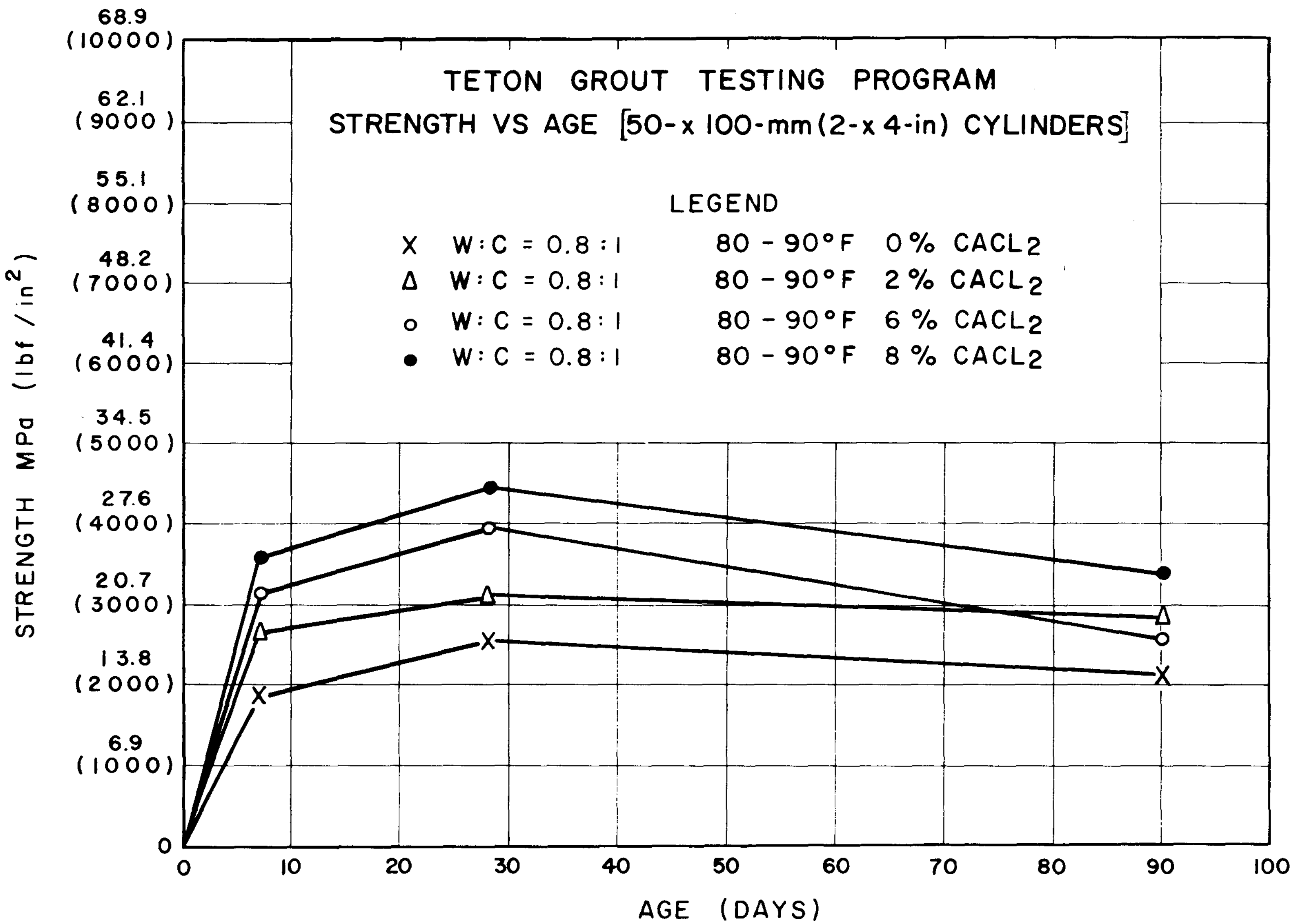


Figure 19.-Unconfined compressive strength, W:C = 0.8:1, 27 to 32 °C (80 to 90 °F).

