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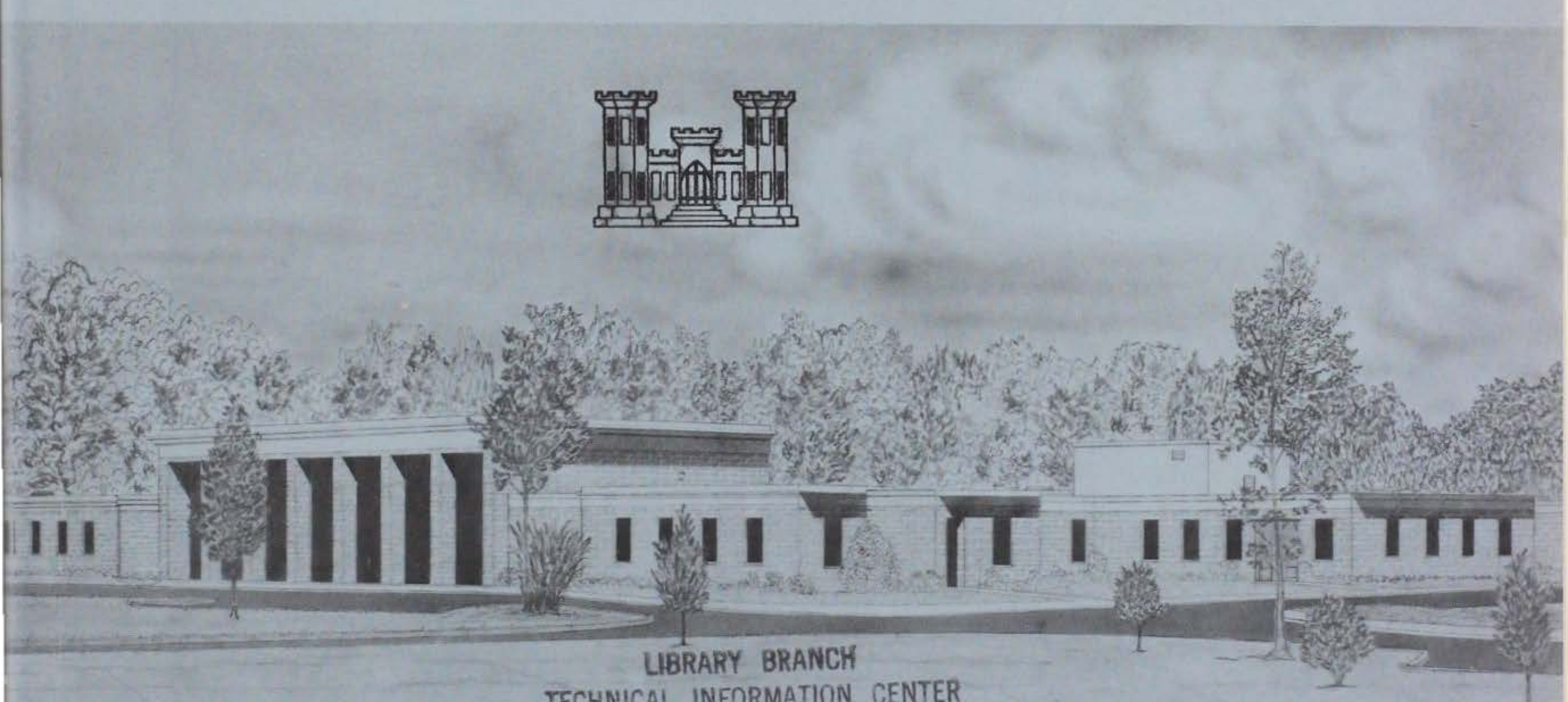
TECHNICAL REPORT C-74-3

LABORATORY INVESTIGATION OF SLIPFORM CONSTRUCTION FOR USE IN MASS CONCRETE STRUCTURES

by

K. L. Saucier



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Conducted by U. S. Army Engineer Waterways Experiment Station
Concrete Laboratory
Vicksburg, Mississippi

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FOREWORD

The study reported herein was conducted as part of Civil Works Investigation, Engineering Studies Item ES 617, and was authorized by Mr. James A. Rhodes of the Office, Chief of Engineers, U. S. Army, in a conference at the Concrete Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) on 13 January 1972.

The study was accomplished at the Concrete Laboratory, WES, during the period January 1972-June 1973. The research was conducted under the general supervision of Messrs. Bryant Mather, James M. Polatty, and William O. Tynes, and under the direct supervision of Mr. Kenneth L. Saucier, who prepared this report. Mr. A. A. Bombich was responsible for the temperature studies.

Directors of WES during the conduct of this study and the preparation and publication of this report were BG E. D. Peixotto, CE, and COL G. H. Hilt, CE. Technical Director was Mr. F. R. Brown.

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

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

Multiply	By	To Obtain
inches	25.4	millimetres
feet	0.3048	metres
cubic yards	0.8361274	cubic metres
pounds (mass)	0.45359237	kilograms
pounds (mass) per cubic yard	0.59327638	kilograms per cubic metre
pounds (force) per square inch	0.00689476	megapascals
cubic feet	0.0283168	cubic metres
square inches	645.16	square millimetres
pounds (force)	4.448222	newtons
feet per second	0.3048	metres per second
inches per hour	25.4	millimetres per hour
pounds (force) per linear foot	14.5939	newtons per linear metre
inches per linear foot	83.333	millimetres per linear metre
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*

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

SUMMARY

A laboratory investigation was conducted to study applications of the slipforming technique in mass concrete construction. Opposite sides of large blocks (3 by 6 by 10 ft high (0.9 by 1.8 by 3.0 m)) were slipformed in a specially fabricated test frame using mass concrete mixtures. Variables included casting temperature, type and maximum size of aggregate, use of a lubricating admixture, slipping rate, type of form anchors, and type of slipform surface.

Based on the results of this study the following conclusions appear warranted:

a. The slipforming technique appears feasible for use in mass concrete construction. Esthetically, the appearance of slipformed concrete should be similar to that of conventionally placed concrete.

b. No discernible effects of type of aggregate, whether natural or crushed stone, or of maximum size of aggregate, whether 3 or 6 in. (76.2 or 152.4 mm), were noted.

c. The maximum feasible slipping rate determined for the variables in this study (mass concrete, concrete temperature of 60 F (15.5 C), and 4-ft (1.2-m) height of slip form) was found to be 18 in./hr (457.2 mm/hr). A minimum of 6 in./hr (152.4 mm/hr) is recommended. However, rates less than 6 in./hr may be satisfactory if consideration is given for avoidance of cold joints.

d. Steel-lined slip forms appear to be superior to tongue and groove lumber and impregnated plywood slip forms for use in mass concrete slipforming.

e. Form lifting pressures are likely to be approximately twice those for structural concrete (250 versus 125 lb per linear foot (3648.5 versus 1824.2 N per linear metre) of form). The use of a lubricating admixture reduced drag pressures by about 50 lb per linear foot (729.7 N per linear metre) of form width.

f. A shear-plate type of form anchor offers good strength for use in design of a form-support apparatus.

g. A definitive method of determining the degree of hardening as related to slip rate was not determined. The method normally used for structural slipforming, i.e., forcefully jamming a rod down to the hardened concrete, does not appear practical for use with mass concrete.

h. Temperature measurements in the laboratory blocks indicated that peak slipform temperatures did not exceed those that were calculated for conventionally placed 5-ft (1.5-m) layers in the same block. However, other calculations, for larger structures, indicate that slipforming should result in higher peak temperatures than would be attained using conventional 5-ft layers.

LABORATORY INVESTIGATION OF SLIPFORM CONSTRUCTION FOR USE IN MASS CONCRETE STRUCTURES

PART I: INTRODUCTION

Background

1. Placing of concrete by use of slip forms is similar to an extrusion process. Freshly mixed concrete is placed or pumped into the forms, and the forms act as moving dies to shape the concrete. The rate of movement of the forms is regulated so that the forms leave the formed concrete only after it is strong enough to retain its shape while supporting its own weight. Formwork of this type can be used for vertical structures such as silos and storage bins,[1] shaft buildings,[2] and nuclear power plants[3] or for horizontal structures[4] such as tunnel inverts, water conduits, drainage channels, canal linings, and pavements. There may be fixed forms on one side (such as sheathing, rock, earth, or existing masonry) and a sliding form on the other. For other types of work, there are sliding forms on both or all sides. Vertical slip forms are usually moved by jacks that ride on smooth steel rods or pipe embedded in or attached to the hardened concrete, whereas horizontal slip forms generally move on a rail system or on a shaped berm. Working decks, concrete supply hoppers, and worker or finisher's scaffolding, where required, are attached to and carried by the moving formwork. The vertical or horizontal movement of the forms may be a continuous process carried on 24 hr of the day until the structure is completed or may be a planned sequence of finite placements. Although continuous slides are desirable, the sliding operation may be stopped and later resumed. The resulting joints will be no different from those between lifts of fixed-form construction.

2. Savings of as much as 25 percent have been attributed to the use of slip forms;[5] however, there are many procedures in slipforming different from those of conventional concrete construction that require precautionary measures. In order to secure the most efficient job, the

usual objective is to slip as fast as possible consistent with material supply, setting time of the concrete, work schedule, etc. Thorough planning is essential. An adequate supply of concrete must be available to sustain continuous operation at the maximum rate. Adequate equipment, including hoisting equipment, and personnel familiar with the operation must be available. In addition, a supervisor experienced in slipforming must be on the job at all times to determine maximum and minimum rates of slide consistent with changes in weather, workability, and exigencies that arise during the operation. It is essential that an alternative method be considered and the necessary plant be supplied so that, in the event of a breakdown, the sliding operation can be sustained.[6]

Purpose

3. Despite the increased use of slipform construction and automation on the jobsite[7] in recent years, slipform techniques have apparently not been applied to mass concrete construction in the U. S. A companion study[8,9] has revealed the potential benefits of using slipformed mass concrete on a small gravity dam. The objectives of this study included:

a. Determining if slipformed concrete can be utilized for mass concrete construction.

b. Development of procedures and techniques for mass concrete slipforming that can be applied in actual field construction.

c. Development of information relative to possible problem areas and solutions thereto.

d. Determination of basic quantitative measurements for representative mixtures, i.e., required lifting pressures, type of form facing, etc.

Scope

4. Using typical mass concrete mixtures (6-in. (152.4-mm)* maximum-size aggregate), tests were conducted in the laboratory to

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

develop information relative to mass concrete slipforming. A special form was constructed (representing a typical mass section) that had two stationary sides and two sliding sides. Test variables included the slip rate, placing temperature, type and maximum size of aggregates, and form facing material.

PART II: MATERIALS, MIXTURES, AND TEST EQUIPMENT

Materials

5. Type II portland cement (RC-658) from Texas and pozzolan (fly ash, AD-3(11)) from Illinois were used in this investigation. Physical and chemical properties of the cement and pozzolan are given in table 1. Limestone fine (CRD MS-17) and coarse aggregates (CRD G-31) from Tennessee were used in two mixtures. Natural fine and coarse aggregates from an undeveloped site (NED-13 G-1) were processed in the laboratory for use in one mixture. The physical properties and gradings of the aggregates are given in tables 2-4. The air-entraining admixture (AEA-896) was a solution of neutralized Vinsol resin. A commercially available "pump aid" marketed as a lubricant was used on one occasion in an attempt to reduce drag of the slip forms.

Mixtures

6. The use of admixtures, immersion vibrators,[10] and lightweight aggregates[11] indicates that the versatility of slipforming has greatly increased in recent years. However, the large size of the aggregate and the relatively slow rate of strength development of lean mass concrete signal a need for specific investigation of these two factors. Three mass concrete mixtures were proportioned to study the effect of large aggregate on slipforming techniques:

Mixture	Maximum Size of Aggregate		
Designation	in.	mm	Type of Aggregate
A	3	75	Limestone (see table 2)
B	6	150	Limestone (see table 3)
C	6	150	Natural (see table 4)

All mixtures were proportioned to have a cementitious content of approximately 260 lb/yd^3, and air content of 5 ± 1 percent, a slump of 2 ± 1/2 in., and a fly ash content of 35 percent by weight. Details of

the proportions of the three mixtures are given in tables 5-7.

7. Four individual slipform blocks were cast during the course of the study as indicated below:

Block No.	Mixture Designation	Test Factors
I	A,B	Mixture A in bottom half of block Mixture B in top half
II	C	Precooled materials
III	B	Precooled materials
IV	B	Lubricant experiment Precooled materials

Test Equipment

8. A special apparatus was constructed to cast the four 3- by 6- by 10-ft-high (0.9- by 1.8- by 3.0-m-high) test blocks. The 3-ft (0.9-m) sides of the apparatus were stationary bulkhead forms, and the two 6-ft (1.8-m) sides were movable slip forms. Fig. 1 shows the

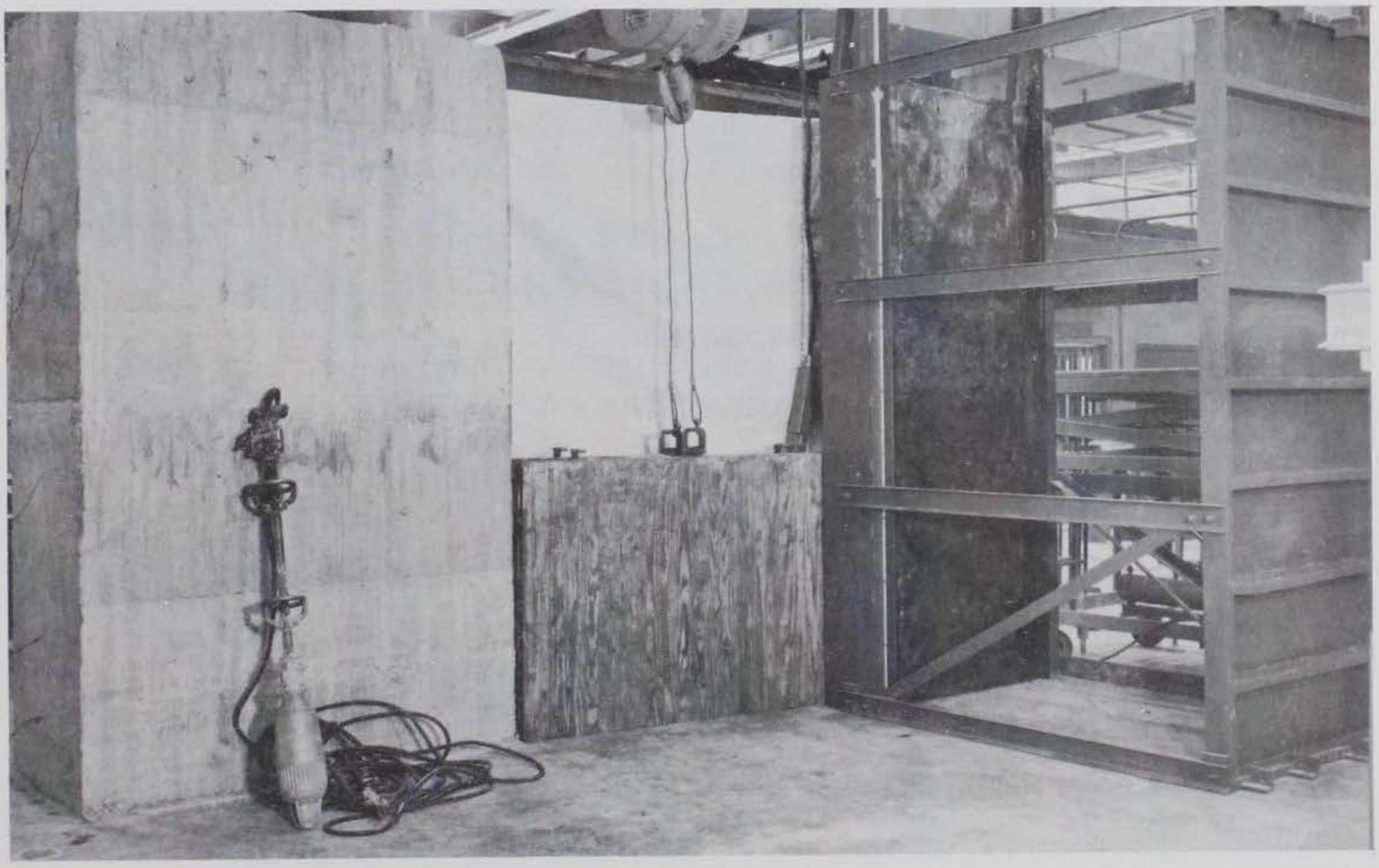


Fig. 1. Block I, vibrator, slip forms, and bulkhead form

apparatus assembled to receive the slip forms, which were 6 ft (1.8 m) wide and 4 ft (1.2 m) high. The slip forms were raised by means of hydraulic jacks connected to a small electric pump operated from a platform 4 ft (1.2 m) above the top of the block.

9. Each slip form was raised individually in small increments of 1 to 2 in. (25.4 to 50.8 mm) during the test at a predetermined rate that varied between 6 and 18 in./hr (152.4 and 457.2 mm/hr) depending upon the test variables. The slip forms were supported by and moved on roller bearing casters. The force required to lift the forms resulting from the friction imposed on the casters by the plastic concrete was monitored on the hydraulic pump and translated to drag pressure in pounds per linear foot of form. The forms were fabricated so that the slip forms could be changed to accommodate three different form-surface materials: tongue and groove lumber, impregnated plywood, or 1/8-in.-thick steel (sheet metal). In order to reduce the pressure required to free the slip forms from the compacted concrete during lifting, the forms were constructed to have a batter of 1/4 in. per foot of height (20.8 mm per meter of height) on the slipped faces.

10. The concrete was mixed in the laboratory at 73 F (22.8 C) in a 16-ft^3-capacity (0.453-m^3) drum mixer, transported to the form in a self-dumping hopper, discharged into the form, and consolidated with a two-man vibrator. Fig. 2 shows the operation in the form. The vibrator had a 6-in.-diam (152.4-mm) head, 18 in. (457.2 mm) long, and an operating frequency of approximately 7000 cps.

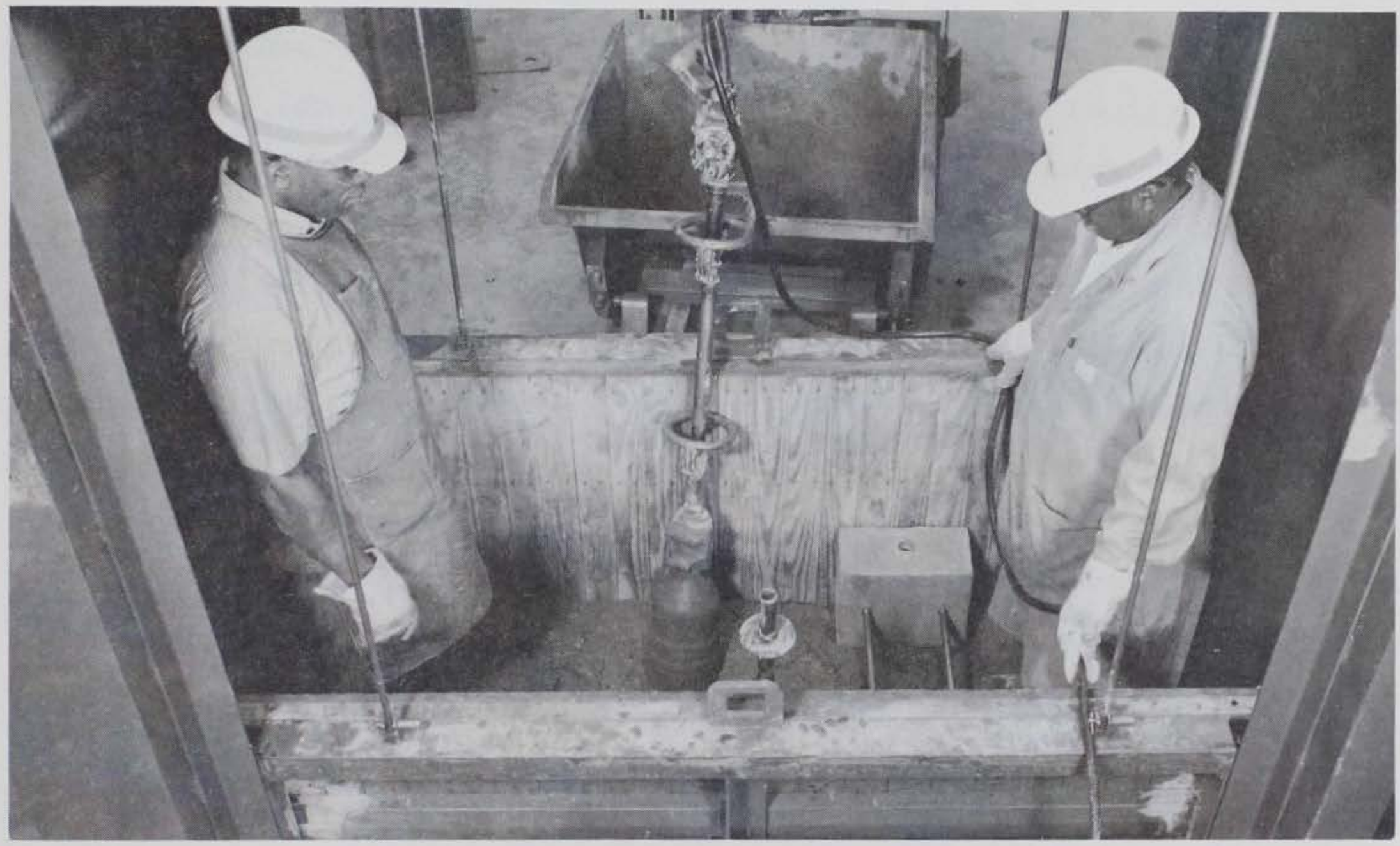


Fig. 2. Operation in form during construction of block II. Note precast form anchor block at lower right

PART III: TESTS

Block I

11. The essential considerations in casting the first block were to determine if slipforming mass concrete is feasible and if the test apparatus satisfactorily simulated actual conditions. The casting and curing temperature was approximately 73 F (22.8 C). Half of the block (a 5-ft-high section) was completed in 1 day using mixture A (3-in. (76.2-mm) maximum-size limestone aggregate), and the second half was completed the following day using mixture B (6-in. (152.4-mm) maximum-size limestone aggregate). Pertinent casting information (table 8) indicates that the concrete was rather consistent throughout.

12. The chronological progress of casting for block I is shown graphically in fig. 3. The initial objective was to determine some basic information on the rate of slipping and the perils of allowing the concrete to become low in the form, i.e., working with only a small layer of plastic concrete above the bottom of the slip form. Slipping was initiated at 1125 hours the first day at a rate of 10 in./hr (254.0 mm/hr) after three batches of concrete (24 in. (609.6 mm)) had been consolidated in the form. Immediately prior to the placement of batch 4, there was only about 1 ft of concrete above the bottom of the form. A sloughing of concrete out from under the slip form was detected as shown in fig. 4. Consequently, batches 5-7 were mixed and placed in rapid order, and the slipping rate was slowed to 2 to 3 in./hr (50.8 to 76.2 mm/hr) until 1800 hours. Significantly, the drag pressures increased substantially as the form was filled up to 1500 hours and then began to decrease as less plastic concrete was left to press against the slip forms.

