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MISCELLANEOUS PAPER C-75-11

COLD WEATHER CONSTRUCTION MATERIALS

Part 2

REGULATED-SET CEMENT FOR COLD WEATHER CONCRETING; FIELD VALIDATION OF LABORATORY TESTS

by

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September 1981

Part 2 of a Series

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The U. S. Army carries on construction projects in localities such as Alaska, the northern tier of the United States, northern Europe, and the Arctic where the concrete placing system is shortened by the cold climate. At ambient temperatures below 50°F, concreting operations become more expensive since Corps of Engineers specifications require freshly mixed and placed concrete to be protected from low ambient temperatures. The overall military construction and maintenance in cold regions program was initiated to locate and evaluate

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20. ABSTRACT (Continued).

existing and new cementing materials that would allow concrete to be placed at ambient temperatures as low as 15°F. A relatively newly developed cement called "regulated-set" cement, which is a fast setting, rapid strength gain cement, appeared to have promise and was selected for a detailed study.

Both mortars and concretes made with regulated-set cement were studied in the laboratory. Test results were favorable, so the decision was made to validate the laboratory results with field testing. The U. S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) located in Hanover, New Hampshire, was selected for the prototype study.

Two 12- by 12-ft by 8-in. test slabs were cast in January 1975 when the mean temperature in New Hampshire was approximately 15°F. Test cylinders, push-out cylinders, drilled cores, and beams were tested for strength at various ages. The only difference in the two slabs was the concrete mixture temperature. Slabs 1 and 2 had concrete temperatures at discharge from the mixer of 33°F and 49°F, respectively. The higher temperature in slab 2 was accomplished by heating the water prior to mixing. The slabs received no special protection from the ambient temperatures. Neither slab attained any appreciable compressive strength at 1 day, but slab 1 had compressive strengths of approximately 1200 and 2000 psi at 7 and 28 days, respectively, while slab 2 had 2200 and 3300 psi, respectively. The concrete in both slabs was wetter than intended due to inexperience with the continuous batching and mixing equipment.

Since there was no strength gain at 1 day age whereas there had been a strength gain in laboratory tests of approximately the same concrete mixture but with an earlier shipment of regulated-set cement, a sample of the cement was brought to the laboratory for comparison with the earlier cement. Chemical and physical tests indicated that there was a difference in chemical composition. The factor suspected of being most significant in causing significant early strength gain in the laboratory cement sample and none in the CRREL cement was sulfate content. The earlier shipment had a higher sulfate content. These differences point out the need for a responsive purchase specification which is presently not available.

PREFACE

This study involves the evaluation of existing and new binder materials which could be used in concrete and concrete-like composites in cold weather environments. The study was part of the project, Military Construction and Maintenance in Cold Regions; DA Project 4K078012AAM1, Task 00, Work Unit 004, Evaluation of Innovative Concepts for Structure and Materials in Cold Regions, undertaken for the Directorate of Military Construction, Office, Chief of Engineers. This specific investigation was performed at the request of the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) under the general guidance of Mr. Francis Sayles. The study was authorized by Inter-Army Order No. CRREL 75-18, dated 23 October 1974, and No. CRREL 75-27, dated 24 December 1974. This is the second report in the series.

Funds for the publication of this paper as a U. S. Army Engineer Waterways Experiment Station (WES) Miscellaneous Paper were provided from those made available for operation of the Department of Defense Concrete Technology Information Analysis Center (CTIAC). This is CTIAC Report No. 45.

The work reported herein was conducted at WES and at CRREL under the direction of Messrs. B. Mather, J. M. Scanlon, G. C. Hoff, and B. J. Houston. This report was prepared by Messrs. Houston and Hoff.

Commanders and Directors of WES during the investigation and the preparation and publication of this report were COL George H. Hilt, CE, COL John L. Cannon, CE, COL Nelson P. Conover, CE, and COL Tilford C. Creel, CE. Mr. F. R. Brown was the Technical Director.

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CONVERSION FACTORS, INCH-POUND TO METRIC (SI) UNITS OF MEASUREMENT

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

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
pounds (mass)	0.4535924	kilograms
cubic yards	0.7645549	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	0.5932764	kilograms per cubic metre
pounds (force) per square inch	0.006894757	megapascals

* 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: $K = (5/9)(F - 32) + 273.15$.

COLD WEATHER CONSTRUCTION MATERIALS

REGULATED-SET CEMENT FOR COLD WEATHER CONCRETING; FIELD VALIDATION OF LABORATORY TESTS

PART I: INTRODUCTION

1. The U. S. Army has construction projects in localities of varying climatic conditions. In many areas, the construction season is shortened considerably by extended periods of cold weather. The problems and proposed solutions associated with the mixing, placing, and curing of concrete in cold weather are well known and documented, but a permanent, universal solution has not been found. In arctic and subarctic areas, concreting must frequently be done at temperatures near and below freezing. Even in the Arctic, the placing of concrete at temperatures below 32°F* is generally not practicable except for small projects or extremely large-scale operations with sizable plants. Concrete can thus be placed only during a short work season averaging 1 to 2 months in the Arctic and 2 to 3 months in most subarctic areas. The minimum practicable temperature limit for concreting as viewed by various countries with long periods of cold weather varied from 23°F in Denmark to -4°F in Sweden.

Background

2. A research investigation was conducted in 1973 and 1974 at the U. S. Army Engineer Waterways Experiment Station (WES) to evaluate regulated-set cement for use in concrete for cold weather construction. The results of these tests were reported in Part 1 of this

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* A table of factors for converting inch-pound units of measurement to metric (SI) units is presented on page 3.

series* and indicated that concrete made with regulated-set cement mixed at above-freezing temperatures would begin hydration within a few minutes even when placed at subfreezing temperatures and would sustain hydration by chemical heat generation long enough for sufficient strength to develop to resist initial freezing damage.

Objectives and Scope

3. The overall objective of this program is the evaluation of existing and new binder materials which could be used in concrete and concrete-like composites in cold weather environments. These materials should be able to be placed in the field at temperatures as low as 15°F, and require a minimum of attention after placement. The specific objective of the portion of the program reported herein is the field validation of laboratory tests of regulated-set cement as a binder for concrete that is to be placed at low temperatures.

4. The objective was accomplished in two phases. Phase I involved developing a synthesis of field experience on the use of regulated-set cement in concrete in field construction. Phase II was a prototype evaluation of concrete slabs cast and cured at 15°F and below. Two concrete slabs containing regulated-set cement were cast at low temperature in the field to validate laboratory test results and to evaluate casting procedures and equipment.

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* B. J. Houston and G. C. Hoff. 1975 (Dec). "Cold Weather Construction Materials; Part 1: Regulated-Set Cement for Cold Weather Concreting," Miscellaneous Paper C-75-11, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.; also published as Special Report 245, U. S. Army Cold Regions Research and Engineering Laboratory, Hanover, N. H.

PART II: PHASE I, SYNTHESIS OF FIELD EXPERIENCE

5. Since regulated-set cement has been used by the civilian sector for a number of years in such activities as highway patching, slip-form tunnel liners, and cast-in-place roof decking, letters requesting information on such uses were written to Corps of Engineers districts, cement producers, Portland Cement Association, construction companies, and others who may have had experience with the use of regulated-set cement. The information requested concerned construction problems, cracking, durability, cost, etc. Very little information was received because the people contacted could not or did not provide any documentation of their efforts.

6. None of the Corps of Engineers districts or divisions reported any use of regulated-set cement except for the Missouri River Division Laboratory where regulated-set cement was used in some experimental shotcrete panels at Chatfield Dam in 1972. A mortar mix of 1 part cement to 3 parts sand by weight was used in the shotcrete work. Table 1 gives the results of the comparison of regulated-set cement and a number of set accelerators. These data indicate that there appears to be no significant advantage in the use of regulated-set cement over the use of accelerators.

7. A reply from the Alaska District states that market conditions in Alaska have not developed to the point where regulated-set cement is attractive to potential users. This is primarily due to lack of experience, higher costs, and potential difficulties. Bechtel, Inc., in planning for the Alaska oil pipeline work, had not seriously considered regulated-set cement but expected to accomplish set acceleration where required with chemical admixtures.

PART III: PHASE II, PROTOTYPE EVALUATION

8. Two test slabs were constructed in January 1975 in an area adjacent to the U. S. Cold Regions Research and Engineering Laboratory (CRREL), Hanover, New Hampshire. This location was selected because of the low temperatures in January and the presence of CRREL to lend support.