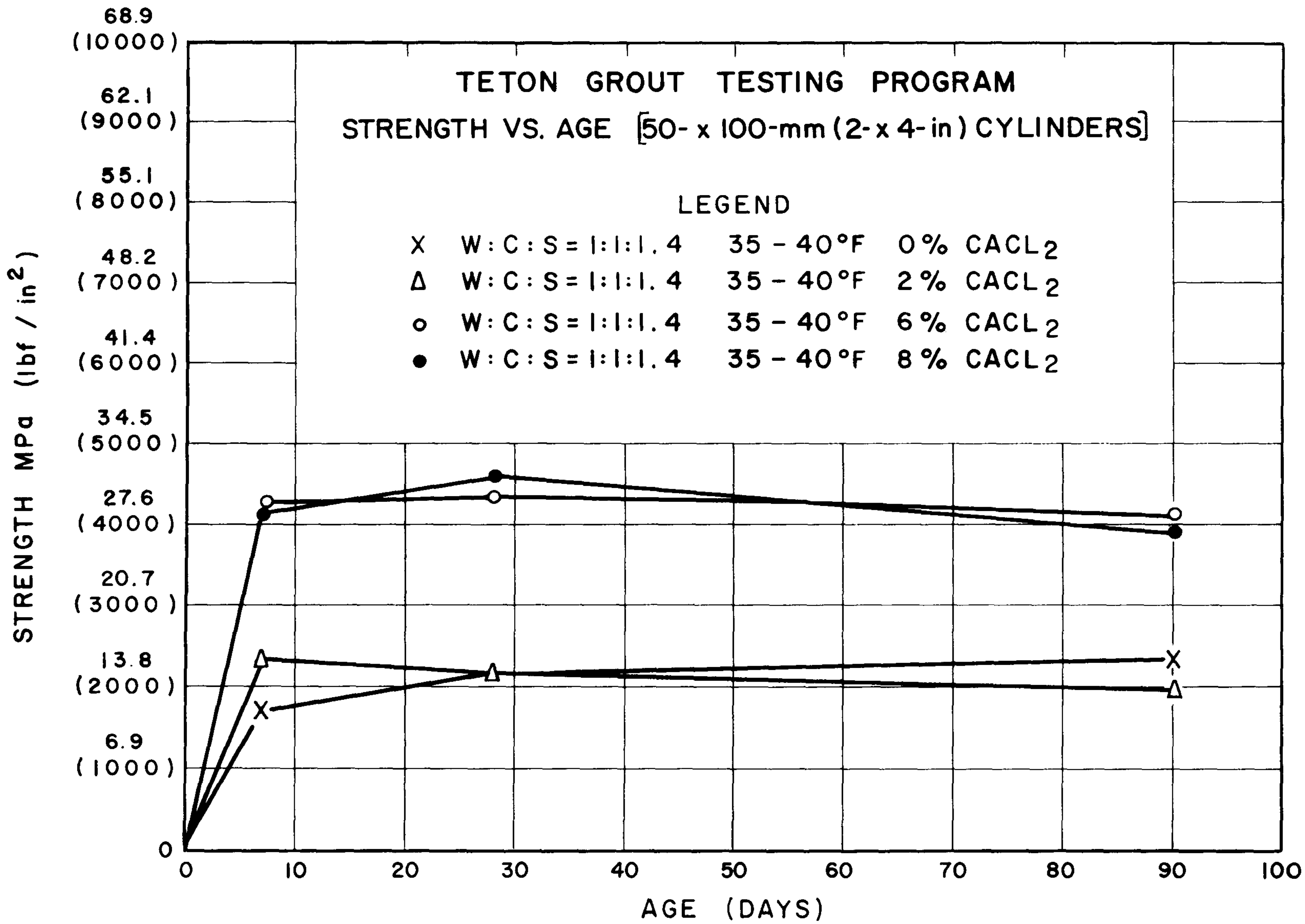


Figure 20.-Unconfined compressive strength, W:C:S = 1:1:1.4, 2 to 4 °C (35 to 40 °F).

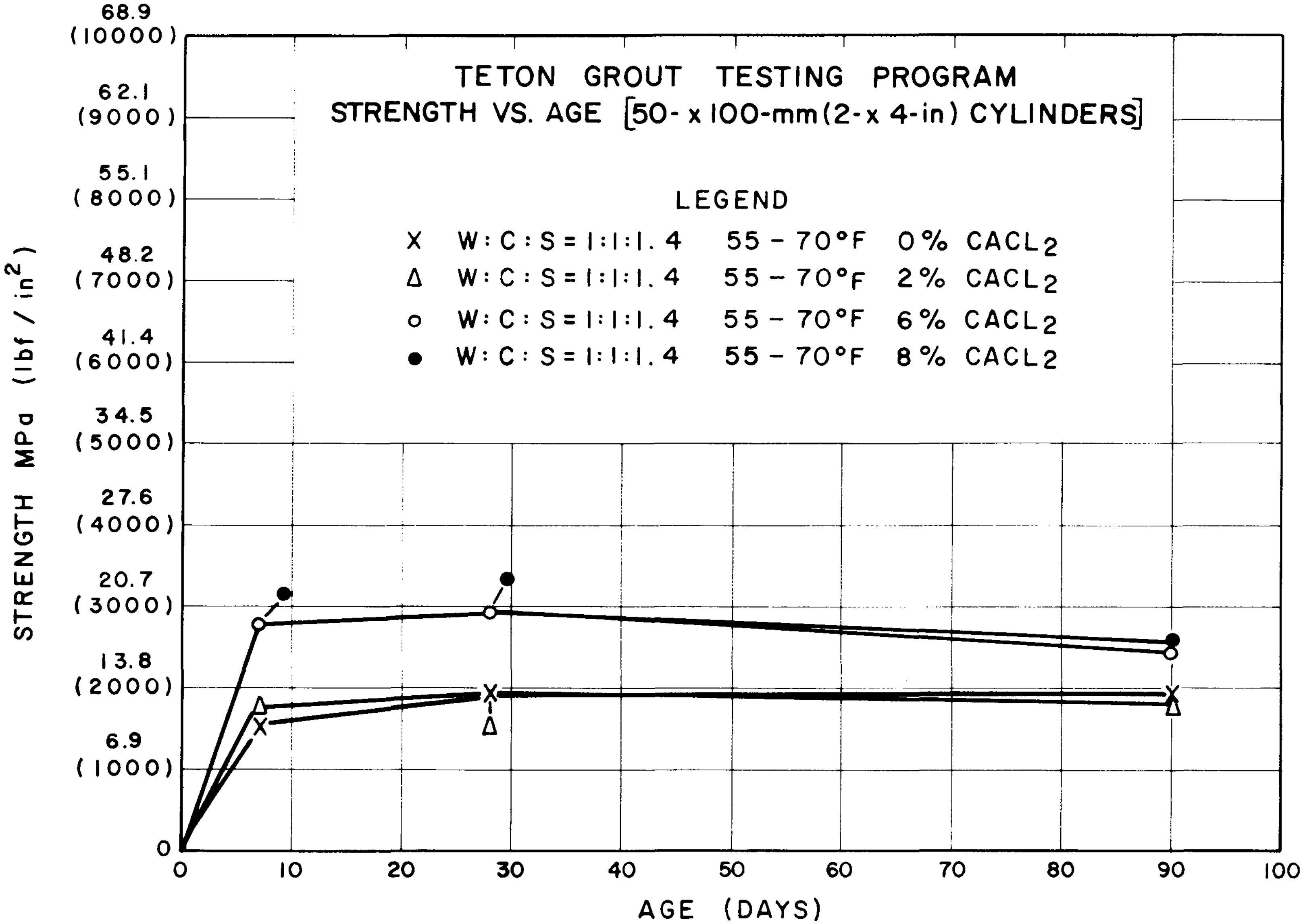


Figure 21.-Unconfined compressive strength, W:C:S = 1:1:1.4, 13 to 21 °C (55 to 70 °F).