13. In order to obtain information on slipping with a full form, the form was filled and maintained full with concrete (mixture B) on the second day. Again, the concrete was relatively uniform, and this time the slipping rate was maintained at 6 in./hr (152.4 mm/hr). The overall operation progressed in a much more orderly fashion during the uniform

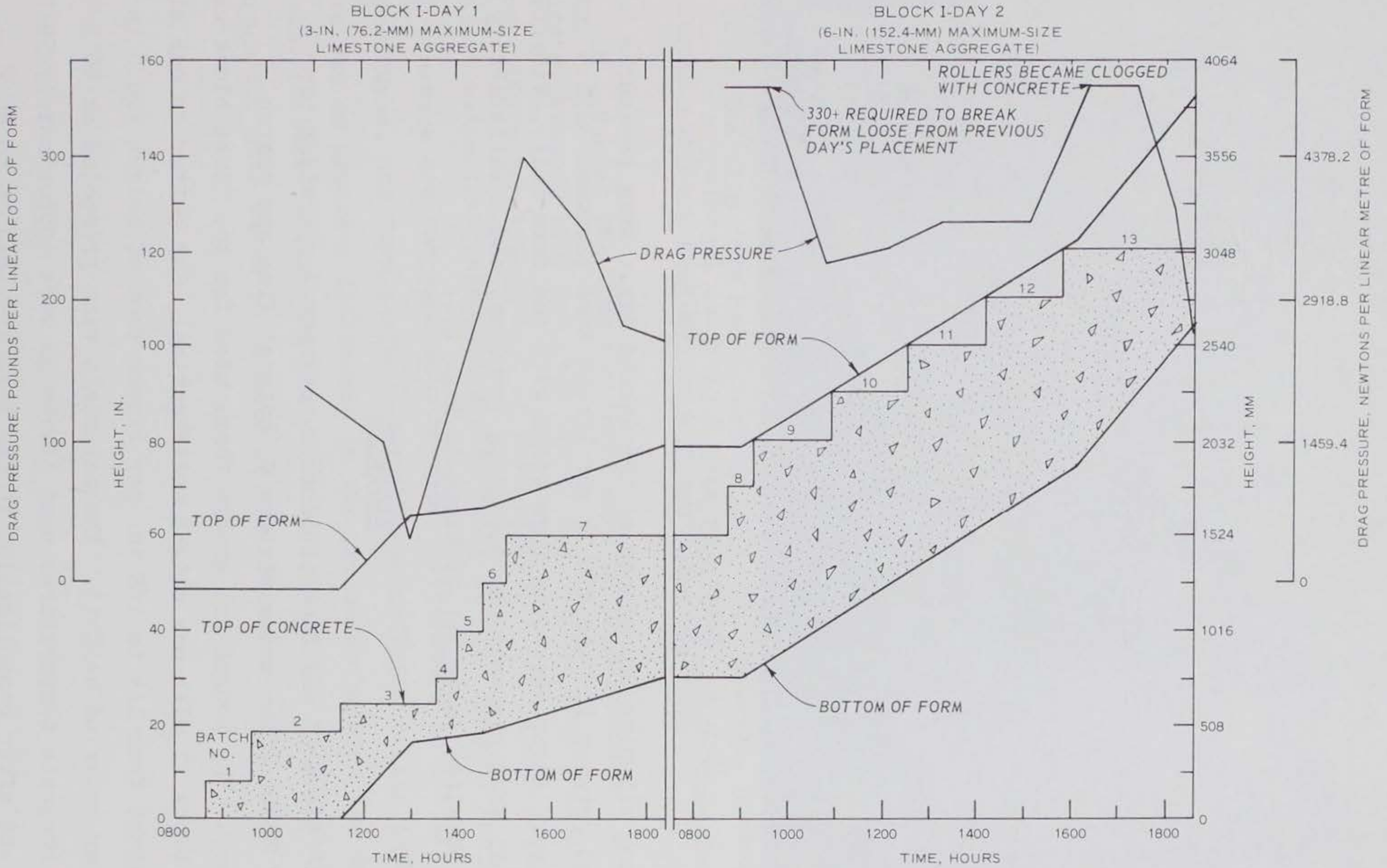


Fig. 3. Chronological progress of casting for block I

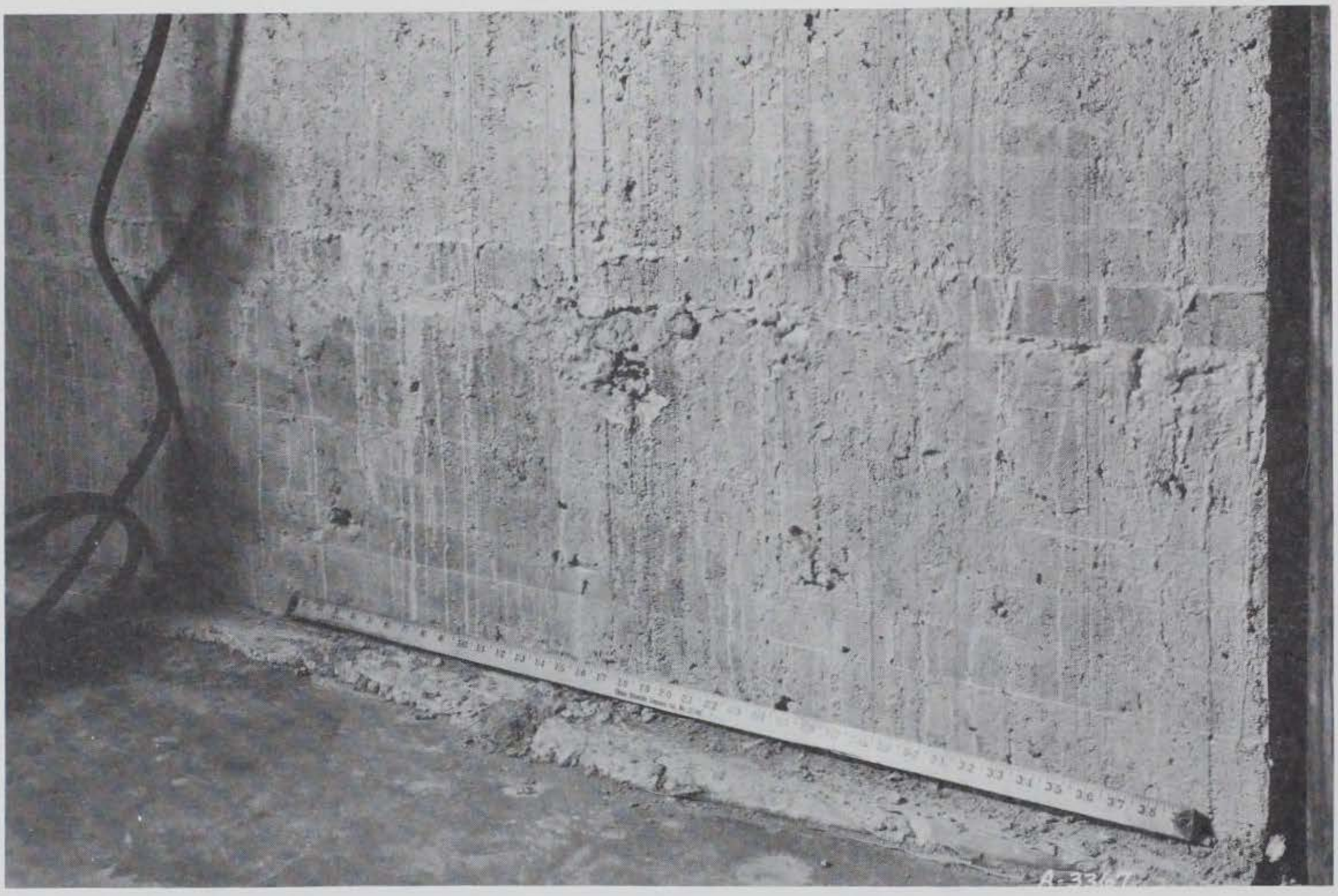


Fig. 4. Bottom of side A of block I where concrete moved out below slip form

filling and slipping procedures of the second day. Drag pressures stabilized between 230 and 250 lb per linear foot (between 3356.6 and 3648.5 N per linear metre) of form width with the form full. Vibration in the full form presented no sloughing problems, and a satisfactory surface was obtained (note top of block in fig. 1).

Block II

14. Block II was fabricated in a continuous operation over a period of about 20 hr using mixture C (natural fine and coarse aggregates). The tongue and groove forms used for the first block were used for block II with one slight modification: the batter on one side was increased from 1/4 to 1/2 in. per linear foot of height (20.8 to 41.7 mm per meter of height). The materials were precooled at 40 F (4.4 C); concrete temperatures upon discharge were approximately 50 F (10.0 C) and after consolidation in the form averaged 58 to 60 F

(14.4 to 15.5 C). Plans were made to place two 20-in. (508.0-mm) layers or courses at the end of the placement; however, it was subsequently discovered that the form would not hold a 20-in. (508.0-mm) layer of unconsolidated concrete with only 20 in. (508.0 mm) of freeboard. Therefore, batches 9 and 10 had to be placed in essentially two 10-in. (254.0-mm) layers each. The mixture and casting data for block II are given in table 9.

15. The placing and jacking procedures are given chronologically in fig. 5. Two slip rates were utilized, 6 in./hr (152.4 mm/hr) (for comparison with the rate used for the top portion of block I) and 12 in./hr (304.8 mm/hr). No sloughing was observed even with the faster slip rate. Generally it can be said that the plan was followed and completed with only minor difficulties. There was noticeably more bleed water on the surface of the freshly placed layers, and more emerged down the sides of the slip form than had emerged on block I. In one instance, a soft pocket developed (due probably to bleed water) and fell out after the slip form had passed by (fig. 6). Overall, however, the slipformed surfaces of block II had a better appearance than those of block I.

16. During the time the forms were in maximum contact with the concrete (between 1500 and 2400 hours, fig. 5) the drag pressure averaged almost 500 lb per linear foot of form (7297.0 N per linear metre of form) or about twice that experienced with block I. The reasons for the higher drag pressure are not apparent; however, differences in mixtures, casting temperatures, and form surface certainly contributed to the increase. There was no apparent difference in the pressures between the side with 1/4-in. (6.4-mm) batter and the one with 1/2-in. (12.7-mm) batter. The average for both sides is plotted on the procedure curve shown in fig. 5.

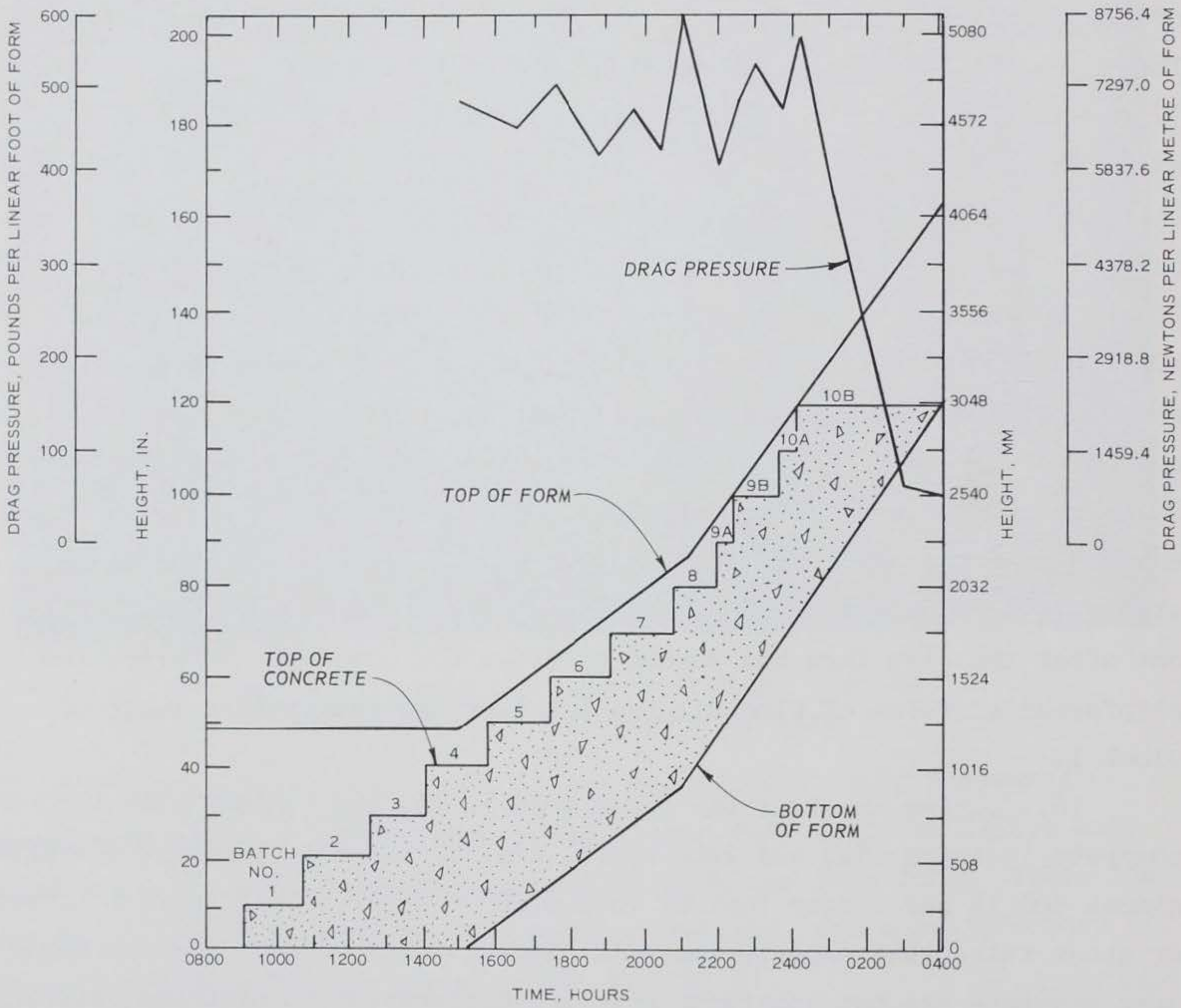


Fig. 5. Chronological progress of casting for block II

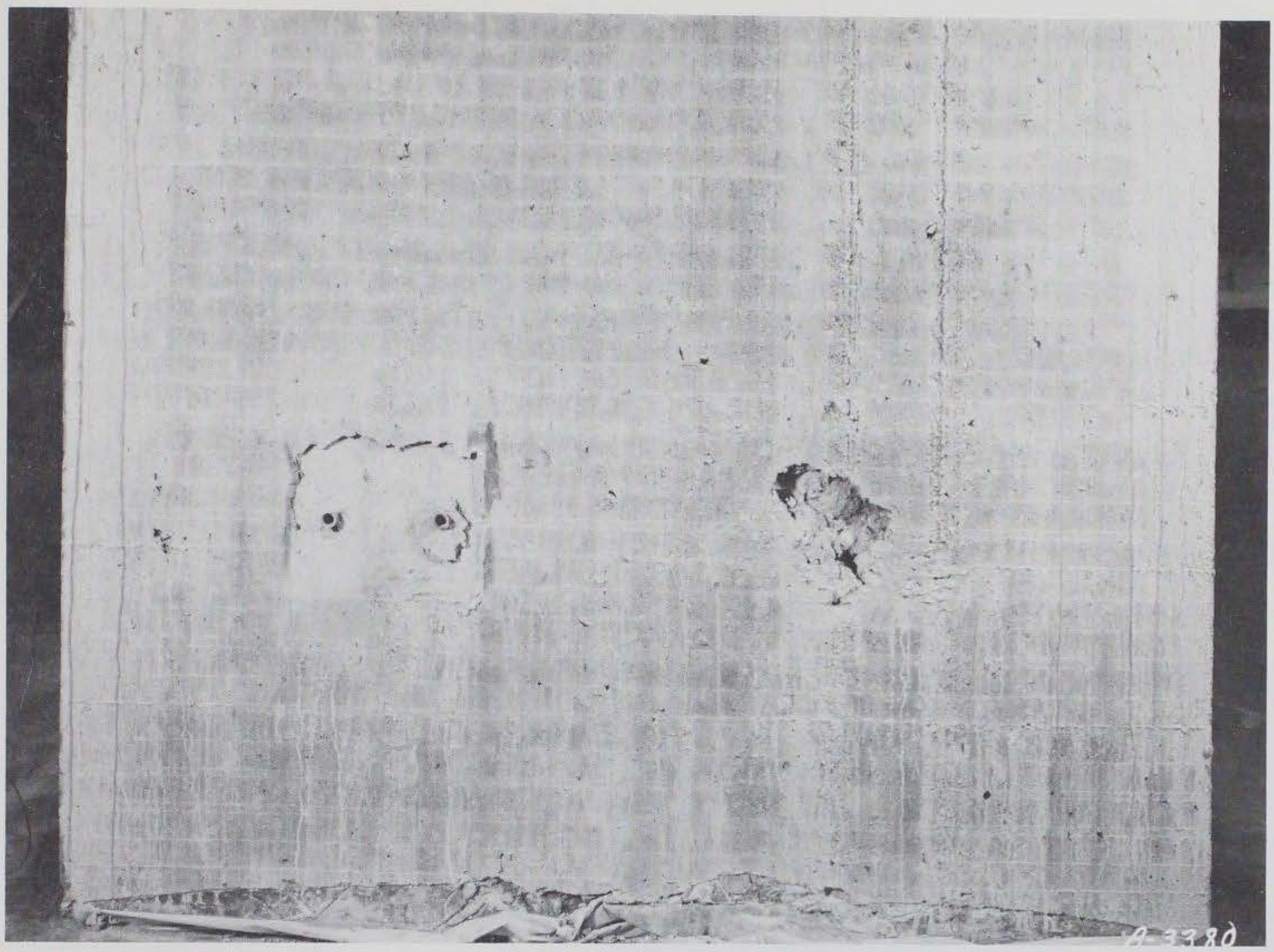


Fig. 6. Bottom side of block II. Note form anchor block which sustained bond failure of coupling (left) and soft spot formed by accumulation of bleed water (right)

Block III

17. Block III was fabricated in a continuous operation over a period of about 13 hr using mixture B (6-in. (152.4-mm) maximum-size crushed aggregate). Materials were precooled to 35 F (1.7 C); concrete temperature upon discharge was 47 F (8.3 C) and after consolidation in the form was 56 to 58 F (13.3 to 14.4 C). Phenolic-resin-impregnated plywood (1/2 in. (12.7 mm) thick) was used on one slip form, and 1/8-in.-thick (3.2-mm) steel (sheet metal) was used on the other. The sheet metal was supported by plywood to prevent bending under load. Mixture and casting data are given in table 10.

18. The test procedure is given chronologically in fig. 7. Initially, the placing and jacking rate was 18 in./hr (457.2 mm/hr).

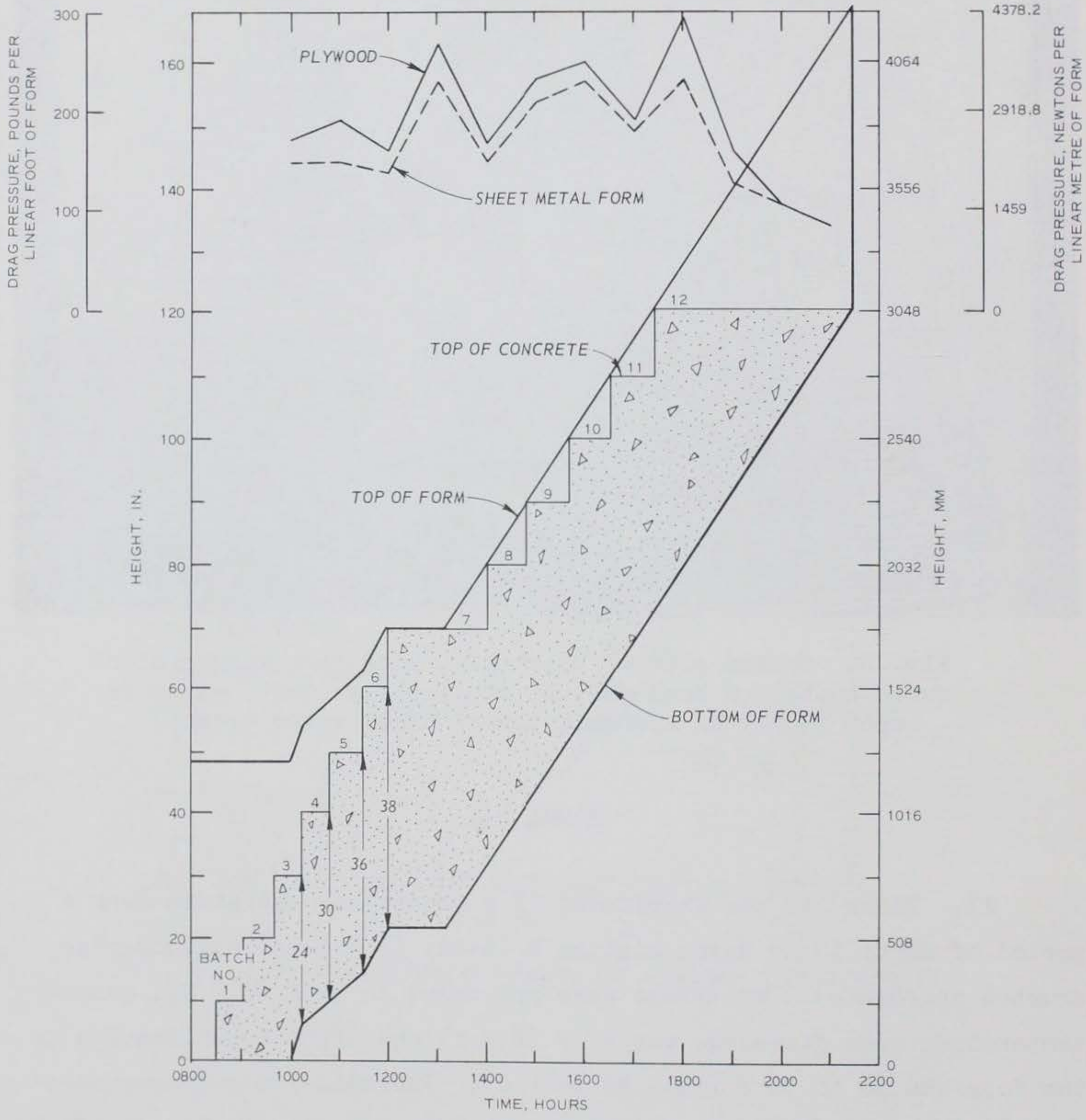


Fig. 7. Chronological progress of casting for block III

During the casting of block I, it was discovered that vibration of additional layers when only 10 to 12 in. (254.0 to 304.8 mm) of concrete was in the forms caused sloughing of the concrete from under the slip forms. Consequently, vibration was tried when there was 24 and 30 in. (609.6 and 762.0 mm) of concrete in the form. Again, the fresh concrete sloughed below the forms profusely at the 24-in. (609.6-mm) level (when layer 4 was placed) and moderately with 30 in. (762.0 mm) in the form (layer 5). With 36 in. (914.4 mm) or more of concrete in the form, the loss was limited to water seepage beneath the slip forms.

19. The top half of block III was completed at a placing and jacking rate of 12 in./hr (304 mm/hr) in order to compare the results of the form surfaces with those of the tongue and groove surfaces used previously. Observation of the slipped surfaces indicated no discernible differences obtained with the three different types of forms. Form pressures were appreciably less than those obtained under comparable conditions with the tongue and groove lumber (block II). The metal form appeared to produce pressures slightly less than those of the plywood surface. Fig. 8 shows side A of the completed block.

