DEPARTMENT OF THE ARMY
OFFICE OF THE CHIEF OF ENGINEERS
WASHINGTON

ENGWE

5 December 1952

MEMORANDUM TO ALL CONCERNED

SUBJECT: Vacuum Treatment of Mass Concrete Surfaces

1. The data contained in this Technical Memorandum No. 6-353, entitled "Investigation of Vacuum Treatment of Mass Concrete Surfaces" have been prepared by the Waterways Experiment Station under Item CW 605 "Vacuum Concrete Investigation" and are being issued for general information.

2. Vacuum treatment of mass concrete surfaces has been used on limited portions of several concrete dams constructed under the Civil Works program during the last several years. In almost every instance difficulties have been encountered in making a satisfactory application of the process. These difficulties have nullified to a great degree the effectiveness of the vacuum process in improving the qualities of the concrete, which is theoretically possible. Specimens of hardened concrete have been secured from a number of these structures and have been examined in the laboratory to determine to what extent the vacuum processing was effective. Results of these examinations have indicated very little, if any, improvement of the quality of the concrete resulting from the use of vacuum processing. On all but one project, field experience was either unsatisfactory or inconclusive. The principal tangible benefit obtained on one project, which reported fairly satisfactory results, was reduced time required for finishing where finished surfaces were involved.

3. The results of the tests reported in this technical memorandum indicated that, in general, surfaces of good appearance were obtained but the depth to which the vacuum processing was effected was very difficult to determine. The strengths of cores from processed concrete as compared to nonprocessed concrete were erratic, indicating that the effectiveness of the process was variable and uncertain. Pull-out tests on form anchors indicated the same general trend. Petrographic examination of cores indicated a pattern of "strings" and "planes" of entrained air peculiar to vacuum-processed concrete. Whether these peculiar patterns of coalesced bubbles of air would eventually prove detrimental is still to be determined. The presence, however, of such a condition is abnormal for air-entrained concrete and cannot therefore be considered a desirable phenomenon. The test program cannot be considered to have yielded information that could serve as a basis for establishing definite and positive techniques and procedures that would guarantee improvement in the quality of mass concrete.

4. In general, the vacuum process for concrete will not be specified or used. Its use will require the prior approval of the Chief of Engineers. Such approval will be based on the submission of a separate design memorandum which will contain a detailed statement outlining why vacuum process is required. If approved for use, applicable specification requirements will be developed for the specific feature involved, and these requirements will be submitted for review and approved by the Chief of Engineers prior to the development of contract plans and specifications. General distribution of this technical memorandum is being restricted to Corps of Engineers personnel and field offices only.

BY ORDER OF THE CHIEF OF ENGINEERS:

Wm Whipple

WM. WHIPPLE
Colonel, Corps of Engineers
Executive
Civil Works

CORPS OF ENGINEERS, U. S. ARMY

INVESTIGATION OF VACUUM TREATMENT OF MASS CONCRETE SURFACES

TECHNICAL MEMORANDUM NO. 6-353

CONDUCTED FOR

OFFICE, CHIEF OF ENGINEERS

BY

WATERWAYS EXPERIMENT STATION

VICKSBURG, MISSISSIPPI

ARMY-MRC VICKSBURG MISS

FEBRUARY 1953

PREFACE

The Office, Chief of Engineers authorized the investigation described in this report in correspondence dated 4 May 1949 to the President, Mississippi River Commission, subject, "Authorization of Item CW-605 'Vacuum Concrete Investigation.'"

The investigation was performed by and at the Concrete Research Division of the Waterways Experiment Station in cooperation with Vacuum Concrete, Inc., during the summer of 1949. Approximately 100 visitors from various offices of the Corps of Engineers, other Government agencies, private corporations, trade publications and technical societies witnessed the construction and vacuum treatment of test models.

The vacuum treatment of concrete requires the use of equipment and methods patented by Vacuum Concrete, Inc., Philadelphia.

It is desired to acknowledge the assistance rendered in the prosecution of this program by the Blaw-Knox Company, the Vibro-Plus Products Corp., and Superior Concrete Accessories, Inc., who supplied the steel forms, form vibrators, and screw anchors, form bolts and templet bolts. In particular the assistance of Vacuum Concrete, Inc., in supplying vacuum pumps, vacuum mats and other equipment together with valuable advice and supervision is acknowledged. The loan of a Whiteman mechanical trowel by the Mississippi Road Builders Association is also acknowledged.

CONTENTS

SYNOPSIS

The series of tests described in this report was conducted in an attempt to determine the proper procedures and techniques for applying vacuum treatment to both formed and unformed surfaces of mass concrete. Test models consisted of a number of slabs varying in thickness from 9 to 36 in., and a 133-cu-yd block simulating three lifts of a monolith in a concrete gravity dam.

Field mixes of 3- and 6-in. aggregate concrete, and field methods of consolidation were employed. Processing time and technique varied from test to test, and an attempt was made to determine the amount of water removed from the concrete. The effectiveness of the treatment was evaluated visually and by physical tests and microscopic examination of diamond-drilled cores from the test slabs and block.

The processing of horizontal surfaces was relatively simple and presented no difficulties. It was found that less water was removed from sloping formed surfaces than from horizontal surfaces (unformed), and least of all from vertical formed surfaces. The depth to which processing was effective was very difficult to determine. Good surface appearance was imparted to all three types of surfaces. Standard steel form panels were readily converted to use as vacuum mats.

Experiences with vacuum treatment of mass concrete surfaces at eight large dams being constructed by the Corps of Engineers are described in an appendix.

INVESTIGATION OF VACUUM TREATMENT OF MASS CONCRETE SURFACES

PART I: INTRODUCTION

Vacuum Treatment

1. Vacuum treatment is a process whereby some of the "extra" water required in the concrete for workability and which is in excess of that required for the hydration of the cement is extracted from the concrete after placing and consolidating, but while the concrete is still in a plastic state. The process, as the name implies, utilizes the principle of application of vacuum through suitable chambers that are in contact with the concrete surface.

Purpose and Scope of Investigation

2. The purpose of the present investigation was to determine proper procedures and techniques for the application of vacuum treatment to horizontal, sloping, and vertical surfaces of mass concrete. The secondary purpose of this investigation was to determine by test on the processed concrete how the process itself, and the procedures and techniques used, influenced the properties of the hardened concrete. Observations and tests were made to determine:

a. Optimum time for processing.

b. Influence of processing time on the quantity of water removed.

c. Influence of processing on form deflection.

d. The proper method for coordinating vacuum processing and consolidation by vibration.

Physical tests and microscopic examinations were made on cores to determine the influence of the vacuum processing in general, and of the variations in vacuum techniques, on the properties of the hardened concrete. A 133-cu-yd concrete test block and seven horizontal slabs of from 0.75 to 3.0 ft in thickness were constructed for testing purposes.

PART II: EQUIPMENT, MODELS AND TESTS

Equipment

Mixing and handling

3. The concrete mixing plant consisted of two 10S Koehring rocking, tilting mixers installed in the laboratory building. The mixed concrete was transported from the mixers by truck in 21-cu-ft straight-sided dump buckets which were conveyed to the forms by crane.

Vibrators

4. The following vibrators were used in consolidating the concrete:

   a. ERSB Vibro-Plus electric vibrator with 19-3/4- by 2-3/16-in. element rated at approximately 15,000 vpm.

   b. MRSB, Vibro-Plus gasoline-driven vibrator with 28- by 4-in. element rated at approximately 12,000 vpm.

   c. Chicago Pneumatic Model 518, two-man vibrator with 18- by 5-1/2-in. vibrating element operating at approximately 5600 vpm at 90-psi air pressure.

   d. ER Vibro-Plus, Top Dog Form vibrator, 3600 vpm.

Vibrating screed

5. A vibrating screed was devised by mounting a Type ER 3600-vpm Vibro-Plus Top Dog Form vibrator on a piece of 6- by 2-in. channel iron, 8.5 ft long (fig. 1).

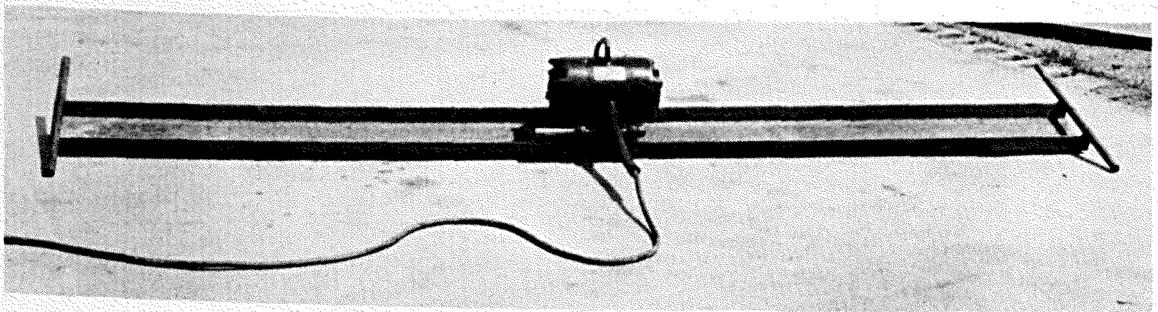


Figure 1. Vibrating screed for striking off concrete

Mechanical trowel

6. A gasoline-driven 36-in.-diameter Whiteman mechanical trowel was used in construction of the models.

Vacuum pump

7. The vacuum pump was gasoline-powered and of 1000-cu-ft capacity, capable of producing a 25-in. vacuum and of processing 600 sq ft of concrete at a 20-in. vacuum at one time (fig. 2).

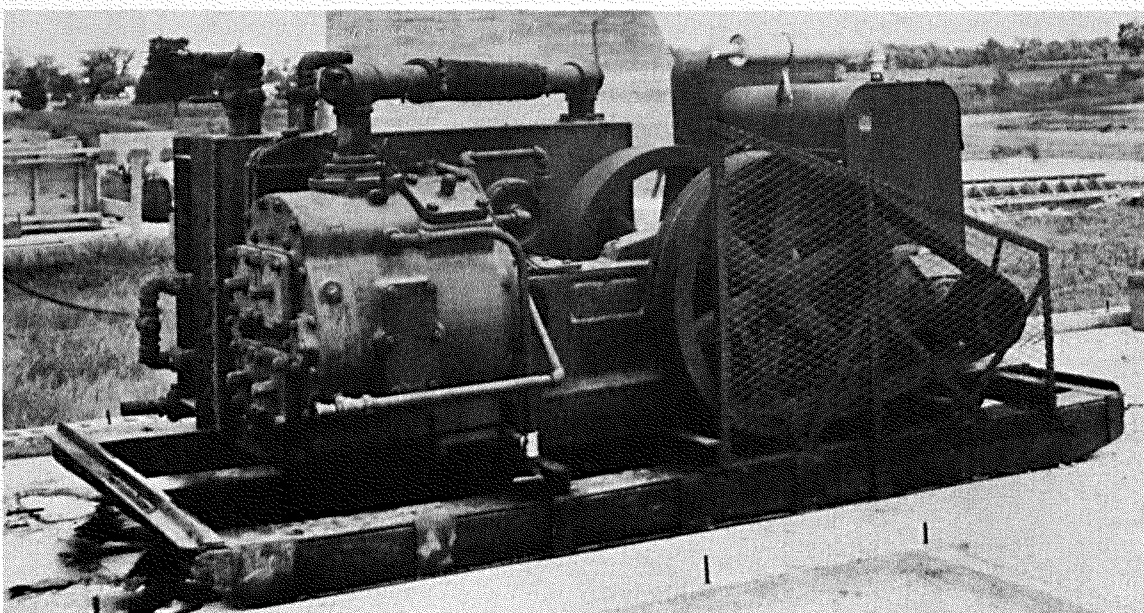


Figure 2. Gasoline-powered vacuum pump

Vacuum mats

8. The vacuum mats used on the horizontal slabs were constructed of approximately 16-gage sheet metal. One side of the mat was covered with insect screen wire. The screen wire was in turn covered with unbleached muslin sheeting. A rubber seal approximately one inch wide surrounded the screen-wire-covered area. Soft, thin, rubber flaps were cemented around the perimeter of the mat to lay on the concrete and prevent leakage through the concrete itself immediately adjacent to the

edge of the mat. The mats were furnished in two sizes, 2 by 4 ft and 3 by 4 ft, and are shown in figure 3.

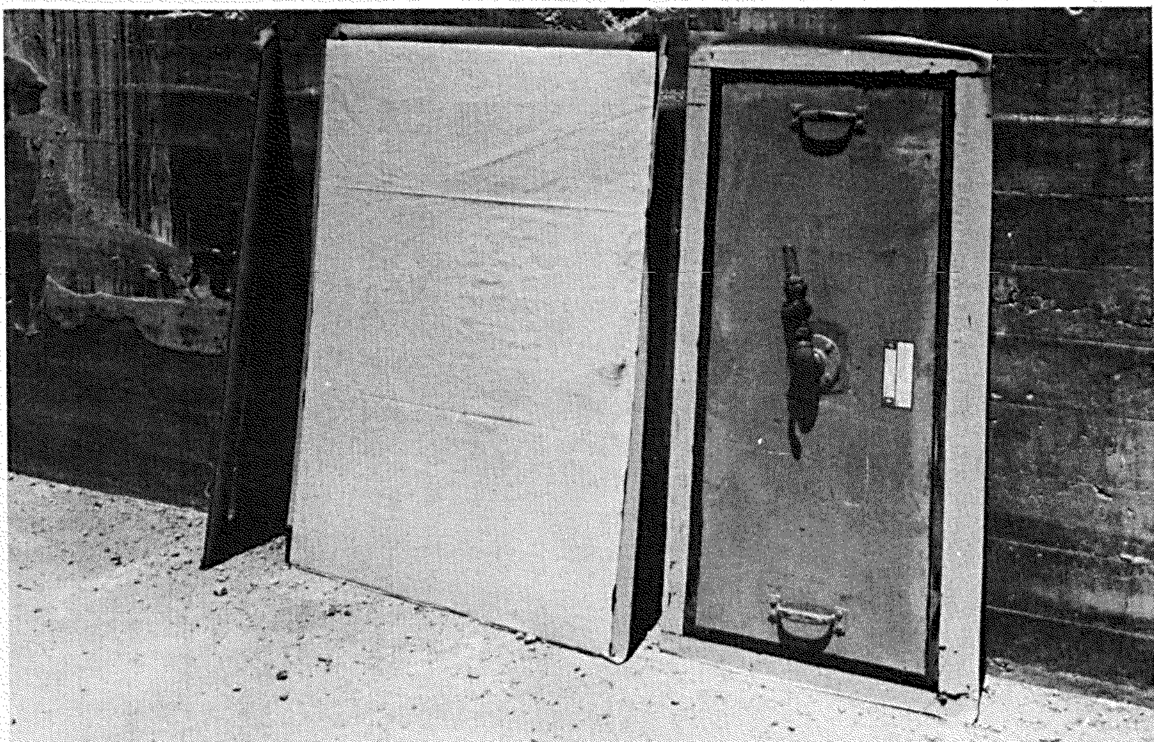


Figure 3. Vacuum mats for treatment of slab surfaces

Steel forms

9. The form panels were regular stock units manufactured for full-scale use in dam construction, and consisted of one 10-ft upstream and one 10-ft downstream cantilever face form, together with two 10-ft bulkhead forms. The panel sections were fabricated of 3/16-in. skin plate stiffened by five (or six, depending on the panel) horizontal 4-in. channels. The form panels were held in place by 1-1/4-in.-diameter anchor bolts embedded in the previous lift and two cantilever walers each made up of a pair of 8-in. channels about 9 ft long. The cantilever walers were adjustable to allow for form alignment. A bulkhead form in place can be seen in figure 4. Schematic assembly of all

forms is shown in plate 1. Construction details, similar for both upstream and downstream panels, are shown for the upstream panel on plates 2-6.

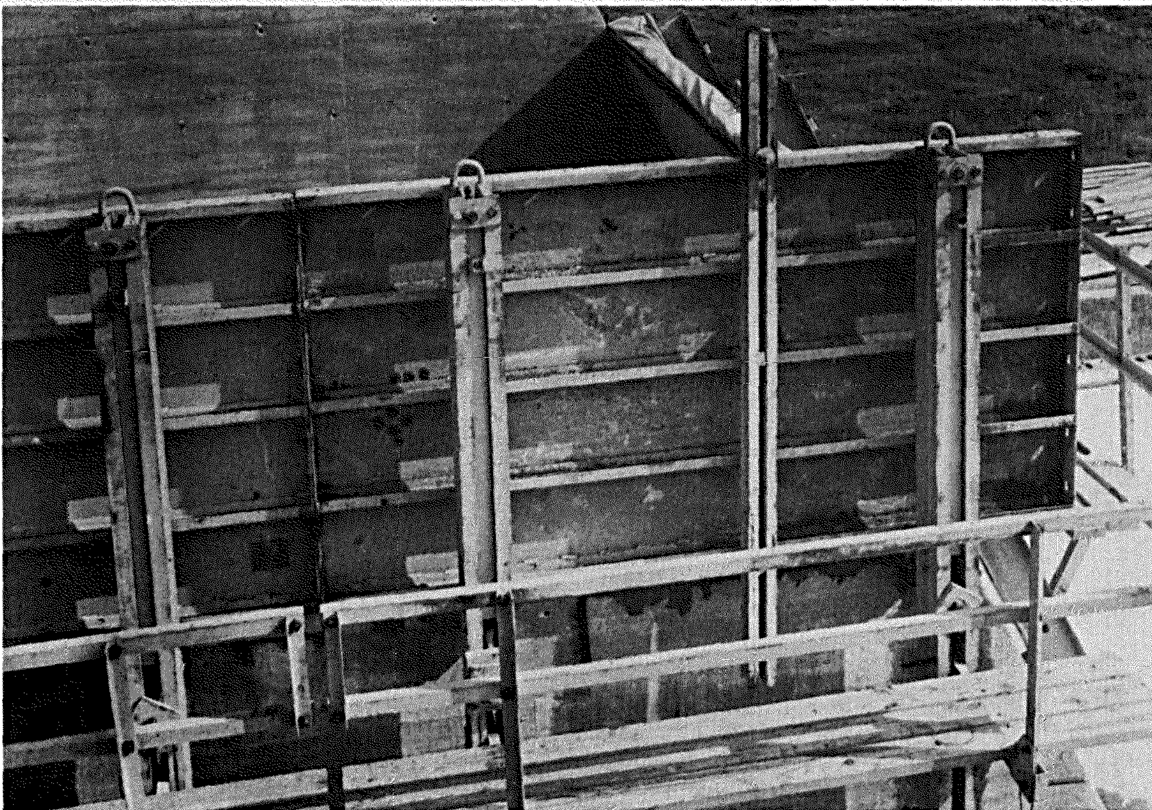


Figure 4. Cantilever-type steel bulkhead form panels in place

10. The upstream and downstream form panels were converted to serve as large vacuum mats while the bulkhead panels were used as received. Two layers of bronze screen-wire cloth were used between the skin plate and muslin. The wire was fastened to the skin plate by spot soldering and by lacing it on with fine wire passed through the mesh and through 5/16-in. holes in the skin plate under the vacuum manifold. The top was sealed by means of a 6-in.-wide flap of thin soft rubber laid on the fresh concrete. Seal along the hardened surfaces and between panels was obtained by sponge rubber strips. The horizontal seal between courses for the lowest lift was made with caulking compound applied to

the screen wire. Figure 5 is a view of workmen attaching the screen wire to a form panel. Figure 6 shows a panel ready to be lifted into

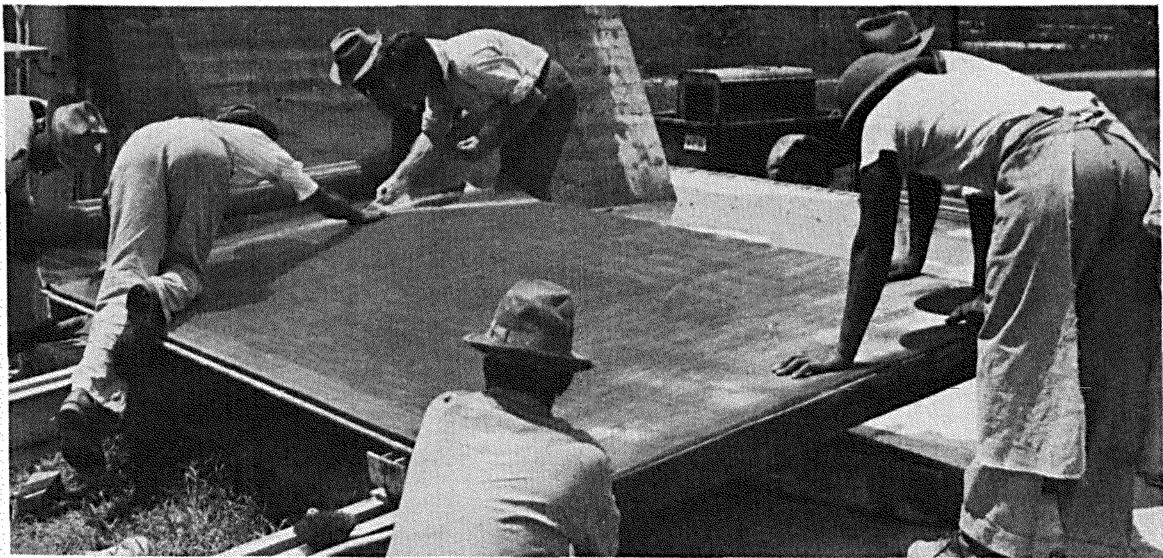


Figure 5. Attaching screen wire to steel form panel

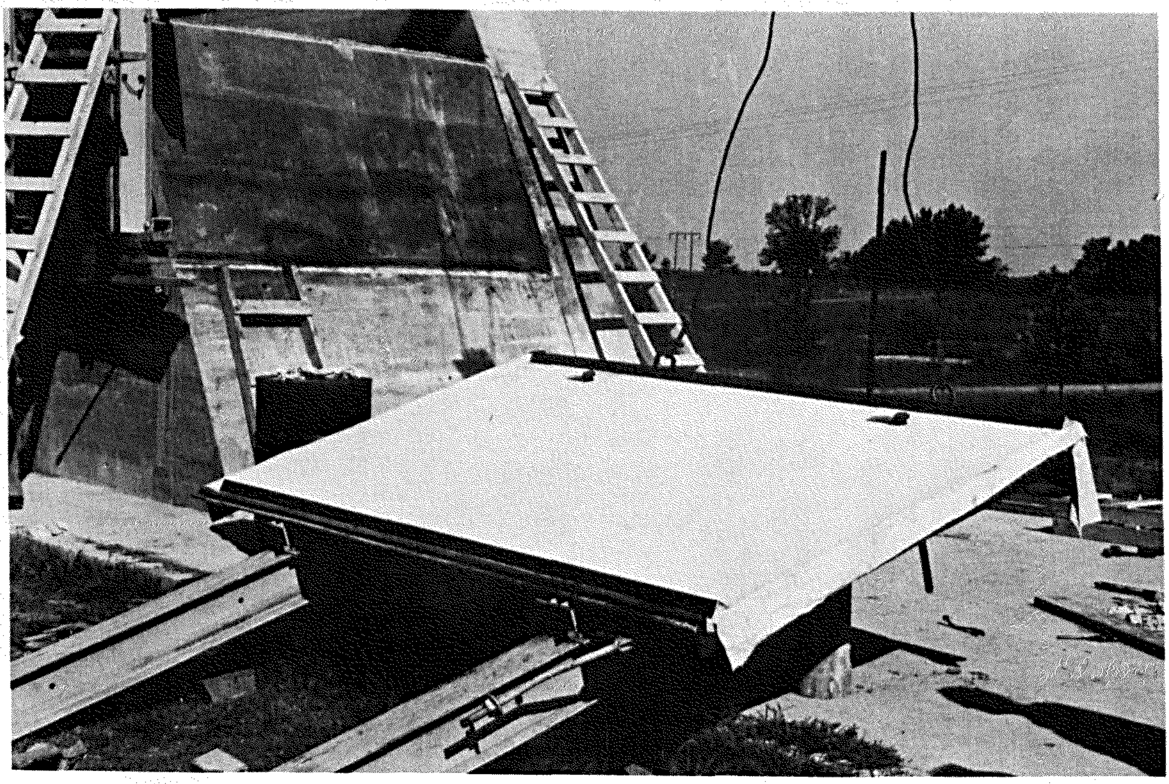


Figure 6. Downstream (sloping) form panel converted to act as vacuum mat ready to be hoisted into place

place, and figure 7 shows a panel in place, ready to receive concrete.