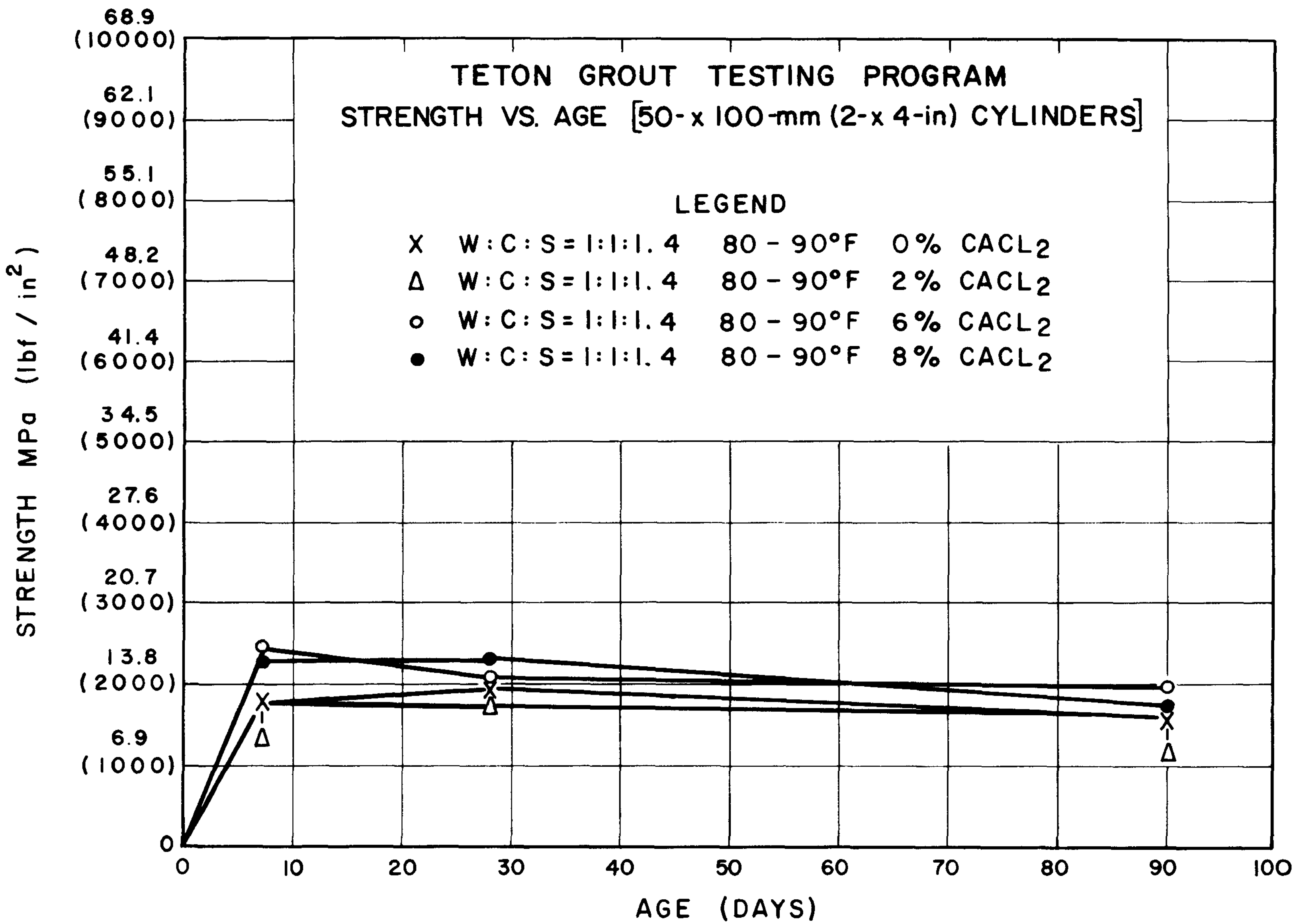


Figure 22.-Unconfined compressive strength, W:C:S = 1:1:1.4, 27 to 32 °C (80 to 90 °F).