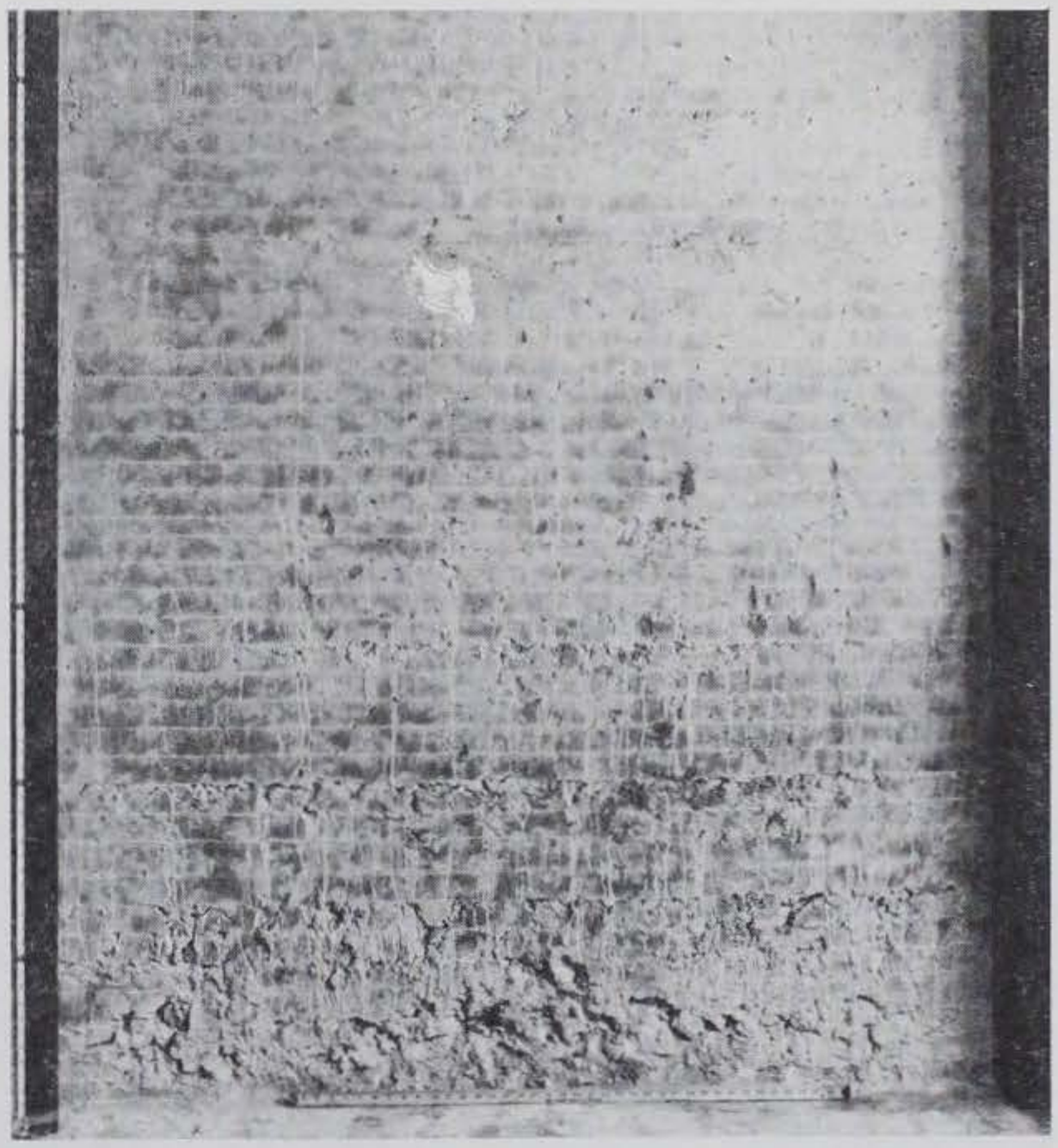


Fig. 8. Side A of block III showing voids remaining after sloughing beneath form at slip rate of 18 in./hr (457.2 mm/hr)

Block IV

20. Block IV was cast to determine if an admixture marketed as a pump aid would lubricate the slip forms and reduce form pressure. Six-inch (152.4-mm) maximum-size crushed limestone aggregate concrete precooled to 35 F (1.7 C) was used (mixture B). Concrete temperature upon discharge was 49 F (9.4 C) and after consolidation in the form was 58 to 60 F (14.4 to 15.5 C). Phenolic-impregnated plywood was used on one slip form, and 1/8-in. (3.2-mm) sheet metal was used on the other.

21. Mixture and casting data are given in table 11. One-tenth pound (0.045 kg) of pump-aid lubricant was used per cubic yard of mixture in all batches. Some difficulty was experienced initially due to use of the pump aid in the concrete. Batches 2 and 3 had excessive slumps, 4-1/2 and 6 in. (114.3 and 152.4 mm), respectively. Very pronounced sloughing occurred in the area where batch 3 was placed during vibration of subsequent batches (fig. 9). Batches 2 and 4 were utilized

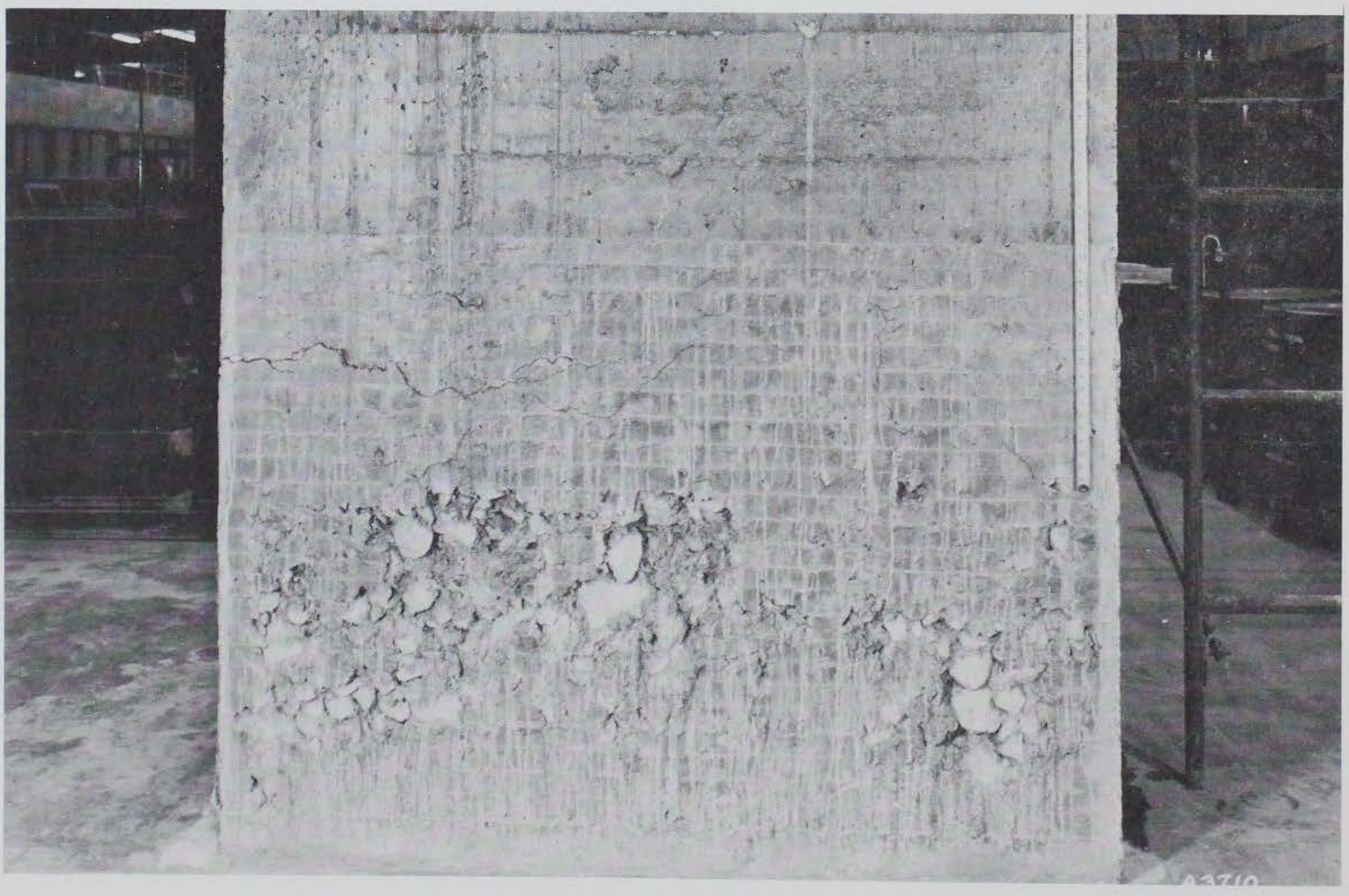


Fig. 9. Side B (finnform surface) of block IV showing pronounced sloughing due to excessively wet concrete

in the fabrication of two small form anchor test blocks. Batches 4-9 had slumps ranging between 1-1/4 and 2 in. (31.8 and 50.8 mm). Observations indicated that the concrete was more workable and easier to consolidate than that of block III, which contained no pump aid. However, this may have been due partially to the excess water in batch 3 that found its way into subsequent batches during consolidation in the form.

22. The test procedure is given chronologically in fig. 10. Due to a shortage of materials, the height of the block was reduced to 6 ft (1.8 m). However, the results may be compared with those of block III in which no pump aid was used. Drag pressures obtained on the slip forms of block IV averaged approximately 150 psi (1.034 MPa) or about 25 to 30 percent less than those of block III. Apparently the pump aid did have a lubricating effect on both the steel and the plywood.

Form Anchor Tests

23. Form anchor tests were conducted on two types of form anchors to develop data for design of the slipforming system. The two types of anchors are shown in fig. 11. Dimensions for the shear-block type of form anchor (type 1) are given in fig. 12, and for the spiral type of anchor (type 2) in fig. 13. Three form anchors were placed in block II for testing, two of type 1 in side A and one of type 2 in side B. Pull-out tests were conducted when the concrete surrounding the precast anchor block was approximately 8 hr old. Two 6- by 12-in. (152.4- by 304.8-mm) cylinders representing each test were cast for determinations of tensile splitting strength at 8-hr age from concrete placed around the anchors. Results of these determinations are given below:

Anchor Type	Maximum Load Sustained		Displacement		Tensile Splitting Strength	
	lb	N	in.	mm	psi	MPa
1	5100	22,685.9	1.0	25.4	2.1	0.014
2	2500	11,121.0	0.7	17.8	1.2	0.008
1	6000	26,689.3	0.8	20.3	1.4	0.010

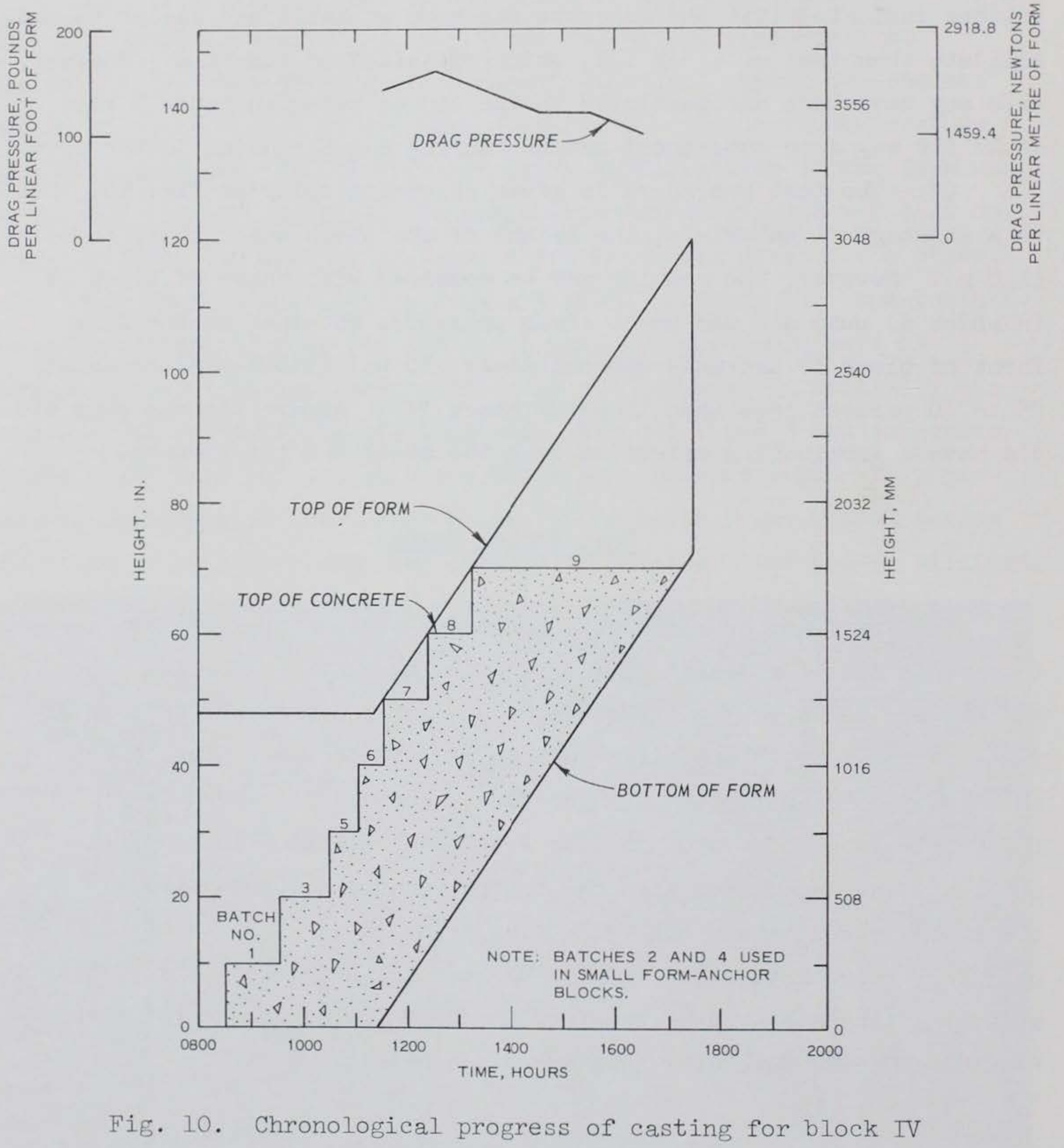


Fig. 10. Chronological progress of casting for block IV

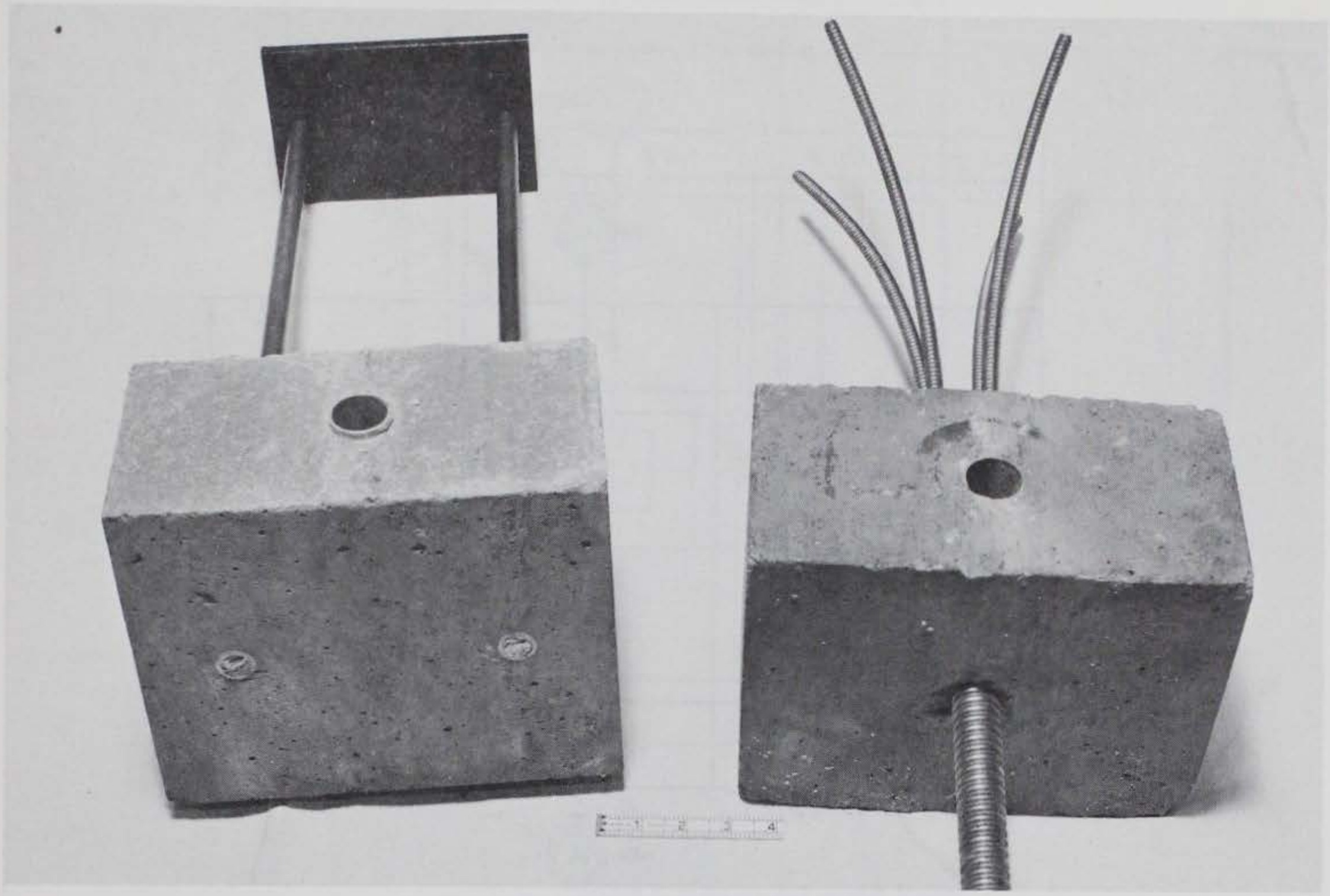
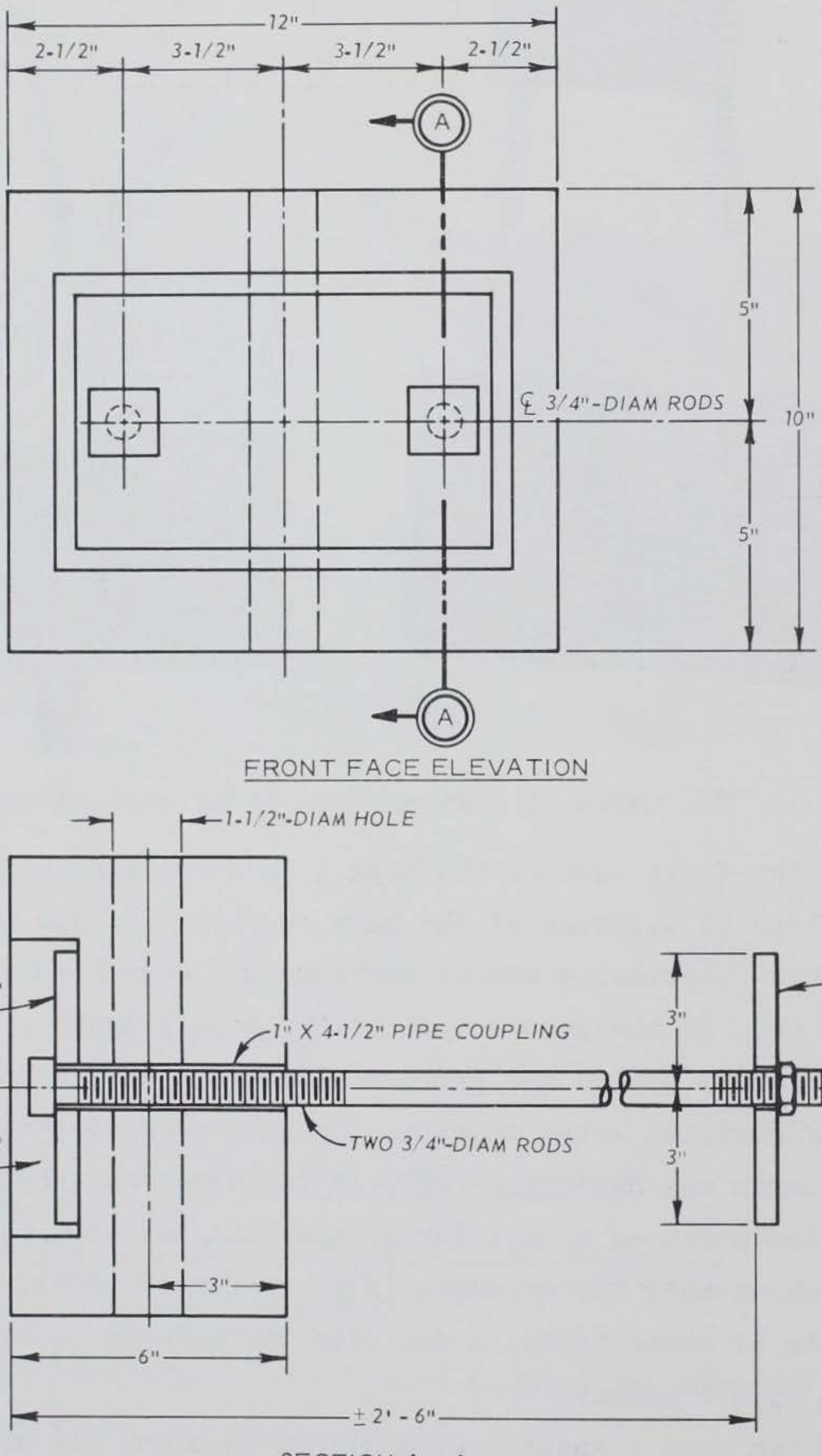


Fig. 11. Two types of form anchors in precast blocks (block II)

24. The first test of the type 1 anchor (5100-lb (22,685.9-N) load) resulted in slippage of the pipe coupling through the precast block so that practically all of the strength developed was due to the anchor per se. In the second test of the type 1 anchor, a nut was fastened immediately behind the precast block in such a manner that the entire configuration acted together during the pullout test; thus, additional strength was developed (6000-lb (26,689.3-N) load sustained). Anchor 2 also acted as a unit during the load test but obviously developed only about half the strength (2500 lb (11,121.0 N)) of the type 1. On the basis of these tests, a decision was made to concentrate on testing of the type 1 anchor.

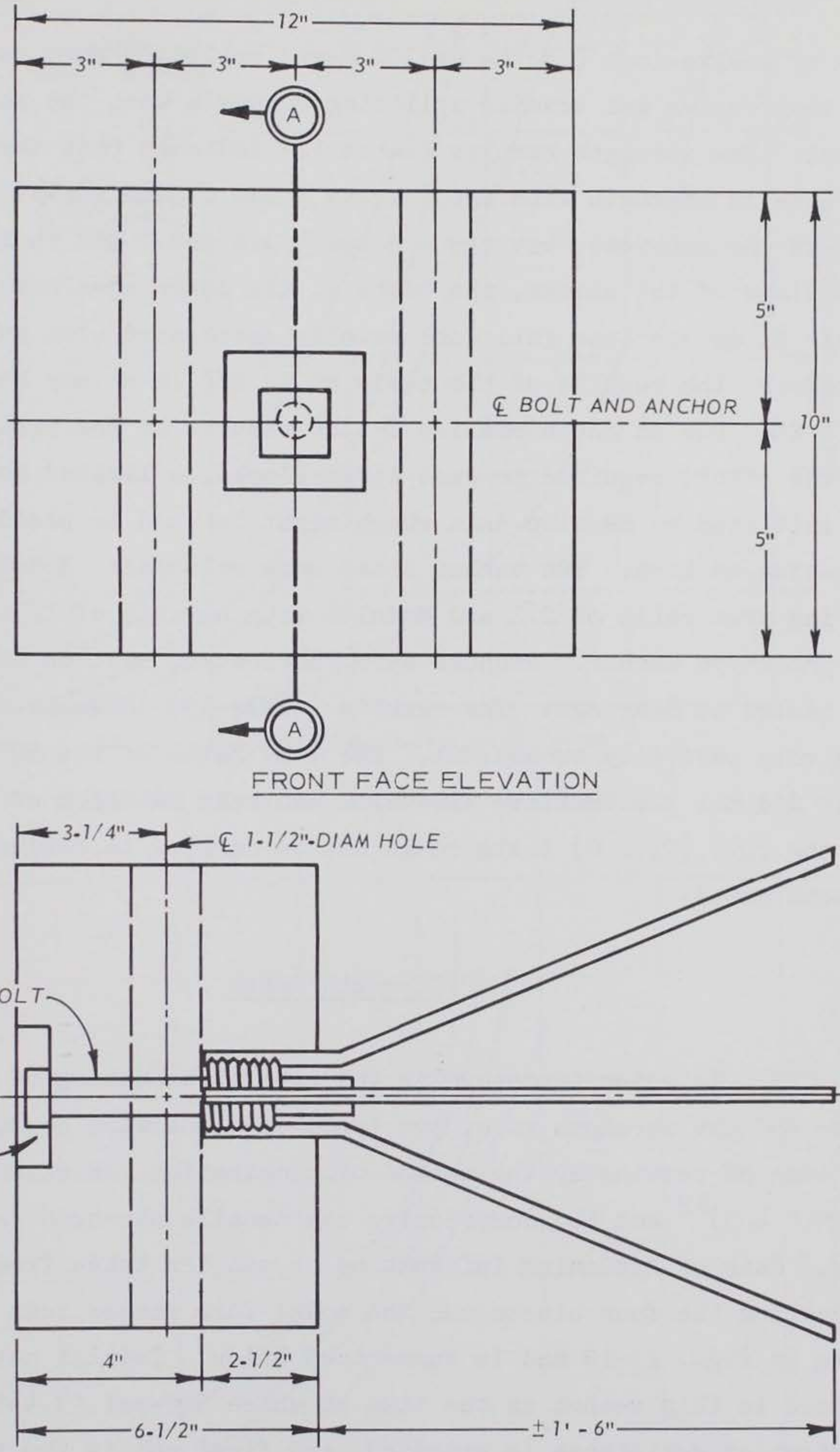
25. Two type 1 anchors were placed in block III and two were placed in block IV for pullout tests. The precast blocks were eliminated from the anchor design. All anchors were vertically embedded 4.5 ft (1.4 m) deep in the blocks. Some difficulty was experienced in maintaining proper alignment when concrete was being placed in the form.