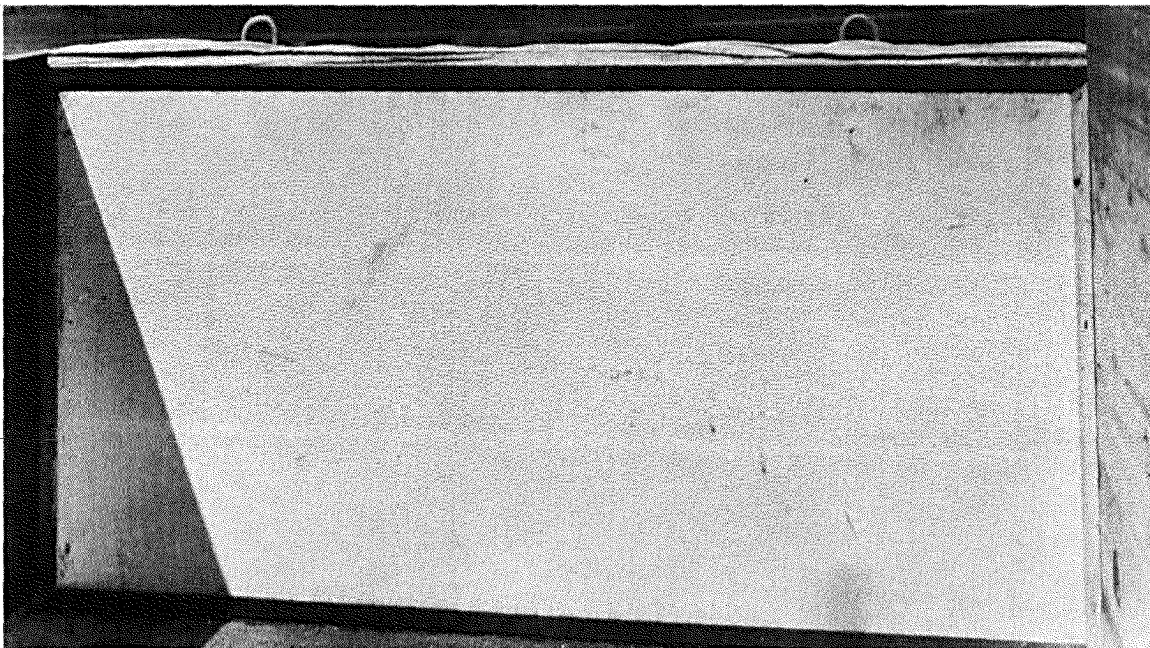


Figure 7. Upstream (vertical) converted form panel in place ready to receive concrete

Wood forms

11. Wood forms were used for the slab specimens.

Anchor and templet bolts

12. A screw anchor and bolt may be seen in figure 8. The templet bolts should have been 2 in. longer than the anchor bolts; however, the templet and anchor bolts used were actually the same length, owing to an error in the original detailing. This is mentioned because it became a source of form movement as described later.

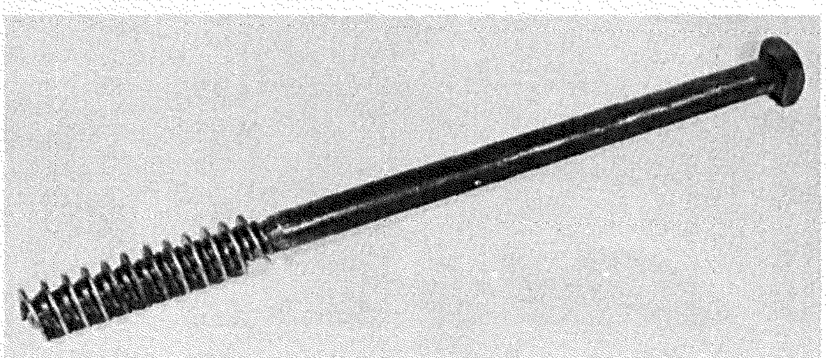


Figure 8. Screw anchor and bolt

Models

Horizontal slabs

13. Seven slabs containing a total of 17.3 cu yd of concrete were made as follows:

Specimen No.	Size, Ft	Coarse Aggregate, In.	Cement Factor Bags/Cu Yd	Treatment
a	6.5 x 8.5 x 0.75	3	4	None
b	6.5 x 8.5 x 0.75	3	4	Vacuum
c	6.5 x 8.5 x 0.75	3	4	Vacuum
d	6.5 x 8.5 x 0.75	3	4	Vacuum
e	6.5 x 8.5 x 1.5	6	3	Vacuum
f	6.5 x 8.5 x 3.0	6	3	Vacuum
h	6.5 x 8.5 x 0.75	3	4	Vacuum

Note: The large block was called specimen g in the program.

Block

14. The test block (specimen g) contained a total of 76.4 cu yd

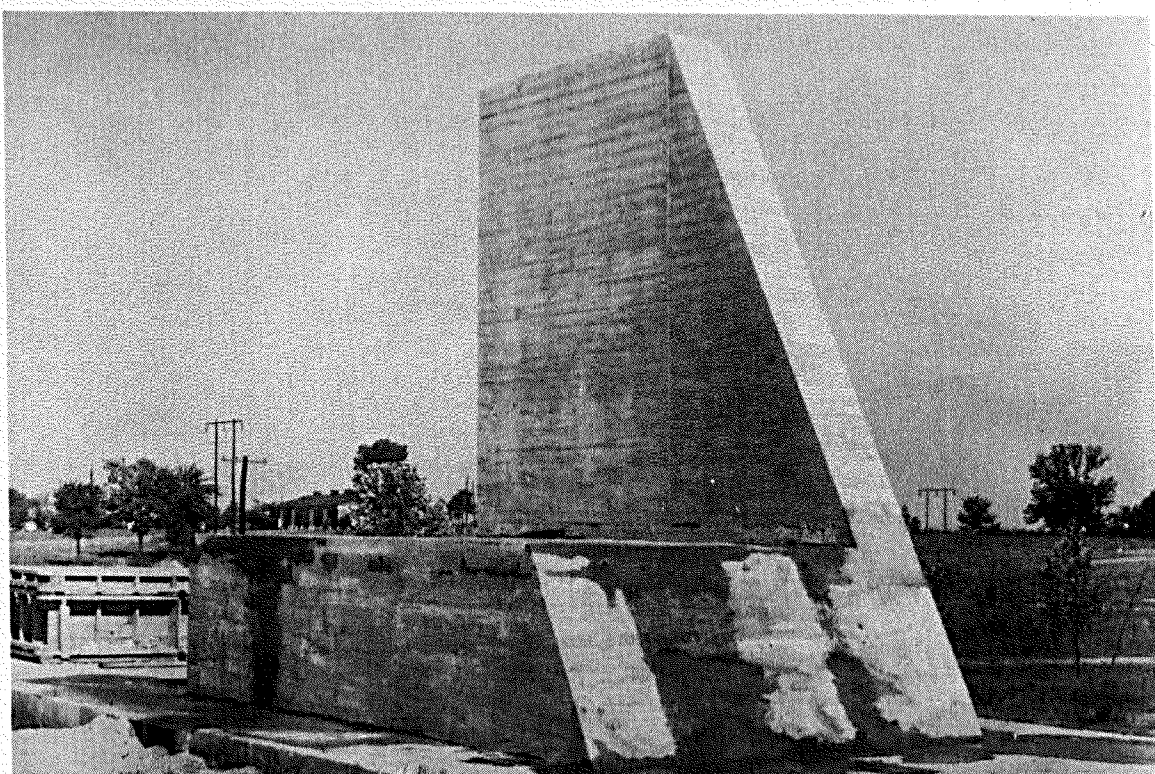


Figure 9. Foundation block and bulkhead wall

of 6-in.-aggregate concrete. The base lift and bulkhead wall (fig. 9) contained a total of 56.9 cu yd of commercial ready-mixed concrete.

15. The processed portion of the test block was 10 by 10 ft in horizontal dimensions at the top, 15 ft high, and 10 by approximately 17.5 ft at the bottom. The back (upstream) was vertical and the face (downstream) was on a 1-on-2 slope. The three lifts placed during the investigation required the following quantities of concrete:

Item	Cu Yd	
Lift 1, course 1	10.6	
Lift 1, course 2	10.0	
Lift 1, course 3	9.5	
Lift 1, total		30.1
Lift 2, total		25.5
Lift 3, total		20.8
Total		76.4

Materials

16. Cement. Type II cement, laboratory serial no. RC-179, was used. Test data are given in table 1.

17. Aggregates. Both fine and coarse aggregates were crushed limestone from the Bull Shoals Dam project. Test data are contained in table 2.

18. Air-entraining admixture. The air-entraining admixture was a solution of neutralized vinsol resin.

Mixture designs

19. Three concrete mixtures were designed as follows:

a. Three-inch coarse aggregate, 4.0-bags-per-cu-yd actual cement factor; air content 4.5 ± 1-1/2% in the portion passing the 1-1/2-in. sieve; plastic, workable, and with approximately 2-1/2-in. slump (for the 0.75-ft slabs).

b. Six-inch coarse aggregate, 3.0-bags-per-cu-yd actual cement factor; air content 4.5 ± 1-1/2% in the portion passing the 1-1/2-in. sieve; plastic, workable, and with approximately 2-1/2-in. slump (for the interior of the block and for the 1.5- and 3-ft slabs).

c. Six-inch coarse aggregate, 4.0-bags-per-cu-yd actual cement factor; air content 4.5 ± 1-1/2% in the portion passing the 1-1/2-in. sieve; plastic, workable, and with approximately 2-1/2-in. slump ("exterior"). The details of these mixtures are given in table 3.

Tests

20. Tests and observations were made during the casting of the six slabs and large block to determine the following:

a. Surface appearance after treatment.

b. Deflection of forms.

c. Amount of water removed and optimum time for processing.

d. Compressive strength of:

   (1) Cast cylinders for information on the concrete itself.

   (2) Diamond-drilled cores for information on concrete in the models. Cores drilled according to plate 7 and disposed of as shown in table 4.

e. Pull-out strength of pigtail-type screw anchors.

f. Resistance to laboratory freezing-and-thawing, determined by testing cores.

g. Resistance to natural weathering of core sections exposed on the half-tide exposure rack at Treat Island, Eastport, Maine.

h. Amount, distribution, and bubble size of entrained air in cores as revealed by petrographic examination.

PART III: TEST RESULTS

Fabrication of Models

Casting horizontal slabs

21. No difficulty was encountered in placing or processing the slab specimens. The seal between mat and slab surface was excellent and a high vacuum was attained. Concrete was carried 1/4 in. above grade for each foot of slab thickness to allow for settlement caused by removal of water. Slab a was a control slab and was not processed. Slab b was processed for 30 minutes, starting immediately after screeding and floating. Slab c was processed for 30 minutes starting approximately three and one-half hours after mixing. The other slabs were all processed approximately two hours after mixing. Slabs d and f were processed 30 minutes each, slab e, 18 minutes, and slab h, 9 minutes. The processing time of 30 minutes represented maximum practicable treatment. Processing times of 9 and 18 minutes for slabs h and e, respectively, corresponded to one minute of processing for each inch of slab depth.

22. All slabs were screeded with the vibrating screed. Slabs e and f were machine-troweled, all the others were hand-troweled immediately after processing. All surfaces were too hard for good hand-troweling, and the machine had a tendency to tear the surface over large cobbles. Curing was by wet sand for 14 days.

23. Table 5 presents placing and plastic concrete data on the slab specimens and amount of water removed.

Casting block

24. The block was cast in three lifts on three separate days, with

approximately 48 hr between lifts. Forms were all removed at 24 hr. Refrigerated mixing water was used in all concrete placed in the block to reduce concrete temperatures and to retard the setting rate. The influence of the use of refrigerated water on the placing temperature of the concrete was relatively minor, as is indicated by data given in table 6. The concrete in the block was placed at a temperature range from 73° F to 77° F which averages approximately 6° F below the placing temperature of the concrete in the slabs where no refrigerated water was used. The forms were checked for deflection. Concrete buckets were handled by crane as shown in figure 10. Curing of the vertical and sloping surfaces was by a membrane-forming curing compound. Horizontal surfaces were water-cured

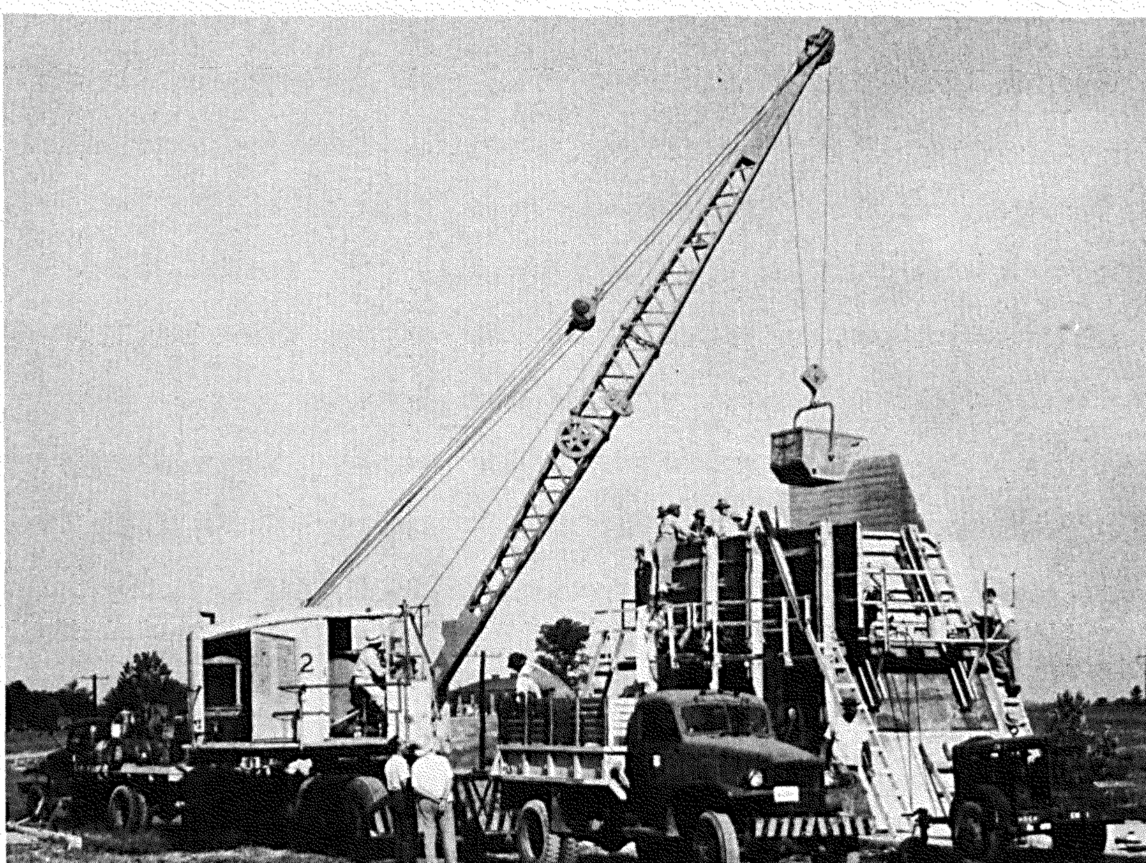


Figure 10. Handling concrete for vacuum test block

for 14 days or until covered by new concrete. Clean-up between lifts was accomplished by air-water jet.

25. Placing and plastic concrete data and amount of water removed for the three lifts of the large block are summarized in table 6.

26. Placement of first lift. The first lift (5 ft) was placed in three 20-in. courses in conventional manner, with face concrete (6-in. aggregate, 4.0-bags-per-cu-yd cement factor) against the upstream and downstream faces only. Interior concrete (6-in. aggregate, 3.0-bags-per-cu-yd cement factor) was used against the bulkheads and in the interior of the block. The concrete was vacuum-treated at 25 to 27 in. of vacuum, gaged at the pump, for 30 minutes after each 20-in. course had been placed. The downstream half of the monolith was consolidated by means of the Vibro-Plus 4-in., high-frequency vibrator, while the upstream half was consolidated by means of the Chicago Pneumatic two-man vibrator. After vacuum treatment the surface adjacent to the form in each course was revibrated by the vibrators used in the original consolidation, to break up and reconsolidate any channels formed by water withdrawn during processing. No difficulty was experienced in revibration.

27. The horizontal surface of the lift was cut with an air-water jet at the appropriate time after placement. Curing was by water, and the surface was flushed prior to placement of the second lift.

28. Appearance of surfaces of first lift. The forms were removed at approximately 24 hr. The vertical surface was fairly free of blemishes and pleasing in appearance. There were, however, horizontal lines corresponding to the seal marks under the muslin of the vacuum form, and in addition there was evidence of slight movement of the form. This

movement was believed caused by compression of the wood spacer blocks under the heads of the long anchor bolts, when the concrete was vibrated against the form.

29. The sloping downstream surface contained seal marks and in addition had several scattered patches of honeycomb areas which were doubtless due to insufficient use of the vibrator. These areas were patched immediately after form removal.

30. Placement of second lift. Immediately prior to placement of the second lift (5 ft), the surface to receive concrete was flushed and broomed with a coating of grout of the same water-cement ratio and proportions as the mortar phase of the exterior mix. The concrete mix for this lift was altered by addition of one pound of a retarder per bag of cement in order to delay the setting time. The retarder permitted a reduction of 0.6 gal per bag in the water-cement ratio. Use of a retarder was believed desirable since the concrete was to be placed to the full 5-ft depth of the lift (in the standard three courses) prior to application of vacuum and it would have been difficult, because of limited mixing plant capacity, to bring the concrete to full depth before hardening started.

31. Face and interior concrete were used in the second lift. The first course was consolidated by the Chicago Pneumatic vibrator, the second course by the Vibro-Plus, and the third course was consolidated along the vertical face by the Vibro-Plus and along the sloping face by the Chicago Pneumatic. Each face was processed for 30 minutes at a vacuum of 17-20 in. on the vertical face and 20 in. on the sloping face, as measured at the form.

32. It had been intended to process for 10 minutes, then shut off

the vacuum and vibrate the form for one minute, repeating the process three times. However, considerable difficulty was experienced in vibrating during processing because the vibrator mountings, being on strap iron welded to the walers, allowed whip to develop, and loss of efficiency resulted. It is believed that the forms were sufficiently vibrated, nevertheless, although not exactly according to the pre-arranged schedule. The form vibrator mountings were later welded to angle iron which was in turn welded to the form in planes 18 in. above and below the edges of the form and at the quarter points, in the manner shown in figure 11, before placement of the final lift. This arrangement proved satisfactory.