9. The slabs were 12 by 12 ft by 8 in. thick and were constructed with a sand subbase covered with polyethylene as shown in Figure 1. Thermocouples were positioned in the center of the form at locations in the center of each slab and also slightly above the top of the slab so that temperature records during both placing and curing could be obtained for the concrete and the environment, respectively. Plastic push-out molds, as shown in Figures 1 and 2, were placed in the form to obtain and evaluate specimens that were cured in exactly the same manner as the test slabs. This type of mold, if strengths are representative of the in situ concrete, would eliminate the need for drilling test cores. For comparison purposes cast cylinders and beams were made and test cores were drilled from the slabs. Results of the strength tests are presented in Tables 2-5.

Concrete Mixture

10. The mixture used at CRREL was essentially the same as that used in the laboratory work at WES* with adjustments being made for the aggregate used in the CRREL mixture. This mixture had a compressive strength of approximately 3000 psi at 3 days age under laboratory conditions. The fine and coarse aggregate used in the laboratory was limestone, whereas the aggregate used in the CRREL concrete was a siliceous material (trap rock) from a local source. The physical properties of the trap rock were as follows:

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* Houston and Hoff, op cit.

	Coarse Aggregate	Fine Aggregate
Specific gravity	2.90	2.71
Absorption, %	0.6	0.8
Sieve size, cumulative passing, %		
3/4 in.	98	100
1/2 in.	54	100
3/8 in.	25	100
No. 4	5	100
No. 8	3	87
No. 16	0	63
No. 30	0	36
No. 50	0	15
No. 100	0	7
No. 200	0	6

11. There was 1.0 percent total moisture in the coarse aggregate as sampled at the batch plant and 4.4 percent in the sand. This was taken into account in adjusting the mixture proportions. The gradation of both the coarse and fine aggregate met the Federal Specifications for Concrete Aggregate as specified in CRD-C 131-55. Saturated surface-dry batch weights of the mixture used at CRREL were as follows:

Material	Saturated Surface Dry Batch Weights (1 cu yd), lb
Cement (regulated-set)	500
Fine aggregate	1289
Coarse aggregate (3/4 in. max)	1985
Water	265
Air-entraining agent	40 ml

12. The slump, air content, and temperature of the ingredients of the two mixtures were as follows:

Slump in.	Air Content %	Temperature of Ingredients Prior to Mixing, °F Cement	Fine Aggregate	Coarse Aggregate	Water	Air	Temperature of Mixture at Discharge, °F
				Slab 1			
8	13	27*	32	30	54	23	31
				Slab 2			
5-1/2	4	28	36	28	106	22	49

Note: Concrete strength samples were cast from the last of the concrete to be discharged from the mixer.
* Temperature in storage barrels in warehouse.

13. The primary difference between the mixtures for slabs 1 and 2 was the temperature of the water. In slab 1 the water temperature prior to batching was 54°F giving a concrete temperature at discharge of 31°F, whereas the water added to the concrete in slab 2 was 106°F prior to batching giving a concrete temperature at discharge of 49°F. The concrete was mixed in a 6-cu-yd mobile unit as shown in Figure 3. This unit is compartmentalized with bins or tanks for cement, coarse aggregate, fine aggregate, and water. The aggregate bins were charged at the batch plant by means of an end loader as shown in Figure 3, and the cement bin was loaded by hand from drums. This unit operates by opening bin gates a calibrated amount onto a screw auger which mixes the proportional ingredients and either pumps or chutes the freshly mixed concrete into the form. The entire operation takes only a few minutes to produce 6 cu yd of concrete. The concrete used for each slab was not actually as designed due to the inexperience of both WES and CRREL personnel in the operation of the mobile batching equipment. Slumps were higher than desired for both slab placements indicating a higher water content in the concrete than desired. The air content of the mixture placed in slab 1 was higher than desired because there was no opportunity to adjust air-entraining admixture content in trial mixtures with the mobile unit using CRREL aggregate prior to actual placing.

14. The setting of the concrete in both test slabs at CRREL was

not as fast as the laboratory work indicated it would be. This could have been caused by a number of factors. As noted earlier, the mixtures were wetter (higher slumps) and the air contents were higher than the mixture designed in the laboratory. Both of these factors would have extended setting times but neither should have delayed the setting time to the extent evidenced. It was also suspected that the shipment of regulated-set cement used in prototype evaluation at CRREL was somehow different from the cement used in the earlier work at WES although both were from the same producer. A sample of the cement used at CRREL was brought to the laboratory for comparison with the earlier cement.

Strength Tests

15. The schedule for testing cylinders, cores, and beams, is shown in Table 6.

16. The locations of the push-out cylinders and test cores taken from the test slabs are shown in Figure 4. The results of the strength tests are shown in Tables 2-5 and Figures 5-9. A temperature record of the air above the slabs and in the center of the slabs was also kept and is shown in Figures 10-12.

17. The strength of the concrete in both slabs as shown by the test results of the push-out and drilled cores was 0-200 psi at 1 day, 1200-1300 psi for slab 1 and 2200-2300 psi for slab 2 at 7 days, and 1800-2200 psi for slab 1 and 3100-3500 psi for slab 2 at 28 days.

Comparison of Regulated-Set Cement Shipments

18. A sample of the cement used at CRREL (RC-663(4))* was brought to WES for testing to determine if the sample was different from the earlier sample used in the laboratory work (RC-663(3)).* X-ray diffraction patterns were run on both cements with the following results.

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* WES cement serial number.

	663(3)	663(4)
$C_{11}A_7 \cdot CaF_2$	Major*	Major
Anhydrite ($CaSO_4$)	Major*	Major
$C_6A_xF_y$	Common	Common
MgO	Minor	Minor
Quartz	Minor-	Trace+
$CaSO_4 \cdot 1/2H_2O$	Trace	Trace
$CaSO_4 \cdot 2H_2O$	Trace	Not detected
Calcite	--	Common

* Although both compounds are a major ingredient in both cements, the results indicated that RC-663(3) contained more than RC-663(4).

19. It was also apparent that RC-663(3) contains more calcium sulfate than RC-663(4) and a little more $C_{11}A_7 \cdot CaF_2$. The calcium aluminoferrite is more aluminous in RC-663(3) than in RC-663(4) but both aluminoferrites have fairly high iron contents. About the same amount is found in each cement.

20. The tabulation below compares the composition of the whole cements.

	As-Received Cements	
	RC-663(3)	RC-663(4)
Alite	Major	Major
Belite	Trace?	Trace?
MgO	Trace+	Trace
$C_{11}A_7 \cdot CaF_2$	Common	Common
$CaSO_4$	Common	Common
CaO	Trace	Trace+
$CaCO_3$	Minor+	Minor+
Calcium aluminoferrite	Minor+	A little less than in 663(3)
Quartz	Minor-	Minor-

21. These two cements are very similar by X-ray diffraction.

There seems to be very little more $C_{11}A_7 \cdot CaF_2$ in RC-663(3) judging by the diffraction chart of the residue insoluble in maleic acid, but in the diffraction charts of the whole cements no consistent difference was found.

22. In addition to the X-ray diffraction tests, physical and chemical tests were conducted to compare the two cements. The results are shown in Table 7.

23. The fluoride determination was made with an Orion fluoride specification electrode. The difference suspected of being most significant between RC-663(3), which set and gained strength at low temperature, and RC-663(4), which did not, is the higher sulfate content of RC-663(3).

Hydration Heat Rise Tests

24. The temperature rise of both the laboratory regulated-set cement (RC-663(3)) and the CRREL regulated-set cement (RC-663(4)) due to hydration of the cement was determined by two different methods. The first method involved testing neat pastes of each cement with a water-cement ratio of 0.5. The pastes were placed in insulated containers and thermocouples inserted in the pastes for monitoring the temperature changes. The results are shown in Table 8 and Figure 13. There was no apparent difference in the hydration heat developed.

25. The second method involved casting a 2- by 2-ft by 8-in. slab from each of two concrete mixtures of the same proportions. The proportions of that mixture were as follows:

Material	Saturated Surface Dry Batch Weights (1 cu yd), lb
Cement (regulated-set)	500
Fine aggregate	1265
Coarse aggregate (3/4-in. max)	1855
Water	265
Air-entraining agent	40 ml

26. The only difference in the two mixtures was that one contained RC-663(3) cement while the other contained RC-663(4). The cement,

water, mixer, molds, etc., were at 35°F prior to mixing and the aggregate was at 15°F. As soon as the test specimens were cast a thermocouple was inserted in the center of each of the concrete slabs, and they were placed at 15°F with the temperature changes monitored. The results are shown in Table 9 and in Figure 14. Contrary to the data obtained for temperature development in the neat pastes, there was a marked difference in the heat generated in the concrete slabs. The heat in the slab containing the cement used at CRREL peaked at about 15°F below that of the laboratory stock, indicating a difference in the cements. This paralleled the observations made in the field.