FRONT FACE ELEVATION

SECTION A - A

Fig. 12. Details of type 1 form anchor



FRONT FACE ELEVATION

SECTION A - A

Fig. 13. Details of type 2 form anchor

Six- by twelve-inch (152.4- by 304.8-mm) cylinders were cast and tested for compressive and tensile splitting strength when the anchors were tested. The strength results (table 12) indicate that there was a slow increase in strength with age. Tests 1 and 2 also showed the strength gain in the concrete, but tests 3 and 4 did not. Due to the limiting dimensions of the blocks, the tests at the later ages were probably unable to develop the full cone usually associated with pullout tests. Therefore, the results of the tests at 10 and 12 hr may be suspect.

26. Due to the anomalies in the results of the prototype tests and the effort required to cast large blocks, a limited modeling program was initiated to develop data which might be used to predict loads for full-size anchors. Two anchor sizes were selected: Model A with a bearing area ratio of 2/3 and Model B with a ratio of 1/3 compared with the prototype anchor. Anchors were fabricated, cast in model blocks, and tested at 8-hr age. The results (table 13) indicate that the tests were only partially successful. The load ratio of the 50 F (10.0 C) tests did not substantiate the depth and area relation of the prototype, and the 70 F (21.1 C) tests could not be carried to failure for the reasons noted.

Strength Tests

27. In order to determine the rate of hardening of the fresh concrete and the strength gain, two types of tests were conducted: (a) time of setting by the method of penetration resistance CRD-C86 (ASTM:C 403)[12] and (b) compressive and tensile strength tests at early ages. Rate of hardening information on samples taken from concrete used in casting the four blocks and the model form anchor test blocks is given in figs. 14-19 and is summarized below. Initial setting time is defined in this method as the time at which 500-psi (3.447-MPa) penetration resistance is attained, and final set is the time at which 4000-psi (27.579-MPa) penetration resistance is reached.

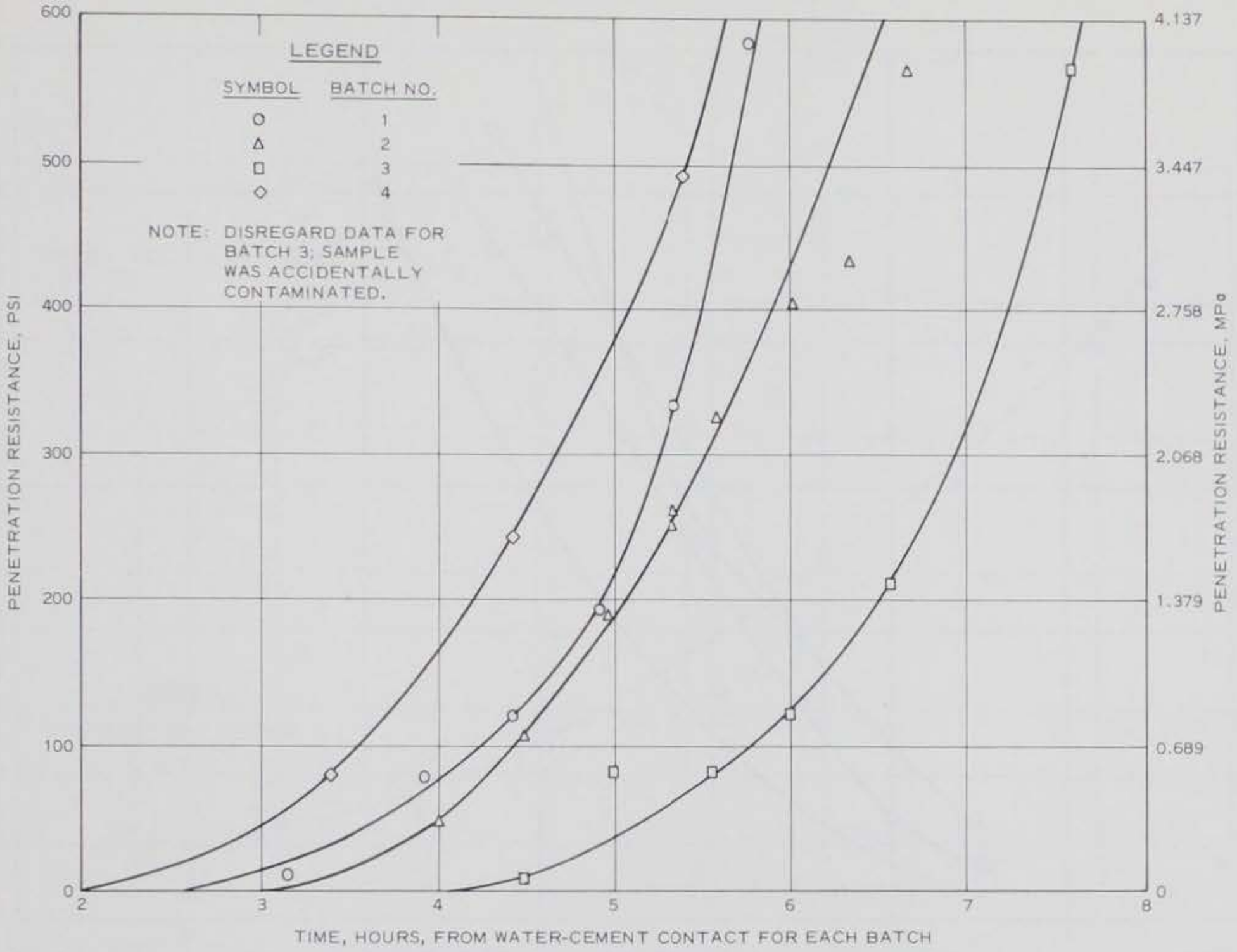


Fig. 14. Rate of hardening of block I

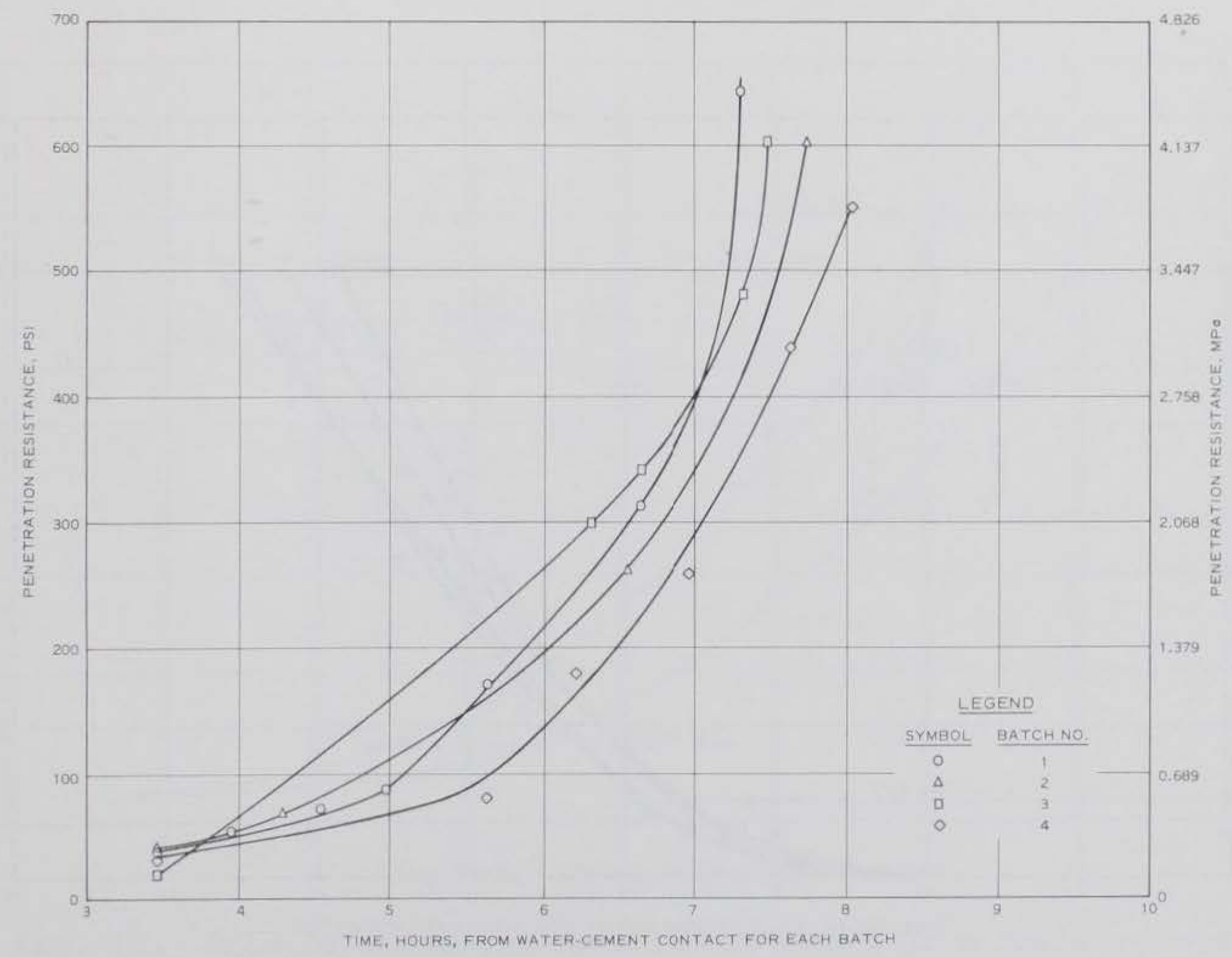


Fig. 15. Rate of hardening of block II

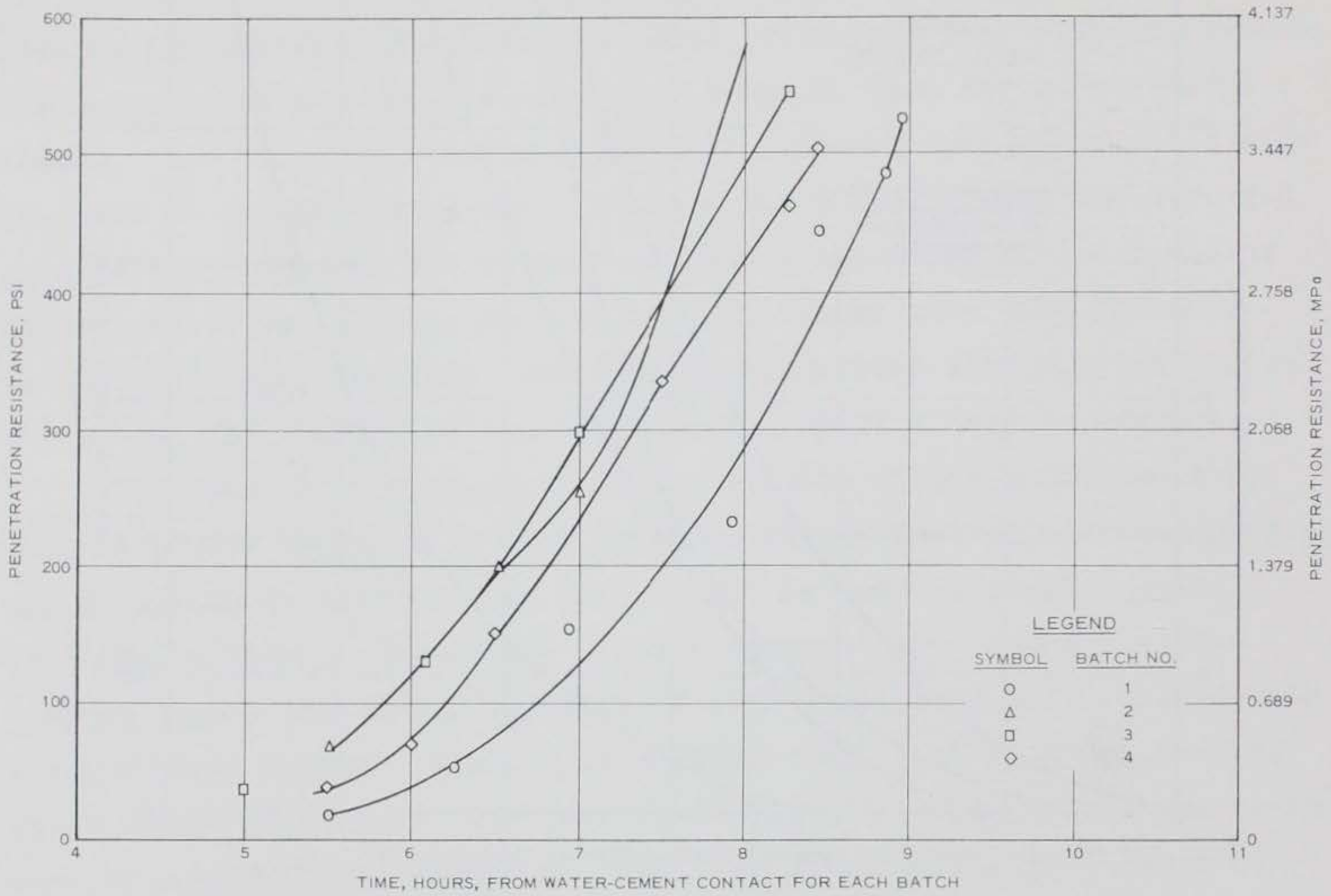


Fig. 16. Rate of hardening of block III

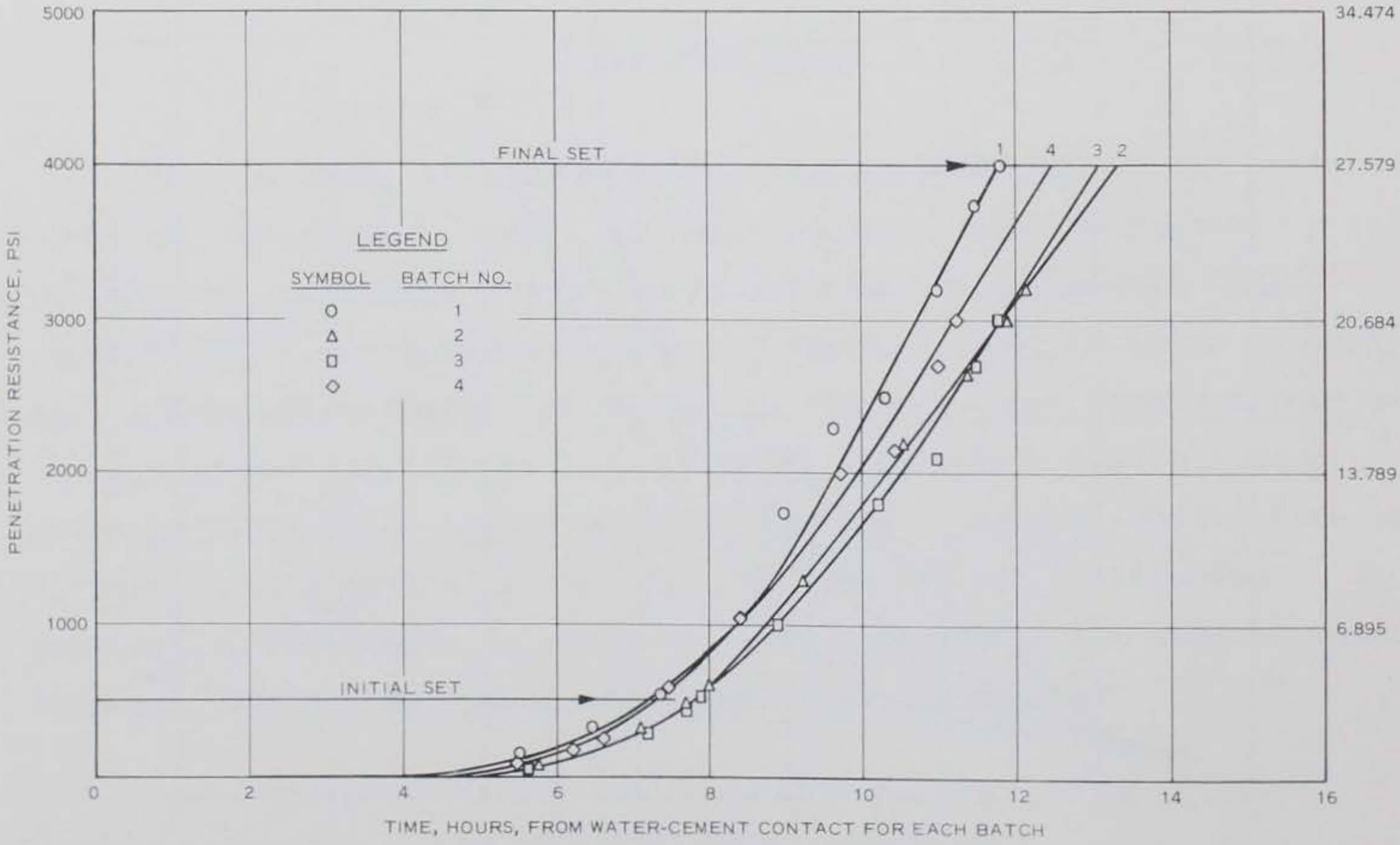


Fig. 17. Rate of hardening of block IV

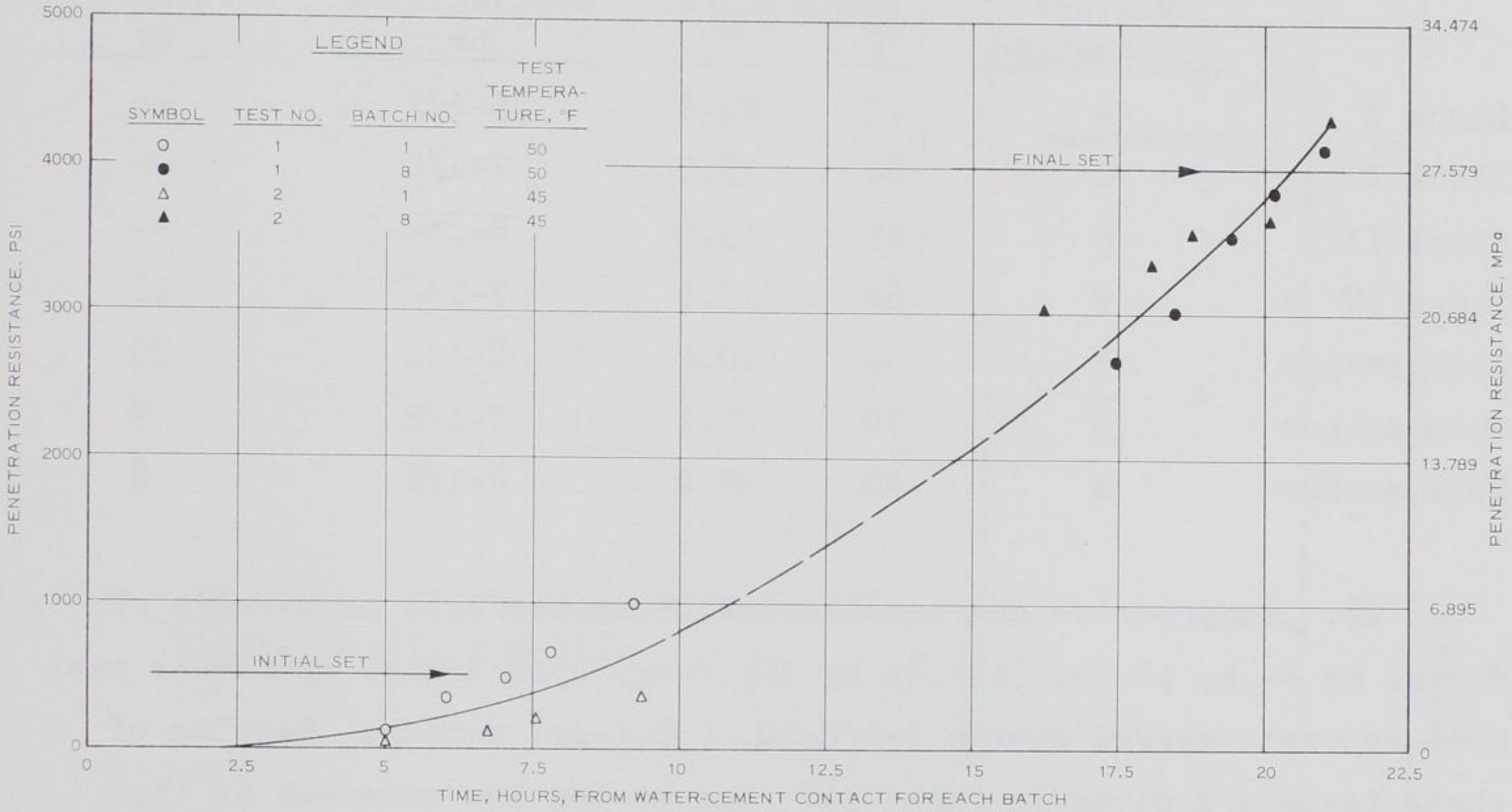


Fig. 18. Rate of hardening results for model form anchor tests

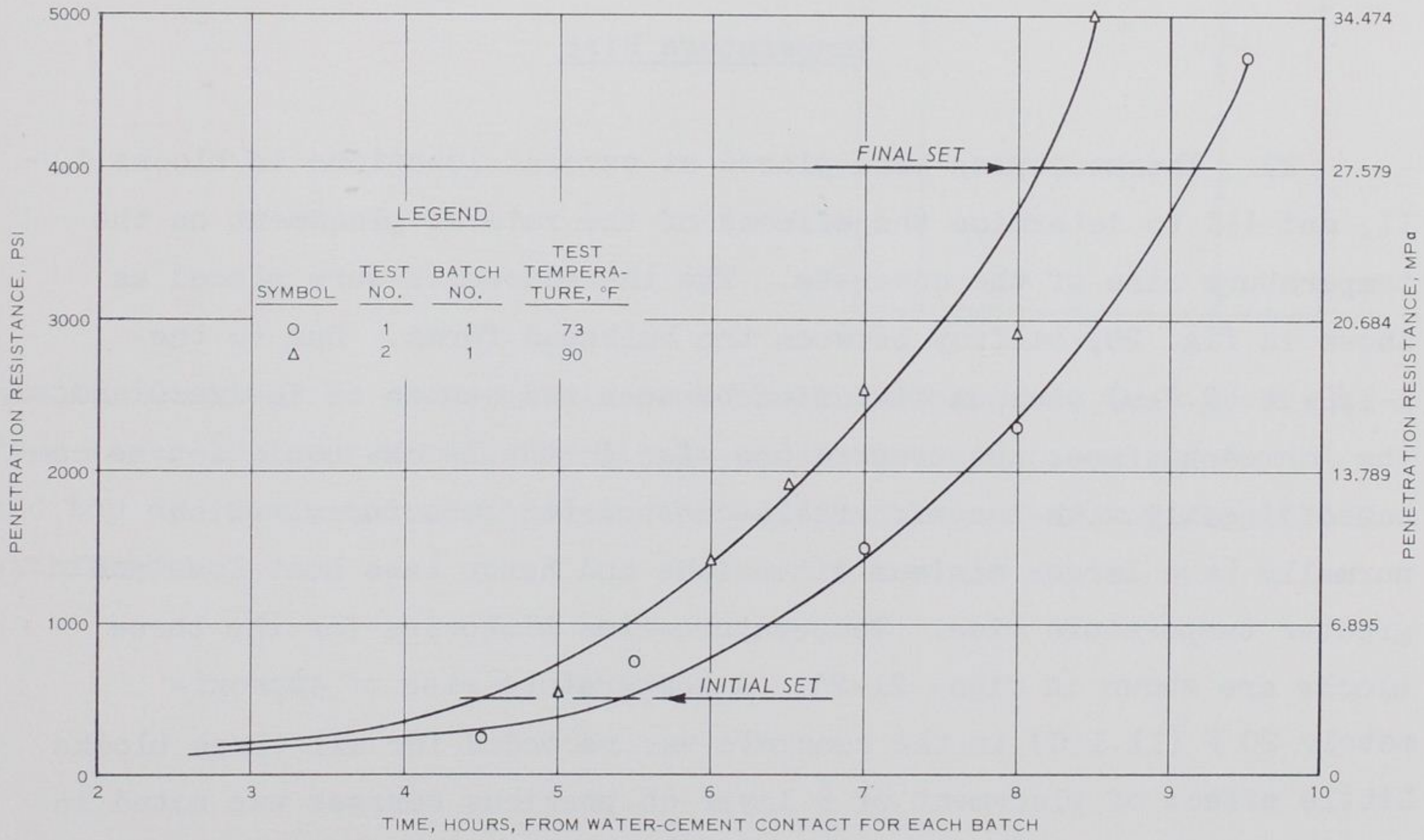


Fig. 19. Rate of hardening results for model form anchor tests

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	Mixture Designation	Initial Concrete Temperature °F	°C	Initial Setting Time hr	Final Setting Time hr
Block I	A	73	22.8	5-1/2	--
Block II	C	60	15.5	7-1/2	--
Block III	B	57	13.9	8-1/2	--
Block IV	B	60	15.5	7-1/2	13
Form anchor	B	50	10.0	8-1/2	20
Form anchor	B	70	21.1	5-1/2	9
Form anchor	B	90	32.2	4-1/2	8

28. Compressive and tensile splitting strength tests were conducted on 6- by 12-in. (152.4- by 304.8-mm) cylindrical specimens cast from concrete sieved over a 1-1/2-in. (38.1-mm) screen. Results of these tests are given in table 14. Due to the low strength of the freshly cast concrete specimens, the compressive strength specimens tested at 24-hr age or less were not capped but were struck smooth with a straightedge prior to testing.