33. Movement of nearly an inch occurred at the top of the vertical

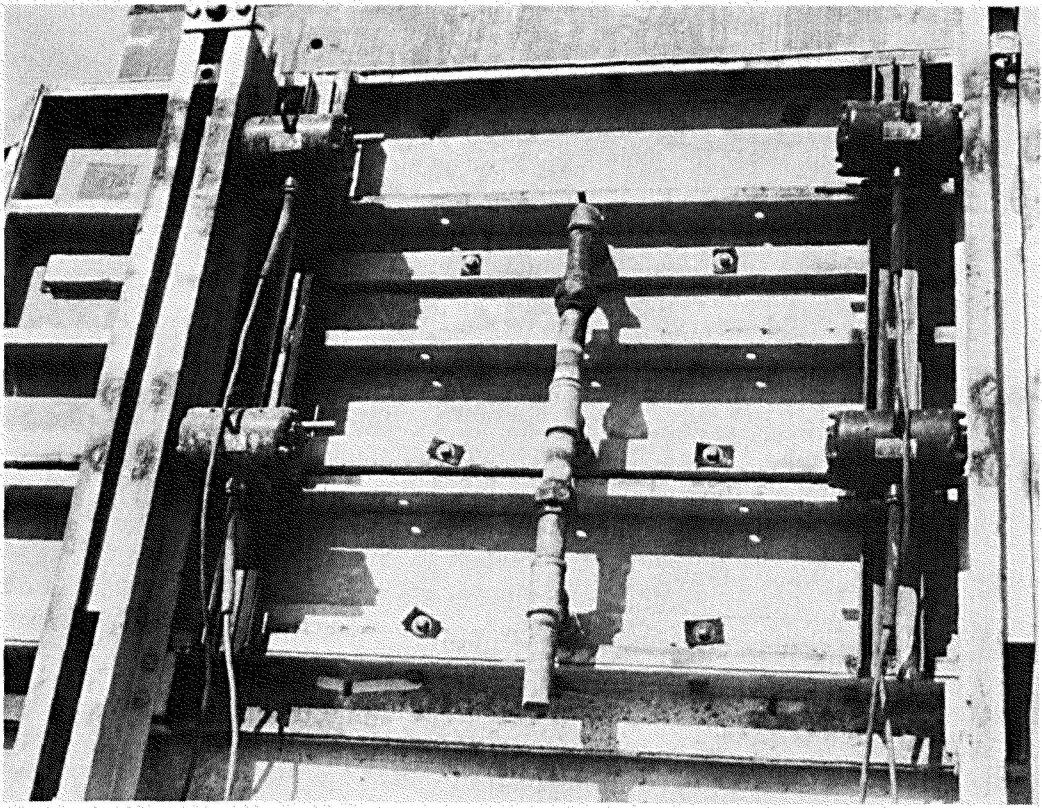


Figure 11. Form panel with four vibrators in place

form because of compression of the wood spacer blocks under the heads of the long anchor bolts when the concrete was vibrated. This movement made a vacuum-tight seal difficult to establish as indicated by the relatively low vacuum of 17 in. obtained.

34. Appearance of surfaces of second lift. The treated vertical surface was free of blemishes. The fact that the surface showed no blemishes even though the form moved indicates that the concrete was plastic throughout the 5-ft depth during the processing, and remolded itself against the form as the form moved. The sloping surface was free of blemishes except for a chipped area along the bottom V-strip which was damaged in removing the form.

35. Placement of third lift. The final lift was composed of 3-bag (interior) concrete throughout. Placing was done as on the previous lifts; however, the concrete was kept back from the exposed faces until the major portion of two courses had been placed. Then the concrete in the first course to be in contact with the mat was deposited and vibrated. This was followed by the second-course concrete against the face, thus bringing up the first and second courses against one face, then against the other, followed by the complete third course. This method insured that the concrete against the vacuum forms was fully plastic when processing was carried on. All concrete in this lift was consolidated by means of the Chicago Pneumatic vibrator. The vertical face was processed in cycles of 10-min vacuum followed by 1-min external vibration with the four regular form vibrators, until a total of 30-min vacuum had been applied. The vacuum attained was between 21 and 22 in. at the form. Leaks were detected along the top rubber seal and at the

bottom of the lift against the bulkhead wall. Vacuum and vibration were applied alternately to the sloping surface also; however, vibration was by means of the large Vibro-Plus vibrator which had been mounted on a shop-made vacuum holder as shown in figure 12. Trouble was experienced

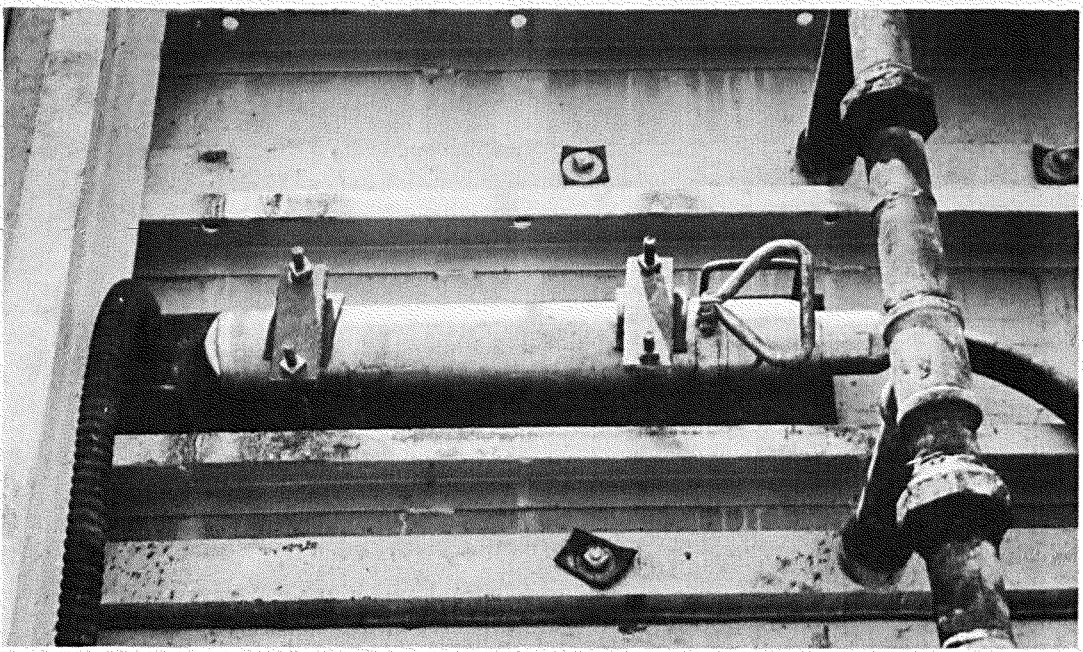


Figure 12. Shop-made vacuum holder for adapting internal vibrator to form vibration

with shop welds. One of the bolts holding the vibrator crystallized and broke under vibration. This one vibrator was not as effective as the battery of four external form vibrators used on the vertical surface. However, two of the large internal vibrators used in this manner would have been fully as effective. Use of the vacuum holder was successful, the vibrator being held firmly to the form during use with no rigid or permanent connections necessary.

36. Appearance of surfaces of third lift. The vertical face, upon form removal, was found to be pleasing in appearance and free of blemishes. The appearance of the sloping face was marred by patches of

honeycomb caused by insufficient internal vibration. The vertical and sloping faces of all three lifts are shown in figures 13 and 14.

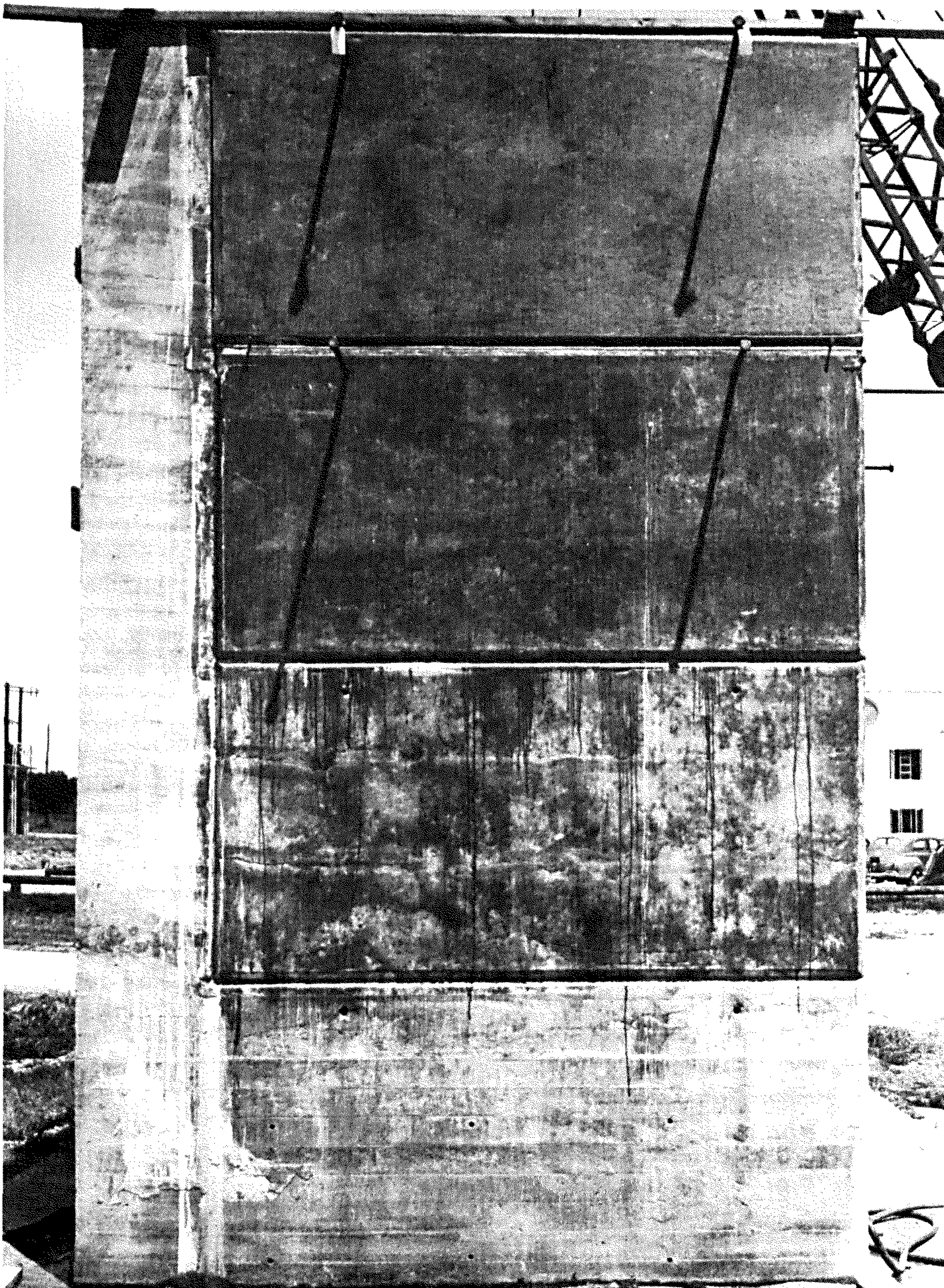


Figure 13. Vertical face of block after form removal

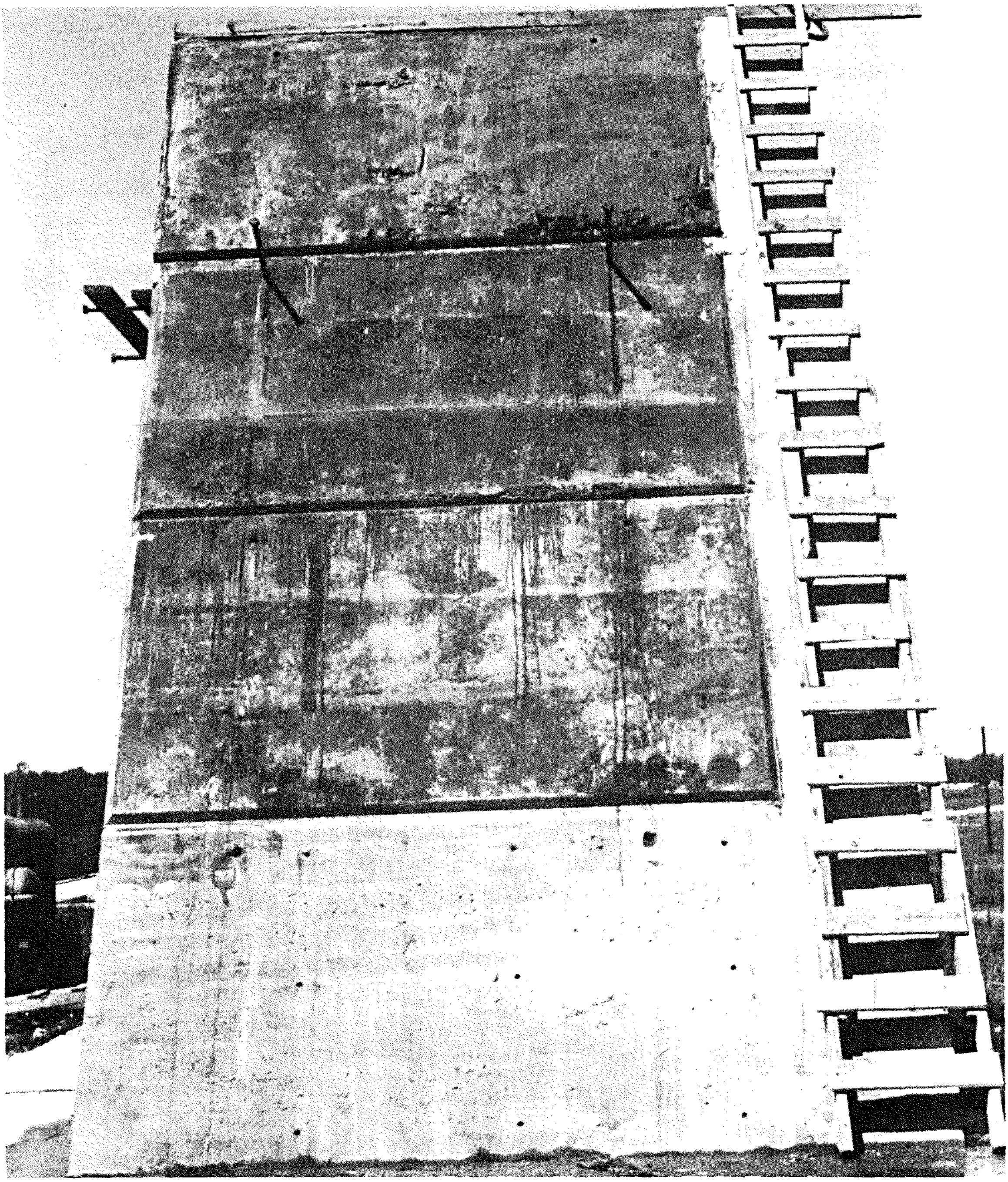


Figure 14. Sloping face of block after form removal

37. Discussion of placing and processing procedures. Use of the regular Blaw-Knox form panels as vacuum mats presented no unusual problems and would have occasioned no trouble had the anchor bolts been of the

correct length instead of being 2 in. too long, thus necessitating the use of blocking under the bolt heads. Wood blocking used on the first and second lifts permitted the form panels to move as the concrete was consolidated. Steel shims used on the third lift held the forms true to line.

38. Good seal between the forms and the hardened concrete bulkhead wall was sometimes difficult to achieve owing to the unevenness of the bulkhead concrete. Also some leakage occurred under the soft rubber flap seal used on the horizontal surface of the concrete. A flap seal wider than the approximately 6-in. seal used might be an improvement. Leaks difficult to locate also developed; these were later believed to have been caused by honeycomb areas near the lift joint or the concrete bulkhead wall.

39. Revibration with internal vibrators to break up any water channels caused by the movement of water under the vacuum treatment was successful, and no difficulty was experienced.

40. Vibration of the full depth of concrete by means of the external form vibrators alternated with vacuum treatment produced the best-looking surfaces.

41. Both the Chicago Pneumatic two-man vibrator and the Vibro-Plus 4-in. vibrator performed efficiently in concrete consolidation judging from the ease with which they handled the 6-in. concrete in these tests.

Deflection of Forms

42. Deflection in the steel forms during vacuum-processing was

checked by transit and found too small for measurement.

Water Removed by and Optimum Time for Processing

Slabs

43. The measured amount of water extracted varied slightly with the depth of slab treated and to a greater extent with length of processing and age of concrete when processing began. The optimum age for starting vacuum treatment judged by quantity of water removed seemed to be approximately two hours after mixing.

44. Figure 15 shows the relationship between length of treatment, age of concrete, depth of slab, and amount of water removed. The greatest amount of water was extracted from the 36-in.-thick slab processed 30 min and the least amount from slab h, 9 in. thick processed 9 min. The next greatest amount was removed from slab d, 9 in. thick processed 30 min. Total amount of water removed per square foot of treated surface varied from about 0.04 to 0.08 gal. The amount removed

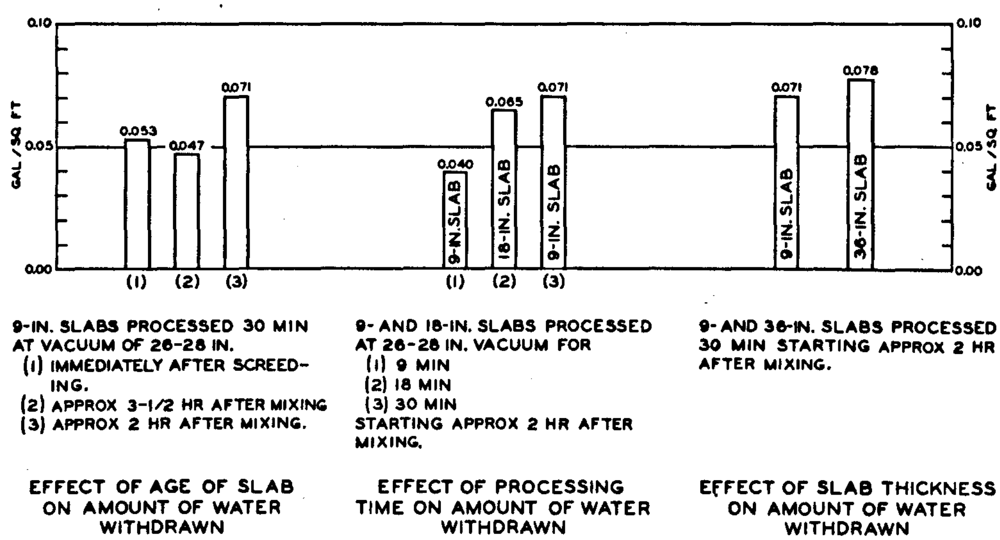


Figure 15. Effects of age of slab, processing time, and slab thickness on amount of water withdrawn

under the conditions of test employed was somewhat less than had been expected (see table 5).

Block

45. The water removed per square foot of sloping or vertical surface was small (see table 6). Generally more water was removed from the sloping surfaces than from the vertical. This was to be expected since settlement of solids and the relative movement of water in a concrete mixture occur in the vertical direction. The sloping surface approaching, as it does, the horizontal (normal to the bleeding plane) intersects bleeding water channels and a vertical surface does not. The extraction of water by vacuum from a vertical surface requires the changing of the natural upward movement of bleed water to a lateral movement.

46. Concrete mixtures having more pronounced tendencies to bleed than those used in this test series would have permitted a greater amount of water to be withdrawn from both the horizontal and vertical surfaces. Footnote 2 of table 3 gives a probable explanation for the low bleeding characteristics of the concrete used. The already low bleeding tendency of the mixes was further reduced by use of the retarder which caused a reduction in water-cement ratio of 0.6 gal per bag when the second lift of the large block was placed.

47. Examination of table 6 shows values for bleeding of 1.3 per cent for the first lift, 0.5 per cent for the second, and 2.3 per cent for the third. All these values are negligible, with the value of 0.5 per cent being extraordinarily low, thus indicating the "tightness" of the mixes used. These mixes were almost identical with those used on Bull Shoals Dam, the aggregates having been obtained from that project.

The low bleeding and tight mixes, from which it is difficult to extract water by vacuum, are not unusual and may be expected where limestone fine and coarse aggregate is used in mass concrete.

Compressive Strength

Cylinders

48. Table 7 lists the compressive strength of 8- by 16-in. cylinders made of concrete wet-sieved through the 2-in. sieve from concrete entering the slabs and block. These specimens were made purely as controls, to furnish information on the concrete in the test structures. The retarder used appeared to reduce the compressive strength, with this influence more pronounced in the 4-bag than the 3-bag mixes.

Cores from slabs

49. Figure 16 shows the typical appearance of cores with 3-in.

Figure 16. Eight-inch cores with 3-in. aggregate taken from slab d

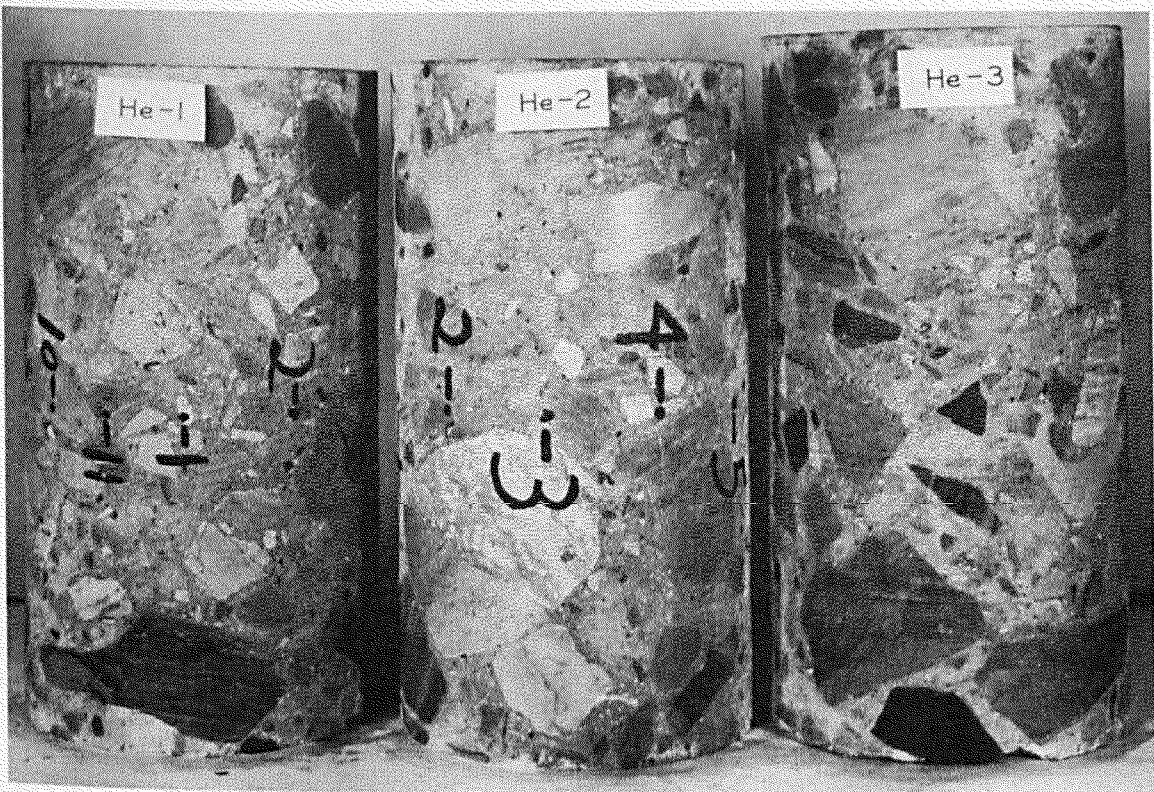


Figure 17. Typical 10-in. cores of 6-in. concrete from 18-in. slab e

aggregate taken from the 9-in. slabs. Figure 17 shows typical 10-in. cores with 6-in. aggregate taken from the 18-in. slab; strengths of these cores are listed in table 8. Positive conclusions as to the effect of the vacuum process on compressive strength cannot be drawn from these data because of the small number of test specimens. Two of the cores from the vacuum processed 4-bag concrete (Hc-4 and Hh-4) showed lower strengths than core Ha-4 which was from nonprocessed 4-bag concrete. The other two cores from processed 4-bag concrete had higher strengths, but only core Hd-4 had appreciably higher strength than core Hh-4. The strength data from the two cores drilled from 3-bag concrete were also inconclusive. The top section of core Hf-4, however, did show appreciably higher strength than the bottom section which apparently received little or no benefit from the processing. The general conclusion to be drawn from limited strength data on these cores is that a positive and definite uniform improvement in strength may not be realized from vacuum processing under field conditions. Judging from the values obtained, the optimum time for processing, based on water extracted per square foot and on strength, appears to be approximately two hours after mixing. Also, indications are that for optimum results with a tight mix, such as used in these tests, the length of processing time possibly should exceed the rule of thumb, "one minute of processing per inch of slab depth."