Strength Comparisons

27. When the 2- by 2-ft by 8-in. slabs were cast for the temperature studies, six 6- by 6- by 6-in. cubes were cast from each of the two mixtures and placed at 15°F immediately after casting. Four cubes, two each representing the concrete from each slab, were evaluated in compression at ages of 1, 4, and 7 days. The cubes were allowed to thaw for 2 hours at room temperature prior to testing. The results are shown in Table 10. It is apparent that the cubes made with the CRREL cement froze without gaining strength. The cube containing the CRREL cement appeared wet and particles of the concrete could be crumbled by hand.

28. The field and laboratory tests confirm that the shipment of cement used at CRREL was significantly different from the regulated-set cement used at WES for the earlier laboratory tests. It is suspected that the high water content in the concrete at CRREL had a delaying effect on the setting time but there were other factors also contributing to a delayed set as the laboratory comparisons show. This probably can be attributed to the differences in sulfate content (6.5 for RC-663(3) and 5.2 for RC-663(4)) although this fact has not been definitely shown.

PART IV: DISCUSSION AND RECOMMENDATIONS

Discussion

29. The prototype tests at CRREL confirmed that concrete containing regulated-set cement can be placed with mean ambient temperatures as low as 15°F and that hydration and considerable strength gain will occur. With a mixture temperature at discharge of 32°F the compressive strength at 28 days age was approximately two-thirds that of similar specimens cast and cured at 72 ± 5°F, and with a discharge temperature of 50°F the strength was 90-100 percent. This was even more positively demonstrated by the fact that there was a considerable strength gain at low temperatures regardless of the fact that the unhardened mixtures were wetter than intended (5- to 8-in. slump), due to inexperience with the mixing equipment. This increased amount of moisture is known to delay the setting time of regulated-set cement. Also, the particular shipment of regulated-set cement used at CRREL was not of the exact chemical composition of the earlier shipment of regulated-set cement used in the laboratory tests and did not exhibit the same type of setting behavior. These differences suggest a need for a purchase specification for regulated-set cement in order to ensure reproducibility of cement behavior from lot to lot.

30. The fact that concrete whose temperature was 32°F when placed did not achieve the same level of strength at later ages as concrete whose temperature was 50°F when placed for the same cement indicates a need to examine the placing temperature effects more thoroughly. Some additional concrete protection may be necessary for a short period of time in order to get the hydration reaction started in the cement. For what length of time this protection would be needed would have to be determined by additional evaluation. This time period should be dictated by maturity of the cement paste in resisting damage to the first cycle of freezing. A compressive strength of 500 psi has been suggested*

* ACI Committee 306. 1973. "ACI Standard, Recommended Practice for Cold Weather Concreting," ACI Manual of Concrete Practice, Part 1, ACI 306-66 (Reaffirmed 1972), American Concrete Institute, Detroit, Mich.

as being the minimum strength (or maturity) the concrete should attain before the concrete is allowed to freeze. Other requirement values of minimum strength have also been reported.* A more exact value for this minimum needs to be verified. Once known, this will also dictate the earliest times at which formwork or concrete protection could be removed.

31. The efforts reported in Houston and Hoff** and in this report have dealt solely with the use of regulated-set cement. There may be other binders however which may give comparable results in cold weather, and these should also be identified and evaluated. These might include a recently developed gypsum-portland cement blend called VHE cement and cold-setting polymers.

Recommendations

32. In order to continue to develop sufficient supplemental background and additional criteria necessary for cold weather concreting and construction operations, it is recommended that the following tasks be undertaken.

Maturity evaluations

33. The American Concrete Institute (ACI) Recommended Practice for Cold Weather Concreting* states that concrete which has reached a compressive strength of 500 psi has had its degree of saturation reduced below a level where an initial freezing would not cause damage to the concrete. The requirement for this critical strength value has been reported as varying from 350 to 2100 psi,** therefore a validation of this 500-psi requirement is necessary before judgments regarding adequate length of protective curing can be made.

34. The validation should include concretes of varying proportions so that the influence of both available moisture and concrete strength development can be evaluated. The evaluations should be

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* ACI Committee 306, op. cit.
** Op. Cit.

conducted using the procedures of ASTM C 671.* This type of information could be used in the application of a "maturity concept" for protective curing and form removal times.

Evaluation of other binders

35. Other hydraulic binders such as the recently developed gypsum-portland cement (VHE cement) and cold-setting polymers should also be examined as possible alternatives to regulated-set cement in cold weather concreting operations. These materials should be examined for such characteristics as strength gain, handling times, heat development, special construction equipment and techniques and cost.

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* American Society for Testing and Materials. 1977. "Tentative Method of Test for Critical Dilation of Concrete Specimens Subjected to Freezing," Designation: C 671-77T, 1977 Book of ASTM Standards, Part 14, Philadelphia, Pa.

Figure 1. Forms for slabs 1 and 2 showing push-out molds in place prior to placing concrete

Figure 2. Plastic "push-out" cylinder molds

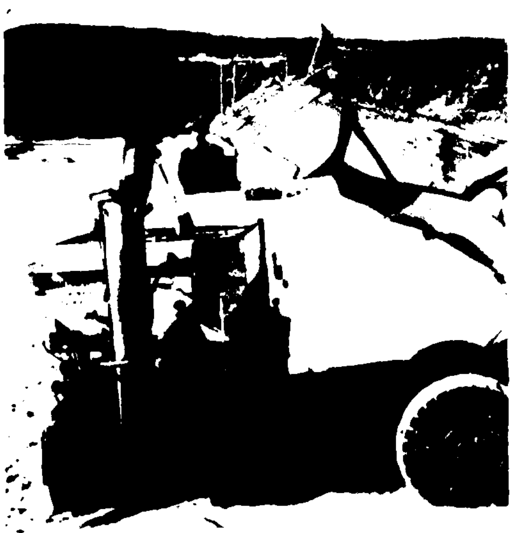


Figure 3. Mobile batching and mixing unit showing charging of aggregate bins by use of an end loader