Temperature Rise

29. Thermocouples were placed at several locations in blocks I, II, and III to determine the effects of the rate of placement on the temperature rise of the concrete. The thermocouples were placed as shown in fig. 20, halfway between the bulkhead forms. Due to the 1-1/2-ft (0.4-m) minimum dimension between the center of the mass and the formed surface, the temperature rise in the blocks could not be compared directly with that for field-constructed structures, which normally have larger minimum dimensions and hence less heat loss and greater temperature rise. Temperature-time histories for the three blocks are shown in figs. 21-23. A temperature rise of approximately 20 F (11.1 C) in the concrete was recorded for all three blocks. Little effect of placement of a layer on previous courses was noted in the temperature curves during the first 24-48 hr, i.e., the curves are

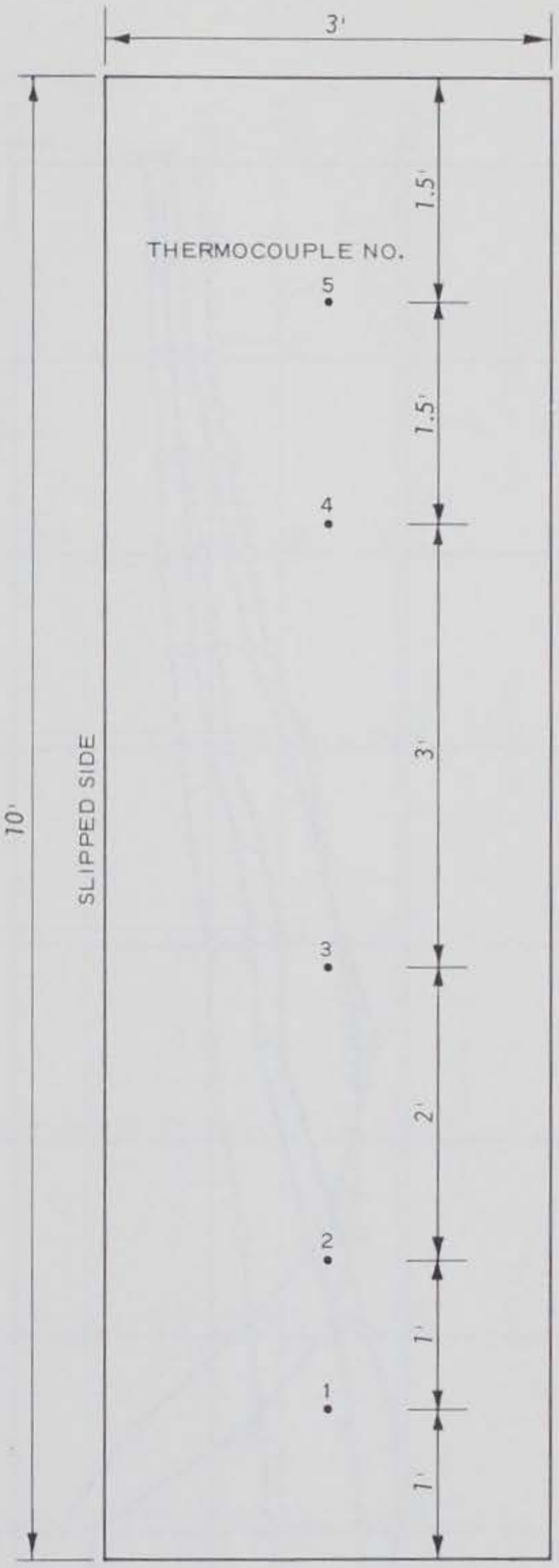

Fig. 20. Placement of thermocouples in blocks I, II, and III

almost identical in shape within each block. Subsequent heat movements from layer to layer within the blocks and from the exposed sides and top did occur and resulted in the uniform temperature of about 78 F within 48 hr.

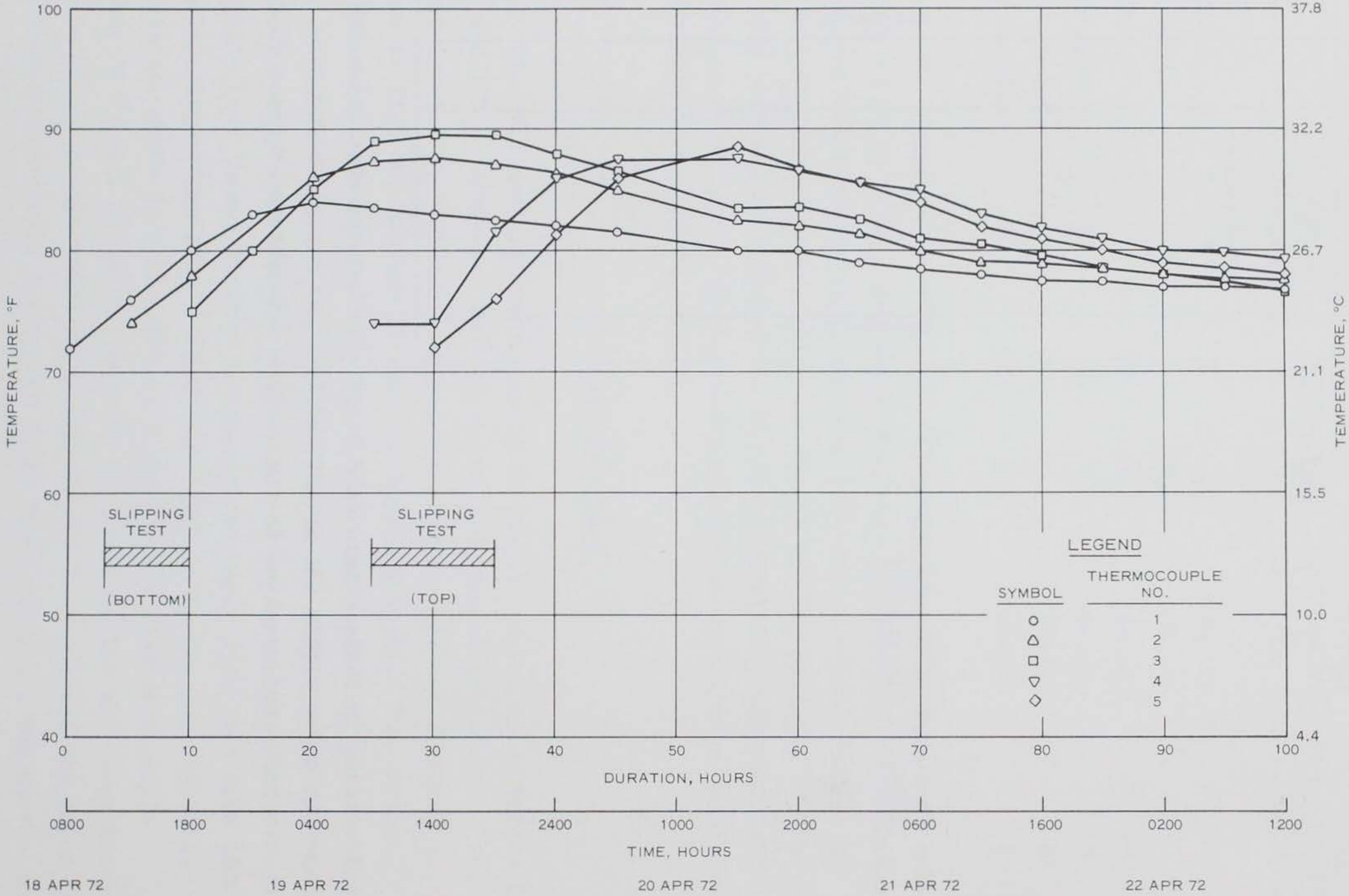

Fig. 21. Temperature rise of block I

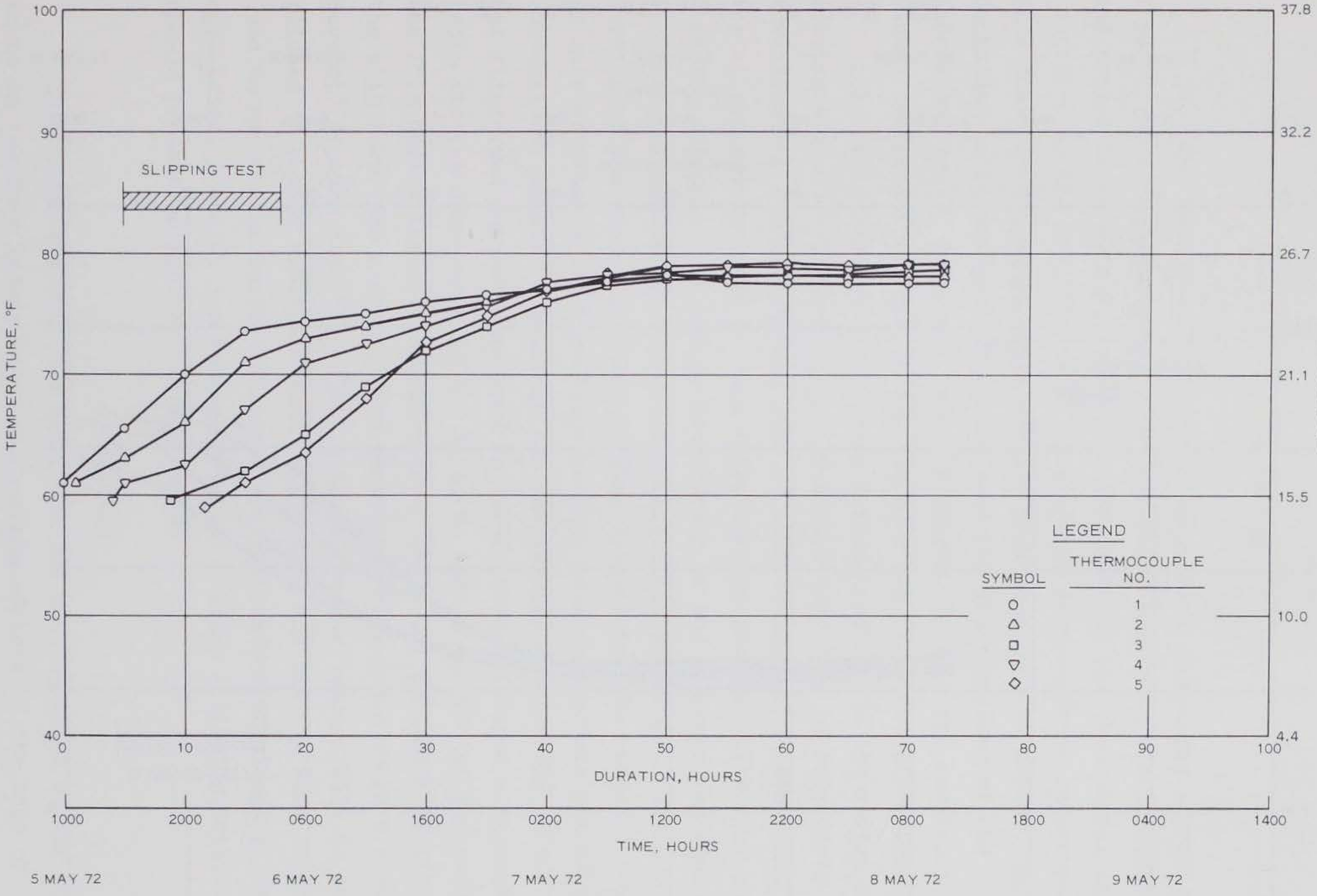

Fig. 22. Temperature rise of block II

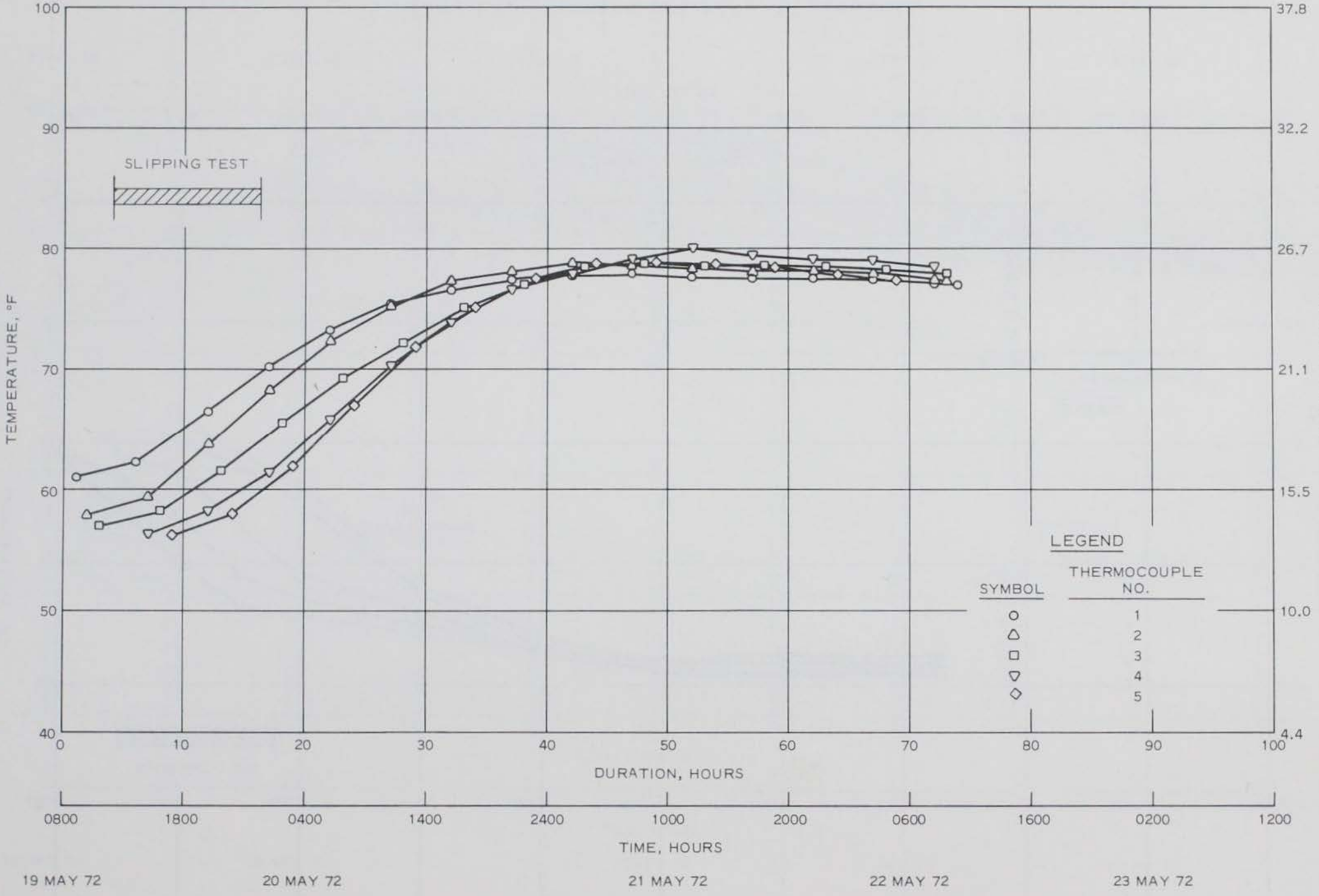

Fig. 23. Temperature rise of block III

PART IV: DISCUSSION OF RESULTS

Esthetics

30. The fact that four test blocks, each containing approximately 7 yd^3 (5.35 m^3) of concrete, were cast under simulated field conditions and proved to be relatively true in dimension to the theoretical size testifies to the feasibility of slipforming mass concrete structures. This does not mean that there are not many questions of methodology and technique to be answered--thus the need for the remainder of the laboratory work. The final test, of course, will be the construction of a mass concrete structure in the field by use of the slipform technique.

31. Esthetics is, of course, a consideration in the design and construction of most structures and should therefore be considered when investigating a new technique such as slipforming. The appearance of the slipformed surfaces in this investigation was generally very good when the slipping rate and/or consistency of the concrete was such that sloughing or sagging of the fresh concrete did not occur. The top portion of the block pictured in fig. 1 indicates the hardened concrete to have as pleasing an appearance as that of mass concrete placed by conventional methods. Although not necessarily displeasing to the eye, the slipformed concrete produced in these tests developed a characteristic slatted appearance (figs. 4, 6, 8, and 9) due to the pauses of the form during the lifting operation. The usual procedure of following the slip form with a hand finish where desirable (when rough places develop) appears feasible. Such a technique was successfully accomplished to a very limited degree on blocks I and III. A wood float was used to smooth the surface where slight protrusions or sloughing developed (figs. 1 and 8, top center of block). Light finishing activity should present no problems in the field.

Mixtures

32. Observation of the placement and consolidation of the concrete in the form indicated no discernible effects of the type of

aggregate (natural or crushed) or maximum size of aggregate (3 in. (76.2 mm) versus 6 in. (152.4 mm)) on the slipforming operation. All mixtures were proportioned to have slumps of 2 ± 1/2 in. (50.8 ± 12.7 mm), and, as expected, consistency and workability appeared to be the critical mixture factors. When the slump was maintained consistently at 2 in. (50.8 mm), as it was on blocks I, II, and III, all mixtures were placed and vibrated with little difficulty. However, with concrete having a slump of 4 to 6 in. (101.6 to 152.4 mm), pronounced sloughing of material from beneath the slip form developed (block IV). Although no excessively dry concrete was used during these placement operations, the need for consistency between batches is obviously of prime importance. Occasional pockets of bleed water developed even with the uniform placements and resulted in localized sloughing. However, minor slough areas should be repairable with a minimum of effort by the finishing crew. The significant aspect with respect to mixtures is the need for awareness by the appropriate people when a change is made in the mixture, such as the addition of a lubricant, that prompt adjustment is required to maintain consistency of concrete being supplied to the form.

Slip Rate

33. The rate at which the slip forms may be raised theoretically should approach some maximum and minimum values for any given set of conditions. However, the conditions rarely remain constant, so adjustments will often be required in the field depending on the weather and the temperature (hence, hardening rate) of concrete in the forms. Very slow slipping rates should present few problems. Six inches per hour (152.4 mm/hr) appears to be about the minimum design slip rate; however, with slow setting concrete, even slower rates (2 to 3 in./hr (50.8 to 76.2 mm/hr)) should be feasible if desired. The limiting factor may well be the maximum time allowed between courses to prevent cold joints in the concrete. Actually, a joint was obtained in one test (block I) and did not adversely affect the slipping operation. Substantially greater

jack pressure was required to break the bond of the hardened concrete after setting overnight, but there did not appear to be any other detrimental effects (fig. 1).

34. The maximum slip rate will vary according to mixture proportions, setting time, height of slip form, etc. The maximum slip rate that appears feasible for the variables in this study (mixtures A, B, and C; the concrete temperature of 60 F (21.1 C); and the height of slip form of 4 ft (1.2 m)) is 18 in./hr (457.2 mm/hr). The limiting factor was discovered to be the requirement to have approximately 36 in. (914.4 mm) of concrete above the bottom of the form during vibration (block III). Since the concrete was being placed in 10-in. (254.0-mm) layers, the minimum form height was 48 in. (1219.2 mm). For comparable conditions with a greater layer thickness, the slipform height would have to be increased accordingly. For example, a form height of 60 in. (1524.0 mm) would probably be required if 18-in. (457.2-mm) layers were used (allowing 6 in. (152.4 mm) for bulking prior to consolidation). Also, it should be noted that the slipping and placing rates in this study were optimized, i.e., when sufficient freeboard was obtained from the slipping operation, another course was placed. Such optimization could not be expected on a continuous basis in the field. Therefore, it would appear highly desirable to either add to the slipform height or reduce the maximum slipping rate so as to have several increments of extra slip available when unexpected delays occur in the concreting operation. Assuming an uninterrupted supply of concrete, theoretically it should be possible to slip at a rate as fast as the rate of placement since the 36 in. (914.4 mm) of material in the form provides the buffer between the vibrator and the concrete tending to slough off immediately below the slip form. As a practical matter, however, 18 in./hr (457.2 mm/hr) appears to be about as rapid a slipping rate as could be effectively controlled. Planning is essential and should be done prior to starting the field operation.

Form Material

35. Sheet-steel-lined slip forms appear to be superior to the two types of wood, tongue and groove and impregnated plywood, used in the investigation. Tongue and groove wood forms were used on blocks I and II. Fig. 24 shows the deterioration on one of the forms after only one

Fig. 24. Detail of slipform side B of block I

use. After use on block II, some boards of the form showed worn areas up to 3/16 in. (4.8 mm) deep. The plywood form used as one side of blocks III and IV also showed abrasion after one use, although not as extensive as the damage sustained with tongue and groove lumber (fig. 25). The large pieces of aggregate dented and tore the wooden forms sufficiently after only two uses each to make the use of wood for mass concrete slipforming very questionable. The metal form showed no apparent damage after two uses (blocks III and IV).