Cores from block

50. The compressive strength of cores from the large block are listed in table 9. The locations from which these cores were taken are indicated on plate 7. It is believed that the amount of water per square foot of vertical and sloping surface removed in processing the vertical monolith was too small to have a measurable effect on the compressive strength of cores extracted therefrom. The cores secured from the vertical and sloping surfaces generally were long enough to provide two test specimens. Cores Vf-1 and Vf-10 provided only single specimens because they intersected the plane of the lifts underlying them at a core length, thus precluding the possibility of making two test specimens. Vf-19 inner section was broken after drilling, and thus was too short for testing. Figure 18 shows typical appearance of cores drilled from the block.

51. The processed section (outer) of each core showed higher compressive strength in all cases except one (Vb-10) than the unprocessed (inner) section. This does not necessarily indicate that the outer

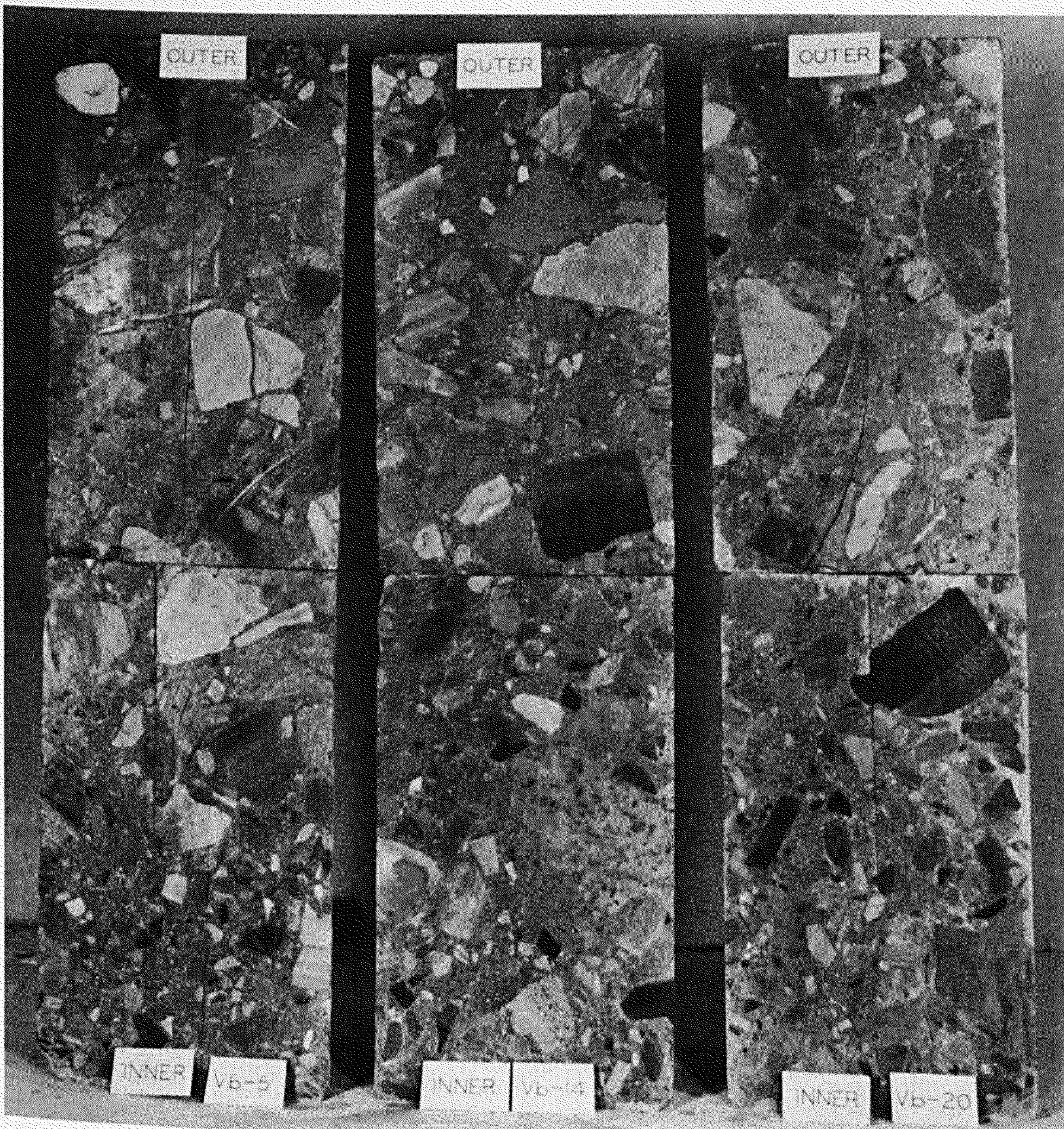


Figure 18. Typical appearance of 10-in. cores from all three lifts, vertical face, after cutting open

sections were stronger due to the processing because they were expected to be stronger due to the lower water-cement ratio since the face concrete contained 4.0 bags per cu yd of cement as compared with 3.0 bags for the interior. The outer section of Vb-10 showed slightly lower strength than the inner section of the same core despite processing and higher cement factor of the outer section. Concrete in this lift contained the retarder which affected the compressive strength of the 4.0-bag outer concrete to a greater degree than it did that of the 3.0-bag inner concrete. All concrete in the second lift generally showed erratic and lowered strength results.

Pull-out Strength of Screw Anchors

52. Five bolts and screw anchors were set in regular position near the top of the third pour for test of pull-out strength. The bolts were all 1-1/4 in. in diameter embedded 6 in. from the top surface; however, the length of the screw insert and the depth of the insert from the surfaces varied. These anchors were tested, using a hydraulic jack and the test setup shown in figure 19. The tests were conducted approximately 24 hr after placing to determine the direct pull-out load required to cause failure. The results are tabulated as follows:

Concrete Age 24 Hr

Bolt No.	Embedment In. (3)	Length of Screw In.	Load on Bolt at Failure, Lb Total	Per In. Embed.
1 (1)	3-1/2	4-1/2	31,000	8,850
2 (1)	3-1/2	3-1/2	22,600	6,450
3 (2)	5-1/2	7	41,700	7,600
4 (1)	3-1/2	2-1/2	23,400	6,700
5 (1)	3-1/2	3-1/2	26,000	7,400

(1) Vacuum-treated.
(2) Nonvacuum-treated.
(3) Nearest end of anchor to surface.

The pull-out load placed by the fresh concrete on each anchor bolt of the 5- by 10-ft cantilever panels was a possible maximum of approximately 15,800 lb. This, of course, does not include the load placed on the

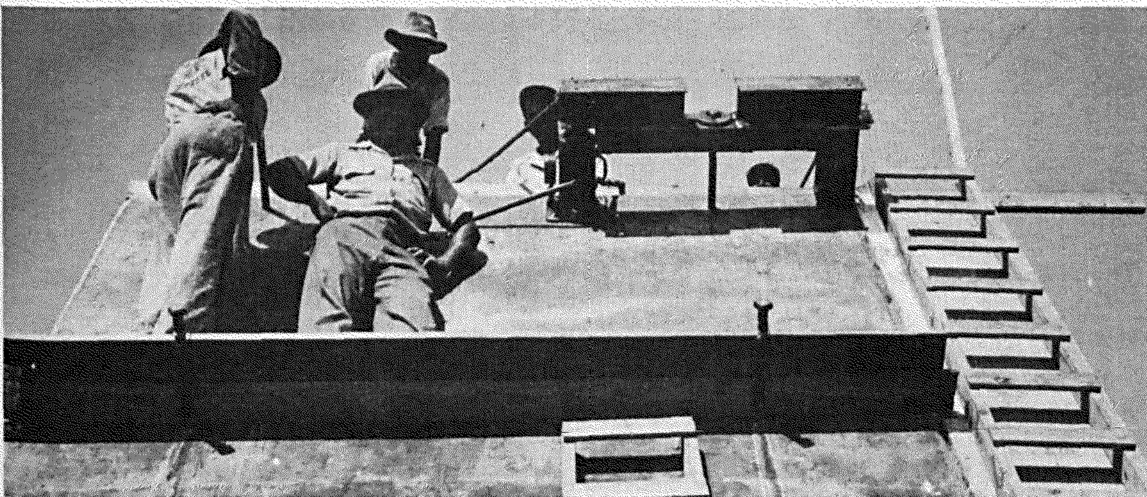


Figure 19. Setup for testing pull-out resistance of screw anchors

screw anchor by the weight of the panels and tightening of the bolts when the forms were set. If allowance is made for these factors, the short screws embedded only 3-1/2 in. would not be safe for use at the early age tested.

Durability of Cores

Laboratory freezing-and-thawing

53. Laboratory freezing-and-thawing tests on the cores so designated in table 4 were made in connection with the development of a freezing-and-thawing test method, and are not reported herein.

Field durability, Treat Island

54. The core sections designated "Treat Island" in table 4 were placed at half-tide elevation on the exposure rack at Treat Island, Cobscook Bay, Eastport, Maine, in the autumn of 1949. At the time of publication of this report they have undergone three winters of exposure, being subjected to more than 350 cycles of freezing-and-thawing in air and sea water. All the core sections except four have relative

modulus-of-elasticity values greater than 100 per cent. One core was found to be cracked when inspected after approximately 350 cycles, one core failed to give sonic response after 350 cycles, and four showed slight spalling with no decrement in modulus of elasticity. No correlation between deterioration and location of cores and processing has yet developed.

Petrographic Examination

55. Petrographic examination was made on 18 cores from the horizontal slabs and test block. The cores are identified and described in table 10. Four cores from vacuum-treated concrete at Whitney Dam were examined for comparison.

56. The distribution of entrained and entrapped air in cores from the horizontal slabs and test block is summarized in tables 11 and 12. The air content of several cores from the slabs and test block is reported in tables 13 and 14, and the calculated average diameter of the voids is shown in table 15. The distribution of entrained and entrapped air in the cores from Whitney Dam is summarized in plate 8. Plates 9 through 13 illustrate several features of the cores.

57. All of the cores from the horizontal slabs and the test block contained strings and planes of entrained air voids adjoining coarse aggregate particles. In many instances, the bubbles had coalesced partly or completely to form boundary voids along coarse aggregate (plates 9, 10, and 12). Many of the boundary voids were not on the underside of the coarse aggregate, but were located on steeply sloping sides or at the top of coarse aggregate. Conditions similar to this had been found in

other concrete samples previously examined, but the concrete cores examined in this program exhibited the strings of bubbles and boundary voids to a greater degree than most mass concrete which had been previously examined. The difference is striking when these cores are compared with cores from Mt. Morris and Whitney Dams, and with cores from Bull Shoals Dam made with the same aggregate. The Bull Shoals cores show more strings of voids and boundary voids than the cores from Mt. Morris or Whitney, but the difference between the Bull Shoals concrete and that made in the vacuum program with the same aggregate is considerable. The relative abundance of strings and planes of bubbles and boundary voids in the model block is not believed to be related to the vacuum process, but may be related to the use of high-speed vibrators or to conditions brought about by the placement of fairly large amounts of mass concrete without equipment of the kind and scale used in mass concrete construction and without experienced crews. This peculiarity of the concrete in the test program may affect other aspects considered in the examination, and the extent of these effects cannot be measured. The cores from vacuum-processed concrete placed in Whitney Dam provided a useful comparison. It is believed that the features possessed in common by the vacuum-treated concrete from Whitney and that made in this program can be used as a basis for some generalizations about the effects of vacuum-processing on mass concrete recognizable in petrographic examination.

58. Only one characteristic of the cores from the horizontal vacuum-processed slabs could reasonably be ascribed to the influence of the vacuum process. That was the darker color of the mortar in the layer adjoining the vacuum-processed surface. The color difference diminished away from

the vacuumed surface and was not sharp or conspicuous in every core. The arrangement of air voids near the surface appeared to be affected more by the finishing than by vacuum treatment under a horizontal vacuum mat.

59. The outer dark layer of mortar was present in several of the cores cut normal to vacuum-treated formed surfaces of the test block. The entrained air voids were smaller and less numerous in the outer 1/2 in. of all of the cores; in five out of six the entrained air voids increased gradually inside that zone and became fairly constant 5 or 6 in. from the surface. Two of the three cores normal to the inclined face had accumulations of large entrapped air voids in the outer 4 in.; these entrapped voids tended to have their maximum dimension subparallel the vacuumed surface.

60. Three out of four of the cores from Whitney Dam had an outer layer of dark mortar. All had an outer zone 1 to 4 in. thick which was relatively high in entrapped air, and in which the maximum dimensions of the entrapped voids were generally subparallel the vacuumed surface. Three out of four had a zone inside the zone of high entrapped air in which the entrapped air content was relatively low; the zone differed in thickness from core to core. The entrained and entrapped air content became fairly constant toward the inner ends of the cores (plate 8).

61. No direct unequivocal evidence of channels caused by the removal of water during the vacuum treatment was found. Bleeding was evident on part of the surface of core Vf-20 from the inclined surface of the third lift where the form was not completely filled.

PART IV: SUMMARY AND CONCLUSIONS

Summary

62. The primary purpose of the investigation was to determine the proper procedures and techniques for vacuum treatment of formed and unformed surfaces of mass concrete. The secondary purpose was to determine the influence of the various procedures and techniques used in the vacuum processing on the properties of the hardened concrete to form a basis for evaluating the success of the primary purpose.

63. Vacuum treatment of horizontal unformed surfaces presents no problem, and processing can be done effectively by means of standard vacuum mats as shown in figure 3 (page 5). Strike off is readily accomplished by means of a vibrating screed such as the one pictured in figure 1 (page 3). The optimum time for starting to process appears to be approximately two hours after mixing; however, good results can be obtained up to about three and one-half hours after mixing. It does appear that the length of processing time, where tight mixes are used, should exceed somewhat the rule of thumb of "one minute processing for each inch of slab thickness."

64. The treated surfaces were hard enough immediately upon removal of the vacuum mats to be walked on with care without damage to the concrete. The concrete had to be finished immediately after removal of the mats and even then the surfaces were too hard for good hand-troweling. Use of the Whiteman power trowel was helpful, although some tearing of the surface under the trowel occurred, probably because of lack of experience by the operator. A more satisfactory finishing tool would have

been a disc-type power float.

65. The standard Blaw-Knox steel form panels were readily converted to satisfactory vertical and sloping vacuum forms. Satisfactory results were obtained when the forms were either divided into three separate vacuum zones, each 20 in. wide, or into a single 5-ft vacuum mat. The greatest amount of water per square foot of sloping or vertical surface was extracted when each course was vacuum-treated and the concrete was revibrated by internal vibration after the processing (see table 5). The general appearance of the concrete lift was better when the whole lift was processed after the concrete against the form (vacuum mat) had been brought to grade. When processing was done by courses seal marks were visible outlining the edge seal of the mat under the muslin filter cloth.

66. The external form vibrators are efficient provided they are firmly welded to the form at the correct location so that vibration is transmitted through the wales. The large high-frequency vibrator firmly clamped to steel plate and held against the form face by vacuum made an effective form vibrator. However, the use of external vibrators subjects the forms to stresses not experienced with internal vibration, and the present tests showed the concrete to be readily amenable to reconsolidation by internal vibration after vacuum treatment. Therefore, consolidation by internal vibration plus vacuum, followed by revibration with internal vibrators is believed preferable to the use of the external vibrators during the vacuum treatment.

67. The forms showed no measurable deflection under vacuum, so that deflection could not be used to estimate the amount of water removed. However, the amount of water removed from the sloping and vertical

surfaces was quite small (table 6), owing largely to the mixes themselves.

68. Seal between the vacuum forms and a bulkhead surface can be obtained by sponge rubber strips as shown in plate 4, provided the concrete placed in the corners adjacent to the seal is thoroughly vibrated into place. It is obvious that a seal cannot be made where a honeycomb condition exists.

69. Vacuum should be measured at the form, as a higher value is always shown at the pump than at the form where the processing is being accomplished. Care must be exercised in depositing large aggregate concrete to prevent large cobbles from striking the form, possibly tearing the filter cloth, and leaving indentations which mar the surface. If the filter cloth becomes torn it should be repaired immediately by patching the tear. Care must also be exercised in vibrating the concrete to avoid contact between the vibrator and form.

70. Both the Chicago Pneumatic two-man vibrator, which vibrated at approximately 5600 vpm in the concrete at 80 to 90 psi air pressure, and the Vibro-Plus, 4-in. diameter, one-man vibrator operating at approximately 12,000 vpm in the concrete performed satisfactorily in consolidating the concrete. The high frequency of the Vibro-Plus instrument necessitates more care in its use to prevent over-vibration, segregation, loss of entrained air and induced bleeding, than is required in the use of the Chicago Pneumatic. It was impossible to correlate, in the petrographic examination, appearance of core with the type of vibrator used for consolidation. No difference in air or aggregate distribution was noted among the cores that could be identified with the vibrator employed.

71. Improved compressive strength could not be correlated with the

vacuum-processing. Possibly the effect of the processing did not extend deeply enough below the surface, because of the tight mixes used, to produce measurable differences in the test specimens. Also, evaluation of the data obtained may have been complicated by the fact that higher cement factor, lower water-cement ratio concrete was used on the exposed surfaces of lifts 1 and 2 of the large test block than in the interior.

72. A considerable amount of information on the use of the vacuum process has been collected from various Corps of Engineers' projects, and is presented as an appendix hereto.

Conclusions

73. Steel panel forms can be readily adapted for use in applying the vacuum process to mass concrete.

74. No measurable deflection occurred in the steel forms in the experiments described herein.

75. The vertical and sloping lift surfaces after vacuum-processing appeared smooth and even. If each course is processed separately seal joints between the courses become visible.

76. Care must be taken to vibrate the concrete thoroughly into contact with the vacuum form to prevent honeycomb and to insure a vacuum seal at all corners and edges.

77. Processing can be accomplished by starting application of the vacuum as late as approximately three and one-half hours after mixing and optimum time for starting appears to be about two hours after mixing for the conditions of temperature, etc., that prevailed for these tests.

78. Reconsolidation by internal vibration after processing vertical

or sloping surfaces appears preferable to the use of form vibrators.

79. Horizontal surfaces present no processing problems and can be treated by the use of standard mats.

80. Finishing can be done immediately after removal of the mats. At this time the concrete is too hard for good hand finishing and mechanical finishing is required for best results.

81. A low bleeding mix does not lend itself to vacuum-processing as readily as a mix with a developed tendency to bleed.

82. The rule of thumb requiring one minute of processing time for each inch of slab depth probably should be altered where tight mixes are used to require more processing time.

TABLES

Table 1

TEST DATA ON PORTLAND CEMENT

Serial No. RC-179

Chemical Data	Per Cent	Physical Data	
SiO_2	22.78	Fineness:	
Al_2O_3	4.63	Wagner	1780 sq cm/g
Fe_2O_3	3.79	Blaine	3140 sq cm/g
CaO	62.74	Autoclave expansion	0.09 per cent
MgO	2.92	Compressive strength:	
SO_3	1.49	3 days	1165 psi
Loss on ignition	1.21	7 days	2185 psi
Insoluble residue	0.19	Air content, mortar	7.7%
Na_2O	0.18	Normal consistency	25.8%
K_2O	0.51	Time of set, Gillmore:	
Total alkali as Na_2O	0.52	Initial	4 hr, 35 min
C_3S	41.44	Final	6 hr, 5 min
C_2S	34.13		
C_3A	5.86		
C_4AF	11.52		
$CaSO_4$	2.53		

Table 2

TEST DATA ON AGGREGATES

Serial No.	LR-1 G-69(2)S	LR-1 G-69(2)	LR-1 G-69(2)	LR-1 G-69(2)	LR-1 G-69(2)
Size	Sand	No. 4 to 3/4 In.	3/4 to 1-1/2 In.	1-1/2 to 3 In.	3 to 6 In.
Bulk sp gr (ssd)	2.69	2.71	2.73	2.73	2.70
Absorption, %	1.6	0.8	0.6	0.8	0.6
Soundness, % loss*	10.4	7.3	2.9	----	----
Abrasion loss, %**	----	32.2	----	----	----
Thin and elongated, %	----	9.6	8.9	0.0	0.0
Soft pieces, %	----	0.0	0.0	0.0	0.0
Grading, cum % passing,					
6 in.	----	----	----	----	100
5 in.	----	----	----	----	89
4 in.	----	----	----	100	41
3 in.	----	----	100	78	3
2 in.	----	----	97	14	0
1-1/2 in.	----	----	79	2	----
1 in.	----	100	29	0	----
3/4 in.	----	96	6	----	----
1/2 in.	----	54	0	----	----
3/8 in.	----	22	----	----	----
No. 4	98	2	----	----	----
No. 8	81	----	----	----	----
No. 16	57	----	----	----	----
No. 30	44	----	----	----	----
No. 50	29	----	----	----	----
No. 100	16	----	----	----	----
No. 200	10	----	----	----	----
Fineness modulus	2.75	----	----	----	----

* After 5 cycles of magnesium sulfate soundness test.