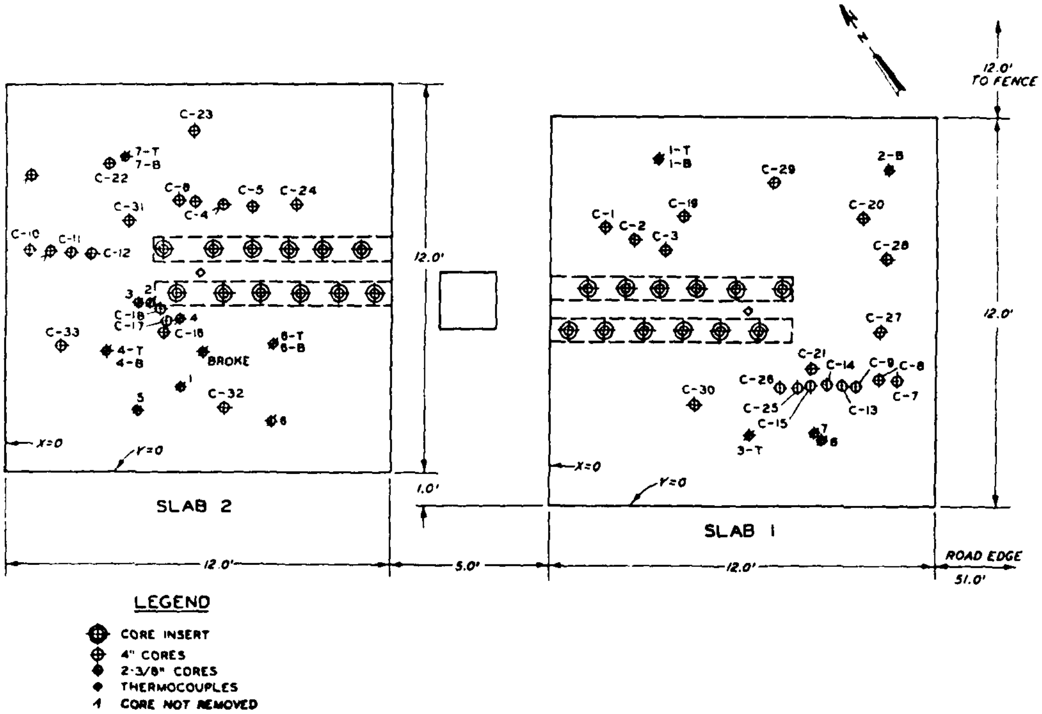


Figure 4. Locations of test cylinders and cores taken from slabs 1 and 2

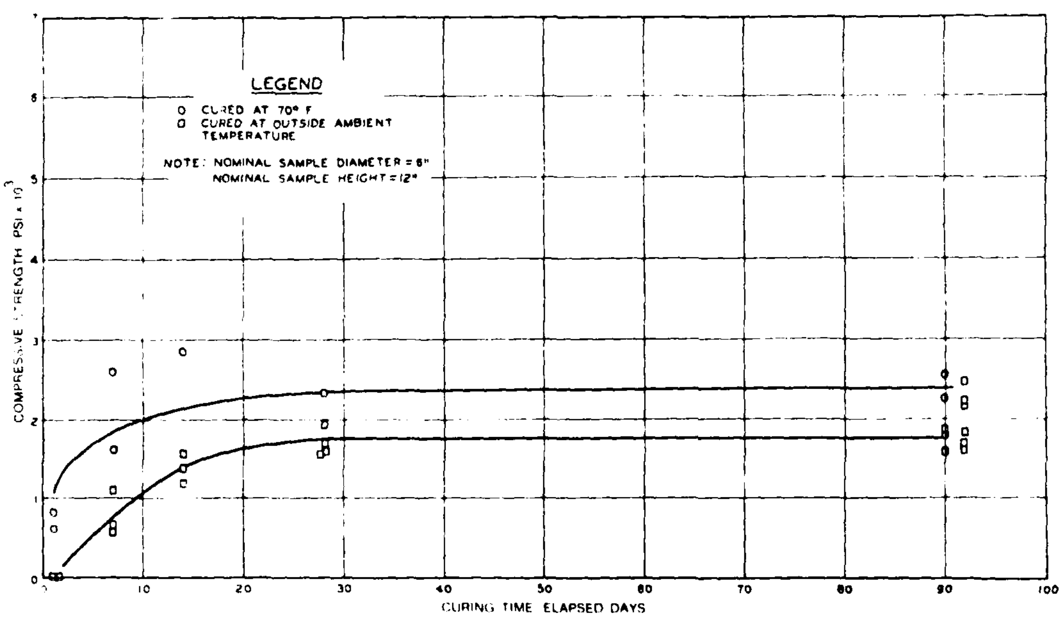


Figure 5. Compressive strength versus time relation for 6- by 12-in. cylinders from slab 1

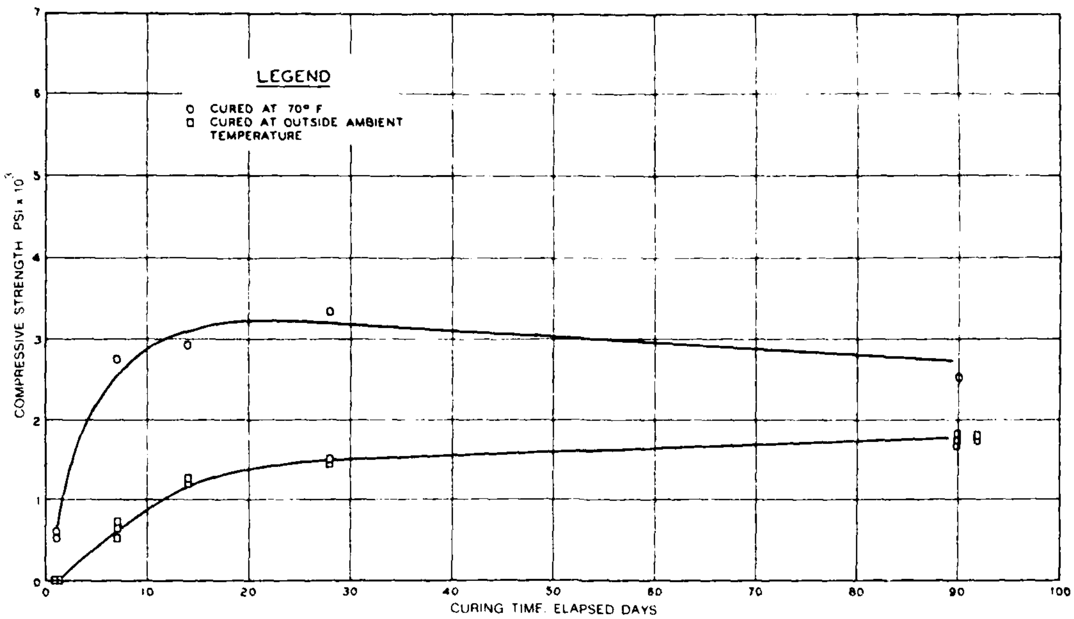


Figure 6. Compressive strength versus time relation for 6- by 12-in. cylinders from slab 2

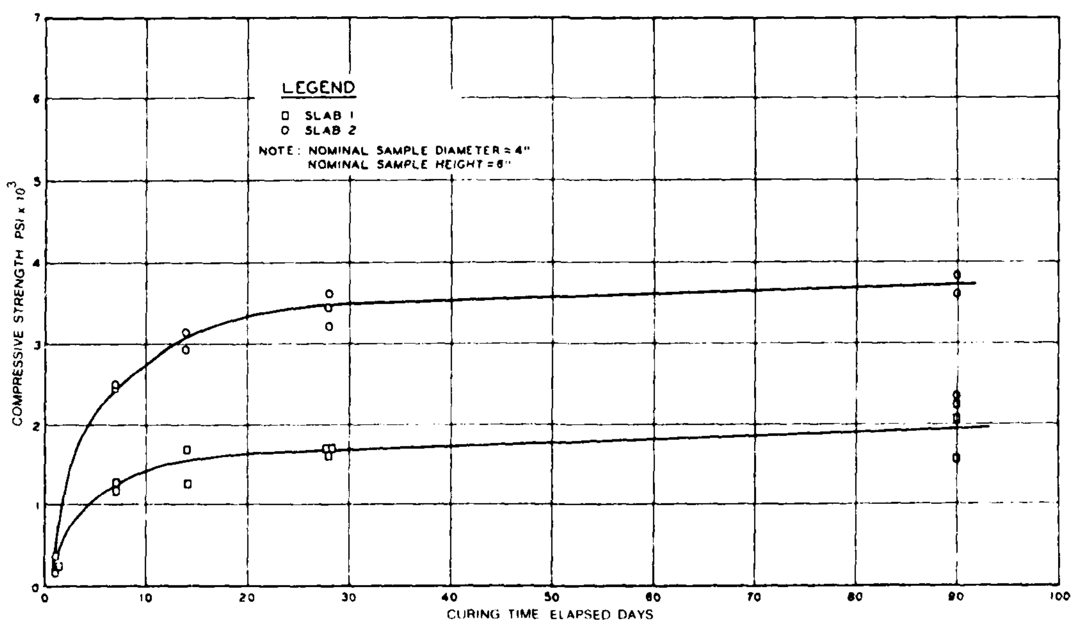


Figure 7. Compressive strength versus time relation for cylinders from slabs 1 and 2

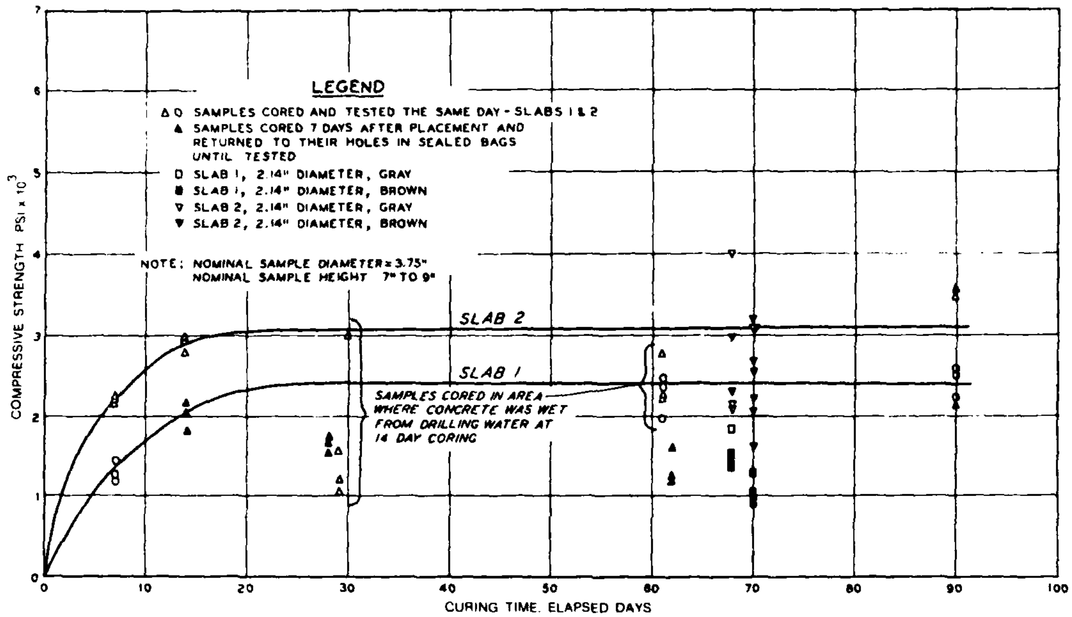


Figure 8. Compressive strength versus time relation for drilled cores from slabs 1 and 2