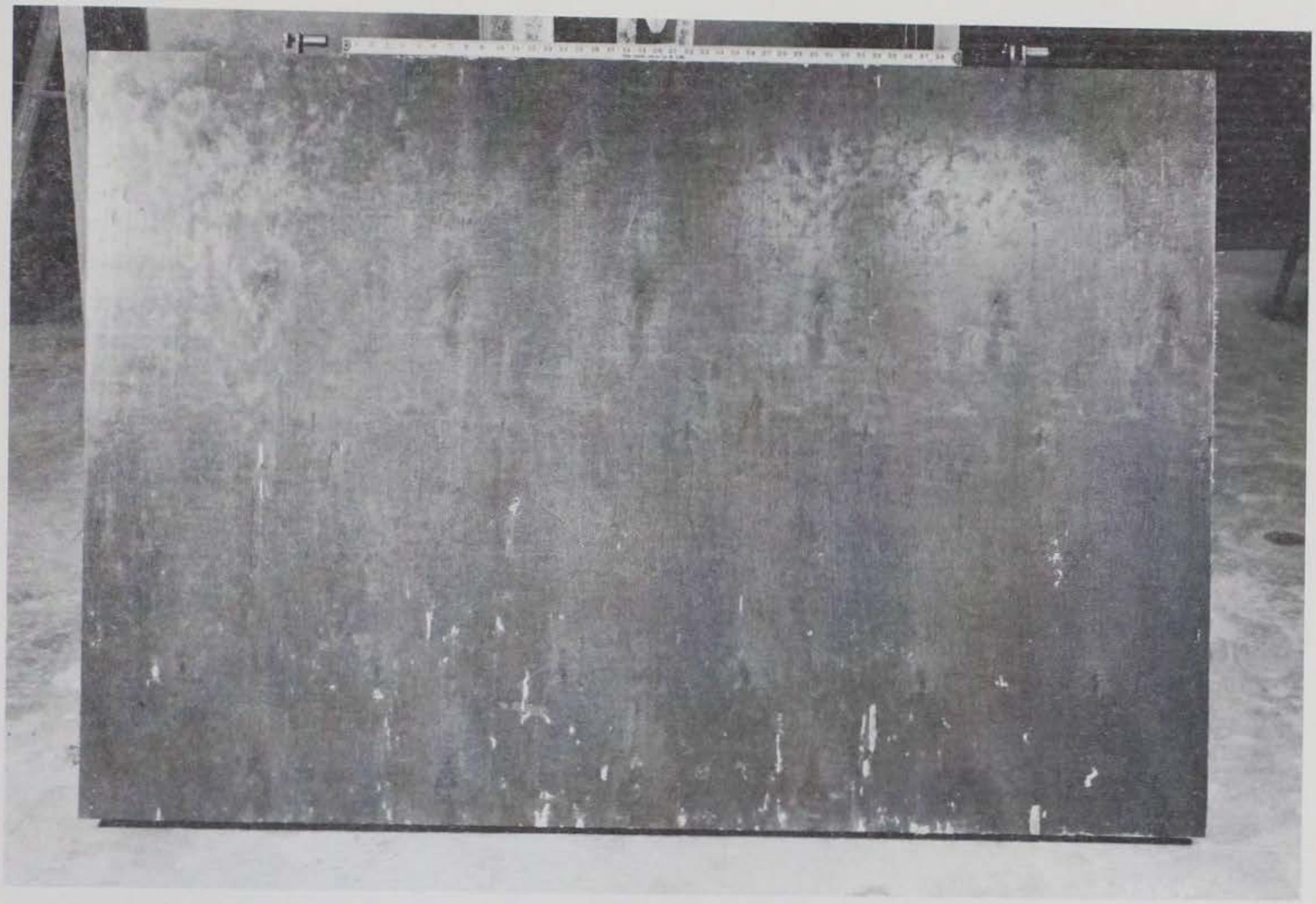

Fig. 25. Block III plywood after one use

Form Lifting Pressure

36. The force required to raise the forms is of prime importance to the designer since, in practice, the slip forms move on a frame that is embedded in the fresh concrete. The engineer must design the support frame to adequately support the weights imposed by the concreting operation and the stresses induced by the lifting jacks. Due to differences in design configurations, the lifting pressures determined in this study should not be rigidly applied to other design problems. However, the data should provide a relative measure of the pressures involved. Given below are the average lifting pressures required to raise the slip forms under the variables studied herein:

Condition No.	Condition	Block No.	Form Material	Average Lifting Pressure (Drag Pressure) lb/lin ft of Form Width	Average Lifting Pressure (Drag Pressure) N/lin m of Form Width
1	Breakaway, 15 hr age	I	Tongue and groove wood	330+ (30-in. form contact)	4816.0 (762.0-mm form contact)
2	Form full 73 F (22.8 C) concrete	I	Tongue and groove wood	230 to 250	3356.6 to 3648.5
3	Form full 58 F (14.4 C) concrete	II	Tongue and groove wood	400 to 500	5837.6 to 7297.0
4	Form full 58 F (14.4 C) concrete	III	Plywood	180 to 250	2626.9 to 3648.5
5	Form full 58 F (14.4 C) concrete	III	Steel sheet	160 to 230	2335.0 to 3356.6
6	Form full 58 F (14.4 C) concrete	IV	Steel sheet	130 to 170*	1897.2 to 2481.0

* Lubricating admixture used.

37. When the concrete was allowed to harden overnight, rather high pressure (330 lb/lin ft (4816.0 N/lin m)) was required to break the bond. However, the breakaway presented no other problems. The top half of the block was slipped the second day, and the joint appeared very tight. The pressure difference between conditions 2 and 3 was probably due to two factors: (a) the 58 F (14.4 C) concrete hardened more slowly, resulting in greater fluid pressures against the slip forms and (b) the tongue and groove surfaces were damaged by the first use, and the rips and tears became entangled with the aggregate particles, producing higher drag pressures. Also, the mixture used for condition 3 may have been more cohesive or sticky than that for condition 2 and thus may have adhered to the surface more tenaciously. For comparable conditions, the use of plywood and sheet metal forms resulted in substantially lower form pressure than those obtained with the tongue and groove lumber. Sheet metal forms are apparently slightly more friction free (20 lb per linear foot of width (291.9 N per linear metre)) than the plywood forms. The addition of a lubricating admixture (pump aid) reduced the drag pressures approximately 50 lb/lin ft (729.7 N/lin m) and thus might

prove beneficial. However, additional work should be conducted on the effects and control of lubricants prior to field use. Comparable pressures for the mass concrete studied herein are approximately twice the lifting pressures required for conventional structural slipforming, 100 to 150 lb per linear foot (1459.4 to 2189.1 N per linear metre) of form.[13] Thus, the structural framing for mass concrete slipforming will need to be somewhat more massive than that for conventional construction.

38. An additional factor that may require consideration when completing a slipformed layer is the tendency for the form to catch and pull large aggregate particles upward near the top of the layer. Fig. 26

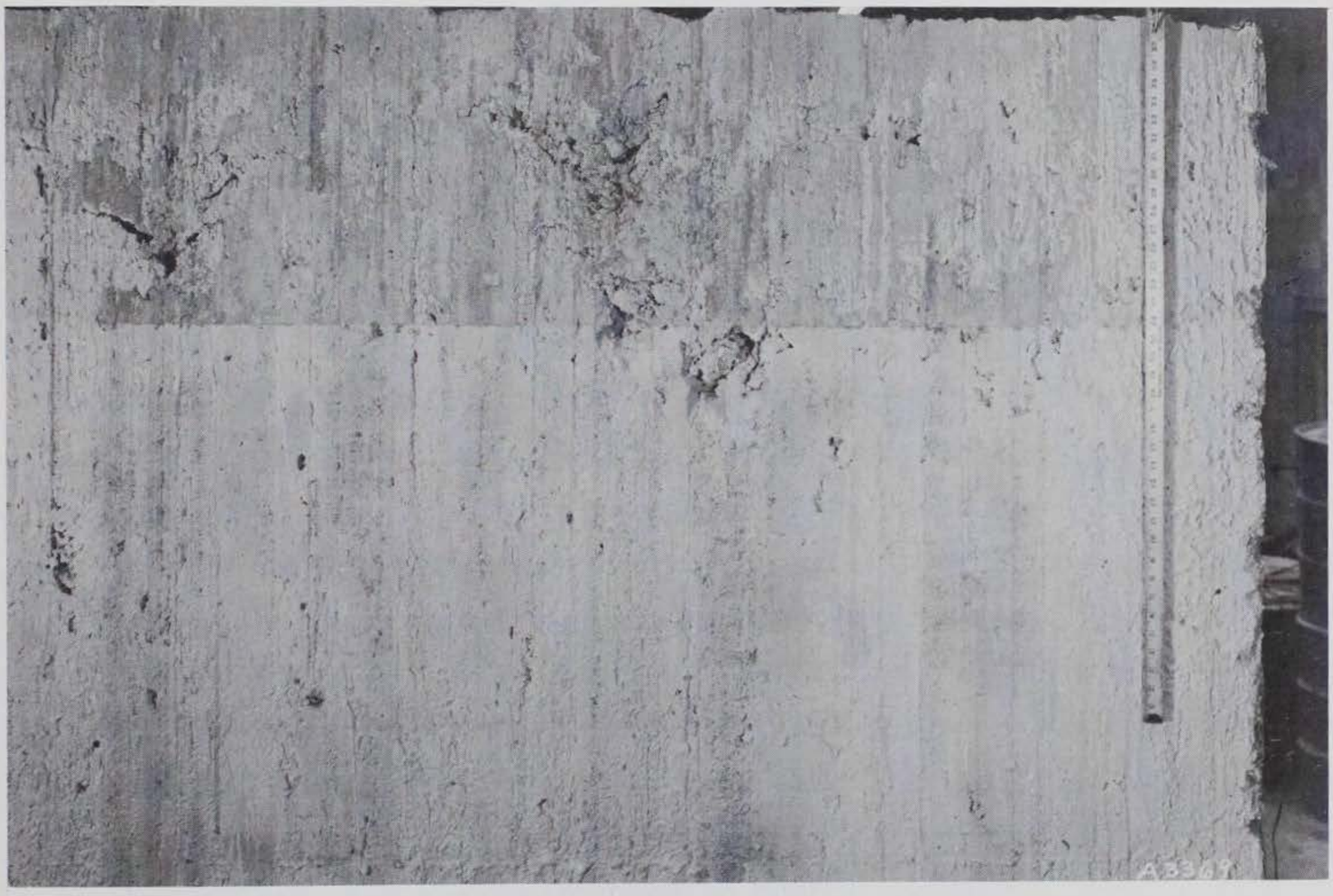

Fig. 26. Top of side B of block I showing area where rocks were caught and pulled upward by the slip form

shows this condition which developed on block I. Apparently the absence of weight above the large aggregate pieces allows them to be pulled upward by the slip form, causing surface voids near the top of the slip-formed area.

Form Anchors

39. If the conventional method of slipforming is utilized, i.e., a moving form anchored into the freshly placed concrete, proper anchor design and a reliable method of determination of anchor support capacity as related to maturity of concrete are essential. The successful use and obvious inherent strength (shear plate design) of the type 1 anchor (fig. 12) tested in this study indicate definite possibilities for field consideration.

40. The study did not, however, provide sufficient information on anchor strengths at depressed temperature for reliable application to design criteria. The one prototype test at 50 F (10.0 C) was apparently valid, but represents only one piece of data. Since the model test at 50 F (10.0 C) sustained more load than the prototype, it is reasonable to conclude that the following pullout strength may be reliably predicted when using type 1 form anchor with a comparable mixture at the designated temperature: 50 F (10.0 C), 14,000 lb (62,275 N); 70 F (21.1 C), 23,000 lb (102,309 N); 90 F (32.2 C), 30,000 lb (133,447 N). It should be noted that the particular field conditions (temperature, moisture, etc.) and the mixture properties (cement content, use of admixtures, etc.) have an overriding effect on anchor strength. Of necessity, a method of reliably estimating degree of hardening and hence form anchor strength on the job will be required. Logically the method selected should be usable with the procedure for determination of lifting time for the slip forms so that only one test need be selected.

Rate of Hardening

41. The rate of hardening of the concrete is, of course, an important parameter in slipforming. For structural concrete, the critical situation develops with rapid hardening due to rich mixtures in very warm weather. The critical situation for mass concrete, if such exists, is likely to be at the opposite extreme--low cement content in cool weather resulting in delayed hardening. Two factors must be

considered: (a) strength development of the form anchors on which the slip form moves and (b) loss of concrete below the form after the slip form moves forward. The form anchor problem has been previously discussed (paragraphs 39 and 40).

42. Sloughing and loss of concrete did occur in these tests due apparently to vibration in the less than full form (block III) and to the use of high-slump concrete (block IV). The most severe condition studied in this investigation was the slipping of blocks at cool temperatures (50 to 60 F (10.0 to 15.5 C)). No problems were encountered slipping full forms of relatively stiff concrete (2-in. (50.8-mm) slump) at the time of initial set (8 hr). This corresponds to 6-in./hr (152.4-mm/hr) slip rate on a 4-ft-high (1.2-m) form. Indeed, slipforming appears to be feasible even when no set (as indicated by the rate of hardening) has been attained. Successful slipping was achieved at a rate of 12 in./hr (304.8 mm/hr) (blocks II, III, and IV), although the rate of hardening curves (figs. 15-17) indicated less than 100 psi (0.689 MPa) of penetration resistance. Other work[14] indicates that a range of 100- to 500- psi (0.689476- to 3.447380-MPa) penetration resistance best defines the optimum time for slipping.

43. Theoretically it should be possible to utilize the compressive or tensile strength data at early ages to determine qualitatively the maturity of freshly placed concrete. The data from table 14 were plotted (figs. 27 and 28) to show the relation of strength to time for the several conditions studied. However, the very low strength values at early ages (<4 hr at 70 F (21.1 C) and above; <10 hr at 60 F (15.5 C) and below) would tend to preclude the use of strength tests as definitive indicators of the degree of hardening in the mass.

44. The method normally used to determine when structural concrete has attained sufficient strength to allow lifting to proceed is the following:

> A 3/4-in. (19.0-mm) steel rod about 6 ft (1.8 m) long and permanently marked at the 4-ft (1.2-m) point is used. The rod is forcefully jammed into the concrete and rodded forcefully several times in the same position until it will penetrate no further.

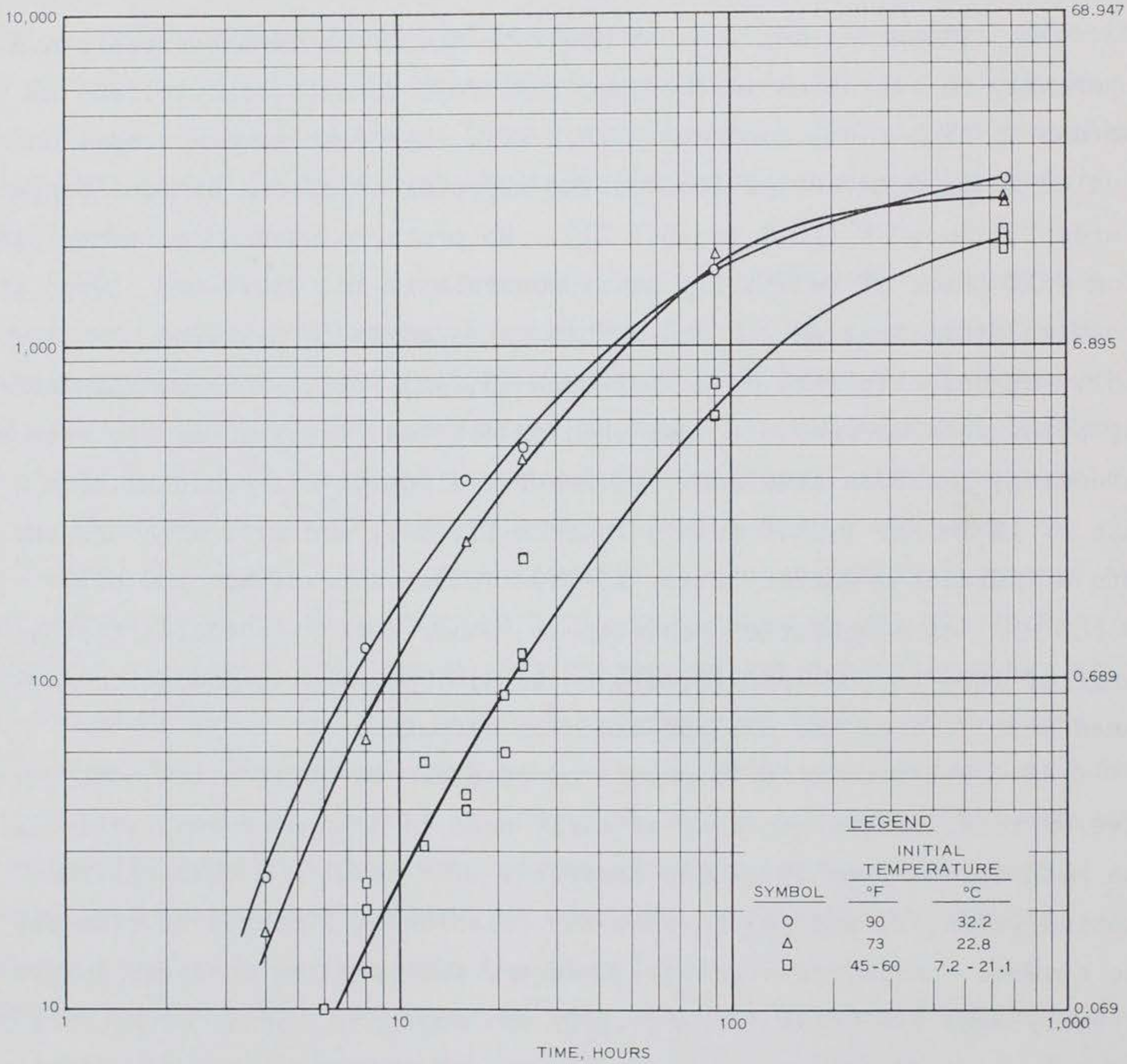

Fig. 27. Relationship of compressive strength to time for various temperatures

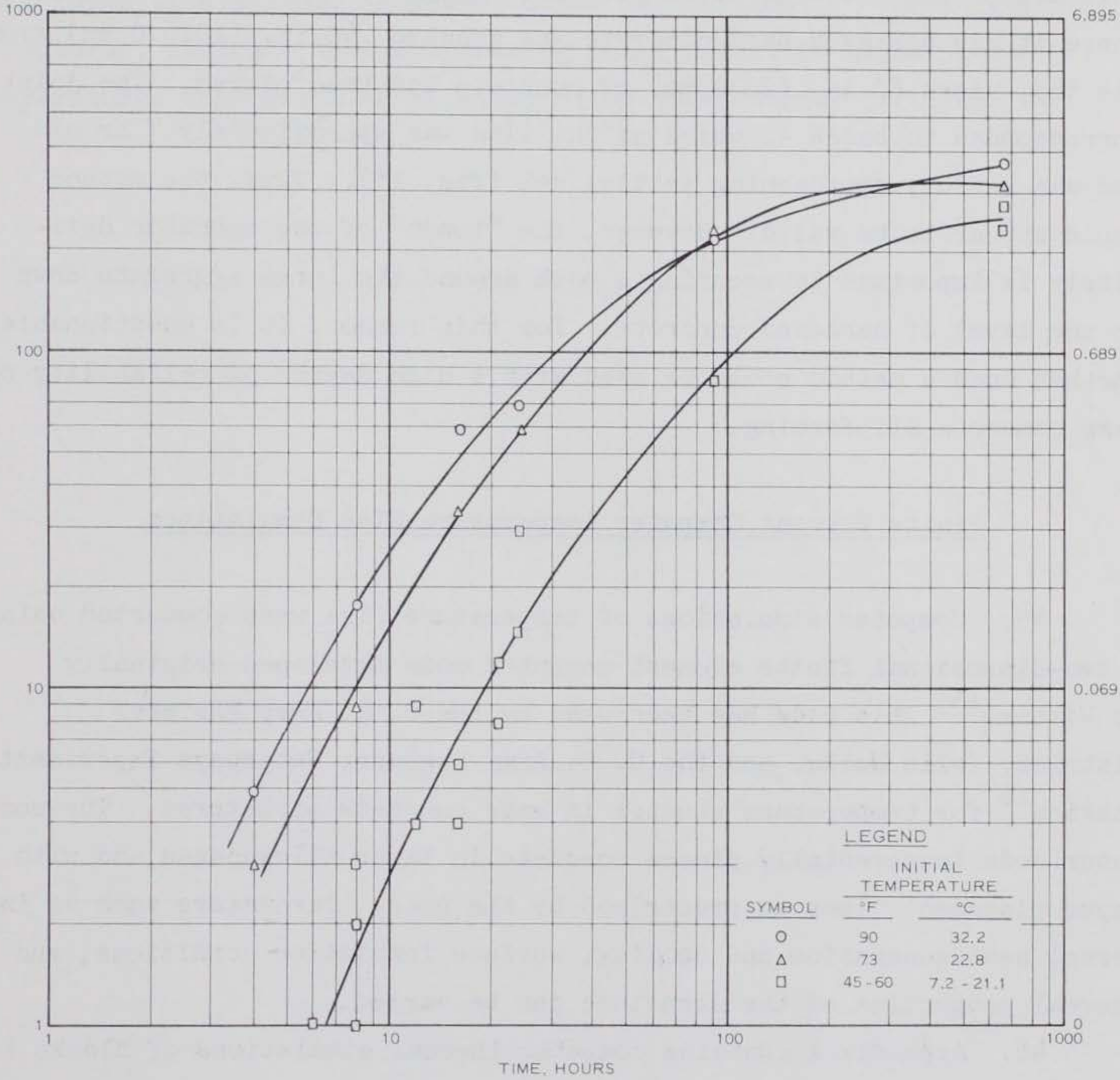

Fig. 28. Relationship of tensile splitting strength to time for various temperatures

> The distance between the top of the form and the 4-ft (1.2-m) mark is the amount of nonplastic concrete in the form.[13]

This method was tried on block II. The rod was jammed down to the joint where it was believed hard concrete was reached, 40 in. (1016.0 mm) from the top, where 80 in. (2032 mm) of concrete had been placed. The joint corresponded to batch 4, which at the time was approximately 7 hr old and was rapidly approaching initial set (fig. 15). Thus, the method would appear to be valid. However, the "touch" of the operator definitely is important in securing a path around the large aggregate down to the level of hardened concrete. For this reason, it is questionable whether such a method could be used with a high degree of reliability on mass concrete slipforming.

Finite Element Computer Temperature Rise Simulations

45. Computer simulations of temperature rise were conducted using a two-dimensional finite element computer code developed originally by Wilson.[15] This code has been used by the U. S. Army Engineer District, Walla Walla, and the U. S. Army Engineer Waterways Experiment Station[16] for temperature studies in mass concrete structures. The computer code incrementally places concrete in layer thicknesses and with layer placement times as prescribed by the user. Parameters such as internal heat generation and cooling, surface insulation conditions, and thermal properties of the structure can be varied.

46. Appendix A contains computer thermal simulations of Blocks I, II, and III and a similar block constructed with 5-ft layers at 5-day intervals. The computer study was conducted to compare measured and computed thermal conditions for the blocks to gain additional insight into the validity and accuracy of computer simulations of thermal spatial and time histories for monolithic blocks under various thermal boundary conditions. Temperature measurements in the laboratory blocks indicated that peak slipform temperatures did not exceed those that were calculated for conventionally placed 5-ft (1.5-m) layers in the same

block. Although the mechanism of heat conduction to subsequent layers was possible, the dimensions of the laboratory blocks allowed sufficient heat loss to bring the peak slipform temperatures below those of the 5-ft layer simulations. However, other calculations,[16] for larger structures, indicate that slipforming could result in higher peak temperatures than would be attained using conventional 5-ft layers.

PART V: CONCLUSIONS

47. Based on the results of this investigation, the following conclusions appear warranted:

a. The slipforming technique appears feasible for use in mass concrete construction. Esthetically, the appearance of slipformed concrete should be similar to that of conventionally placed concrete.

b. No discernible effects of type of aggregate, whether natural or crushed stone, or of maximum size of aggregate, whether 3 or 6 in. (76.2 or 152.4 mm), were noted.

c. The maximum feasible slipping rate determined for the variables in this study (mass concrete, concrete temperature of 60 F (15.5 C), and 4-ft (1.2-m) height of slip form) was found to be 18 in./hr (457.2 mm/hr). A minimum of 6 in./hr (152.4 mm/hr) is recommended. However, rates less than 6 in./hr may be satisfactory if consideration is given for avoidance of cold joints.

d. Steel-lined slip forms appear to be superior to tongue and groove lumber and impregnated plywood slip forms for use in mass concrete slipforming.

e. Form lifting pressures are likely to be approximately twice those for structural concrete (250 versus 125 lb per linear foot of form width (3648.5 versus 1824.2 N per linear metre)). The use of a lubricating admixture reduced drag pressures by about 50 lb per linear foot of form width (729.7 N per linear metre).

f. A shear-plate type of form anchor offers good strength for use in design of a form-support apparatus.

g. A definitive method of determining the degree of hardening in the form as related to slip rate was not determined. The method normally used for structural slipforming, i.e., forcefully jamming a rod down to the hardened concrete, does not appear practical for use with mass concrete. The penetration resistance test apparently can be used as an indicator of the optimum time for slipping.

h. Temperature measurements in the laboratory blocks indicated that peak slipform temperatures did not exceed those that were calculated for conventionally placed 5-ft (1.5-m) layers in the same block. However, other calculations, for larger structures, indicate that slipforming could result in higher peak temperatures than would be attained using conventional 5-ft layers.