** Los Angeles abrasion test, grading "B."

Note: All tests were made on composite samples of not fewer than five individual samples of each size of material.

Table 3

CONCRETE MIXTURE DESIGNS

Mixture		1	2	3
Nominal Cement Factor, Bags/Cu Yd		4.0	3.0	4.0
Aggregate Size, In.		3	6	6
Use		Slabs 9 In. Thick	Interior Concrete in Test Block and 18- and 36-In. Slabs	Exterior Concrete in Test Block
Theo. cement factor, bags/cu yd		4.15	3.1	4.15
Act. cement factor, bags/cu yd		4.0	3.0	4.0
Water-cement ratio, gal/bag		6.5	7.0	6.0(1)
Slump, in.		2-1/2	2-1/4	2-3/4
S/A, % by vol		30	26	24
Air (full mix), %		3.4	3.2	2.8
Air (-1-1/2), %		4.2	4.8	4.2
Bleeding, %		2.1(2)	1.8(2)	2.0(2)
Theo. unit wt, lb/cu ft		157.1	159.2	158.0
Act. unit wt, lb/cu ft		151.8	154.1	153.6
Coarse agg:	No. 4 to 3/4, %	35	20	20
	3/4 to 1-1/2, %	30	25	25
	1-1/2 to 3, %	35	20	20
	3 to 6, %	----	35	35

(1) This water-cement ratio was reduced to 5.4 gal per bag when placing 2nd lift of large block through use of 1 lb of Intrusion Aid per bag of cement, added for the purpose of retarding the setting time.

(2) These values are considered quite low and the concrete had very little tendency to bleed probably due in large part to the excessive amount of material in the sand passing the 100- and 200-mesh sieves.

Table 4

DESIGNATION AND DISPOSITION OF CORES

Location or Description	Identifying Symbol	Diam. In.	Number	Disposition
			Large Block	
Back elevation (upstream, vertical face)	Vb	10	1, 4, 7, 10, 13, 16, 19, inner and outer	Compression
			5, 14, 20, inner and outer	Petrography
			2, 8, 11, 17, inner and outer	Laboratory F & T
			3, 6, 9, 12, 15, 18, 21, inner and outer	Treat Island
Front elevation (downstream, sloping face)	Vf	10	1, 4, 7, 10, 13, 16, 19, inner and outer	Compression
			5, 14, 20, inner and outer	Petrography
			2, 8, 11, 17, inner and outer	Laboratory F & T
			3, 6, 9, 12, 15, 18, 21, inner and outer	Treat Island
Bulkhead	Vs	10	2, 4, 7, inner and outer	Laboratory F & T
			1, 8, inner and outer	Petrography
			3, 6, inner and outer	Treat Island
			5, 9, inner and outer	Compression
Top	T	10	1, 2, 3	Petrography
			Horizontal Slabs	
9-in. slab, nonvacuum	Ha	8	1, 2	Laboratory F & T
			3	Petrography
			4	Compression
			5, 6	Treat Island
9-in. slab, vacuum immediately after screeding	Hb	8	1, 2	Laboratory F & T
			3	Petrography
			4	Compression
			5, 6	Treat Island
9-in. slab, vacuum-process approx. 3-1/2 hr after mixing	Hc	8	1, 2	Laboratory F & T
			3	Petrography
			4	Compression
			5, 6	Treat Island
9-in. slab, vacuum process approx. 2 hr after mixing	Hd	8	1, 2	Laboratory F & T
			3	Petrography
			4	Compression
			5, 6	Treat Island
18-in. slab	He	10	1, 2	Laboratory F & T
			3	Petrography
			4	Compression
			5, 6	Treat Island
36-in. slab	Hf	10	1, 2, top and bottom	Laboratory F & T
			3, top and bottom	Petrography
			4, top and bottom	Compression
			5, 6, top and bottom	Treat Island
9-in. slab, vacuum process approx. 2 hr after mixing Apply 9 minutes only	Hh	8	1, 2	Laboratory F & T
			3	Petrography
			4	Compression
			5, 6	Treat Island

Table 5

PLACING AND PLASTIC CONCRETE DATA -- HORIZONTAL SLABS

1949 Date Placed	Slab No.	Air Temp F	Rel Hum. %	Concrete Temp F	Coarse Aggregate In.	Cement Factor Bags/Cu Yd	W/C Gals/Bag	Slump In.	Air in -1.5 In. %	Bleed %	Time Processed Min
7-26	a	84	69	82	3	4.0	6.5	2	3.9	2.1(1)	None
7-26	b	86	66	82	3	4.0	6.5	2-1/2	4.0	2.1(1)	30(2)
7-27	c	84	76	82	3	4.0	6.5	2	4.0	2.1(1)	30(3)
7-27	d	85	66	82	3	4.0	6.5	2-1/4	4.4	2.1(1)	30(4)
7-28	e	87	63	83	6	3.0	7.0	2-1/2	5.0	1.8(1)	18(4)
7-28	f	84	70	82	6	3.0	7.0	2-1/2	4.4	1.8(1)	30(4)
8-4	h	85	63	74	3	4.0	6.5	2	5.9	2.1(1)	9(4)

Slab No.	Water Extracted Gallons Total	Water Extracted Gallons Sq Ft	Vacuum In.	Finish
a	None	None	None	Hard troweled by hand
b	2.93	0.053	26-27	*Half hand-troweled, half left with finish imparted by mats
c	2.61	0.047	26-27	*Hand-troweled
d	3.94	0.071	26-27	*Hand-troweled
e	3.60	0.065	26-28)	(*Troweled with 36-in. Whiteman, gasoline-driven finishing
f	4.3	0.078	26-28)	(machine. Machine tended to tear surface over large cobbles
h	2.2	0.040	26-28	*Hand-troweled

Notes: All slabs screeded by vibratory screed and floated before vacuum-processing; vacuum measured at pump.

* The surface after processing was too hard for good hand-troweling.

(1) Indicated by the mix design work.

(2) Processed immediately after screeding and floating.

(3) Processed approximately 3-1/2 hr after mixing.

(4) Processed approximately 2 hr after mixing.

Table 6

PLACING AND PLASTIC CONCRETE DATA
TEST BLOCK (Specimen g.)

Placed	Lift and Face	Course	Air Temp F	Rel Hum. %	Concrete Temp F	Coarse Aggregate In.	Cement Factor Bags/Cu Yd	W/C Gals/Bag	Slump In.	Air in -1.5 In. %	Bleed %
8-1	1st Downstream	1st 20 In.	79	70	75	6	4.0	6.0	3	4.4	1.3
8-1	1st Downstream	2nd 20 In.	84	61	77	6	4.0	6.0	3	4.4	1.3
8-1	1st Downstream	3rd 20 In.	86	60	77	6	4.0	6.0	2-3/4	4.4	1.3
8-1	1st Upstream	1st 20 In.	79	70	75	6	4.0	6.0	3	4.4	1.3
8-1	1st Upstream	2nd 20 In.	84	61	77	6	4.0	6.0	3	4.4	1.3
8-1	1st Upstream	3rd 20 In.	86	60	77	6	4.0	6.0	2-3/4	4.4	1.3
8-1	1st Interior	Avg of 3	83	64	76	6	3.0	7.0	2-1/2	4.4	1.7
8-4	2nd Downstream	5 ft depth	83	63	73	6	4.0	5.4 (2)	3-1/2	7.2	0.5
8-4	2nd Upstream	5 ft depth	83	63	73	6	4.0	5.4 (2)	3-1/2	7.2	0.5
8-4	2nd Interior	Avg of 3	83	63	73	6	3.0	6.25(2)	2-1/2	6.4	0.9
8-9	3rd Downstream	5 ft depth	83	73	74	6	3.0	7.0	2-1/4	5.6	2.3
8-9	3rd Upstream	5 ft depth	83	73	74	6	3.0	7.0	2-1/4	5.6	2.3

Time Process Min	Water Extracted Gallons Total	Water Extracted Gallons Sq Ft	Vacuum In.	Consolidation	Treatment After or during Processing	Finished Surface Appearance
30	0.44	0.026	25-27(1)	Vibro-Plus 1-man	Revibrated	Good, but some honeycomb
30	0.60	0.036	25-27(1)	Vibro-Plus 1-man	Revibrated	Good, but some honeycomb
30	1.20	0.072	26-28(1)	Vibro-Plus 1-man	Revibrated	Good appearance, no honeycomb
30	0.82	0.044	25-27(1)	Chicago Pneumatic 2-man	Revibrated	Good appearance but with small honeycomb area
30	0.55	0.029	26-27(1)	Chicago Pneumatic 2-man	Revibrated	Good appearance but with small honeycomb area
30	0.73	0.039	26-27(1)	Chicago Pneumatic 2-man	Revibrated	Good appearance, no honeycomb
-	-	-	-	Both	-	-
30	1.48	0.026	20(3)	1st and 3rd courses with Chi-Pneu., 2nd with Vibro-Plus	Vibrated for 1-min intervals by 4 Vibro-Plus form vibrators during processing cycle after 10- and 20-min processing	Good appearance, form moved slightly, but this could not be detected by blemished surface
30	0.40	0.010	17-20(3)	1st and 3rd courses with Chi-Pneu., 2nd with Vibro-Plus	Vibrated for 1-min intervals by 4 Vibro-Plus form vibrators during processing cycle after 10- and 20-min processing	Good appearance, form moved slightly, but this could not be detected by blemished surface
-	-	-	-	Both	-	-
30	2.18	0.039	22(3)	Chicago Pneumatic	Vibrated for 1-min intervals by the 4-in.-diam. Vibro-Plus vibrator held to form by vacuum holder. Vibrated after 10- and 20-min processing	Good appearance except for honeycomb areas
30	1.40	0.028	22(3)	Chicago Pneumatic	Vibrated for 1-min intervals by 4 Vibro-Plus form vibrators during processing cycle after 10- and 20-min processing	Good appearance, no blemishes

(1) Measured at vacuum pump
(2) One pound Intrusion Aid added per bag of cement to retard set; it also caused a reduction in water-cement ratio, increased slump, and reduced bleeding
(3) Measured at the form

Table 7

COMPRESSIVE STRENGTH OF 8- x 16-IN. CONCRETE CYLINDERS

Cast from Concrete Wet-sieved over 2-in. Sieve at Time Horizontal and Vertical Vacuum Specimens Were Made

W/C Gals/Bag	Cement Factor Bags/Cu Yd	Coarse Aggregate Size, In.	Average Slump In.	Average Air in -1.5 In. %	Average Psi at Days 7	Average Psi at Days 28
6.5	4.0	3	2-1/4	4.4	1915(2)	2620(2)
6.0	4.0	6	3	4.4	2150(3)	3455(3)
5.4(1)	4.0	6	3-1/2	6.1	1695(3)	2405(3)
7.0	3.0	6	2-1/2	4.8	1490(4)	2170(4)
6.25(1)	3.0	6	2-1/2	5.3	1470(3)	2150(3)

(1) Contained 1 lb retarder per bag of cement
(2) Average for 15 specimens
(3) Average for 3 specimens
(4) Average for 12 specimens

Table 8

COMPRESSIVE STRENGTH OF CORES

Diamond Drilled from Vacuum-processed and Unprocessed Slabs, Tested at Approximately 90-days Age

Slab No.	Slab Depth In.	Core No.	Core Diam In.	Coarse Aggregate Size, In.	Cement Factor Bags/Cu Yd	W/C Gal/Bag(1)	Slump In.	Air in -1.5 In., %	Process Time Min	Pump Vac In.	Water Extracted Sq Ft	Corrected for h/d Psi
a	9	Ha4	8	3	4.0	6.5	2	3.9	None	-	-	4220
b	9	Hb4	8	3	4.0	6.5	2-1/2	4.0	30(2)	26-27	0.053	4340
c	9	Hc4	8	3	4.0	6.5	2	4.0	30(3)	26-27	0.047	3900
d	9	Hd4	8	3	4.0	6.5	2-1/4	4.4	30(4)	26-27	0.071	4720
h	9	Hh4	8	3	4.0	6.5	2	5.9	9(4)	26-28	0.040	4075
e	18	He4	10	6	3.0	7.0	2-1/2	5.0	18(4)	26-28	0.065	3140
f	36	Hf4(Top) Hf4(Bottom)	10	6	3.0	7.0	2-1/2	4.4	30(4)	26-28	0.078	4310 3820

(1) Before processing
(2) Vacuum-processed immediately after screeding and floating
(3) Vacuum-processed approximately 3-1/2 hr after mixing
(4) Vacuum-processed approximately 2 hr after mixing

Table 9

COMPRESSIVE STRENGTH OF 10-IN. CORES

Diamond Drilled from Large Vacuum-processed Block
Tested at Approximately 90-days Age
All with 6-in. Coarse Aggregate

Lift No.	Course	Core No. and Location(1)	Cement Factor Bags/Cu Yd	W/C Gal/Bag(2)	Slump In.	Air in -1.5 In. %	Process Time Min	Vacuum In.	Water Extracted Sq Ft/Gal	Corrected for h/d Psi
1	1	Vf-1 outer	4.0	6.0	3	4.4	30	25-27(3)	0.026	4285
1	2	Vf-4 outer	4.0	6.0	3	4.4	30	25-27(3)	0.036	5130
1	2	Vf-4 inner	3.0	7.0	2-1/2	4.4	-	-	-	3680
1	3	Vf-7 outer	4.0	6.0	2-3/4	4.4	30	26-28(3)	0.072	4965
1	3	Vf-7 inner	3.0	7.0	2-1/2	4.4	-	-	-	4090
2	1	Vf-10 outer	4.0	5.4(4)	3-1/2	7.2	30	20(5)	0.026	2550
2	2	Vf-13 outer	4.0	5.4(4)	3-1/2	7.2	30	20(5)	0.026	4080
2	2	Vf-13 inner	3.0	6.25(4)	2-1/2	6.4	-	-	-	3285
2	3	Vf-16 outer	4.0	5.4(4)	3-1/2	7.2	30	20(5)	0.026	3985
2	3	Vf-16 inner	3.0	6.25(4)	2-1/2	6.4	-	-	-	3515
3	2	Vf-19 outer	3.0	7.0	2-1/4	5.6	30	22(5)	0.039	3920
3	2	Vf-19 inner	3.0	7.0	2-1/4	5.6	-	-	-	(6)
1	1	Vb-1 outer	4.0	6.0	3	4.4	30	25-27(3)	0.044	4360
1	2	Vb-4 outer	4.0	6.0	3	4.4	30	26-27(3)	0.029	4270
1	2	Vb-4 inner	3.0	7.0	2-1/2	4.4	-	-	-	4240
1	3	Vb-7 outer	4.0	6.0	2-3/4	4.4	30	26-27(3)	0.039	4280
1	3	Vb-7 inner	3.0	7.0	2-1/2	4.4	-	-	-	3620
2	1	Vb-10 outer	4.0	5.4(4)	3-1/2	7.2	30	17-20(5)	0.010	2625
2	1	Vb-10 inner	3.0	6.25(4)	2	6.4	-	-	-	2745
2	2	Vb-13 outer	4.0	5.4(4)	3-1/2	7.2	30	17-20(5)	0.010	4175
2	2	Vb-13 inner	3.0	6.25(4)	2-1/2	6.4	-	-	-	2270
2	3	Vb-16 outer	4.0	5.4(4)	3-1/2	7.2	30	17-20(5)	0.010	3970
2	3	Vb-16 inner	3.0	6.25(4)	2-1/2	6.4	-	-	-	3505
2	2	Vs-5 outer	3.0	6.25(4)	2-1/2	6.4	-	-	-	2770
2	2	Vs-5 inner	3.0	6.25(4)	2-1/2	6.4	-	-	-	3290
3	2	Vs-9 outer	3.0	7.0	2	5.6	-	-	-	3540
3	2	Vs-9 inner	3.0	7.0	2	5.6	-	-	-	2650

(1) See plate 7 for location on block from which core was taken
(2) Before processing
(3) At pump
(4) Contained 1 lb Intrusion Aid per bag of cement
(5) At form
(6) Core too short for testing

Table 10

VACUUM CONCRETE CORES FOR PETROGRAPHIC EXAMINATION

Lift No.	Face of Test Block	Core Number	Length, In.	Duration, Min	Time of Application
		Cores 8 In. in Diameter, Drilled from Horizontal Slabs			
--	--	Ha-3	9.4	none	--
--	--	Hb-3	9.4	30	Immediately after screeding
--	--	Hc-3	9.4	30	Approximately 3-1/2 hr after mixing
--	--	Hd-3	9.4	30	Approximately 2 hr after mixing
--	--	Hh-3	9.1	9	Approximately 2 hr after mixing
--	--	He-3	18.8	18	Approximately 2 hr after mixing
		Cores 10 In. in Diameter, Drilled from Horizontal Slabs			
--	--	Hf-3 top	18.0	30	Approximately 2 hr after mixing
--	--	Hf-3 bottom	19.0		
		Cores 10 In. in Diameter, Drilled from Test Block			
1	Front	Vf-5 outer	16.1		
		Vf-5 inner	15.0	30	
1	Back	Vb-5 outer	18.3	per	After placing of each of 3, 20-in.
		Vb-5 inner	18.0	course	courses
1	Bulkhead	Vs-1 outer	15.5	none	--
		Vs-1 inner	15.5	none	--
2	Front	Vf-14 outer	15.8		
		Vf-14 inner	15.8	30	
2	Back	Vb-14 outer	18.0	per	After placing of the lift
		Vb-14 inner	17.9	lift	
3	Front	Vf-20 outer	15.8	3	After placing of the lift, with re-
		Vf-20 inner	9.5	10-min	vibration by form vibrators after
3	Back	Vb-20 outer	18.0	periods	each period of vacuum processing
		Vb-20 inner	18.0		
3	Bulkhead	Vs-8 outer	18.0	none	--
		Vs-8 inner	18.0	none	--
3, 2	Top	T-1	10 ft	none	--
3, 2	Top	T-2	10 ft	none	--
3, 2	Top	T-3	10 ft	none	--

Table 11

DISTRIBUTION OF AIR IN CORES FROM HORIZONTAL SLABS

Core No. and Treatment	Entrained Air: In 1/2 In. next to Finished Surface	Entrained Air: Away from Finished Surface	Entrapped Air
Ha-3 None	Smaller, less numerous	Larger, more numerous than in outer 1/2 in.	In the outer 2 to 2-1/2 in. the maximum size is slightly smaller than in the rest of the core. Some of the larger voids in the lower half of the core have their maximum intercept subparallel to the bottom of the slab. Some narrow underside voids. (Plate 9.)
Hb-3 Vacuum	Smaller, less numerous	Voids gradually increase in size and number toward bottom. Small areas of very high air content (frothy mortar). Strings of voids at the edges of coarse aggregate, not limited to underside.	Entrapped air voids not found in the upper 3 in. In the lower 6 in., they are irregular in shape, average about 1/4 in. in diameter, and usually adjoin coarse aggregate. Boundary voids not limited to undersides.
Hc-3 Vacuum	Smaller, less numerous	Voids evenly distributed except for concentrations along the edges of coarse aggregate particles.	Average entrapped voids are 1 to 2 mm in diameter. Strings of bubbles and narrow pockets along aggregate particles are common, and are found on any edge of the particle. A few irregular slot voids in mortar.
Hd-3 Vacuum	Smaller, less numerous	From 1/2 to 6 in. below surface, voids evenly distributed and more abundant than in Ha, Hb, Hc. From 6 to 9 in. below surface there are 2 to 3 times as many voids as in any area in the top 6 in.	Entrapped air voids more numerous than in cores Ha, Hb, Hc. In the upper 1-1/2 in. entrapped and/or entrained air has coalesced along the surfaces of coarse aggregate leaving open slots adjoining the sides of the particles (Plate 10).
He-3 Vacuum	Upper 1 in. contains smaller, less numerous entrained voids	Evenly distributed except for a few small areas where voids are more abundant and except for concentrations along the periphery of coarse aggregate, which are most common in the upper 6 in.	Average diameter about 1/4 in.; distributed through the core in a haphazard manner. A number of boundary voids, and slot voids in mortar. Boundary voids most common in upper 6 in.
Hf-3 Vacuum	Smaller, less numerous in outer 1/2 in.	More and larger in concrete below the outer 1/2 in.	Randomly distributed entrapped air voids up to 3/4 in. in maximum dimension, with the average size about 1/4 in. Small and one large slot void in paste.
Hh-3 Vacuum	Smaller, less numerous in outer 1/2 in.	Below the outer 1/2 in. the voids gradually increase in size and number. The amount of entrained air is comparable to that in Hd-3 and greater than in the other cores from the horizontal slabs. The voids are evenly distributed except for a few concentrations along the edges of coarse aggregate particles.	Randomly distributed entrapped air voids up to 1/4 in. in maximum dimension, with the average 1 to 2 mm. A few are located beneath aggregate particles.