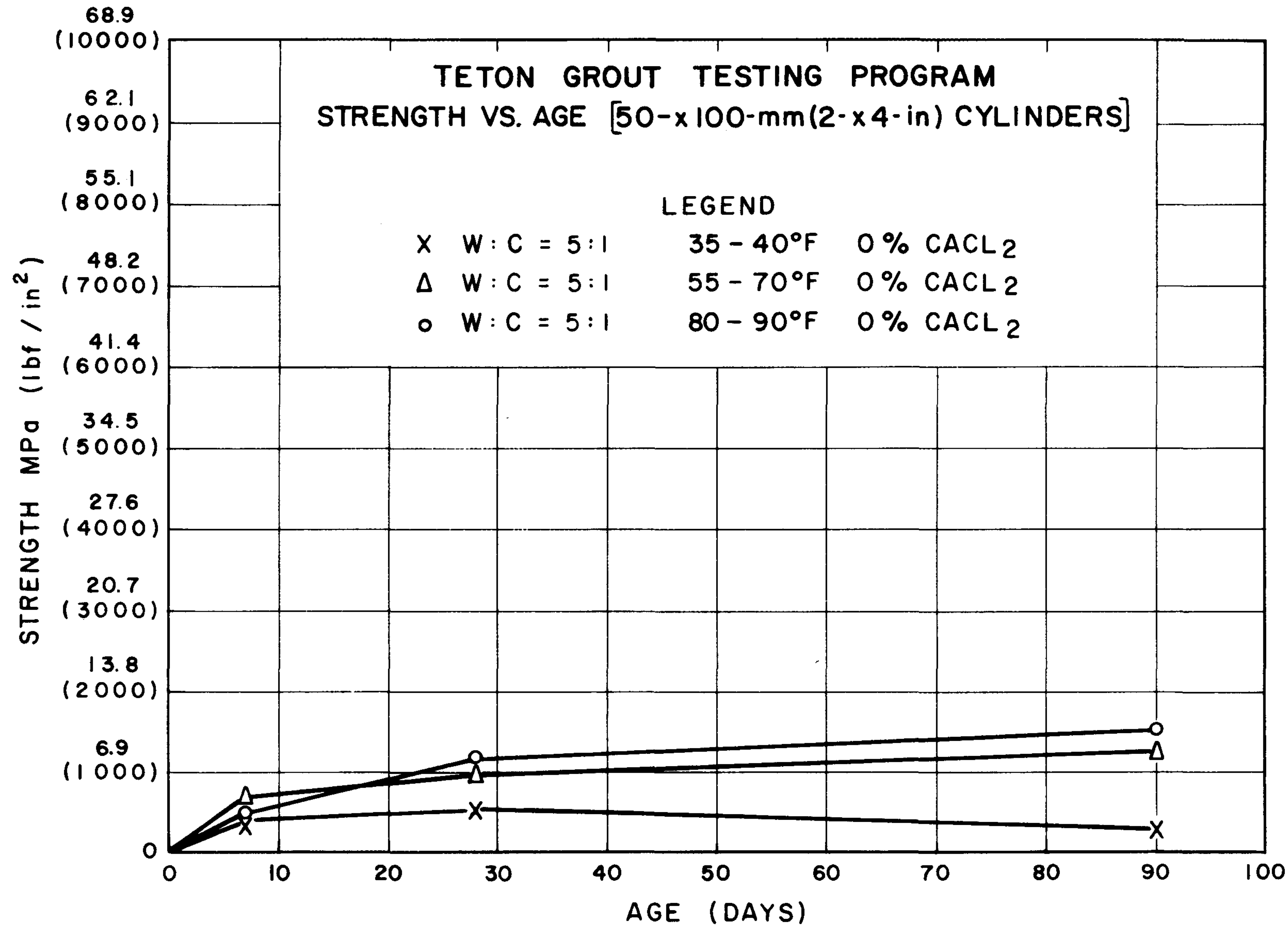


Figure 23.-Unconfined compressive strength, W:C = 5:1.

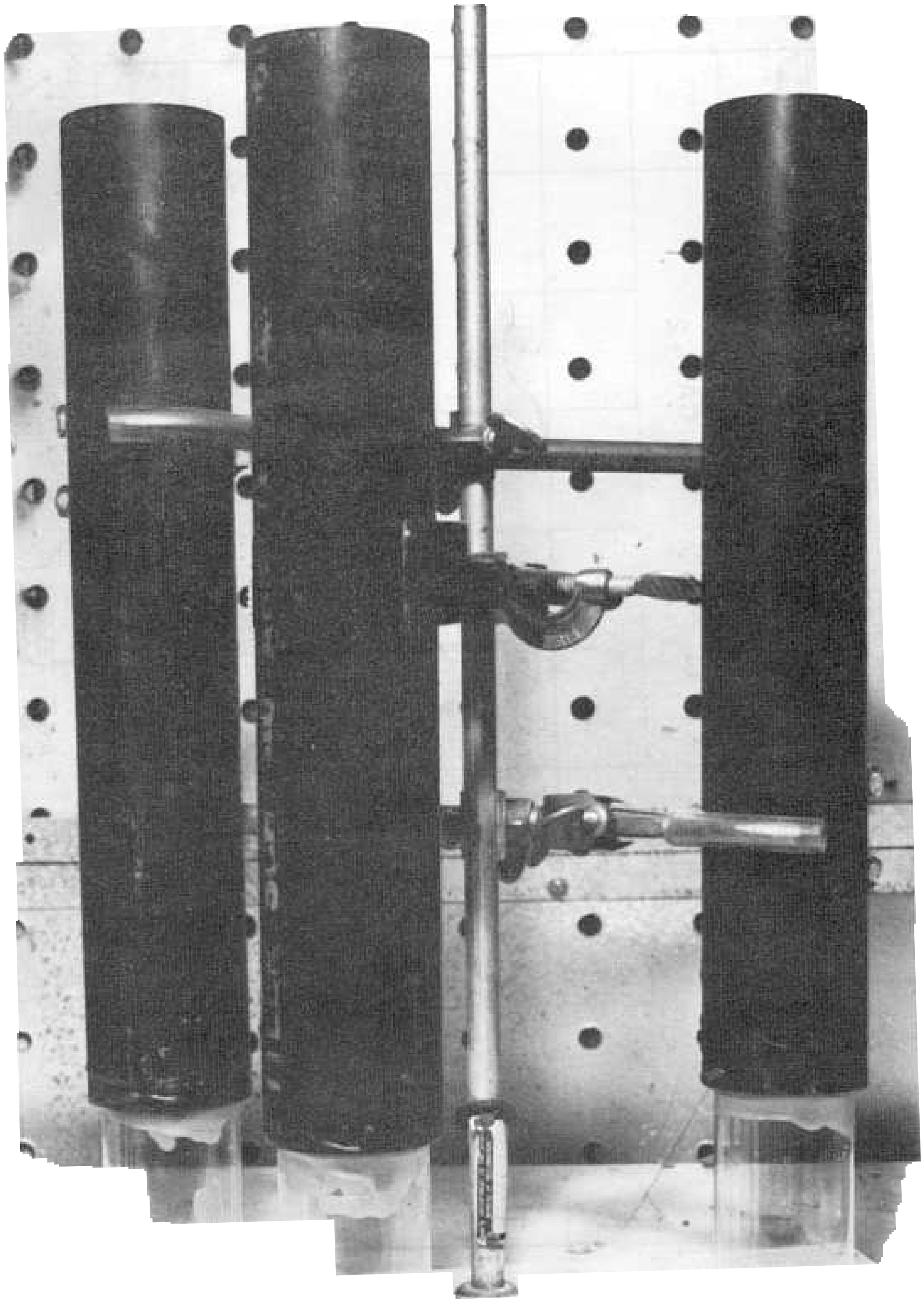


Figure 24.-Apparatus for casting 50-mm (2-in) diameter cylinders using grouts with W:C ratios of 5:1 and 8:1. Joint between PVC pipe and plastic mold sealed with wax. Photograph C-8481-127.