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Table 1

Results of Physical and Chemical Tests of Type II Portland Cement

(RC-658 and Fly Ash (AD-3(11))

	RC-658	AD-3(11)
Results of Physical Tests		
Specific gravity	3.14	2.49
Fineness, air permeability, cm^2/g	3295	--
Fineness, air permeability, cm^2/cm^3	--	7695
Normal consistency, water requirement, %	24.8	--
Time of setting, Gillmore test:		
Initial, hr:min	3:20	--
Final, hr:min	5:45	--
Mortar expansion, autoclave test, %	0.00	0.07
Air content, %	8.1	--
Compressive strength, psi (MPa)		
1 day	1010 (6.964)	--
3 days	2180 (15.030)	--
7 days	3160 (21.787)	1135 (7.825)*
28 days	4800 (33.094)	--
Results of Chemical Tests		
SiO_2, %	22.4	
Al_2O_3, %	4.9	82.6
Fe_2O_3, %	3.9	
CaO, %	65.0	--
MgO, %	1.0	1.1
SO_3, %	2.0	1.6
Loss on ignition, %	0.8	2.0
Insoluble residue, %	0.12	--
Na_2O, %	0.45	--
K_2O, %	0.14	--
Total alkalies, as Na_2O, %	0.54	0.9
C_3S, %	50.5	--
C_2S, %	26.0	--
C_3A, %	6.4	--
C_4AF, %	11.8	--

* Lime pozzolan.

Table 2

Physical Properties of Fine and Coarse Aggregates and Gradings of Coarse Aggregates, Mixture A

	Size Range				
	Fine	No. 4 to 3/4 in. (4.75 to 19.0 mm)	3/4 to 1-1/2 in. (19.0 mm to 37.5 mm)	1-1/2 to 3 in. (37.5 mm to 75 mm)	Combined Coarse Aggregate*
Physical Properties					
Test					
Bulk specific gravity, saturated surface dry	2.66	2.72	2.71	2.70	
Absorption, %	1.6	0.5	0.5	0.3	
Cumulative Percent Passing					
Sieve Size					
4 in. (100 mm)				100	100
3 in. (75 mm)				93	97
2 in. (50 mm)			100	47	79
1-1/2 in. (37.5 mm)			98	14	65
1 in. (25.0 mm)	100		30	3	40
3/4 in. (19.0 mm)	97		1	2	30
1/2 in. (12.5 mm)	67		0	0	20
3/8 in. (9.5 mm)	35		0	0	11
No. 4 (4.75 mm)	5		0	0	

* Gradings of each of the three aggregates were combined as follows: 1-1/2- to 3-in. (37.5- to 75-mm) aggregate, 40%; 3/4- to 1-1/2-in. (19.0- to 37.5-mm) aggregate, 30%; No. 4 to 3/4-in. (4.75- to 19.0-mm) aggregate, 30%.

Table 3

Physical Properties of Fine and Coarse Aggregates and Gradings of Coarse Aggregates, Mixture B

	Size Range					
	Fine	No. 4 to 3/4 in. (4.75 to 19.0 mm)	3/4 to 1-1/2 in. (19.0 mm to 37.5 mm)	1-1/2 to 3 in. (37.5 mm to 75 mm)	3 to 6 in. (75 mm to 150 mm)	Combined Coarse Aggregate*
Physical Properties						
Test						
Bulk specific gravity, saturated surface dry	2.66	2.72	2.71	2.70	2.69	
Absorption, %	1.6	0.5	0.5	0.3	0.3	
Cumulative Percent Passing						
Sieve Size						
6 in. (152.4 mm)					100	100
5 in. (127.0 mm)					87	95
4 in. (100 mm)				100	65	86
3 in. (75 mm)				93	35	73
2 in. (50 mm)			100	47	8	53
1-1/2 in. (37.5 mm)			98	14	2	46
1 in. (25.0 mm)		100	30	3	0	29
3/4 in. (19.0 mm)		97	1	2	0	21
1/2 in. (12.5 mm)		67	0	0	0	15
3/8 in. (9.5 mm)		35	0	0	0	8
No. 4 (4.75 mm)		5	0	0	0	

* Gradings of each of the four aggregates were combined as follows: 3- to 6-in. (75- to 150-mm) aggregate, 40%; 1-1/2- to 3-in. (37.5- to 75-mm) aggregate, 18%; 3/4- to 1-1/2-in. (19.0- to 37.5-mm) aggregate, 20%; No. 4 to 3/4-in. (4.75- to 19.0-mm) aggregate, 22%.

Table 4

Physical Properties of Fine and Coarse Aggregates and Gradings of Coarse Aggregates, Mixture C

	Size Range					
	Fine	No. 4 to 3/4 in. (4.75 to 19.0 mm)	3/4 to 1-1/2 in. (19.0 mm to 37.5 mm)	1-1/2 to 3 in. (37.5 mm to 75 mm)	3 to 6 in. (75 mm to 150 mm)	Combined Coarse Aggregate*
Physical Properties						
Test						
Bulk specific gravity, saturated surface dry	2.67	2.66	2.70	2.70	2.70	
Absorption, %	1.0	0.9	0.6	0.6	0.6	
Cumulative Percent Passing						
Sieve Size						
6 in. (152.4 mm)					100	100
5 in. (127.0 mm)					88	98
4 in. (100 mm)					53	92
3 in. (75 mm)				100	0	84
2 in. (50 mm)				41	0	64
1-1/2 in. (37.5 mm)			100	0	0	50
1 in. (25.0 mm)			40	0	0	35
3/4 in. (19.0 mm)	100		0	0	0	25
1/2 in. (12.5 mm)	56		0	0	0	14
3/8 in. (9.5 mm)	34		0	0	0	8
No. 4 (4.75 mm)	0		0	0	0	

* Gradings of each of the four aggregates were combined as follows: 3- to 6-in. (75- to 150-mm) aggregate, 16%; 1-1/2- to 3-in. (37.5- to 75-mm) aggregate, 34%; 3/4- to 1-1/2-in. (19.0- to 37.5-mm) aggregate, 25%; No. 4 to 3/4 in. (4.75- to 19.0-mm) aggregate, 25%.

Table 5

Mixture Proportions, Mixture A

	Solid Volume		Weight, Saturated Surface Dry	
	ft^3	m^3	lb/yd^3	kg/m^3
Material				
Portland cement	0.933	0.026	184	109.2
Fly ash	0.502	0.014	78	46.3
Fine aggregate	6.242	0.177	1036	614.6
Coarse aggregate	15.281	0.433	2583	1532.4
Water	3.016	0.085	188	111.5
Air	1.026	0.029	--	--
	27.000	0.764	4069	2414.0
Slump, in. (mm)*	1-3/4	(44.4)		
Air content, %*	4.7			

* Portion passing 1-1/2-in. (37.5-mm) sieve.

Table 6

Mixture Proportions, Mixture B

	Solid Volume		Weight, Saturated Surface Dry	
	ft^3	m^3	lb/yd^3	kg/m^3
Material				
Portland cement	0.933	0.026	183	108.6
Fly ash	0.502	0.014	78	46.3
Fine aggregate	4.904	0.139	814	482.9
Coarse aggregate	17.389	0.492	2932	1739.5
Water	2.435	0.069	162	96.1
Air	0.837	0.024	--	--
	27.000	0.764	4169	2473.4
Slump, in. (mm)*	1-3/4	(44.4)		
Air content, %*	4.7			

* Portion passing 1-1/2-in. (37.5-mm) sieve.

Table 7

Mixture Proportions, Mixture C

	Solid Volume		Weight, Saturated Surface Dry	
	ft^3	m^3	lb/yd^3	kg/m^3
Material				
Portland cement	0.977	0.028	192	113.9
Fly ash	0.527	0.015	79	46.9
Fine aggregate	5.642	0.160	940	557.7
Coarse aggregate	16.061	0.455	2696	1599.5
Water	2.740	0.077	171	101.4
Air	1.053	0.030	--	--
	27.000	0.764	4078	2419.4
Slump, in. (mm)*	1-3/4	(44.4)		
Air content, %*	5.0			

* Portion passing 1-1/2-in. (37.5-mm) sieve.

Table 8

Casting Data for Block I

Batch No.	Yield ft3	Yield m3	Time Consolidation Completed hr	Slump in.	Slump mm	Air Content percent	Concrete Height in Form: Individual Batch in.	Individual Batch mm	Cumulative in.	Cumulative mm
			Layer 1, Day 1, Mixture A (3-in. (76.2-mm) Aggregate)							
1	16	0.453	0840	1-1/2	38.1	3.6	8	203.2	8	203.2
2	16	0.453	0950	1-1/2	38.1	4.2	10	254.0	18	457.2
3	10	0.283	1125	1-3/4	44.4	--	6	152.4	24	609.6
4	10	0.283	1325	1-3/4	44.4	--	6	152.4	30	762.0
5	16	0.453	1405	2	50.8	--	10	254.0	40	1016.0
6	16	0.453	1430	1-3/4	44.4	--	10	254.0	50	1270.0
7	16	0.453	1505	1-1/2	38.1	4.2	10	254.0	60	1524.0
			Layer 2, Day 2, Mixture B (6-in. (152.4-mm) Aggregate)							
8	16	0.453	0850	1-1/2	38.1	3.5	10	254.0	70	1778.0
9	16	0.453	0910	2	50.8	4.3	10	254.0	80	2032.0
10	16	0.453	1100	1-1/2	38.1	--	10	254.0	90	2286.0
11	16	0.453	1250	2	50.8	--	10	254.0	100	2540.0
12	16	0.453	1425	2	50.8	--	10	254.0	110	2794.0
13	16	0.453	1545	2	50.8	--	10	254.0	120	3048.0

Table 9

Casting Data for Block II

Batch No.*	Time Consolidation Completed hr	Slump		Air Content percent	Cumulative Concrete Height in Form	
		in.	mm		in.	mm
1	0910	1-3/4	44.4	4.2	10	254
2	1035	2	50.8	4.5	20	508
3	1210	2	50.8	4.7	30	762
4	1350	2-1/4	57.2	5.5	40	1016
5	1530	1-1/2	38.1	5.3	50	1270
6	1710	1-1/2	38.1	4.0	60	1524
7	1850	2	50.8	5.1	70	1778
8	2040	1-1/2	38.1	4.0	80	2032
9A	2145	2-1/2	63.5	6.0	90	2286
9B	2220	1-1/2	38.1	4.4	100	2540
10A	2315	1-3/4	44.4	5.5	110	2794
10B	2345	1-3/4	44.4	4.7	120	3048

* Batch size, 16 ft^3 (0.453 m^3), resulted in 10-in. (254.0-mm) rise in form.

Table 10

Casting Data for Block III

Batch No.*	Time Consolidation Completed hr	Slump		Air Content percent	Cumulative Concrete Height in Form	
		in.	mm		in.	mm
1	0835	2-1/2	63.5	5.5	10	254
2	0905	1-3/4	44.4	4.8	20	508
3	0930	1-1/2	38.1	4.5	30	762
4	1005	2-1/4	57.2	6.0	40	1016
5	1050	1-1/2	38.1	4.5	50	1270
6	1125	2	50.8	5.0	60	1524
7	1200	1-1/2	38.1	5.3	70	1778
8	1400	1-1/2	38.1	4.8	80	2032
9	1450	1-1/2	38.1	4.8	90	2286
10	1540	2	50.8	5.4	100	2540
11	1630	1-1/2	38.1	4.2	110	2794
12	1720	1-1/2	38.1	4.8	120	3048

* Batch size, 16 ft^3 (0.453 m^3), resulted in 10-in. (254.0-mm) rise in form.

Table 11

Casting Data for Block IV

Batch No.*	Time Consolidation Completed hr	Slump		Air Content percent	Cumulative Concrete Height in Form	
		in.	mm		in.	mm
1	0830	1-3/4	44.4	2.5	10	254
2**	0900	4-1/2	114.3	3.0	--	--
3	0930	6	154.2	4.1	20	508
4**	1000	2	50.8	2.5	--	--
5	1030	2	50.8	3.2	30	762
6	1100	1-3/4	44.4	3.5	40	1016
7	1130	1-1/2	38.1	3.8	50	1270
8	1220	1-1/2	38.1	3.0	60	1524
9	1310	1-3/4	44.4	4.2	70	1778

Note: 0.10 lb/yd^3 (0.059 kg/m^3) pump aid used in all batches.

* Batch size, 16 ft^3 (0.453 m^3), resulted in 10-in. (254.0-mm) rise in form.

** Batches used in small form anchor blocks.

Table 12

Results of Prototype Form Anchor Tests (58 to 60 F (10.0 to 15.5 C))

Test No.	Block No.	Age at Time of Test, hr	Pullout Test				Cylinder Strength			
			Load		Displacement		Compressive		Tensile Splitting	
			lb	N	in.	mm	psi	MPa	psi	MPa
1	IV	6	7,100	31,582.4	1.00	25.4	10.0	0.069	1.0	0.007
2	III	8	12,300	54,713.1	0.50	12.7	24.0	0.165	3.2	0.022
3	IV	10	10,000	44,482.2	1.00	25.4	31.0	0.214	4.0	0.028
4	III	12	14,300	63,609.6	0.30	7.6	56.0	0.386	9.1	0.063

Table 13

Results of Model Form Anchor Tests (8-hr age)

	Prototype	Model A	Model B
Dimensions, ft (m) of block	3 by 6 by 4.5 (0.9 by 1.8 by 1.4)	6 by 6 by 3 (1.8 by 1.8 by 0.9)	3 by 3 by 1-1/2 (0.9 by 0.9 by 0.4)
Embedded depth, ft (m)	4.5 (1.4)	3 (0.9)	1-1/2 (0.4)
Bearing area, sq in. (sq mm)	54 (34,838.6)	36 (23,225.8)	18 (11,612.9)
Depth and area ratios	1	2/3	1/3
50 F (10.0 C) Tests			
Number of tests	1	2	2
Maximum load, lb (N)	12,300 (54,713)	14,800 (65,834)	5,100 (22,686)
Load ratio	2.4	2.9	1
70 F (21.1 C) Tests			
Number of tests	0	1	2
Maximum load, lb (N)	--	23,000 (102,309)	10,900 (48,486)
Load ratio	--	2.1	1
90 F (32.2 C) Tests			
Number of tests	0	1	2
Maximum load, lb (N)	--	30,000+ (133,447+)*	9,000+ (40,034+)**
Load ratio	--	--	--

* Did not fail, exceeded capacity of test frame.
** Did not fail, lifted entire block from mold.

Table 14

Results of Strength Tests

	Temperature °F	Temperature °C	Batch No.	Test	Strength at Various Hours Age, psi 6	8	12	24	672	2160	Strength at Various Hours Age, MPa 6	8	12	24	672	2160
Block I	73	22.8	2	Compressive	--	--	--	--	2710	--	--	--	--	--	18.685	--
Block II	60	21.1	3	Tensile splitting	--	2	--	--	--	--	--	0.014	--	--	--	--
			6	Tensile splitting	--	1	--	--	--	--	--	0.007	--	--	--	--
			10	Tensile splitting	--	2	--	--	--	--	--	0.014	--	--	--	--
Block III	57	13.9		Tensile splitting	--	3	9	--	--	--	--	0.021	0.062	--	--	--
				Compressive	--	24	56	--	2090	--	--	0.165	0.386	--	14.410	--
Block IV	60	21.1		Tensile splitting	1	--	4	30	--	--	0.007	--	0.028	0.207	--	--
				Compressive	10	--	31	230	1980	3780	0.069	--	0.214	1.586	13.652	26.062

				Test	Strength at Various Hours Age, psi 4	8	16	21	24	91	672	Strength at Various Hours Age, MPa 4	8	16	21	24	91	672
Form anchor	50	10.0	1	Tensile	0	3	--	--	15	--	280	0	0.021	--	--	0.103	--	1.930
Form anchor	50	10.0	2	Tensile	0	--	4	8	--	85	--	0	--	0.028	0.056	--	0.586	--
Form anchor	50	10.0	1	Compressive	0	20	--	--	110	--	2300	0	0.138	--	--	0.758	--	15.858
Form anchor	50	10.0	2	Compressive	0	--	40	60	--	780	--	0	--	0.276	0.414	--	5.378	--
Form anchor	45	7.2	1	Tensile	0	2	--	--	15	--	225	0	0.014	--	--	0.103	--	1.551
Form anchor	45	7.2	2	Tensile	0	--	6	12	--	85	--	0	--	0.041	0.082	--	0.586	--
Form anchor	45	7.2	1	Compressive	0	13	--	--	120	--	1930	0	0.090	--	--	0.827	--	13.307
Form anchor	45	7.2	2	Compressive	0	--	45	90	--	620	--	0	--	0.310	0.620	--	4.275	--

				Test	Strength at Various Hours Age, psi 4	8	16	24	91	672	Strength at Various Hours Age, MPa 4	8	16	24	91	672
Form anchor	73	22.8	1	Tensile	3	9	--	60	--	--	0.021	0.062	--	0.414	--	--
Form anchor	73	22.8	2	Tensile	--	--	35	--	235	315	--	--	0.241	--	1.620	2.172
Form anchor	73	22.8	1	Compressive	17	65	--	460	--	--	0.117	0.448	--	3.172	--	--
Form anchor	73	22.8	2	Compressive	--	--	260	--	1900	2880	--	--	1.793	--	13.100	19.857
Form anchor	90	32.2	1	Tensile	5	18	--	70	--	--	0.034	0.124	--	0.483	--	--
Form anchor	90	32.2	2	Tensile	--	--	60	--	220	380	--	--	0.414	--	1.517	2.620
Form anchor	90	32.2	1	Compressive	25	125	--	500	--	--	0.172	0.862	--	3.447	--	--
Form anchor	90	32.2	2	Compressive	--	--	400	--	1700	3190	--	--	2.758	--	11.721	21.994

APPENDIX A: COMPUTER THERMAL SIMULATIONS

1. This study simulated the thermal conditions in slipform blocks I, II, and III for comparison with a simulation of a similar block with 5-ft-high (1.5-m) layers placed at 5-day intervals. Calculation of temperatures was made on the cross section normal to the slipform surfaces. The computer code does not allow heat loss normal to the calculation plane. Since the cast blocks were only 6 ft (1.8 m) long in this direction, it was expected that the calculated temperatures would be higher than the actual temperatures measured because the blocks did experience heat loss through the ends. The finite element model (fig. A1) consisted of a foundation (laboratory floor) with three rows of 2-in.-high by 6-in.-long (50.8- by 152.4-mm) elements and was a total of 36 in. (914.4 mm) wide. The bottom row of element nodes was fixed at 72 F (22.2 C); the remaining nodes were allowed to change temperature depending upon the temperature of the block cast above. The mass concrete block also consisted of a matrix of 2- by 6-in. (50.8- by 152.4-mm) elements placed to a total height of 10 ft (3.0 m) and width of 3 ft (0.9 m). The heights and placement times of the calculated slipform layers were made to correspond to the actual conditions. The 4-ft-high (1.2-m) slip forms of the model were moved to correspond to actual conditions. This was accomplished by determining the convection-conduction heat transfer coefficients for the various form materials and thicknesses and applying these to the concrete surfaces in contact with the forms. Slipping of the forms was simulated by changing the heat transfer coefficients of the element surfaces exposed in slipping from those of the form materials to those corresponding to convection exposure to ambient air conditions. All heat transfer coefficients were based upon an estimated 1.5-ft/sec (0.4-m/sec) velocity of the laboratory air due to the air conditioning system. Ambient temperature was fixed at 72 F (22.2 C).

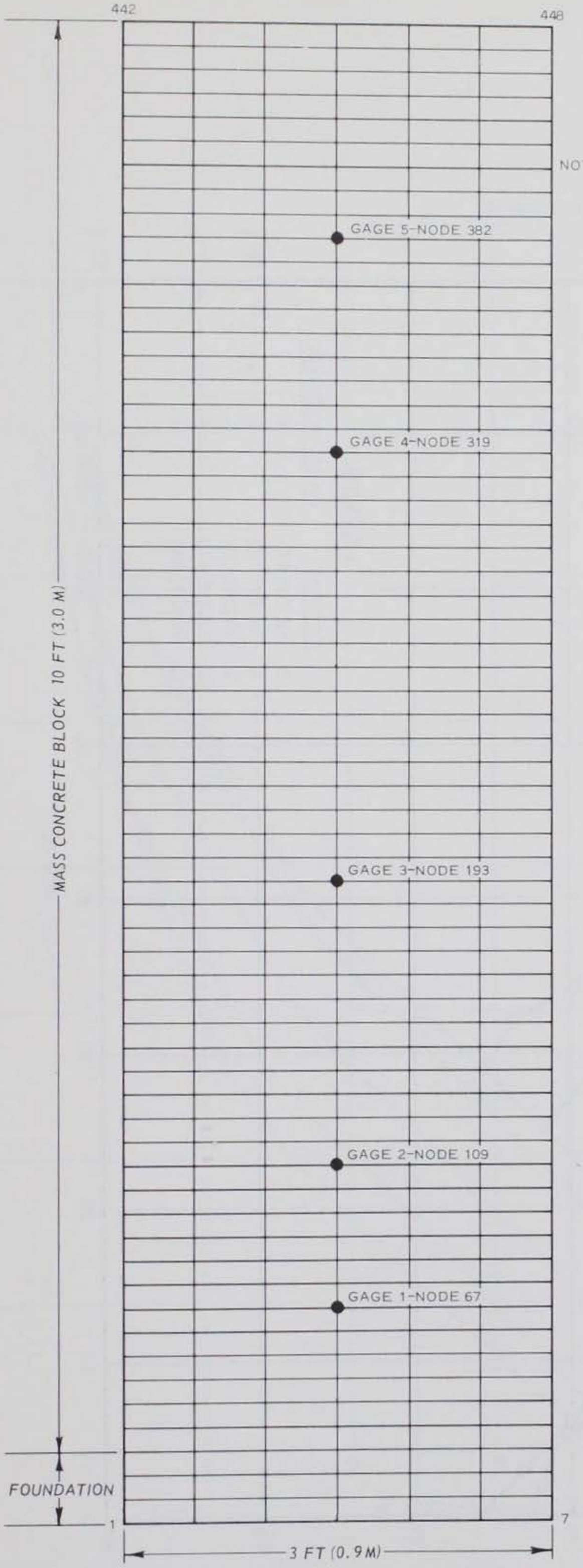
2. Thermal parameters of the concrete such as adiabatic temperature rise, thermal conductivity, and diffusivity were not determined for the concrete used in the slipform blocks. However, the mixtures used were assumed to be sufficiently similar to Trumbull Pond Dam mixture PF[16]

so that the values of thermal parameters of that mixture were used in the computer study.

3. The results, which are plotted in figs. A2-A5, show the temperatures calculated at the thermocouple gage positions in the slipform blocks. These gages were located at 1-, 2-, 4-, 7-, and 8.5-ft (0.3-, 0.6-, 1.2-, 2.1-, and 2.6-m) elevations. Calculated temperatures shown in figs. A2-A5 may be compared with the measured temperatures (main text figs. 21-23) with the consideration that the thermal properties of the actual and calculated concrete mixtures differ by a small but unknown amount and the computer model allows no heat flow (loss) in directions normal to the calculation plane. Assuming these limitations, the actual and calculated temperature-time curves compare favorably. Calculated values for slipform blocks I, II, and III do show higher peak temperatures and a much lower or nonexistent temperature drop at most gage positions within the 72-hr problem time as expected (fig. A5).