Table 12

DISTRIBUTION OF AIR IN CORES FROM TEST BLOCK

Core No.	Lift	Face	Entrained Air	Entrapped Air
Vb-5 (Chicago-Pneumatic Vibrator)	1	Upstream	Smaller and less numerous in outer 1/2 in., increasing in size and number from 1/2 to 6 in. Evenly distributed except for some concentrations along coarse aggregate especially in outer 10 in.	More numerous in outer 2 in. than in any other area. Boundary voids more numerous in outer 10 in. decreasing farther in. Boundary voids not confined to any side of coarse aggregate (horizontal core).
Vf-5 (Vibro-Plus Vibrator)	1	Down-stream	Smaller and less numerous in outer 1/2 in. Concentrations of entrained air around aggregate increase toward inner portion of core but quantity is lower than in Vb-5; in outer half of core, concentrations are more common on the side of the aggregate away from the treated surface (inclined core).	Entrapped air voids more numerous near vacuumed surface, and include the largest entrapped voids found in any core (Plate 11).
Vs-1 (Chicago-Pneumatic Vibrator)	1	Bulkhead	Smaller and less numerous in outer 1/2 in. Air content similar to Vf-5 and Vb-5.	Boundary voids common throughout core but largest and most abundant near the outer formed surface. In the outer zone, most of the voids are on the side of the aggregate nearest the formed vertical surface. (Plate 12.) A few cracks in mortar in inner half of core.
Vb-14 (Vibro-Plus Vibrator)	2	Upstream	Entrained air content about twice that of cores from lifts 1, 3. Entrained voids few and small near vacuumed surface, to depths up to 1/2 in.; increase in size and number to about 5 in. From 5 to 24 in., air content fairly constant; from 24 in. to inner end of core the entrained voids are slightly less abundant and the paste is paler gray. This color change represents the boundary between exterior and interior concrete. A few small areas of frothy mortar and a few concentrations of voids along edges of aggregate.	A few boundary voids and a few small entrapped air voids; more numerous in interior concrete.
Vf-14 (Vibro-Plus Vibrator)	2	Down-stream	Similar in distribution and amount to Vb-14.	Entrapped air content above average. Boundary voids and concentrations adjoining coarse aggregate more numerous near inner end of core. Irregular slot void 2 in. long sub-parallel to treated surface 27-1/2 in. from surface.
Vb-20 (Chicago-Pneumatic Vibrator)	3	Upstream	Similar in quantity to Vb-5. Smaller less numerous voids near treated surface; even distribution in outer half of core. In inner half the entrained air content is variable; near inner end it increases, with an increase in boundary voids and in concentrations of voids around aggregate.	Entrapped air voids slightly larger in average size but less abundant than in cores from lifts 1, 2 (horizontal core).
Vf-20 (Chicago-Pneumatic Vibrator)	3	Down-stream	Similar to Vb-20, with increase in boundary voids and concentrations around aggregate in inner half.	Form was not completely filled; only a portion of surface was in contact with vacuum mat. Honeycomb next to part of surface, and 25 in. inside surface. Outer 4 in. high in entrapped air. Two cracks normal to treated surface; laitance in parts of surface which were not in contact with the vacuum mat.
Vs-8 (Chicago-Pneumatic Vibrator)	3	Bulkhead	Similar amount and distribution to Vb-20 and Vf-20.	Similar to Vb-20.
T-1, 2, 3	3, 2	Top	Similar to cores from lift 3 in. upper portion of cores. Concentration of entrained and entrapped air in upper 6 in. of lift 2 just below contact with lift 3 (Plate 13).	Similar to Vb-20 in lift 3. High concentration of boundary voids in top of lift 2. No crack, cold joint, or void in construction joint.

Table 13

AIR CONTENT OF CONCRETE CORES DETERMINED USING THE STEREOSCOPIC MICROSCOPE

Core No.	Treat-ment	Coarse Aggregate, Per Cent	Air Content of Concrete, %: In Outer 1/2 In.	Air Content of Concrete, %: Rest of Core
		Cores from Horizontal Slabs		
Ha-3	None	56	1.7	3.1
Hb-3	Vac	60(1)	1.9	1.8
Hd-3	Vac	54	2.1	3.4
		Cores from Test Block - Lift 1		
Vf-5	Vac	59	4.4(2)	2.0
Vs-1	None	57	1.9	2.5
		Cores from Test Block - Lift 2		
Vb-14	Vac	58	4.2	4.4
		Cores from Test Block - Lift 3		
Vb-20	Vac	57	2.3	1.9
Vs-8	None	57	1.5	2.3

(1) Abnormal concentration of coarse aggregate.
(2) Large entrapped air voids near vacuumed surface.

Table 14

AIR CONTENT OF CONCRETE CORES FROM THE TEST BLOCK DETERMINED BY STEREOSCOPIC MICROSCOPE AND BY CRD-C 42(1)

Core No.	Treat-ment	Coarse Aggre-gate, Per Cent	Air Content, %: In Outer 1/2 In.: Stereo-scopic	Air Content, %: In Outer 1/2 In.: CRD-C 42	Air Content, %: In Rest of Core: Stereo-scopic	Air Content, %: In Rest of Core: CRD-C 42: Middle	Air Content, %: In Rest of Core: CRD-C 42: Inner	Air Content, %: In Rest of Core: CRD-C 42: Avg
				Lift 1				
Vf-5	Vac	59	4.4(2)	3.1(3)	2.0	1.6	1.1	1.3
Vs-1	---	57	1.9	4.0	2.5	4.0	4.1	4.0
				Lift 3				
Vb-20	Vac	57	2.3	3.4	1.9	1.6	10.2(4)	5.9

(1) Handbook for Concrete and Cement, Waterways Experiment Station, CRD-C 42, Method of Test for Air Content of Hardened Concrete, (Micrometric Procedure).
(2) Large entrapped air voids.
(3) Large entrapped air voids similar to those present in the half core counted with the stereoscopic microscope are present on the reverse of the slice counted by CRD-C 42.
(4) Local concentration of entrained air.

Table 15

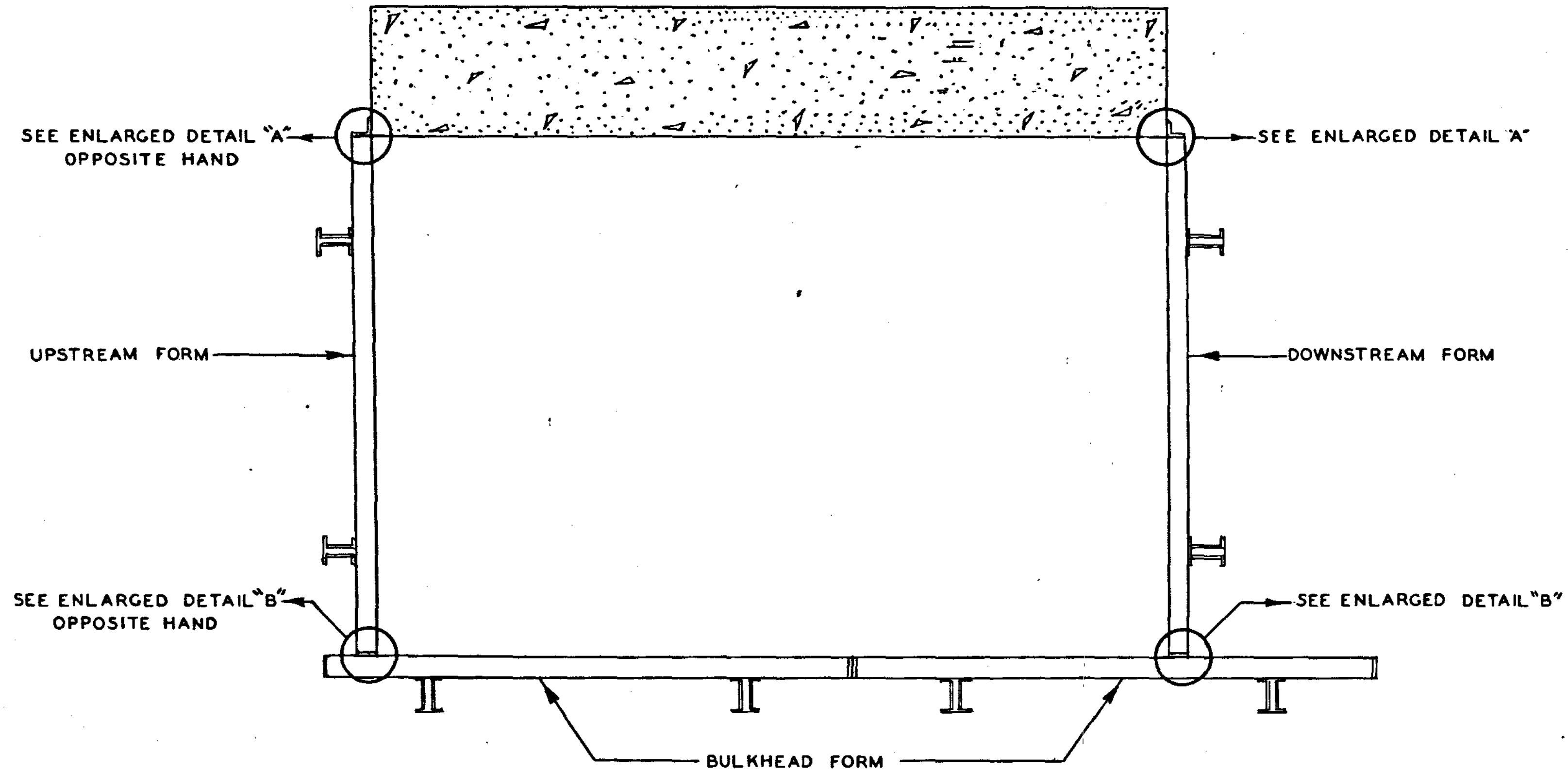
AVERAGE LINEAL INTERCEPTS OF AIR VOIDS AND CALCULATED AVERAGE DIAMETER OF VOIDS CONSIDERED AS SPHERES

Core No.	Outer 1/2 In. Average Lineal Intercept(1), mm	Outer 1/2 In. Average Diameter of Voids(2), mm	Rest of Core Average Lineal Intercept(1), mm	Rest of Core Average Diameter of Voids(2), mm
Ha-3	0.206	0.308	0.305	0.458
Hb-3	0.211	0.316	0.152	0.228
Hc-3	0.224	0.336	0.279	0.418
Vs-1	0.244	0.366	0.226	0.340
Vf-5	0.493	0.740	0.218	0.328
Vb-14	0.183	0.274	0.206	0.308
Vs-8	0.221	0.332	0.254	0.382
Vb-20	0.381	0.572	0.368	0.552

(1) $\frac{\text{Total void intercept, mm}}{\text{Number of voids}}$ = average void intercept, mm.

(2) Average diameter, mm = 3/2 (average void intercept, mm).