and rich neat-cement grouts (0.8:1 W:C ratio) had strengths from 13.8 × 10^3 to 48.2 × 10^3 kPa (2000 to 7000 lbf/in²). Figure 17 shows the highest grout strengths obtained.

Two modes of failure were observed in unconfined compressive strength testing (fig. 25). Stronger grouts, mainly 0.8:1 W:C ratio, displayed a splitting-type failure. A shear-type failure, similar to concrete, was demonstrated by sanded grouts which were usually weaker.

Grouts with no calcium chloride had strength-versus-age curves somewhat typical of concrete, with a rapid increase in strength between ages of 0 and 7 days and a more gradual increase in strength from 7 to 90 days. Grouts containing calcium chloride showed a much steeper slope between 0 and 7 days on strength-versus-age curves, i.e., much faster strength gain. This is consistent with results of time of set tests, which showed that times of setting were generally shorter for grouts containing calcium chloride.

Figures 17 through 22 indicate that calcium chloride grouts had higher or essentially equal strengths at all temperature ranges, with the greatest strength increases at lower temperatures. For grouts with a W:C ratio of 0.8:1, the 8 percent calcium chloride increased 28-day strength by 150 percent at 2 to 4 °C (35 to 40 °F), (fig. 17); while at 27 to 32 °C (80 to 90 °F), the strength was increased only 90 percent (fig. 19). With a dosage of 8 percent calcium chloride, strengths at 90 days' age were increased 120 percent at 2 to 4 °C (35 to 40 °F), (fig. 17); and 80 percent at 27 to 32 °C (80 to 90 °F), (fig. 19). The 1:1:1.4 grouts demonstrate how calcium chloride increased strengths in sanded grouts. At an age of 28 days, 8 percent calcium chloride increased strengths 120 percent at 2 to 4 °C (35 to

Figure 25.-Cylinders 50 by 100 mm (2 by 4 in), tested for unconfined compressive strength at an age of 90 days. Left: W:C = 0.8:1, 8 percent calcium chloride, 2 to 4 °C (35 to 40 °F). Right: W:C:S = 1:1:1.4, 6 percent calcium chloride, 2 to 4 °C (35 to 40 °F). Left cylinder shows splitting failure. Right cylinder shows shear failure on diagonal plane (roughly 1 o'clock to 7 o'clock). Photograph C-8481-116.

40 °F), (fig. 20); and 20 percent at 27 to 32 °C (80 to 90 °F), (fig. 22). Eight percent calcium chloride increased the 90-day strength by 60 percent at 2 to 4 °C (35 to 40 °F), (fig. 20); and 10 percent at 27 to 32 °C (80 to 90 °F), (fig. 22). Typically, sanded grouts realized only small strength gains when calcium chloride contents were incremented from 6 to 8 percent. In summary, the 2-percent calcium chloride had little influence on the strength developed and the 6-percent calcium chloride appeared to be an optimum dosage for strength development.

In general, grouts containing calcium chloride lost strength between 28 and 90 days. Figure 18 shows the largest strength loss for any grout tested: 13.8×10^3 kPa (2000 lbf/in²) with a calcium chloride content of 6 percent. As the figures show, the 90-day strength of practically all grouts containing calcium chloride were still above those of control mixes with no calcium chloride. Only two grout mixes, both sanded, dropped below the strength of their respective control mix at an age of 90 days, and in each case their strength was only 2070 kPa (3000 lbf/in²) lower. One mix was 1:1:1.4, 2 percent calcium chloride, 2 to 4°C (35 to 40°F) (fig. 20), and the other was 1:1:1.8, 2 percent calcium chloride, 2 to 4°C (35 to 40°F).

As grout temperature was decreased, strength was slightly increased for control mixes; furthermore, as higher calcium chloride dosages were used, strength was increased more as temperature was decreased. This can be seen by comparing figure 17 to figure 19, and figure 20 to figure 22, where:

a. For control specimens with a W:C ratio of 0.8:1, grout strength at 28 days was 20 percent greater at 2 to 4°C (35 to 40°F) than at 27 to 32°C (80-90 °F). With 8 percent calcium chloride, the strength was 70 percent greater at 2 to 4 °C (35 to 40 °F) than at 27 to 32 °C (80 to 90 °F), figures 17 and 19.

b. For control specimens with a W:C:S ratio of 1:1:1.4, strength at 28 days was 10 percent greater at 2 to 4 °C (35 to 40 °F) than at 27 to 32 °C (80 to 90 °F). With 8 percent calcium chloride, the strength was 100 percent greater at 2 to 4 °C (35 to 40 °F) than at 27 to 32 °C (80 to 90 °F), figures 20 and 22.

Triaxial Shear Strength

Triaxial shear strengths of the grouts tested generally followed the same trends and magnitudes as found with the unconfined compressive strength tests. An overall average angle of internal friction of 32° corresponding with an average cohesion of 5380 kPa (780 lbf/in²) was determined from the test data; however, since these data were very erratic, their validity is questionable.

Figure 26 shows two triaxial shear specimens with 0.8:1 mix. One had a calcium chloride content of 0 percent, the other 8 percent. These two specimens illustrate inelastic-type failure of stronger grouts by distinct diagonal planes of shear failure. There was very little lateral strain.