4. A comparison was made using computer runs 2 and 3 (blocks II and III) with run 4 (fig. A6), a 5-ft (1.5-m) layer simulation, with 5-day placement intervals. It should be noted that where the slipform simulations were only calculated to 72 hr (3 days), the 5-ft (1.5-m) layer simulation was necessarily taken to 9 days. Therefore, only gage positions 1-3 can be compared on the same time scale. The placement temperature of run 4 was 60 F (15.5 C) or very near the average of placement temperatures of runs 2 and 3. Results show that the 3-day peak temperatures are higher in the first 5-ft (1.5-m) layer of run 4 than in the comparable sections of runs 2 and 3. The maximum temperature reached was in the lower portion of the second 5-ft (1.5-m) layer of run 4. Layer 2 of run 4 was placed at 5 days, and the peak temperature of 85 to 86 F (29.4 to 30.0 C) (extrapolated) would occur at 10 to 13 days. Peak temperatures in the slipform runs all occurred at 2 to 4 days and would reach 81 to 82 F (27.2 to 27.8 C) (extrapolated). These data suggest that 5-ft (1.5-m) layer construction of a test block such as was used in these experiments would have produced higher peak temperatures than slipforming.

5. However, the blocks with which the present study was concerned



NOTE: ELEMENT SIZE, 2 BY 6 IN. (50.8 BY 152.4 MM).

FINITE ELEMENT NODE NUMBERING SEQUENCE IS FROM LEFT TO RIGHT AND BOTTOM TO TOP. NODE NUMBERS OF THE CORNERS OF THE MODEL AND THE THERMOCOUPLE GAGE LOCATIONS ARE SHOWN.

Fig. A1. Finite element model used in slipform computer study

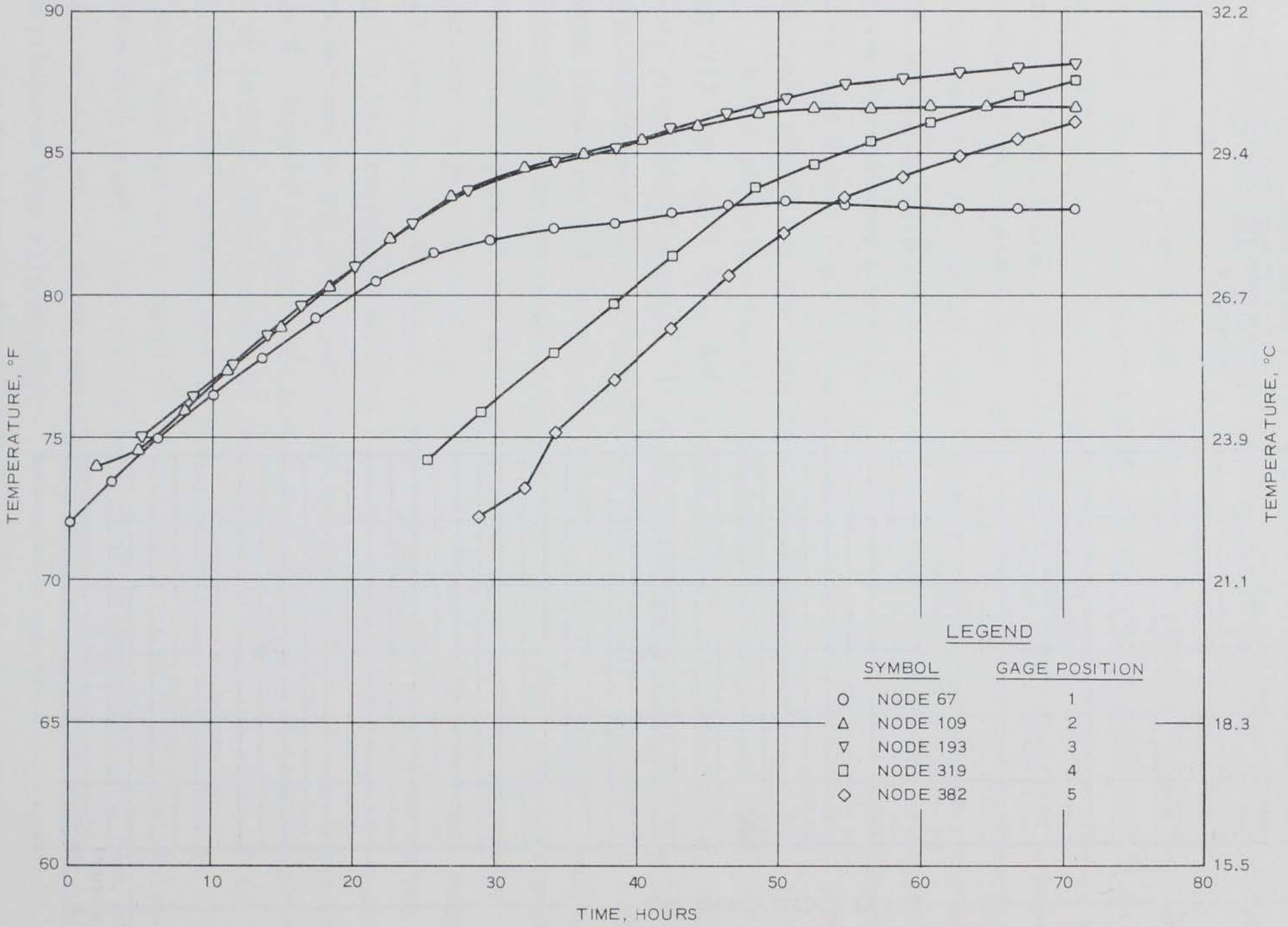


Fig. A2. Calculated temperatures for block I

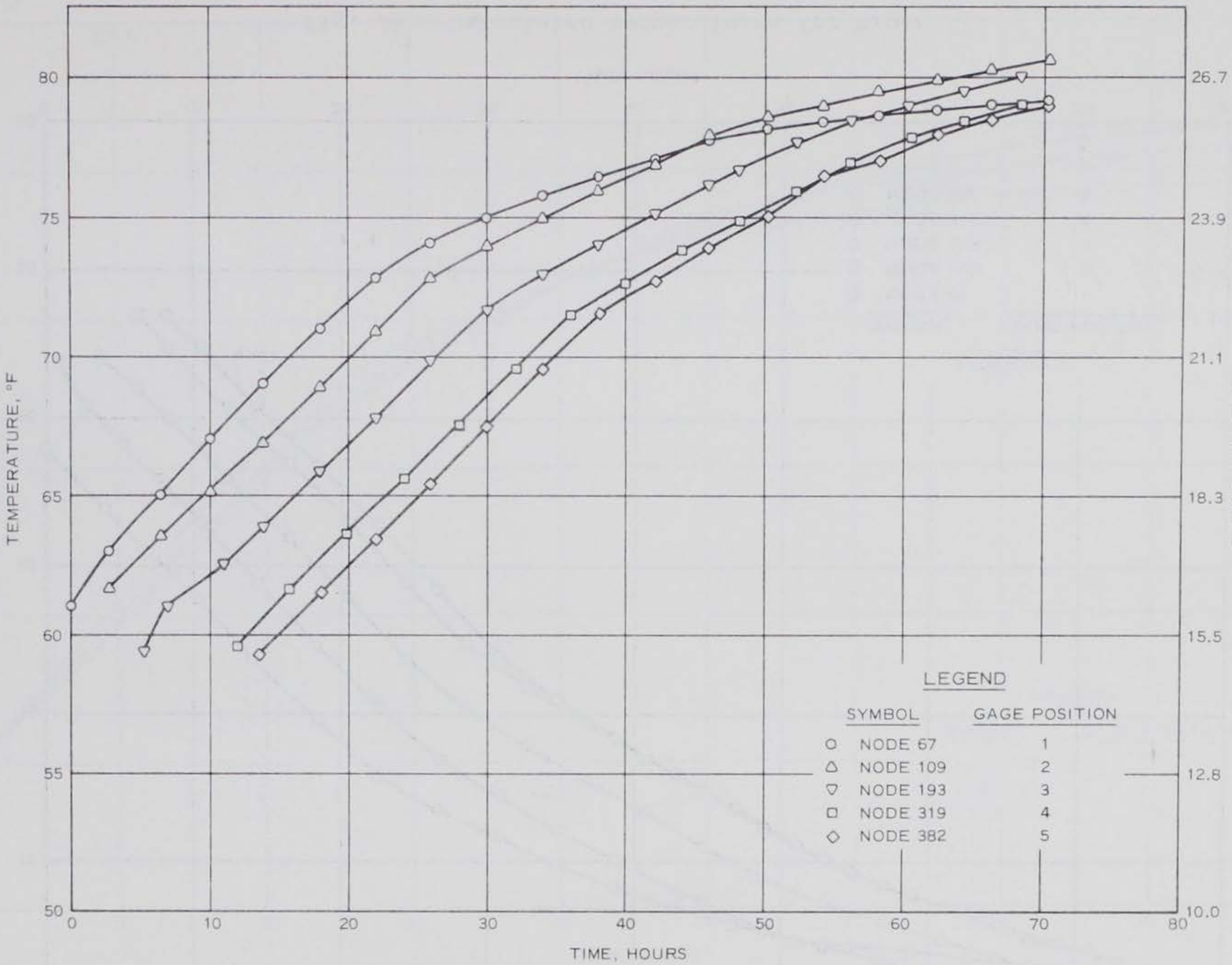


Fig. A3. Calculated temperatures for block II

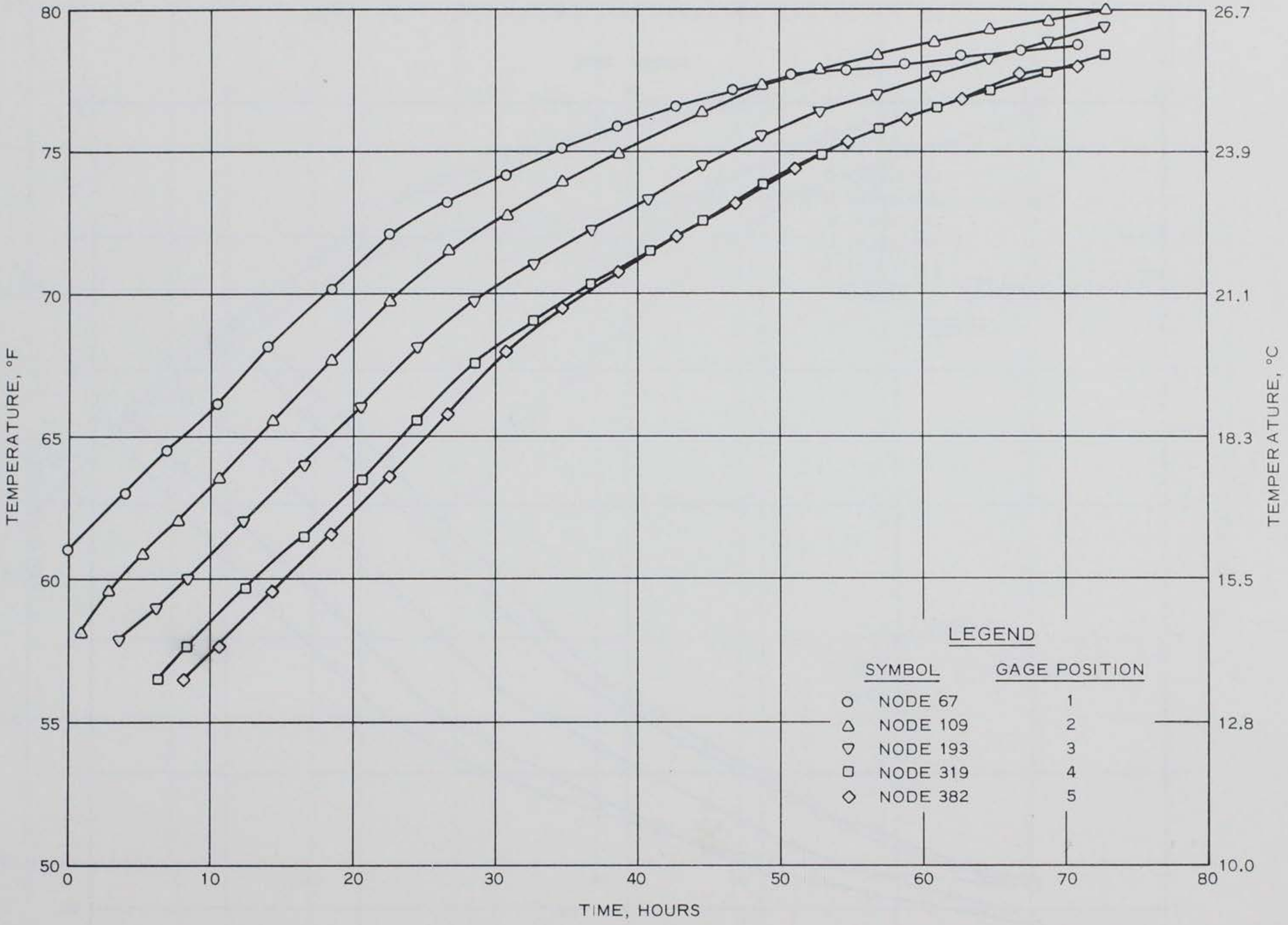


Fig. A4. Calculated temperatures for block III

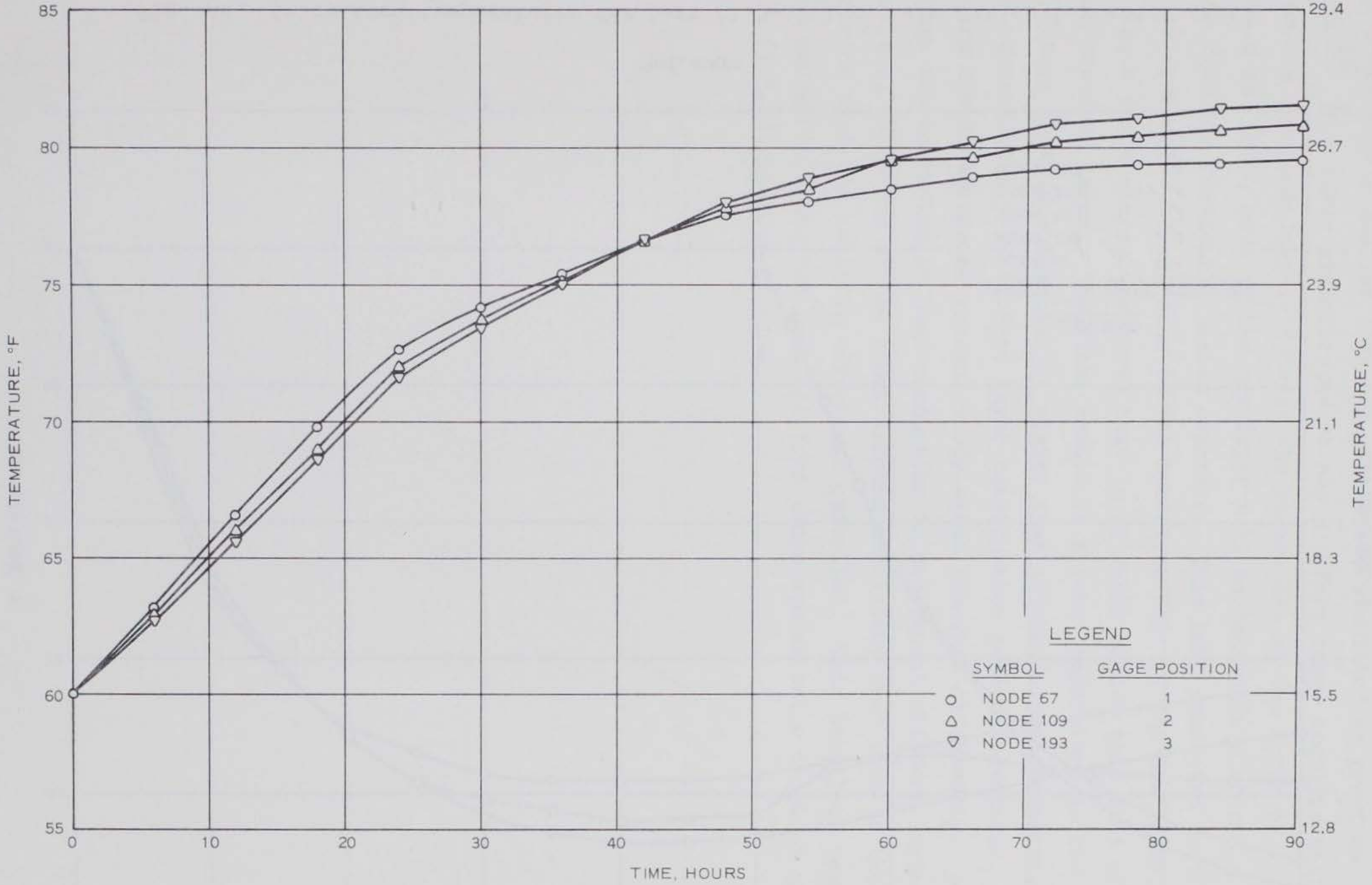


Fig. A5. Calculated temperatures for 5-ft (1.5-m) layer simulation

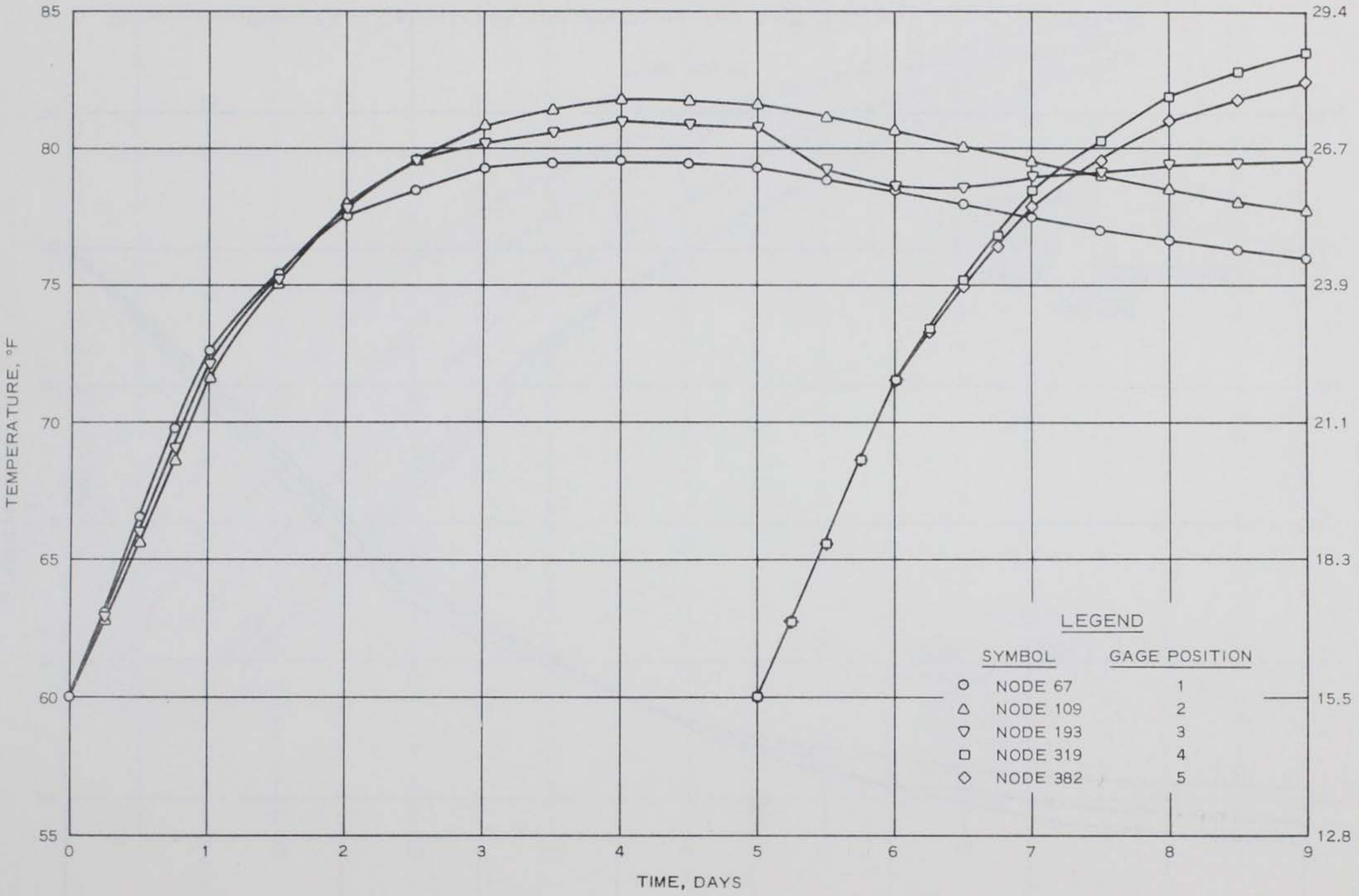


Fig. A6. Calculated temperatures for 5-ft (1.5-m) layer simulation (expanded plot)

are considerably smaller than the structures simulated in previous work.[16] In a large structure, each new slipform layer acquires heat from the previous layer. Because the layers are of the order of 12 in. (304.8 mm) high, most of the new layer will be heated in a short time from the previously placed concrete. This heat conducted vertically from prior layers adds to the hydration heat of the new layer, producing a temperature-time curve that is slightly higher than that of each previous layer. The final result is a peak temperature in the structure that is substantially higher than adiabatic peak temperature and conventional 5-ft (1.5-m) layer construction peak temperatures. The blocks simulated in the present study acted somewhat differently. Although the mechanism of heat conduction to subsequent slipform layers was possible, the width of the block allowed sufficient heat loss to the exterior that the additive effect was cancelled. This heat loss was high enough to bring the peak slipform temperatures below those of the 5-ft (1.5-m) layer simulation.

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13. ABSTRACT

A laboratory investigation was conducted to study applications of the slipforming technique in mass concrete construction. Opposite sides of large blocks (3 by 6 by 10 ft high (0.9 by 1.8 by 3.0 m)) were slipformed in a specially fabricated test frame using mass concrete mixtures. Variables included casting temperature, type and maximum size of aggregate, use of a lubricating admixture, slipping rate, type of form anchors, and type of slipform surface. Based on the results of this study the following conclusions appear warranted: (a) The slipforming technique appears feasible for use in mass concrete construction. Esthetically, the appearance of slipformed concrete should be similar to that of conventionally placed concrete. (b) No discernible effects of type of aggregate, whether natural or crushed stone, or of maximum size of aggregate, whether 3 or 6 in. (76.2 or 152.4 mm), were noted. (c) The maximum feasible slipping rate determined for the variables in this study (mass concrete, concrete temperature of 60 F (15.5 C), and 4-ft (1.2-m) height of slip form) was found to be 18 in./hr (457.2 mm/hr). A minimum of 6 in./hr (152.4 mm/hr) is recommended. However, rates less than 6 in./hr may be satisfactory if consideration is given for avoidance of cold joints. (d) Steel-lined slip forms appear to be superior to tongue and groove lumber and impregnated plywood slip forms for use in mass concrete slipforming. (e) Form lifting pressures are likely to be approximately twice those for structural concrete (250 versus 125 lb per linear foot (3648.5 versus 1824.2 N per linear metre) of form). The use of a lubricating admixture reduced drag pressures by about 50 lb per linear foot (729.7 N per linear metre) of form width. (f) A shear-plate type of form anchor offers good strength for use in design of a form-support apparatus. (g) A definitive method of determining the degree of hardening as related to slip rate was not determined. The method normally used for structural slipforming, i.e., forcefully jamming a rod down to the hardened concrete, does not appear practical for use with mass concrete. (h) Temperature measurements in the laboratory blocks indicated that peak slipform temperatures did not exceed those that were calculated for conventionally placed 5-ft (1.5-m) layers in the same block. However, other calculations, for larger structures, indicate that slipforming should result in higher peak temperatures than would be attained using conventional 5-ft layers.

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