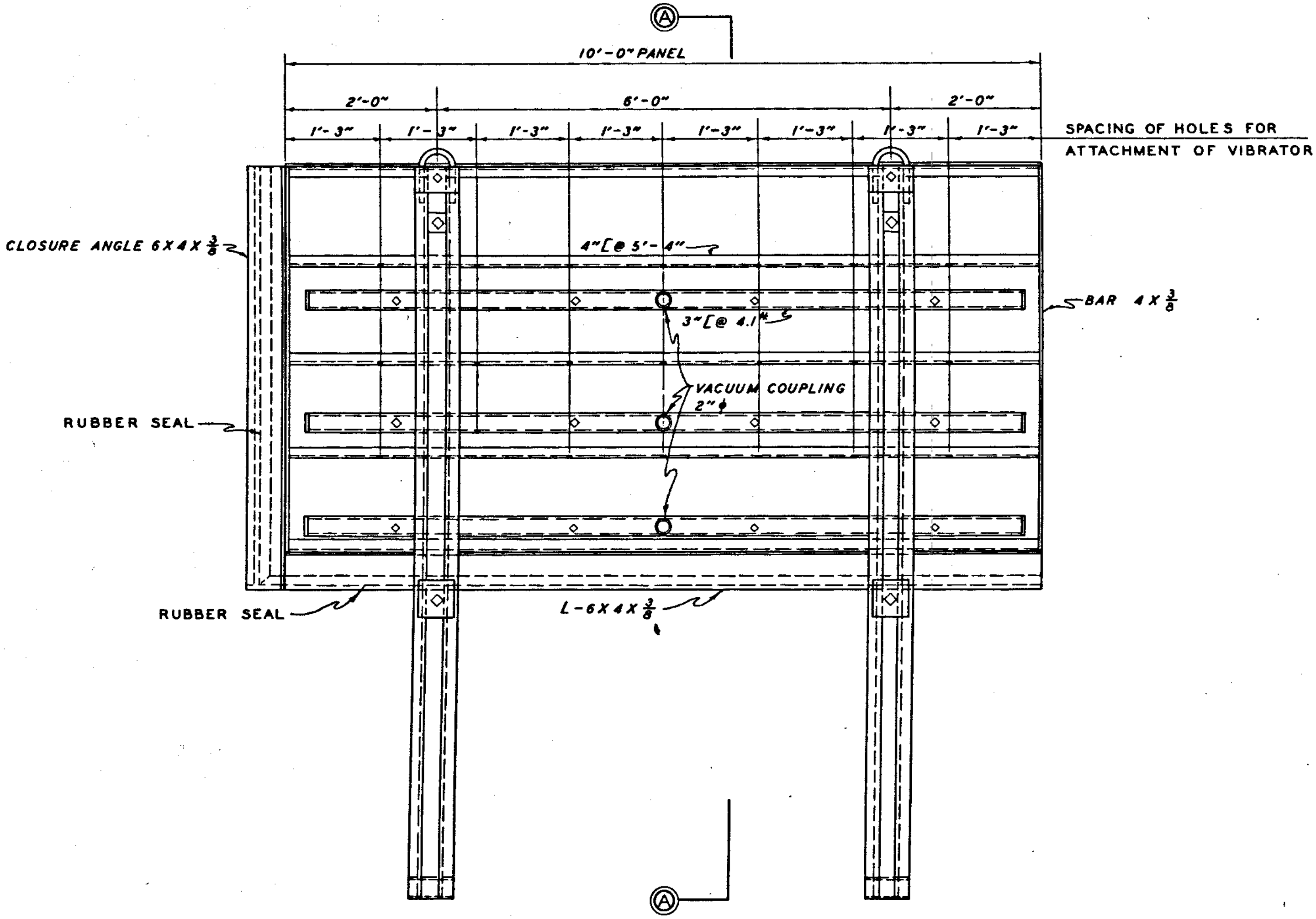
PLATES



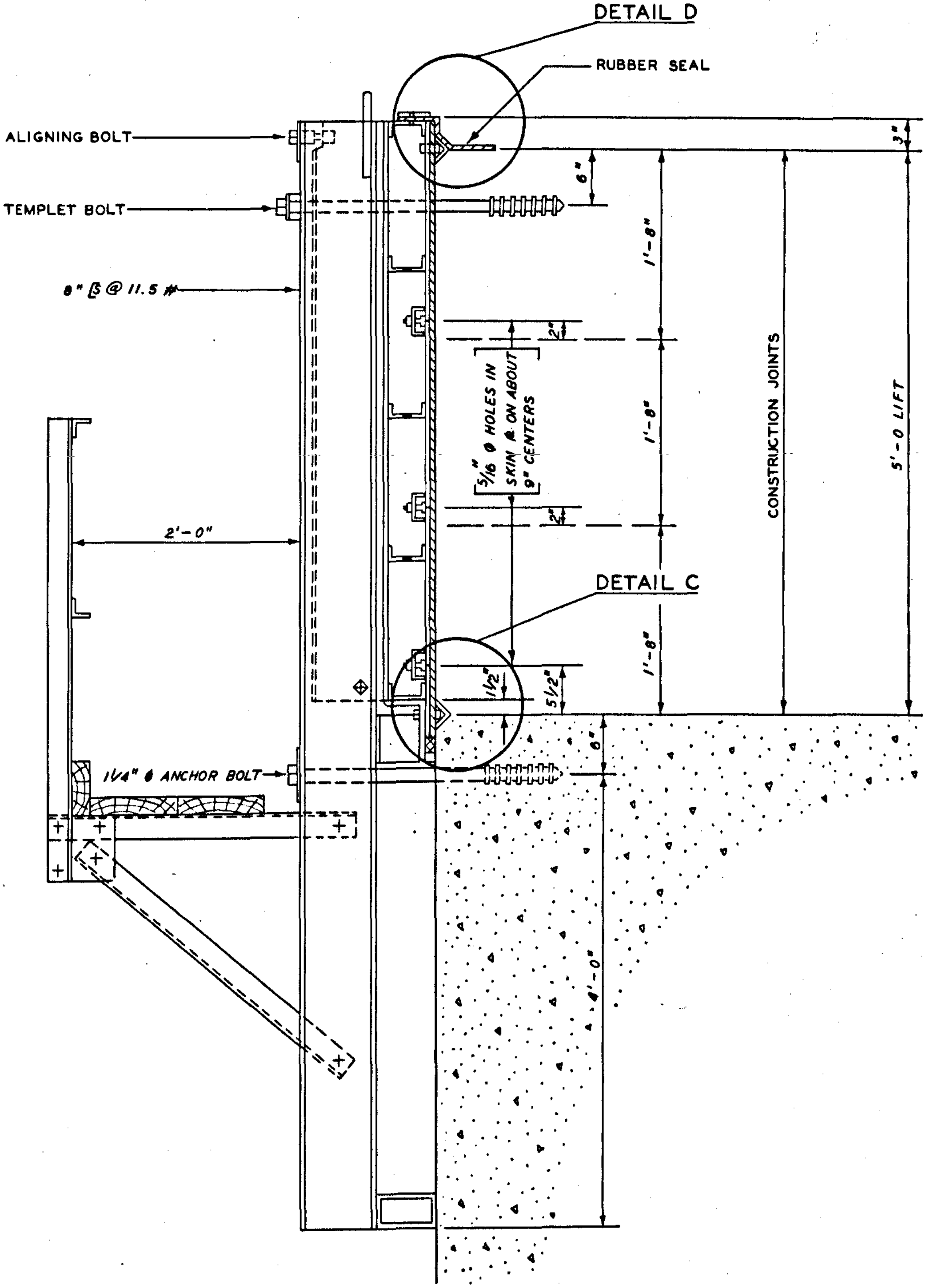
KEY DIAGRAM

VACUUM TEST BLOCK
SCHEMATIC PLAN OF FORM ASSEMBLY

PLATE 1

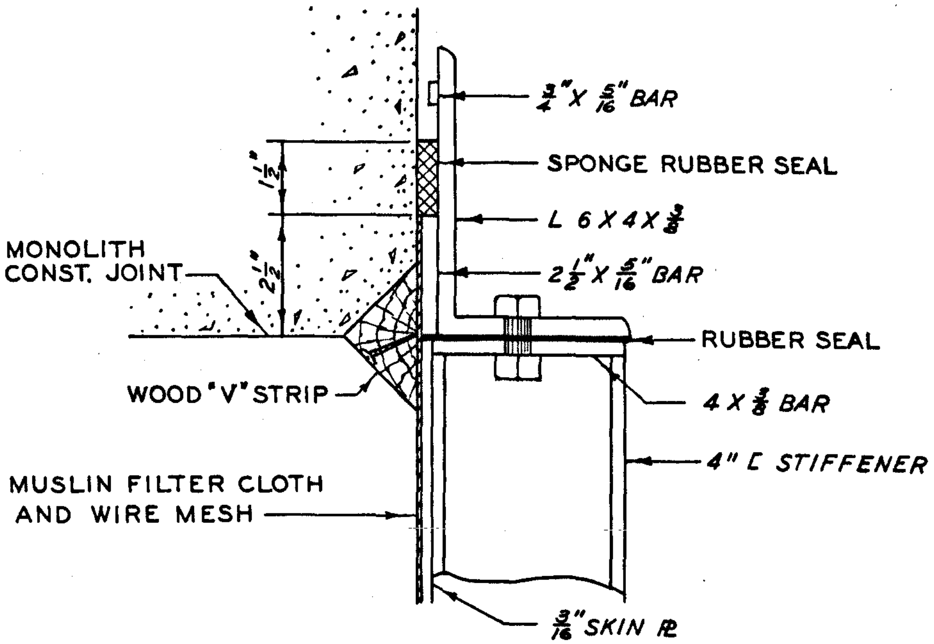


VACUUM TEST BLOCK
UPSTREAM VERTICAL FORM



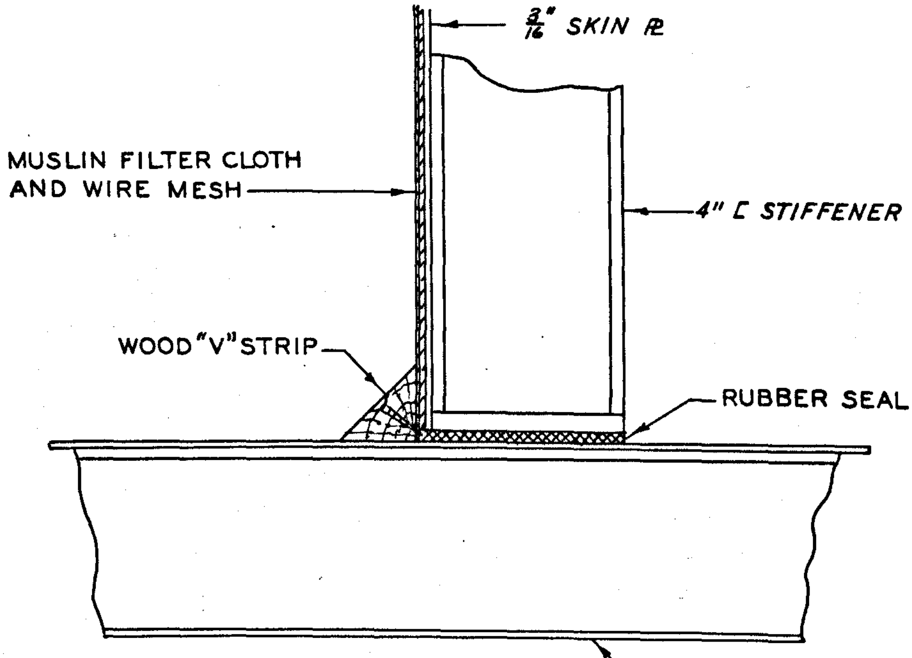
SECTION A-A

VACUUM TEST BLOCK UPSTREAM VERTICAL FORM



DETAIL A

SCALE: 3 IN. = 1 FT

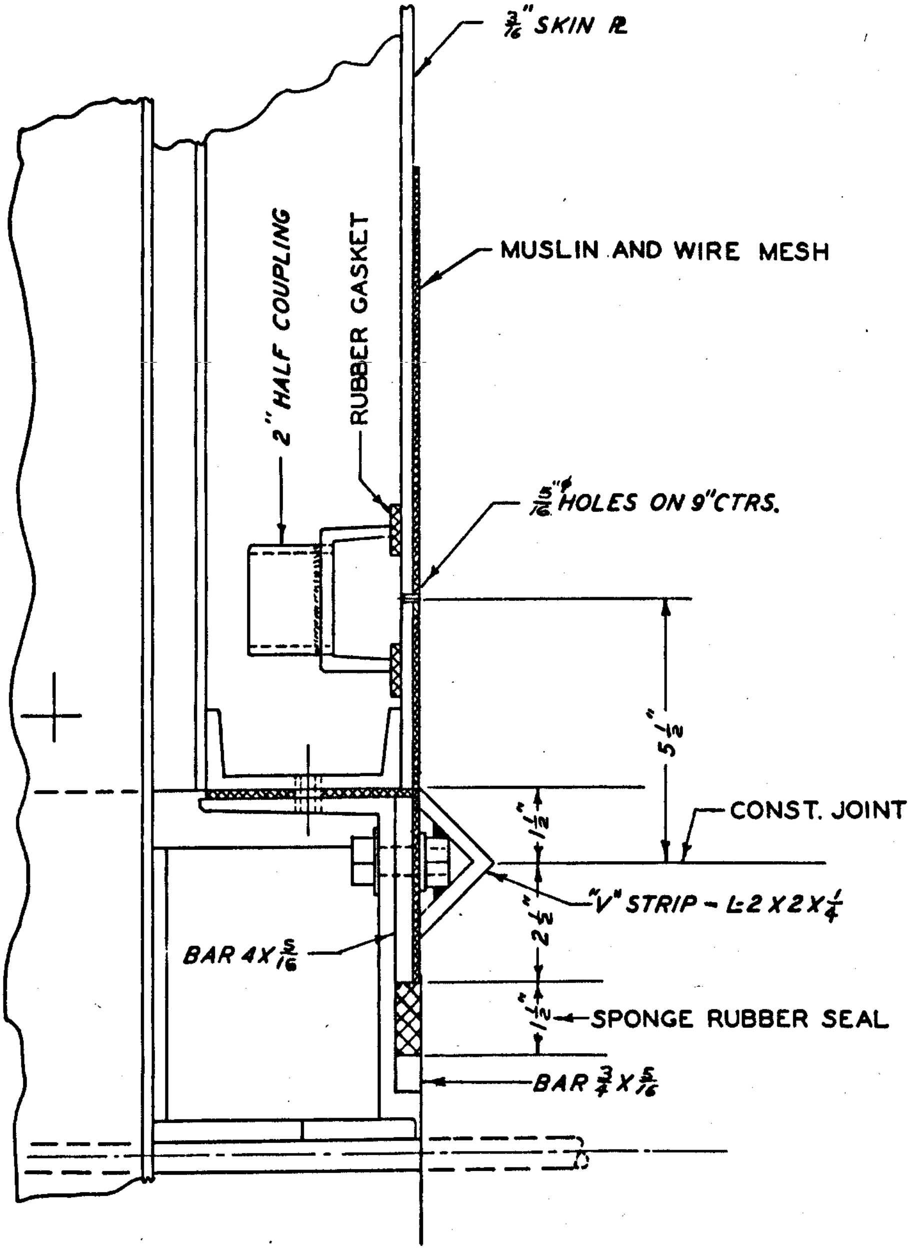


DETAIL B

SCALE: 3 IN. = 1 FT

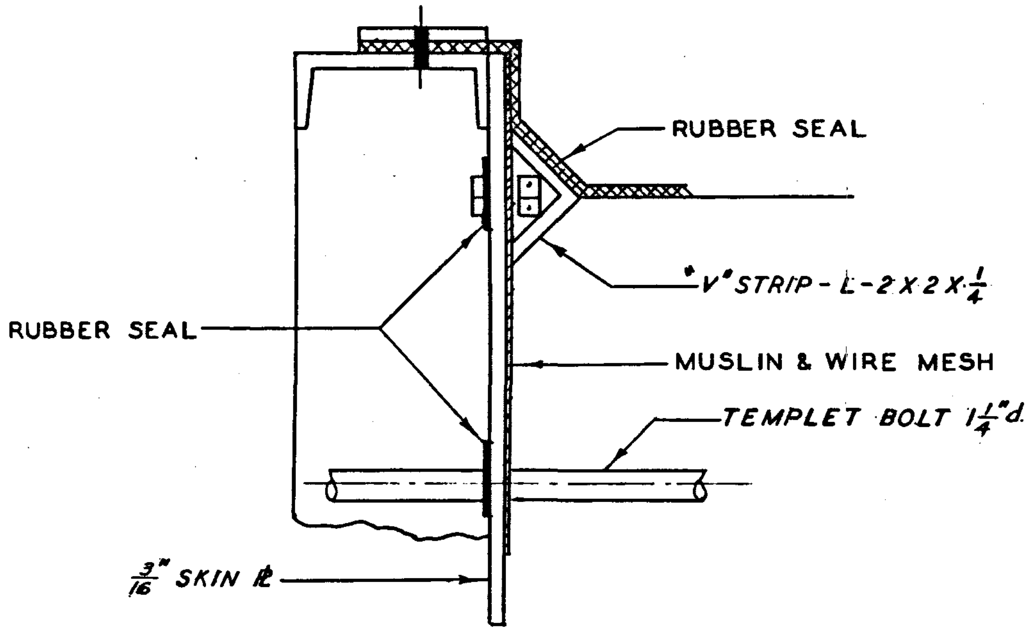
VACUUM TEST BLOCK
UPSTREAM VERTICAL FORM

PLATE 4



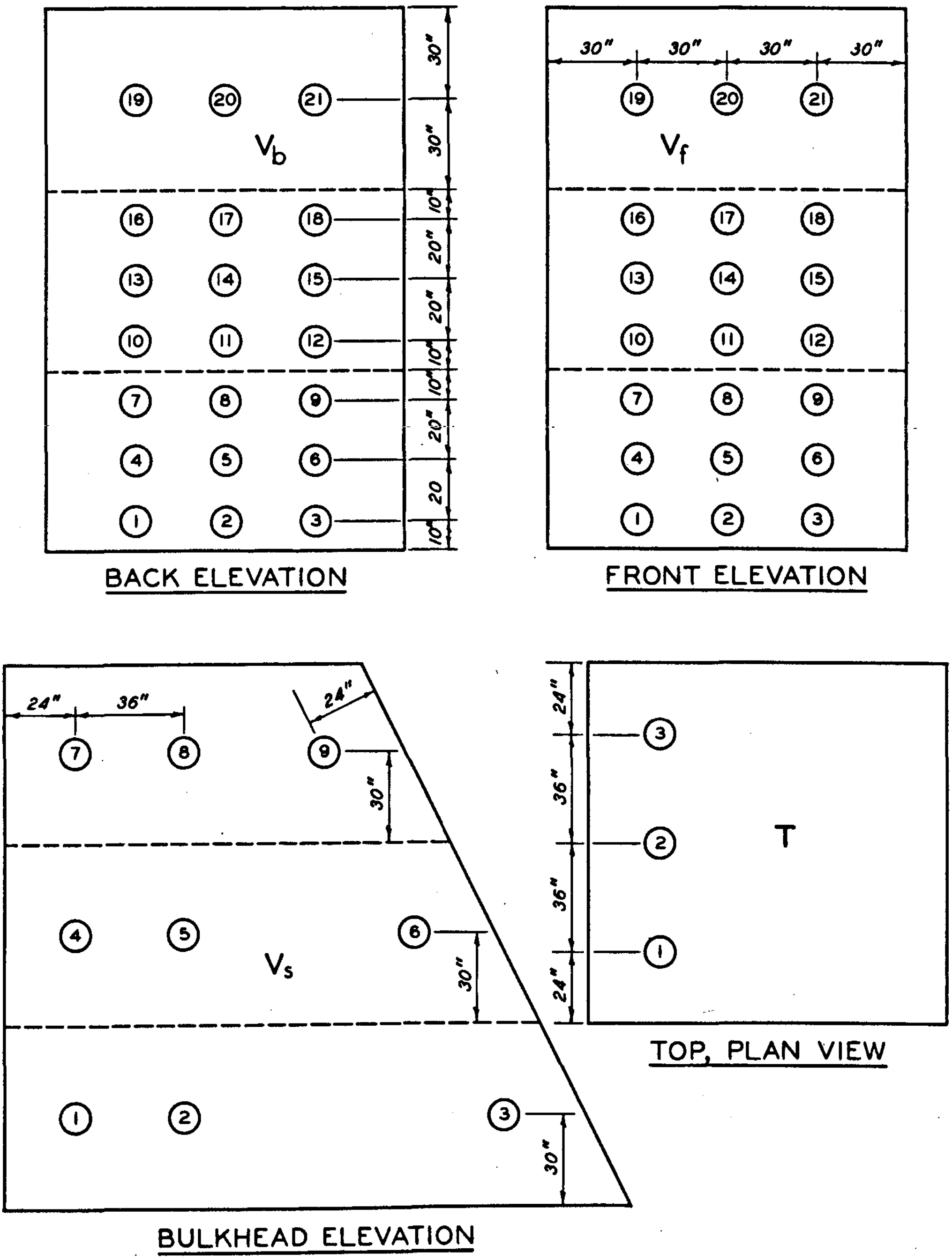
DETAIL C

VACUUM TEST BLOCK
UPSTREAM VERTICAL FORM

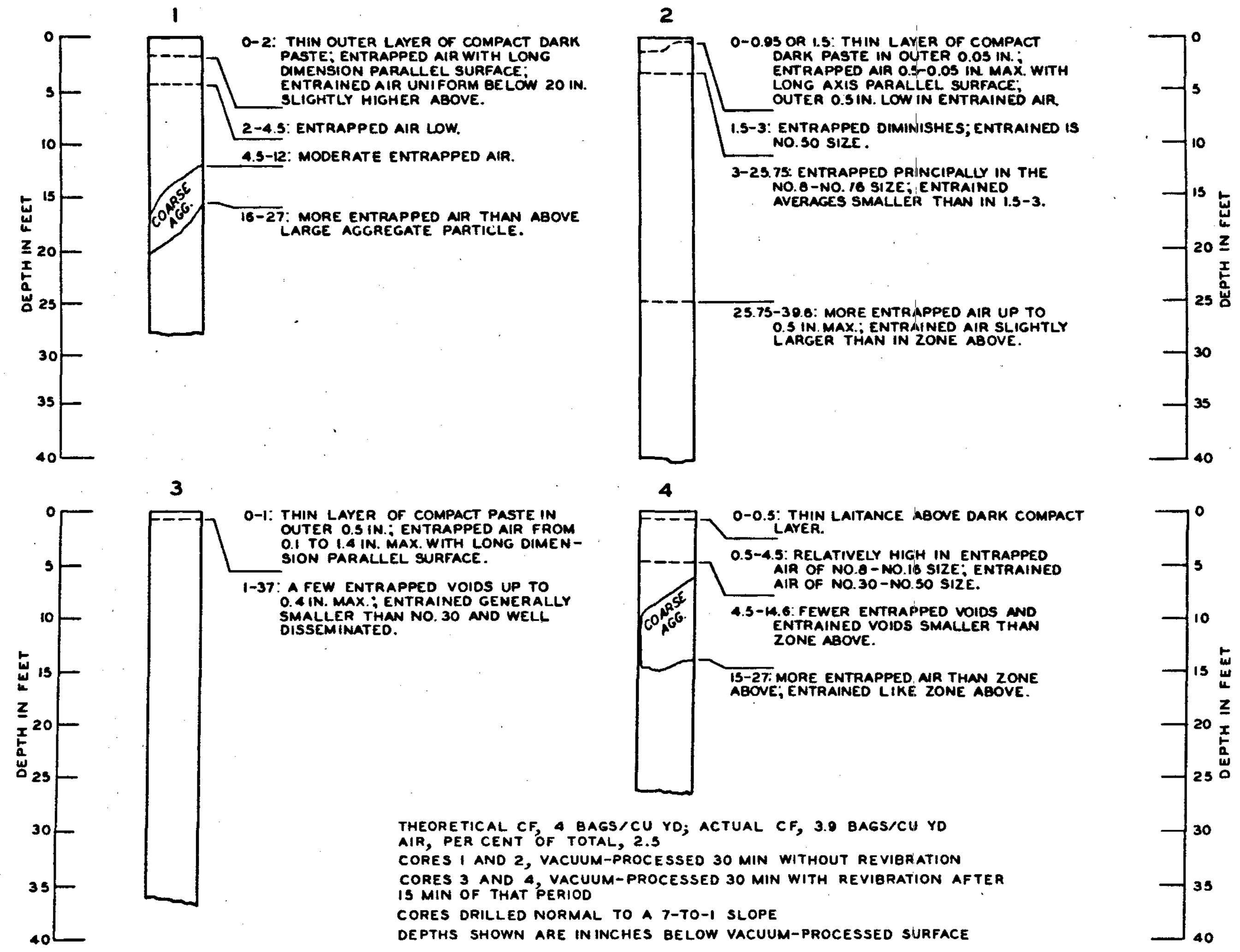


DETAIL D

VACUUM TEST BLOCK
UPSTREAM VERTICAL FORM



LAYOUT FOR DRILLING 10-IN. CORES
IN LARGE VACUUM BLOCK



CONCRETE CORES FROM BLOCK 30, LIFT 20
VACUUM TEST SECTION, WHITNEY DAM

Longitudinal sawed surface of core Ha-3, with the finished surface at the top of the photograph, showing decrease in entrained-air content and entrapped-air content in the concrete adjoining the finished surface. There are concentrations of entrapped and entrained air at the undersides of several coarse aggregate particles. Strings of voids and boundary voids which probably formed from the coalescence of such strings can be seen next to particles in the lower right, center, and upper left of the photograph. The concrete adjoining the lower formed surface is low in entrained and entrapped air.

Vertical Core from Nonvacuum-treated Horizontal Slab

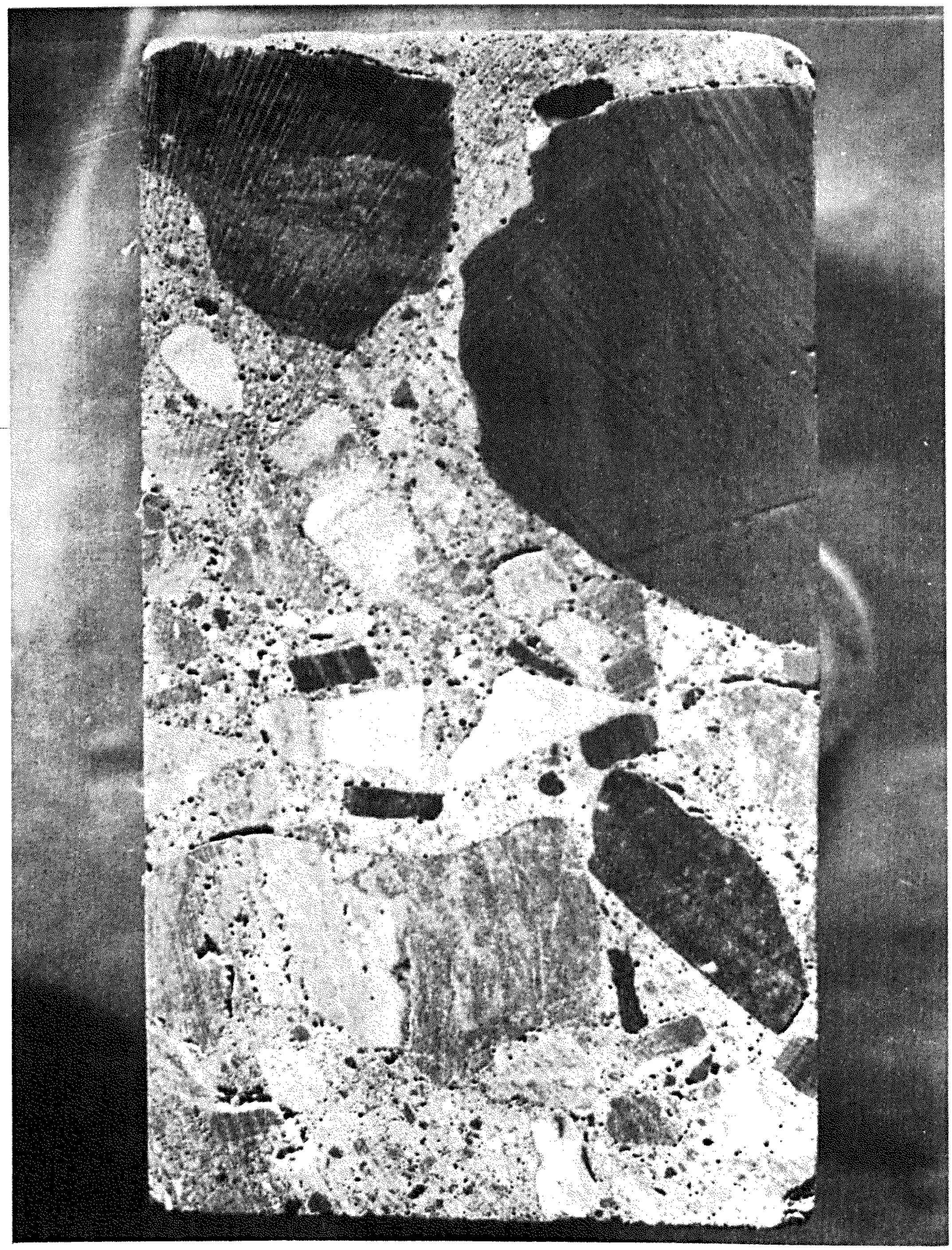
Core Hd-3, showing decrease in entrained-air content and increase in boundary voids, as the vacuum-treated surface, at top of photograph, is approached, and the tendency for voids to accumulate around coarse aggregate particles. Near the upper left corner there is a boundary void nearly parallel to the surface, on the upper side of a coarse aggregate particle. Longitudinal section.

Vertical Core from Vacuum-treated Horizontal Slab

PLATE 10

Core Vf-5, showing decrease of entrained-air content as vacuum-treated surface, at top of photograph, is approached, and large, irregular, entrapped voids near top of core, ending only a fraction of an inch below surface. Longitudinal section.

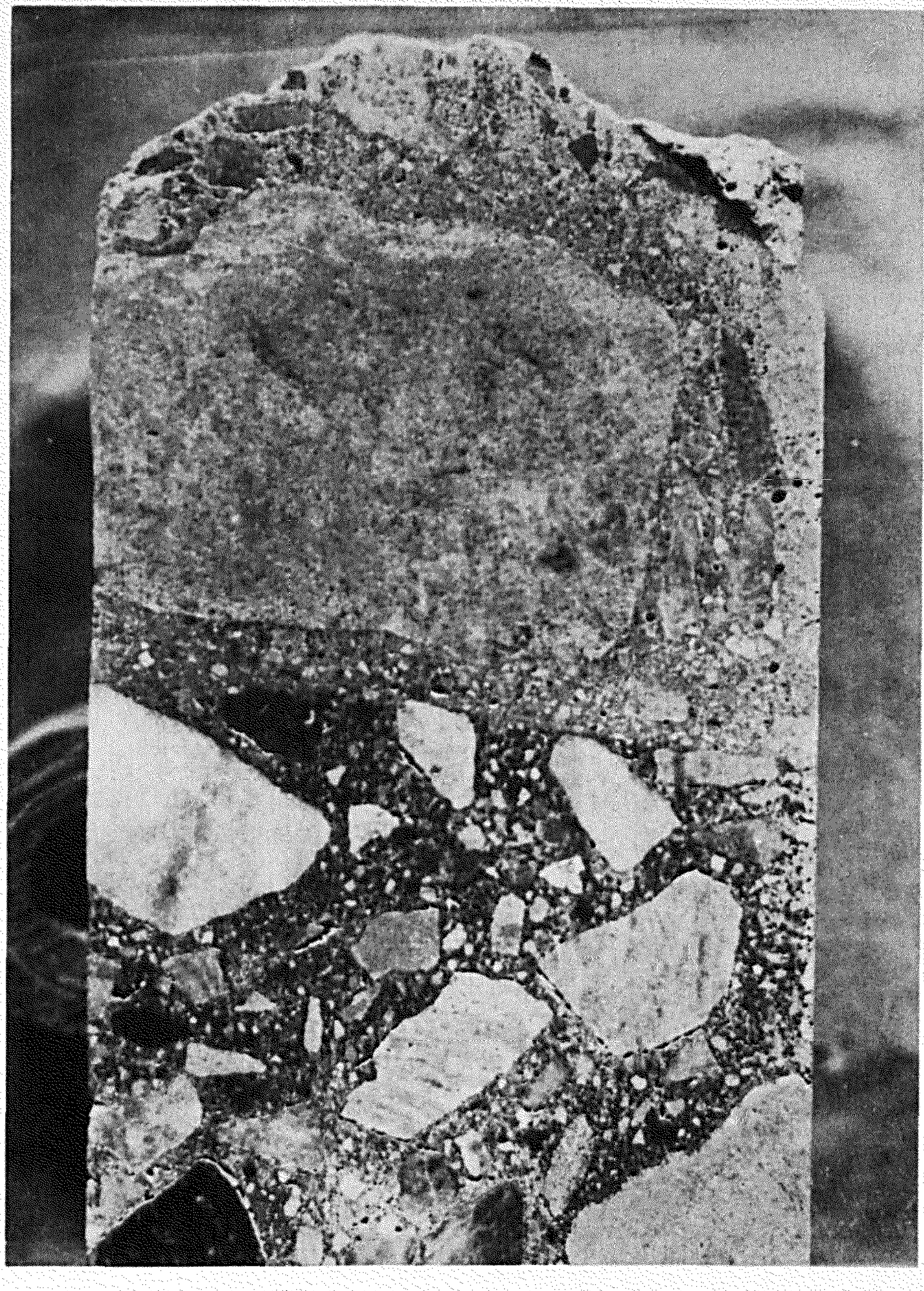
Core Normal to Sloping Face, First Lift, Test Block



Core Vs-1, showing boundary voids along the sides of coarse aggregate particles toward the outer (vertical) surface and roughly parallel to that surface, which is at the top of the photograph. Longitudinal section.

Horizontal Core from Bulkhead, First Lift, Test Block

PLATE 12



Core T-2, showing contact between second lift (lower half) and third lift (upper half). The second lift concrete shows a greater entrained-air content and a much greater tendency toward the accumulation and coalescence of bubbles around coarse aggregate particles. Longitudinal section of vertical core.