Figure 27 shows two sanded grout specimens after triaxial shear testing, both with 0 percent calcium chloride. Their W:C:S ratios were 1:1:1 and 1:1:1.4. Notice the amount of lateral strain typically exhibited by weaker grouts. Planes of shear failure are not as prominent as in stronger grout specimens, but are still evident. Many specimens at early ages, especially 7 days, showed this elastic-type failure since grout was not as hard and brittle as at later ages.

Drying Shrinkage

No shrinkage values for grouts with W:C ratios of 5:1 and 8:1 were obtained because the cement particles settled so much that gage studs (fig. 2) were not held securely enough in hardened specimens to measure length change. Tests on all other mixes with 0, 2, 5, and 8 percent calcium chloride were attempted and these data are contained in table 3.

The addition of calcium chloride to grouts increased the amount of shrinkage. A significant increase was noted in 0.8:1 grouts at 13 to 21 °C (55 to 70 °F), table 3. Increases in shrinkage over the control specimens were 113 percent with a dosage of 2 percent calcium chloride, and 342 percent with a dosage of 5 percent calcium chloride.

Generally, drying shrinkage increased as grout temperature decreased. For 1:1:1.4 mixes with 5 percent calcium chloride, drying shrinkage of the 2 to 4 °C (35 to 40 °F) and 13 to 21 °C (55 to 70 °F) grouts was greater than the 27 to 32 °C (80 to 90 °F) grout by 63 percent and 28 percent, respectively.

All mixes listed in table 3 were tested. Data were not obtained for some mixes due to extensive transverse cracking of specimens which would usually cause a break at that point, thereby making readings impossible (fig. 2).

Figure 26.-Cylinders, 50 by 100 mm (2 by 4 in), tested for triaxial shear strength at an age of 90 days. Left: W:C = 0.8:1, 8 percent calcium chloride, 2 to 4 °C (35 to 40 °F). Right: W:C = 0.8:1, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Photograph C-8481-146.

Erodibility

Since the physical erosion test apparatus was only capable of delivering 138 kPa (20 lbf/in²) water pressure to each specimen, one of the weakest grouts, with a 5:1 W:C ratio at 13 to 21°C (55 to 70°F), was tested to see if there was any indication of erodibility at this low pressure.

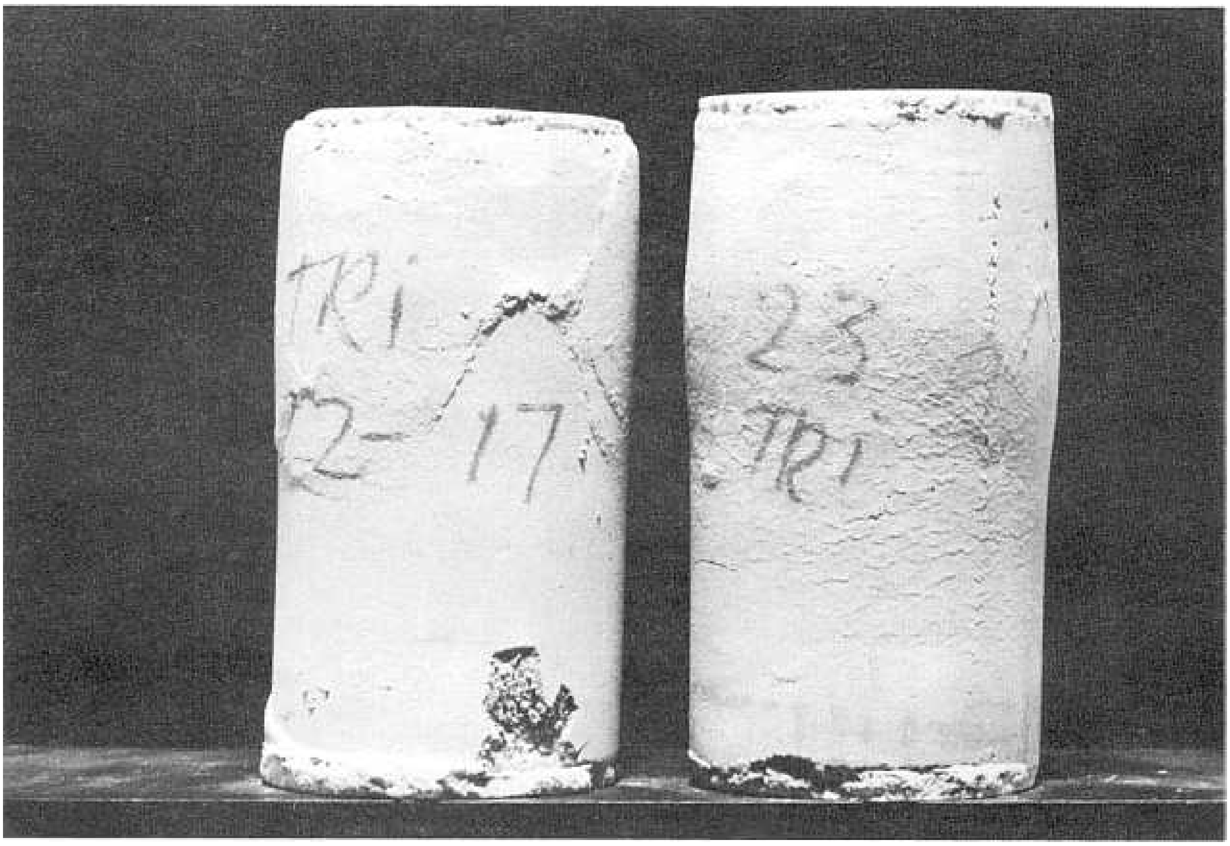
Figure 4 typifies settling of grout shortly after casting of erodibility specimens. Large amounts of laitance accumulated on top of specimens (fig. 6), which helps explain the weakness of 5:1 and 8:1 W:C ratio grouts as indicated by the chipped top surface on figure 5.