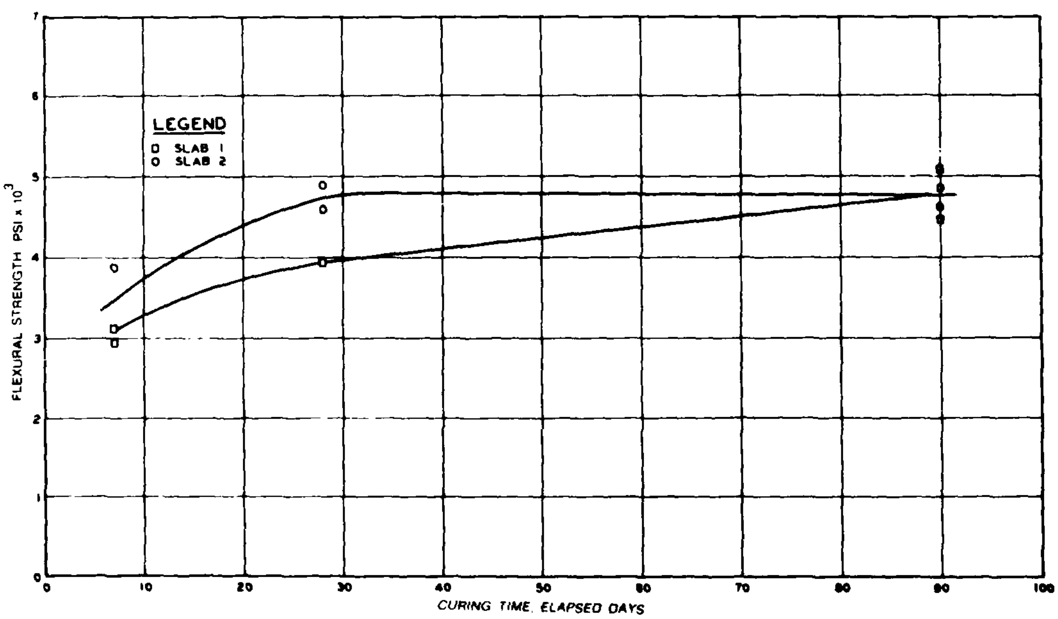
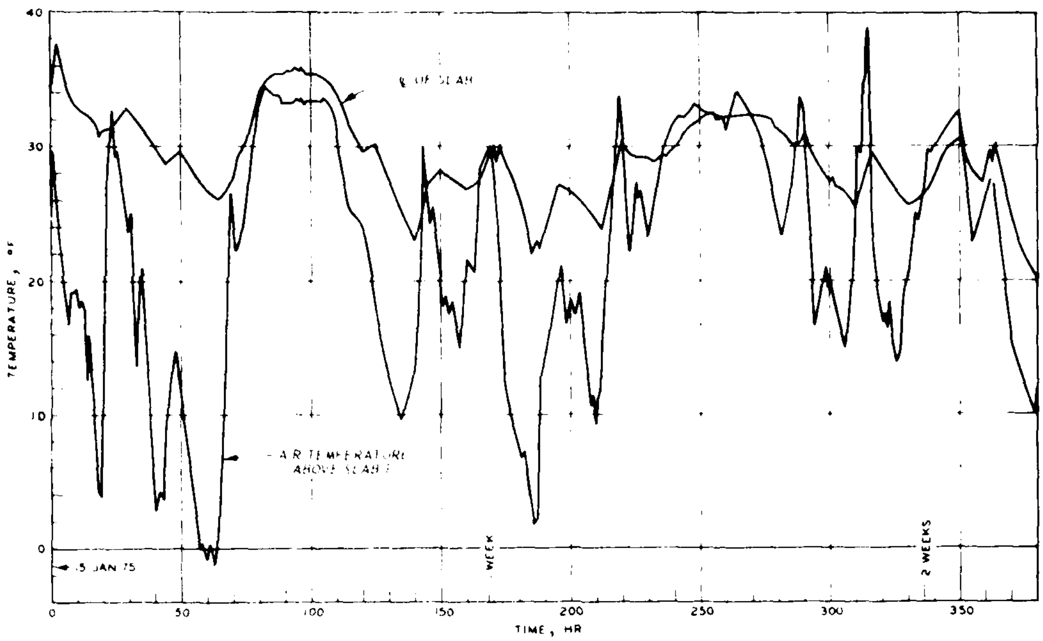
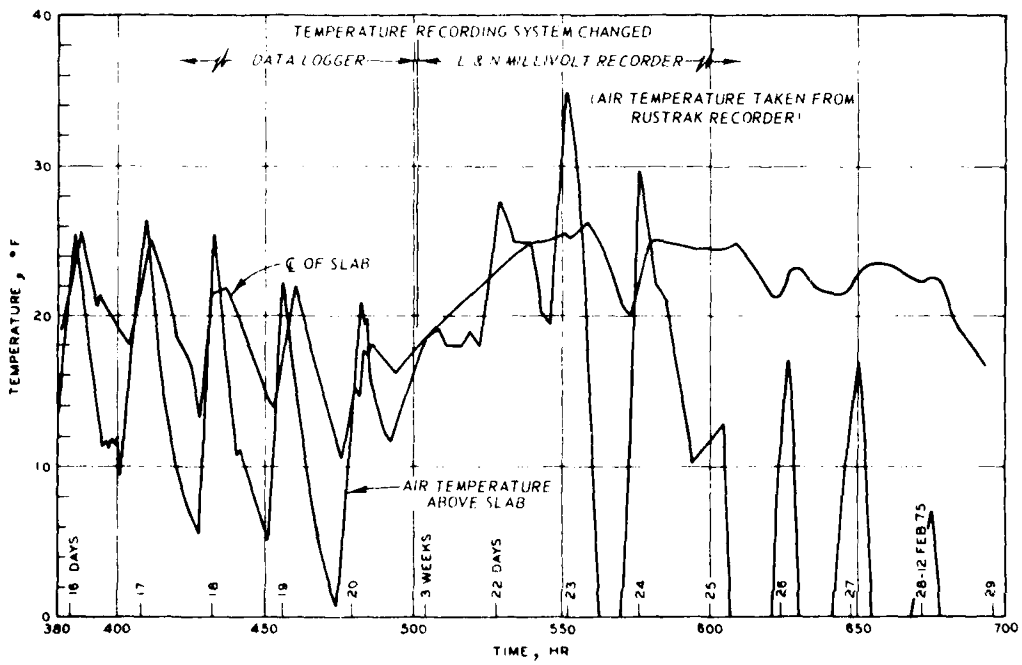


Figure 9. Flexural strength (third-point loading) versus time relation for cast beams from slabs 1 and 2