There was no weight loss in a 5:1 grout after 80 minutes of testing at 138 kPa (20 lbf/in²) pressure head. (Accuracy of weight measurement was within 1 percent of specimen weight). When a comparison was made between a typical specimen before testing and a specimen after testing, some slight erosion could be seen. Holes in the specimen in figure 28 are not as sharp as those shown on figure 5. However, considering the compressive strength of a 5:1 grout (fig. 23), it would seem that these specimens could withstand waterflow under a pressure head of at least 138 kPa (20 lbf/in²), and this seems to be verified since no weight loss occurred under erodibility testing.

Permeability

Grout mixes tested for permeability had: W:C ratio of 0.8:1 at 13 to 21°C (55 to 70°F), and W:C ratio of 5:1 at 13 to 21°C (55 to 70°F). Neither mix contained calcium chloride. These two mixes represented a relatively strong grout (0.8:1 W:C ratio) and a relatively weak grout (5:1 W:C ratio).

One set of permeability specimens was cured at standard conditions of 13 °C (55 °F) and 40 percent



igure 27.-Cylinders, 50 by 100 mm (2 by 4 in), tested for triaxial shear strength at an age of 90 days. Left: W:C:S = 1:1:1, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Right: W:C:S = 1:1:1.4, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Note bulging (i.e., strain) in horizontal direction. Planes of shear failure are evident. Photograph C-8481-148.

relative humidity. These specimens, which included grouts with and without calcium chloride, exhibited cracking problems due to drying and evaporation of moisture. It would have been impractical to test permeability of badly cracked grout; therefore, permeability data were obtained from a second set of specimens which were fog cured prior to testing. This second set of specimens did not contain calcium chloride since grouts with calcium chloride had exhibited the worst cracking under standard curing conditions.

Coefficients of permeability *K* were: 1.09×10^{-4} m/a (3.57×10^{-4} ft/yr) for the 0.8:1 grout and 1.19×10^{-5} m/a (3.91×10^{-5} ft/yr) for the 5:1 grout. The *K* factors were adjusted to represent permeability at an age of 60 days. Concretes and mortars with *K* factors less than 4.57×10^{-4} m/a (15×10^{-4} ft/yr) are considered to have good watertightness. Therefore, both of these grouts would be considered relatively impermeable as measured by this test method.

Bleeding

No test data for bleeding were taker qualitative observations are summarized

Grouts with 5:1 and 8:1 W:C ratio displayed the most bleeding, i.e., settling of solid particles. Figure 4 shows that in a 5:1 grout, resulting specimen height was 25 percent of the original molded height. Likewise for an 8:1 grout, the resulting specimen height was 12 percent of initial molded height.

Less bleeding occurred in grouts with a lower proportion of water to solids. Figure 1, which shows a

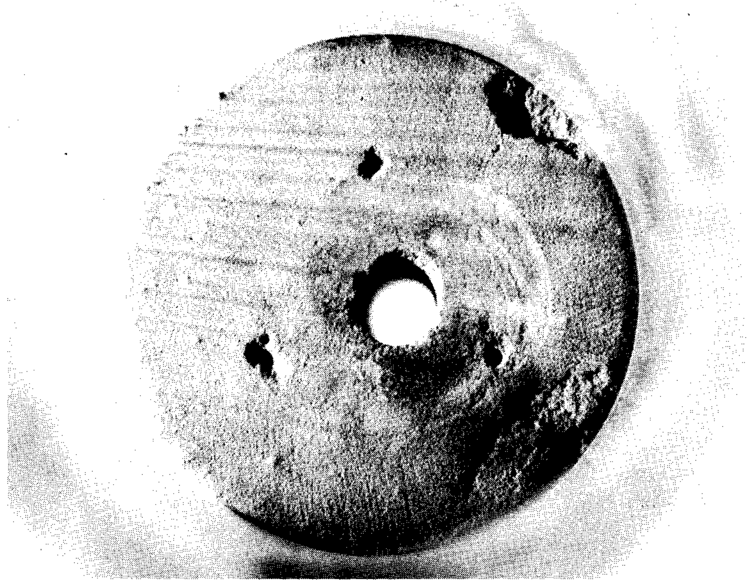


Figure 28.-Top of 30-mm (1¼-in) diameter cylinder after erodibility testing. W:C = 5:1, 0 percent calcium chloride, 13 to 21 °C (55 to 70 °F). Chipped areas around outer edge caused by rubbing with cloth while removing laitance. Center hole is 4.75-mm (3/16-in) diameter. Photograph C-8481-157.

1:1:1 grout at 27 to 32 °C (80 to 90 °F), demonstrates the bleeding characteristic typical of neat-cement and sanded grouts with no calcium chloride. Bleeding in these cylinders caused a reduction in volume of 3 percent. Grouts with a 0.8:1 W:C ratio showed more bleeding and grouts with higher sand contents showed slightly less bleeding than figure 1.

Petrographic Examination

Samples were taken from grout cylinders which had already been tested for compressive strength. A scaly crust was observed on some grout specimens as shown on figure 10. Figure 11 exhibits the same kind of crust at the tops of cylinders, but to a lesser degree. This crust occurred on specimens with and without calcium chloride, and therefore did not seem to be caused by calcium chloride.

A feature which appeared related to this crust formation was discovered during the petrographic examination. All specimens, especially those with a W:C ratio of 0.8:1, demonstrated varying strengths of concentric rings within cylinders. Note on figure 25 the relatively constant thickness of material, or layer, roughly 6.4 mm (1/4 in) thick, which has broken away from the top portion of the cylinder. This feature of layering within grout cylinders was also independent of calcium chloride content.

Specimens were described as relatively porous and absorptive; however, specimens which were fog cured proved to have very low permeability. Porosity of fog-cured specimens was comparable to that of specimens cured at 13 °C (55 °F) and 40 percent humidity.