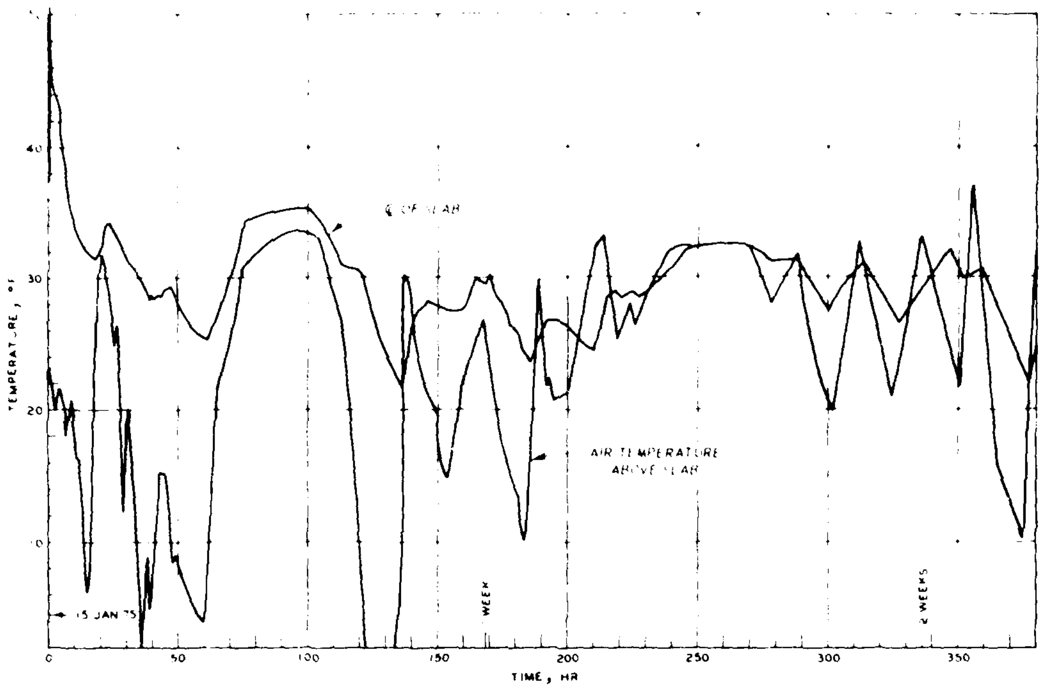


a. Time from 0 to 380 hr

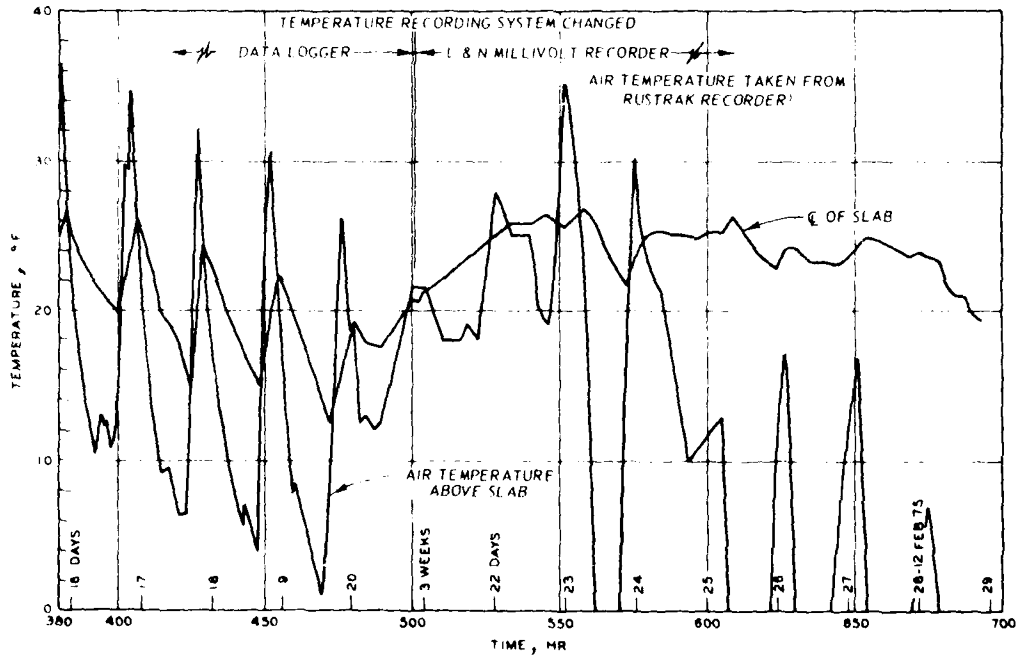


b. Time from 380 to 700 hr

Figure 10. Temperature record--slab 1



a. Time from 0 to 380 hr



b. Time from 380 to 700 hr

Figure 11. Temperature record--slab 2

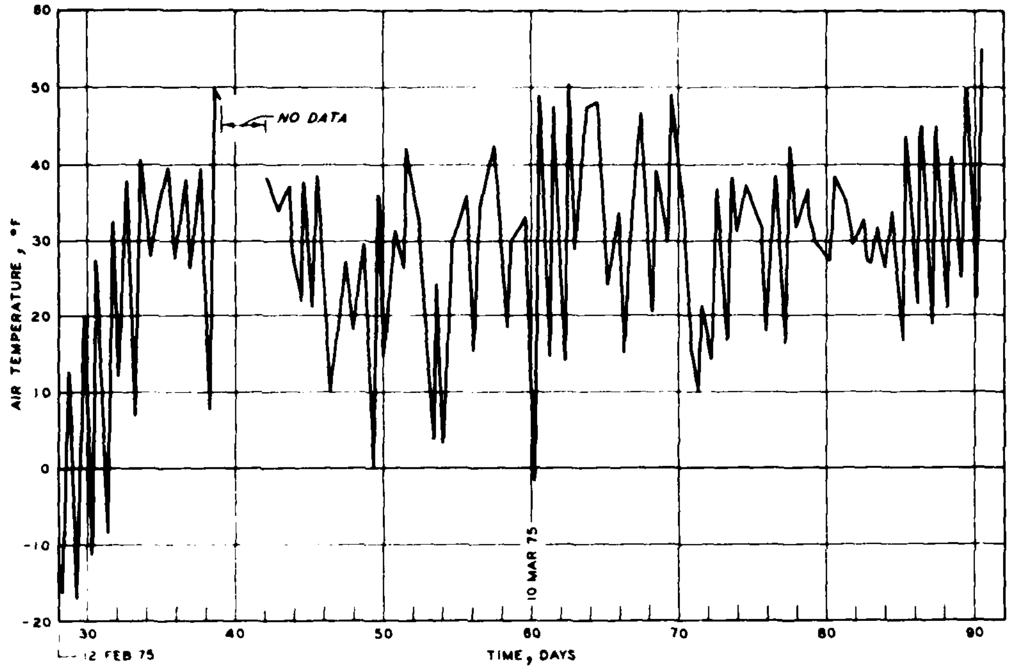


Figure 12. Temperature record for ambient air continued for 90 days

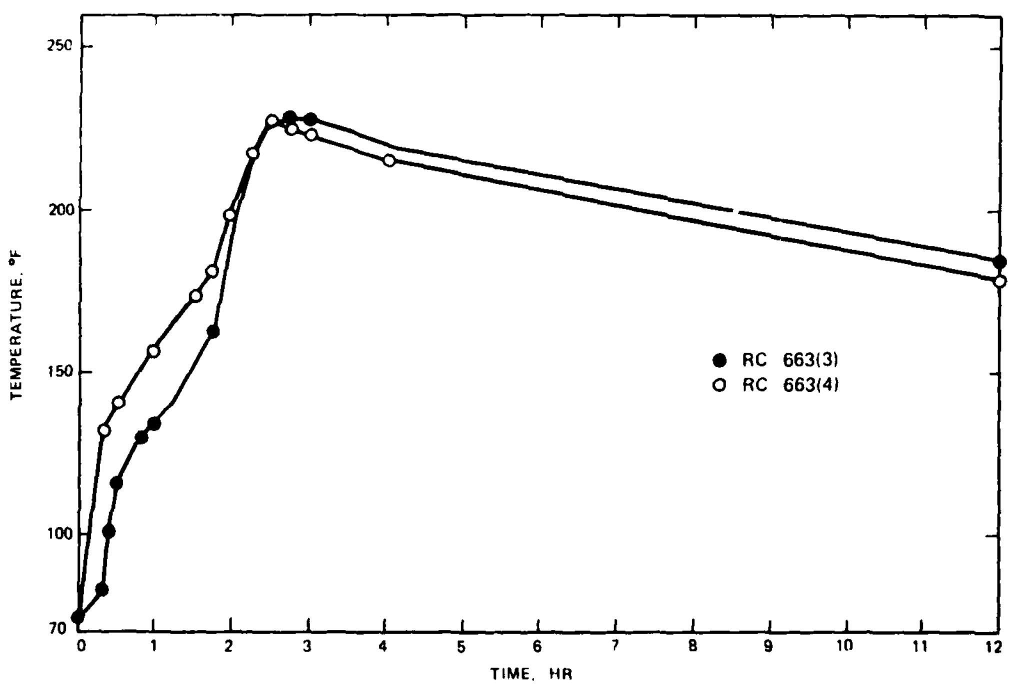


Figure 13. Temperature development history in neat cement paste (w/c = 0.5)

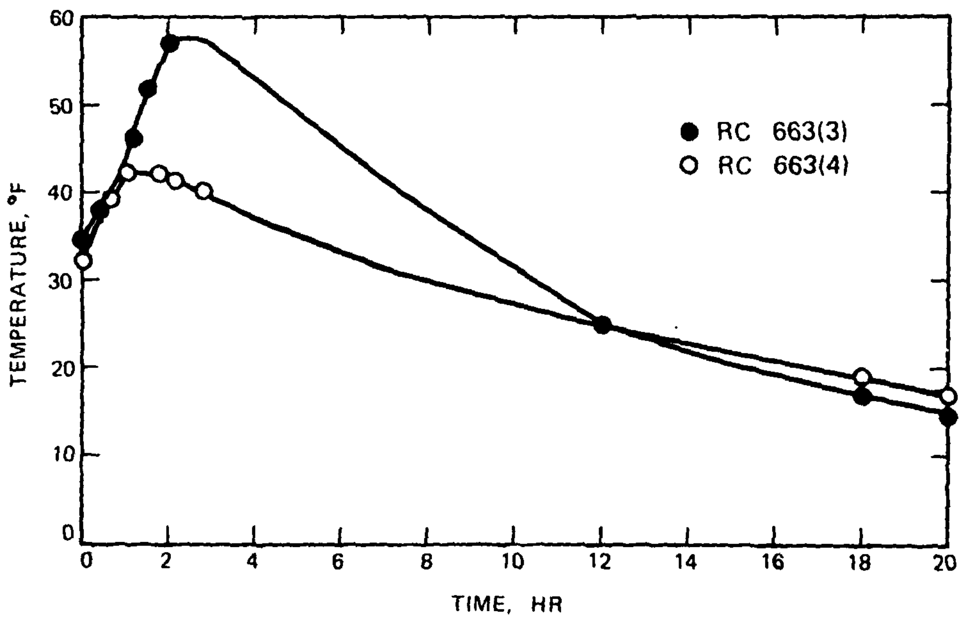


Figure 14. Temperature development history in small slabs

Table 1

Results of Tests on Shotcrete Panels Made at Chatfield Dam, Missouri River Division

Mix	Unit Weight pcf	24-hr Absorption, %	Compressive Strength, psi					
			7 hr	24 hr	8 day	28 day	90 day	1 yr
Control (job cement and mix)	143.7	8.1	Too	2240	5010	7360	8500	9,560
	144.6	8.2	green	2340	5290	7470	8700	9,260
	144.9	8.3	to	2280	5840	7730	9690	9,100
			saw*					
Avg	144.4	8.2		2290	5380	7520	8960	9,310
3% Tricosal T-1	140.4	9.4	1200	2030	3210	4510	6200	6,680
	141.9	9.7	1080	1840	3240	4590	6390	6,110
	142.2	9.9	890	2100	3300	4700	6040	6,090
Avg	141.5	9.7	1060	1900	3250	4600	6210	6,290
3% Tricosal 211-Av	139.9	10.0	1120	1630	3240	4230	5460	6,000
	140.9	10.1	1130	2100	3290	4360	5610	6,260
	140.9	10.5	1130	1780	3310	4440	5530	5,570
Avg	140.6	10.2	1130	1840	3280	4340	5530	5,940
3% Sigunit	141.1	9.0	1370	1930	3500	4520	5840	6,840
	141.7	9.0	1260	2050	3550	4600	6590	5,500
	142.0	9.5	1590	2160	3580	4970	6040	6,430
Avg	141.6	9.2	1410	2050	3540	4700	6160	6,260
2% calcium chloride	144.2	7.6	920	2890	5500	7730	9770	10,130
	144.5	8.0	1080	2880	5530	8100	9060	10,460
	145.3	8.1	1030	3180	5930	8220	9500	9,460
Avg	144.7	7.9	1010	2980	5650	8020	9440	10,020
3% Isocrete Extra P	141.6	9.7	Too	2750	3480	4870	4640	6,680
	142.3	9.7	green	2940	3570	5130	6290	6,200
	142.7	10.4	to	2480	4000	5270	6120	5,560
			saw*					
Avg	142.2	9.9		2720	3680	5090	5680	6,150
3% Isocrete AZ	141.3	9.9	Too	2280	3860	4800	5680	6,290
	141.7	10.3	green	2180	3920	4880	5830	6,340
	142.2	10.4	to	2180	3940	4910	5270	5,830
			saw*					
Avg	141.7	10.2		2210	3910	4860	5590	6,150
Regulated-set cement	142.7	8.7	1160	3050	4310	5420	6610	7,270
	142.9	8.9	860	2470	4540	6400	8090	8,020
	142.9	8.9	860	3400	5520	6800	7530	7,590
Avg	142.8	8.8	960	2970	4790	6210	7410	7,630

* Strength estimated below 600 psi.

Table 2

Summary of Strength Data for Push-Out Cylinders (4 by 6 in.)

Age at Test	Curing: Outdoors*	Curing: 70°F	Temperature in Center of Control Cylinder at Break, °F	Slab No.	Adjusted** Compressive Strength psi	Remarks
27 hr	23 hr	4 hr	55	1	26	Not capped
27 hr	23 hr	4 hr	55	1	38	Not capped
25 hr	23 hr	2 hr	36	2	24	Not capped
25 hr	23 hr	2 hr	36	2	19	Not capped
7 days	7 days	2 hr	44	1	1150	Voids on side of sample
7 days	7 days	2 hr	41	1	1255	
7 days	7 days	2 hr	45	2	2400	
7 days	7 days	2 hr	47	2	2360	
14 days	14 days	5 hr	48	1	1230	Samples broke near top
14 days	14 days	5 hr	48	1	1645	Samples broke near top
14 days	14 days	5 hr	48	2	2840	
14 days	14 days	5 hr	48	2	3050	
28 days	28 days	5 hr	40	1	1715	
28 days	28 days	5 hr	40	1	1635	
28 days	28 days	5 hr	40	1	1710	
28 days	28 days	5 hr	41	2	3135	
28 days	28 days	5 hr	42	2	3350	
28 days	28 days	5 hr	42	2	3505	
90 days	90 days	3 hr	--	1	2180	
90 days	90 days	3 hr	--	1	1540	
90 days	90 days	3 hr	--	1	2010	
90 days	90 days	3 hr	--	2	3505	
90 days	90 days	3 hr	--	2	3720	
90 days	90 days	3 hr	--	2	2265	

* See air temperature record (Figures 10-12).

** Size correction according to test method CRD-C27, paragraph 5.7. In: U. S. Army Engineer Waterways Experiment Station, CE. 1949 (Aug). Handbook for Concrete and Cement (with quarterly supplements), Vicksburg, Miss.

Table 3

Summary of Strength Data for Cylinders Cast at Site (6 by 12 in.)

Age at Test	Curing Outdoors*	Curing 70°F	Temperature in Center of Control Cylinder at Break, °F	Slab No.	Compressive Strength psi	Remarks
27 hr	23 hr	4 hr	47	1	9	
27 hr	23 hr	4 hr	47	1	17	
27 hr	6 hr	21 hr		1	829	
28 hr	6 hr	22 hr		1	603	
25 hr	1 hr	24 hr		2	565	
25 hr	1 hr	24 hr		2	594	
25 hr	23 hr	2 hr	36	2	11	
25 hr	23 hr	2 hr	36	2	9	
7 days	1 hr	7 days		1	2595	Cured 6 days in humid room
7 days	1 hr	7 days		1	1610	Cured 6 days in humid room
7 days	7 days	2 hr	41	1	580	
7 days	7 days	2 hr	41	1	595	
7 days	7 days	2 hr	41	1	1110	
7 days	1 hr	7 days		2	2740	Cured 6 days in humid room
7 days	7 days	2 hr	45	2	525	
7 days	7 days	3 hr	49	2	720	
7 days	7 days	3 hr	49	2	665	
14 days	6 hr	14 days		1	1360	Cured 13 days in humid room; top crumbled; poor cylinder
14 days	6 hr	14 days		1	2855	
14 days	6 hr	14 days		2	2920	
14 days	14 days	4 hr	41	1	1385	Failed at top
14 days	14 days	4 hr	41	1	1555	Failed at top
14 days	14 days	4 hr	41	1	1185	Failed at top
14 days	14 days	4 hr	41	2	1225	Failed at top
14 days	14 days	4 hr	41	2	1235	Failed at top
28 days	6 hr	28 days		1	2325	
28 days	6 hr	28 days		1	1555	Crumbled at top
28 days	6 hr	28 days		2	3315	
28 days	28 days	4 hr	39	1	1925	
28 days	28 days	4 hr	39	1	1680	
28 days	28 days	4 hr	39	1	1580	
28 days	28 days	4 hr	43	2	1405	
28 days	28 days	4 hr	43	2	1485	
28 days	28 days	4 hr	43	2	1490	

(Continued)

* See air temperature record (Figures 10-12).