Three anomalies shown on figure 29 were white streaks, spots of a lighter color than surrounding grout, and white crystals. Another view of the crystals is shown in figure 11. The white streaks were a very shallow surface feature. Chemically, they were composed of alite, a cement compound; vaterite, a product of cement hydration; and a slight trace of calcium chloride. The light gray spots were found on the interior of the specimens, and their mineralogy was no different than darker grout. The white crystals formed on the specimen surface were crystals of calcium hydroxide which is a product of cement hydration.

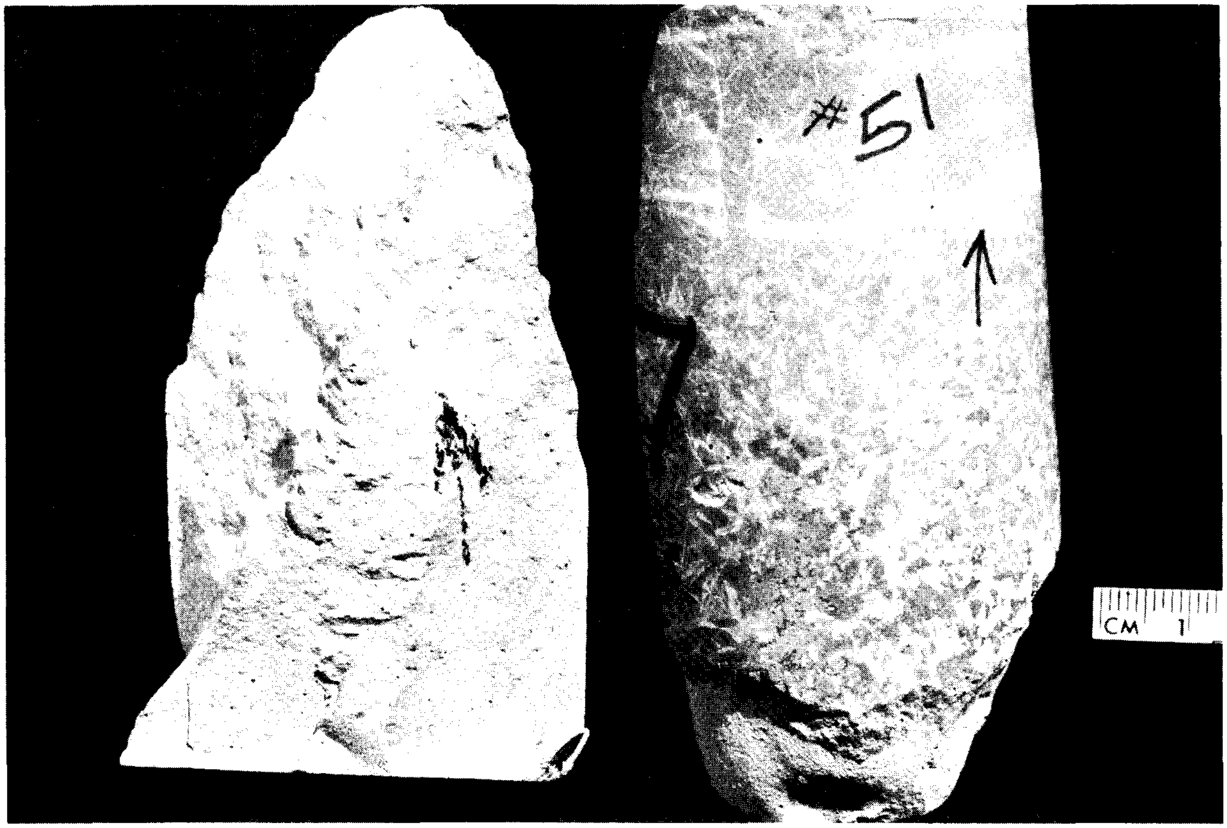


Figure 29.-Anomalies noted in grout mixtures. Left specimen shows light colored spots within darker grout — W:C = 0.8:1, 2 percent calcium chloride, 27 to 32 °C (80 to 90 °F). Right specimen displays white streak and white crystals on cylinder surface — W:C = 0.8:1, 8 percent calcium chloride, 27 to 32 °C (80 to 90 °F). Photograph GE-386-3.

A test for presence of chloride proved positive. However, this test does not determine the form of the chloride. No other information from microscopic analysis, X-ray diffraction, or differential thermal analysis showed chloride to be in an erodible form.

No free calcium chloride could be detected, but calcium chloride was found to exist within the compound "calcium aluminate chloride hydrate." The formation of this compound, when calcium chloride is included in a cement mixture, has also been theorized by other researchers [1, 4, 5, 6].

FUTURE RESEARCH

Possible areas of future research revealed by this program are:

1. Time of setting

a. Since tests did not reveal an optimum calcium chloride content for neat-cement grouts, tests at higher contents might establish an optimum dosage.

b. A method needs to be devised, other than the vicat test, to determine short-term setting characteristics of grouts. Possibilities for this would be some type of consistency test such as a flow table or viscosity test.

c. If a satisfactory consistency test can be developed, grout consistencies in the laboratory should be correlated to consistencies of grouts that can actually be pumped into foundation rock. This may require some type of field testing program.

2. Unconfined strength

a. Very long-term strengths of grouts at ages greater than 90 days should be investigated. This will determine whether grouts containing calcium chloride continue to lose strength after an age of 90 days.

b. A correlation should be made between strengths of grouts cured at (1) a low relative humidity of 40 percent as in this study, and (2) a standard laboratory condition of 100 percent relative humidity. With such a correlation established, further testing could be carried out in standard laboratory conditions. Results could then be used to define strengths in various field situations.

3. Erodibility

Geophysical investigations of foundation grouting jobs could reveal that erodibility of grouts is a concern and should be investigated further at realistically higher pressure heads.

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