Table 3 (Concluded)

Age at Test	Curing Outdoors	Curing 70°F	Temperature in Center of Control Cylinder at Break, °F	Slab No.	Compressive Strength psi	Remarks
90 days	1 hr	90 days	60+	1	2255	
90 days	1 hr	90 days	60+	1	2545	
90 days	1 hr	90 days	60+	2	2520	
90 days	90 days	4 hr	60+	1	1590	
90 days	90 days	4 hr	60+	1	1800	
90 days	90 days	4 hr	60+	1	1845	
90 days	90 days	4 hr	60+	2	1750	
90 days	90 days	4 hr	60+	2	1820	
90 days	90 days	4 hr	60+	2	1655	
92 days	92 days	2 hr	70	1	1680	
92 days	92 days	2 hr	70	1	2210	
92 days	92 days	2 hr	70	1	2165	
92 days	92 days	2 hr	70	1	1800	Temperature control cylinder**
92 days	92 days	2 hr	70	1	1620	Temperature control cylinder**
92 days	92 days	2 hr	70	1	2465	Corner chipped; cut to 6 by 11 in.
92 days	92 days	2 hr	70	2	1750	
92 days	92 days	2 hr	70	2	1845	Temperature control cylinder**

** Thermocouple embedded in center of 6- by 12-in. control cylinder.

Table 4

Summary of Strength Data of Beams (6 by 6 by 36 in.)

Age at Test	Curing** Outdoors	Curing** 70°F	Temperature* in Center of Control Cylinder at Break, °F	Slab No.	Flexural Strength, Third Point Loading, psi	Remarks
7 days	7 days	3 hr	55	1	255	
7 days	7 days	3 hr	55	1	234	
7 days	7 days	2 hr	54	2	253	
7 days	7 days	2 hr	54	2	310	
28 days	28 days	5 hr	53	1	315	
28 days	28 days	5 hr	53	1	180	Failed at old crack
28 days	28 days	5 hr	54	2	390	
28 days	28 days	5 hr	54	2	365	
90 days	90 days	6 hr	Not shown	1	410	
90 days	90 days	6 hr	Not shown	1	360	
90 days	90 days	6 hr	Not shown	2	370	
90 days	90 days	6 hr	Not shown	2	390	

* Thermocouple temperature in center of 6- by 12-in. control cylinder.
** Cured outside--see temperature record (Figures 10-12).

Table 5

Summary of Strength Data for Drilled Cores (3-3/4 by 8 in.)

Age at Test	Curing Outdoors*	Curing 70°F	Temperature in Center of Control Cylinder at Break, °F	Slab No.	Compressive Strength psi	Remarks**
7 days	7 days	3 hr	45	1	1440	
7 days	7 days	3 hr	45	1	1265	
7 days	7 days	3 hr	45	1	1190	
7 days	7 days	2 hr	40	2	2230	
7 days	7 days	2 hr	40	2	2140	
7 days	7 days	2 hr	49	2	2170	
			Estimated			
14 days	14 days	1 hr	34-36	1	2025	
14 days	14 days	1 hr	34-36	1	1810	
14 days	14 days	1 hr	34-36	1	2160	
14 days	14 days	1 hr	34-36	2	2925	Cored with water
14 days	14 days	1 hr	34-36	2	2920	Cored with water
14 days	14 days	1 hr	34-36	2	2790	Cored with water
28 days	28 days	4 hr	42	1	1600	
28 days	28 days	4 hr	42	1	1665	
28 days	28 days	4 hr	42	1	1755	
29 days	29 days	1 hr	32 est	2	1200	Top crumbled
29 days	29 days	1 hr	32	2	1075	Top crumbled
29 days	29 days	1 hr	32	2	1570	Top crumbled
30 days	30 days	10 hr	70	2	2955	Soft top sawed off; then core tested
61 days	61 days	Not shown	50 est	1	2365	Cored with water
61 days	61 days	Not shown	50 est	1	2480	Cored with water
61 days	61 days	Not shown	50 est	1	1960	Cored with water
61 days	61 days	Not shown	50 est	2	2280	Cored with water
61 days	61 days	Not shown	50 est	2	2785	Cored with water
61 days	61 days	Not shown	50 est	2	2205	Cored with water
62 days	62 days	Not shown	50 est	1	1215	Cored with air at 7 days and returned to holes in sealed plastic bags until tested
62 days	62 days	Not shown	50 est	1	1255	
62 days	62 days	Not shown	50 est	1	1610	
90 days	90 days	4 hr	Not shown	1	2575	
90 days	90 days	4 hr	Not shown	1	2510	
90 days	90 days	4 hr	Not shown	1	2230	
90 days	90 days	4 hr	Not shown	2	3455	
90 days	90 days	4 hr	Not shown	2	2150	
90 days	90 days	4 hr	Not shown	2	3545	

* Thermocouple temperature in center of 6- by 12-in. control cylinder.

** Samples cored with air except where shown as cored with water.

Table 6

Testing Schedule for Concrete Slabs at CRREL

Age	Slab 1					Slab 2				
	Cast Cyl		Core	Push-Out	Beam	Cast Cyl		Core	Push-out	Beam
days	70°F	15°	15°	15°	15°	70°F	15°	15°	15°	15°
1	√	√		√		√	√		√	
7	√	√	√	√	√	√	√	√	√	√
14	√	√	√	√		√	√	√	√	
28	√	√	√	√	√	√	√	√	√	√
60			√					√		
90	√	√	√	√	√	√	√	√	√	√

Table 7

Results of Chemical and Physical Tests

Sample No.	RC-663(3)	RC-663(4)
SiO_2, %	13.3	14.1
Al_2O_3, %	11.7	11.5
Fe_2O_3, %	2.4	3.3
MgO, %	1.6	1.6
SO_3, %	6.5	5.2
Loss on ignition, %	3.3	3.8
Alkalies - total as Na_2O, %	1.21	1.27
Na_2O, %	0.58	0.64
K_2O, %	0.95	0.95
Insoluble residue, %	1.09	0.75
CaO, %	57.5	57.8
Fluoride, %	1.13	1.09
Surface area, sq cm/g	6100	6710
Specific gravity	2.99	2.99

Table 8

Temperature Development, °F, in Neat Paste

Time, hr:min	Laboratory Cement, RC-663(3)	CRREL Cement, RC-663(4)
0:00	74	74
0:05	--	76
0:10	--	86
0:15	--	122
0:20	83	132
0:25	101	136
0:30	116	141
0:40	125	146
0:50	130	152
1:00	134	156
1:15	141	164
1:30	152	173
1:45	163	181
2:00	199	200
2:15	219	218
2:30	225	227
2:45	228	225
3:00	227	223
4:00	219	215
20:00	149	140
24:00	135	128
44:00	103	99

Table 9

Temperature Development History of Small Slabs

RC-663(4), CRREL		RC-663(3), Lab	
Time Stored at -10°F, hr:min	Temperature, °F	Time Stored at -10°F, hr:min	Temperature, °F
0:00	32	0:00	34
0:35	39	0:30	38
0:50	42	1:00	42
1:05	42	1:15	46
1:25	42	1:30	52
1:35	42	1:50	56
1:50	42	2:00	57
2:05	41	2:15	57
2:20	41	2:30	57
2:35	41	2:45	57
2:45	40	3:00	56
		3:10	56
		12:00	25
18:15	19	18:40	17
19:15	18	19:40	16
20:15	17	20:40	15

Table 10

Strength Comparisons of Two Samples of Regulated-Set Cement

Cement		Compressive Strength, psi 1 day	4 day	7 day
RC-663(3), lab	1	1550	1475	1680
	2	1600	1600	1710
	Avg	1580	1540	1700
RC-663(4), CRREL	1	46	40	56
	2	29	35	47
	Avg	38	40	52

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Cold weather construction materials : Part 2 : Regulated-set cement for cold weather concreting; field validation of laboratory tests / by Billy J. Houston, George C. Hoff (Structures Laboratory, U.S. Army Engineer Waterways Experiment Station). -- Vicksburg, Miss. : The Station ; Springfield, Va. : available from NTIS, 1981.
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