Vertical Core through Construction Joint between Second and Third Lifts, Vacuum Test Block

APPENDIX

APPENDIX

USE OF VACUUM TREATMENT ON MASS CONCRETE SURFACES IN THE FIELD

1. This appendix is a compilation of information on use of the vacuum process on various Corps of Engineers projects. The data are presented as they were submitted to this office except as noted. Use of the process on the following projects is covered:

- Dorena Dam
- McNary Dam
- Garrison Dam
- Ft. Randall Dam
- Whitney Dam
- Ft. Gibson Dam
- Buggs Island Dam
- Clark Hill Dam

Dorena Dam

Field experience

2. Vacuum treatment was applied to the downstream face of the overflow spillway, to the inboard faces of nonoverflow blocks Nos. 5 and 12, to the interior surfaces of the discharge conduits, to the floors and baffles of the stilling basin, and to the training walls above elevation 740. The vacuum treatment of formed concrete surfaces was estimated by the contractors to result in a $0.25 per square foot total increase in cost over conventional methods of forming and placing. In general, the results of the vacuum treatment were satisfactory. Some irregularities

were observed on the downstream face of the overflow spillway. These are believed to have resulted from penetration of the vibrators into partially set lower layers, or from insertion of vibrators too close to the vacuum panels. The vacuumed surfaces appear to be appreciably hardened, as evidenced by the considerable effort required to chisel out small portions of it during isolated patching operations. The unformed surfaces of the inverts of the discharge conduits were very satisfactory after vacuum treatment, but the walls and ceilings contained some departures from the smooth, plane surfaces desired. The irregularities on the vertical wall surfaces can perhaps be attributed to interference between the relatively closely spaced reinforcing steel and the 3-in. maximum size aggregate in the concrete immediately surrounding the conduit, and to particles lodging under the cloth when the tar paper seal covering the forms for subsequent lifts was accidentally broken. It is conceivable that the steel prevented the concrete from completely readjusting itself to the decreased volume resulting from the vacuum process. Regarding the ceiling surface, the advisability of vacuuming such surfaces is questionable. The water in concrete, owing to gravity and the relative specific gravities of the constituents of concrete, bleeds upward, tending to densify the concrete at the bottom of any section placed. Application of vacuum inhibits this natural densification and is, in turn, partially vitiated by the fact that, with a large quantity of concrete above, water will be available to flow toward the vacuum connection during the entire operation and the desired densification will not be achieved. In connection with the use of the vacuum process on vertical or inclined surfaces, it was noted that special treatment of the horizontal construction joint is required. The application of grout to the hardened concrete near the vacuum-formed surface must be limited to a very thin layer, otherwise a weak, friable strip of mortar at the face of the joint results. On the stilling basin slabs, all of which were greater than 3 feet in depth, a noticeably wet surface condition was observed immediately after the application of the vacuum and prior to finishing. The wet appearance of the slabs suggests the possibility that the benefits of vacuum treatment are not fully realized on thick, horizontal slabs, due to continued bleeding subsequent to the vacuum treatment. It is possible, however, that the moisture merely drained back from the suction system when the vacuum was broken.

Measurements of Water Removed by Vacuum

Location: Block No. 11, Overflow Spillway

Elev Ft	Area Sq Ft	Water Removed, Gallons Total	Water Removed, Gallons Per Sq Ft
795 - 800	200	10.5	0.0525
800 - 805	200	16.5	.0825
810 - 815	200	18.3	.0915
815 - 820	200	20.9	.1045
820 - 825	200	22.1	.1105
825 - 830	200	26.2	.1310

Location: Stilling Basin Baffles

Area* Sq Ft	Volume* Cu Yd	Water Removed, Gallons Total*	Water Removed, Gallons Per Sq Ft
494	25	22.5	0.0455
612	38	37.5	.0613

* Each quantity represents two baffles.

Laboratory tests

3. Abrasion tests. Abrasion tests were made at the National Bureau of Standards, Washington, D. C., on small concrete specimens

(2 in. by 2 in. in cross section) which had been cut from 12-in. concrete cubes cast at Dorena and subjected to vacuum treatment. The concrete was approximately 8 months old at the time of the abrasion tests. All aggregate larger than 3/8 in. was screened from the concrete prior to casting the cubes. One cube received vacuum treatment on the top, horizontal surface; the second cube received vacuum treatment on a side, vertical surface; the third cube received no special treatment other than steel troweling of the top surface as cast. The small specimens were cut from the 12-in. parent cubes in such a manner that the 2-in. by 2-in. surfaces to be abraded were parallel to the plane of the treated top or side of the cube, and at specific distances from it, namely, 0, 1-1/2, 3, 4-1/2, 6, 8, and 10 inches. Two sets of specimens were obtained for each type of treatment. The untreated 12-in. cube provided reference specimens for use in determining the effect of the surface treatments; two sets of reference abrasion specimens with faces oriented parallel to the top of the cube and two sets with faces oriented parallel to the side of the cube were cut from the reference cube. The former served to evaluate the effect of vacuum treatment on the top horizontal surface and the latter to evaluate the effect of vacuum treatment on the side, vertical surface. The results of the abrasion tests are available in a report dated June 20, 1949, from the National Bureau of Standards to the District Engineer, Portland District. The data submitted therein have been rearranged herein on the basis of percentage reduction in wear. The total weights lost due to abrasion have been averaged for like specimens at the end of each of the three, 5-minute abrasion periods.

Depth of Abraded Surface from Treated Surface, In.	Reduction in Wear, Per Cent End 1st Period	End 2nd Period (Total)	End 3rd Period (Total)
	Vacuum Treatment on Top Surface		
0	20.3	20.8	19.3
1-1/2	7.5	6.6	1.0
3	4.8	4.6	3.2
4-1/2	7.3	12.5	13.2
6	7.7	9.3	-
8	6.8	1.4	-
10	18.4	6.6	-
	Vacuum Treatment on One Vertical Surface		
0	1.4	15.3	14.1
1-1/2	1.1	0.0	-3.7
3	2.2	4.9	7.2
4-1/2	18.4	12.4	9.6
6	0	0.5	
8	4.5	-3.8	
10	-	1.8	

The calculated percentages reduction in wear are erratic and do not permit evaluation on the basis of small differences in wear. This is probably caused by nonuniform distribution of relatively large or hard pieces of aggregate in the small surface areas abraded, or by the dislodgment of small aggregate particles during abrasion. However, the results are sufficiently consistent to indicate an increase in abrasive resistance as a result of vacuum treatment.

4. Strength tests. Two-inch compressive strength specimens were also cut from the parent 12-in. cubes previously described, to determine the variation in the compressive strength of concrete at various distances from the vacuumed surface. Comparative specimens were also cut from the untreated cube. The compressive strength tests were made at 245 days age by the North Pacific Division Testing Laboratory. The results are available in their report submitted to the District Engineer,

Portland District, September 15, 1949, as the first indorsement to the basic letter of request dated March 23, 1949, from the Portland District, subject, "Request for Cutting and Testing of Concrete Specimens, Dorena Dam, Contract No. W35-026-eng-2600." Paragraph 8 of the report states in part, "These tests indicate that the vacuum treatment resulted in an increase in compressive strength for a depth of about 4 inches away from the treated surface."

5. Examination of cores. Two 6-in.- and eight 8-in.-diameter cores varying in length from 8 to 18 in. were taken from the Dorena Dam. Four of the 8-in. cores were vacuum-treated and the remaining cores were all nonvacuum-processed. Each core was sawed into appropriate specimens for determination of specific gravity, absorption, resistance to abrasion, determination of air content and microscopic examination. The results of the determinations were as follows:

a. Specific gravity was determined at 1-in.-depth increments on each core. There was a slight trend toward higher specific gravity in the first inch of depth of the vacuum-treated surfaces as compared to the untreated surfaces but the differences were too small to be significant.

b. The absorption was also determined at each 1-in.-depth increment and these results also are inconclusive in indicating differences between types of surface treatment.

c. The abrasion test results, determined by abrading surfaces through means of a series of Desmond Huntington wheel dressers revolving in the chuck of a drill press, were inconclusive. The abrasion loss appeared to be proportional to the area and hardness of the coarse aggregate pieces exposed.

d. Determination of air void percentages showed no apparent difference with increase in depth for the treated or untreated surface.

e. Examinations, both megascopic and microscopic, of thin sections did not reveal any significant difference between untreated and vacuum-treated concrete or between different depths below the surface of vacuum-treated concrete.

McNary Dam

6. In accordance with the McNary Dam Project plans and specifications for construction of a portion of the concrete dam, navigation lock, fishways, and appurtenant structures on the north (Washington) shore, approximately 28,500 sq yd of concrete was treated by the vacuum process.

Description of equipment

7. The vacuum panels, for the most part, were 4 ft 0 in. by 4 ft 0 in. in size, divided in two equal sections and equipped with two nipples through the plywood sheathing for the vacuum hose connection; each connection serviced 8 sq ft of the pad. As specified, the pads were provided with rubber fabric seal strips, two layers of 16-mesh wire screen, and a layer of muslin filter cloth which was fastened to the panel. The pump that produced the vacuum was an inverted 350-cu-ft-capacity air compressor.

Operation of process

8. Vacuum was applied for a duration ranging between 5 and 15 min, and in one isolated case was applied for only 3 min. This variance was directly proportional to the slump of the concrete. In general the vacuum was maintained at or above 17 in. of mercury. The effluent from the suction pipe was cloudy in color and contained a small amount of cement. When concrete having a slump of approximately 1-1/2 in. was used, little or no water was drawn from the surface. However, when concrete having a slump from 3 in. to 4 in. was used, as much as 15 gal of

water was withdrawn from 500 sq ft of surface.

Field laboratory tests

9. A test was conducted to obtain a comparison of the absorption of vacuum-treated and untreated surface concrete at depths of 1-in. intervals up to 10 in. in depth. The procedure used was as follows:

a. Four NX cores approximately 12 in. in length were extracted from the vacuum-treated surface of the spillway dam in monolith SD-8, below elevation 232.88. Concrete on this surface was unformed, vacuum-treated for a duration of 8 min with vacuum to 17 in. of mercury, and lightly steel-trowel finished.

b. Four NX cores approximately 12 in. in length were extracted from the untreated surface in monolith SD-8 between elevation 232.88 and 235.0. Concrete on this surface was formed, and the forms left in place until initial set in the concrete had occurred. The forms were then removed and the surface was steel-trowel finished.

c. Details of the concrete mixture for these areas were as follows:

Concrete	Max. Agg. In.	Mix Parts	Cement Content	Unit Water	W/C	Slump In.	% Air	Age Days
Vacuum-treated	1-1/2	1:2.3:5.0	5 sacks	211#	0.45	3-1/4	4.3	120
Untreated	1-1/2	1:2.3:5.0	5 sacks	211#	0.45	3	4.0	90

d. Preparation of specimens. Each of the cores was cut into discs approximately 1 in. in thickness and numbered from 1 to 10 inclusive.

e. Absorption test. An absorption test was conducted on each disc. The coarse aggregate particles were then removed from the specimens, and the absorption was computed on the basis of the mortar portion of the mix only.

Test results

10. Results of tests are shown graphically on figure A1.

Discussion

11. From the curves shown on figure A1, it appears that a dense

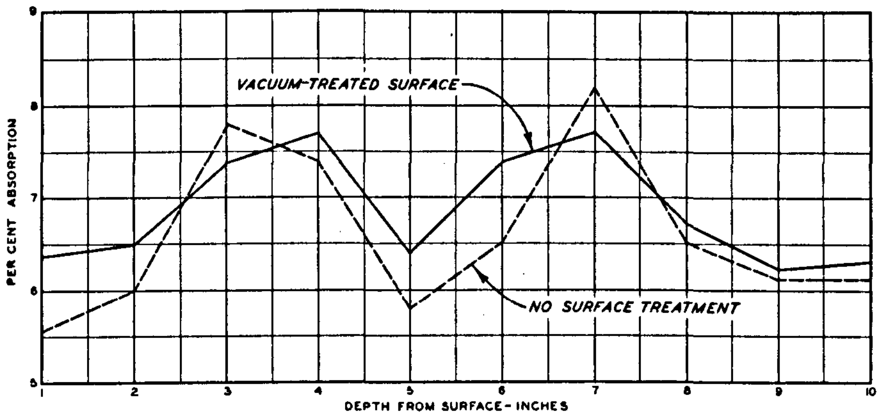


Fig. A1. Effect of surface treatment on absorption of mortar in concrete from ogee section of spillway, McNary Dam. Each value shown is the average of four 1-in. sections from NX cores

concrete has resulted at the surface of both the vacuum-treated and the untreated concrete. From the limited tests, a trowel finish without the vacuum treatment appears more effective in lowering the absorptive characteristics of the surface concrete. The apparent dense, low absorptive characteristics of the concrete at the 5-in. depth are not fully understood, but may be due to the gradient formed by the sudden drawdown effect of the water at the surface in both cases. The zone between the 3-in. and 4-in. depth could have been the result of bleeding subsequent to discontinuance of the vacuum process and troweling prior to initial set of the concrete. Had the concrete remained plastic and the withdrawal of water continued, either by the vacuum process or troweling, it is probable that the curve would have been less abrupt from the 2-in. depth to the 5-in. depth.

12. The stilling basin for McNary Dam is level in section, and extends approximately 274 ft downstream from the toe of the dam. It was treated by the vacuum process. Concrete in this area, for the most part,

was placed during the months of May, June, and July, 1949, when high ambient temperatures, low humidity and high winds prevailed. The portable vacuum pads were applied to the surface immediately after the concrete had been screeded and floated to grade. Frequently after the surface was vacuumed for a period of 10 min, it would become crusted and appear to have "set up," and the concrete immediately below the surface was still "spongy." When this condition occurred the period of vacuum-processing was reduced to as little as 3 min in order to obtain a proper finish.

13. Another condition was observed to occur when the weather was cool and humid, and the concrete being placed had a slump of from 3 to 4 in. It was noted that after vacuuming for a period of 10 min all the excess water had been drawn from the surface. However, 5 to 10 min later it was necessary to reprocess the surface with the vacuum pads as free water had appeared. This may have been the result of capillary action.

14. Colonel Ellison, Mr. Davis, Mr. Thatcher, Mr. Wells and Mr. Morgan discussed this subject in open conference and were in agreement on the following points:

- a. From field observations and limited test data available no definite conclusions can be reached as to the extent of improvement, if any, which may have resulted from the use of vacuum treatment on the McNary Dam Project. It is entirely possible that observations of this concrete over a long period of time may indicate that some appreciable improvement has resulted.

- b. When the vacuum treatment process is used during the summer months in arid and windy areas, care must be exercised not to carry the treatment on for too long a period of time. Further detailed experimentation might indicate the necessity for screening against the sun and dry wind in order that the vacuum treatment can be effective under these conditions.

c. Where it is necessary to place concrete with a relatively high slump there is reason to believe that the surface concrete might actually be damaged by vacuum treatment as a result of formation of water courses around the aggregate particles. This would be particularly true in the case of a properly designed mix which had relatively little or no bleeding when placed without the vacuum treatment.

d. The cost of the vacuum treatment of the concrete at McNary was $2.95 per sq yd, which, in the opinion of this group, is very hard to justify unless conclusive experimental data indicate that considerable improvement in the wearing qualities of the surface concrete results consistently from this treatment, and unless the cost for this improvement would be less than the maintenance cost over a long period of time on concrete which did not receive the vacuum treatment.

e. The above comments and conclusions all apply to the area at McNary Dam where vacuum treatment was carried out. In this area the slab concerned was a minimum thickness of 5 ft. It is possible that vacuum treatment of thinner sections and other types of structures would be very advantageous.

Garrison Dam

15. Presented herewith are results of field tests conducted to determine suitable forms and methods for vacuum-treating the concrete in the invert sections of the transition and portal sections for tunnels 6, 7, and 8. In determining a procedure which would be satisfactory, the contractor constructed and treated 12 separate test sections which will be listed and described in chronological order. Mr. Monaghan of the Vacuum Concrete Co. was present during all the tests. Mr. J. J. Creskoff, also of the Vacuum Concrete Co., was present for tests 4 through 9.

Test No. 1

16. Test section. A section of the invert of portal to tunnel 6. Invert curved to 11-ft radius, width measured along arc, 12 ft 8 in.,

length 15 ft.

17. Form. A rigid metal form 2 in. less in width than the total width of the invert, curved to fit the 11-ft radius of the tunnel invert and 6 ft long. This rigid form was constructed by the Blaw-Knox Company for use as a vacuum mat.

18. Vacuum mat. First layer, black iron expanded metal lath next to metal skin plate. Second layer, standard 16-mesh galvanized fly screen. Third layer, cotton cloth, 64 threads per inch. Metal lath and fly screen extended to 3-1/2 in. from edge of form. A rubber seal composed of two layers of rubber, 1/16 and 1/32 in. thick, bordered the edge of the form on all four sides. The cloth covering extended over the rubber seal and was fastened by staples on the wooden edge of the form.

19. Concrete. Maximum size aggregate, 1-1/2 in.

Cement factor, 5.0 sacks per cu yd.

Water-cement ratio, 5.5 gal per sack.

Air, 4 per cent.

Slump, 1-1/2 in.

20. Procedure. After screeding, which was accomplished with considerable difficulty, the rigid mat was placed in position on the concrete. The rigid vacuum mat did not make exact contact with the concrete, the maximum opening at one end being about 3/4 inch. For this reason it was impossible to seal the edges of the rigid vacuum mat so that vacuuming could be accomplished. The experiment was unsuccessful and the invert could not be vacuum-treated.

Test No. 2

21. Form. Test form constructed of wood with top curved to 11-ft

radius, length measured along the arc, 4 ft 1 in., 3 ft 1 in. wide and 8 in. deep at the center.

22. Vacuum mat. Flexible mat made of 18-gauge galvanized steel, size 3 ft by 4 ft.

23. Vacuum covering. One layer expanded metal covered with one layer of fly screen extending to 1-1/2 in. from edge of mat. Rubber seal 3 in. wide extending from edge of expanded metal to 1-1/2 in. beyond edge of mat. Cloth covering over fly screen and rubber seal to edge of mat, glued to rubber seal.

24. Concrete. Same as in test No. 1, except slump for first trial was 2 in. and second trial was 4 in.

25. Procedure. Form filled, concrete vibrated, screeded and vacuum mat placed. No difficulty experienced in holding 20 in. of vacuum. In order to check the pressure applied by the vacuum, the vacuum mat was pulled loose fairly easily with concrete adhering to the vacuum mat. Leakage through the form was considered responsible for the ease with which the vacuum mat could be removed while vacuum was being applied. The form was again filled with concrete having a 4-in. slump. After vibrating and screeding, the vacuum mat was placed thereon and 20 in. of vacuum applied for 10 min. The surface was good but soft, and it was decided that the treatment had not been entirely effective either because the vacuum mat had been removed too soon or because the hose or mat itself had become clogged. Concrete did not retain the 11-ft arc on surface, because of lack of flexibility of vacuum panel.

Test No. 3

26. Test section. Invert in the portal to tunnel 5. Radius of

invert 14.5 ft, length of section 20 ft.

27. Vacuum mat. Eighteen-gauge galvanized iron, size 4 ft by 8 ft.

28. Vacuum covering. Two layers of 16-mesh galvanized fly screen extending to 1-1/2 in. from the edge of the mat. A rubber seal 1/16 in. thick by 3 in. wide extended from the edge of the fly screen to 1-1/2 in. beyond the edge of the mat. In this mat one layer of fly screen replaced the expanded metal lath in an attempt to make the mat more flexible.

29. Concrete. Same as in test No. 1.

30. Procedure. Vacuum treatment was not specified for this invert and the vacuum treatment was only applied on two 4-by-8 sections in order to determine the effectiveness of the vacuum treatment using the 4-by-8 flexible mat placed with the 8-ft dimension perpendicular to the axis of the tunnel. Screeding of the invert was accomplished with considerable difficulty and about two hours elapsed after concrete was placed before screeding was completed and the vacuum treatment could be applied. On the first trial 20 in. of vacuum was applied for 30 min. This trial was satisfactory, the surface being good but a trifle too hard to successfully steel-trowel. The second time the vacuum mat was left on for only 10 min. The concrete this time was too soft and it was decided that the proper vacuum period lay somewhere between 10 and 30 min.

Test No. 4

31. Test section. Test section constructed to the same scale and dimensions as a 6-ft-2-in. section of the invert of a 22-ft tunnel.

32. Vacuum mat. Flexible panels made of 1/4-in. plywood, size 3 ft by 6 ft and 1 ft by 6 ft.

33. Vacuum covering. One layer of expanded metal extending to

2 in. of edge of mat. One layer of fly screen over expanded metal extending to 1 in. from edge of mat. Cloth covering extended to and was lapped over edge of mat and stapled to the back. Rubber seal strip was not used.

34. Concrete. Same as in test No. 1.

35. Procedure. Mr. J. J. Creskoff of the Vacuum Concrete Company was present and supervised tests Nos. 4 through 9. The procedures used and the construction of the mats were in accordance with instructions by Mr. Creskoff. Concrete was partially screeded off using a vibrating screed, devised by Mr. Creskoff, which consisted of a 4-by-4 angle to which was attached a small vibrator. It was apparent that this screed, in order to be satisfactory, required more width to the screeding edge. As designed and used, the point of the angle was placed in contact with the concrete. Considerable difficulty was encountered in holding the concrete on the rather steep slope at the upper edge during vibration. After the completion of this test, it was evident that these haunches were insufficiently vibrated. The plywood vacuum mats were not flexible enough to conform to the curvature of the 11-ft radius and the edges could not be sealed. The attempt at vacuum treatment was therefore unsuccessful.

Test No. 5

36. Test section. Same form as used in test No. 4.

37. Vacuum mat. Fixed side panels and plywood flexible panels constructed as in test No. 4.

38. Vacuum surface. Same as test No. 4.

39. Concrete. Same as test No. 4.

40. Procedure. In order to correct the difficulty in compacting the concrete in the haunches, rigid forms 24 in. wide were attached to the top of the test form, parallel to the axis of curvature and with the upper edge 6 in. from each side edge of the test form. The 6-in. opening was left to admit concrete. This rigid form had vacuum surfacing attached to the underside and was meant to be used as a fixed vacuum panel. The center of the test form between the two rigid vacuum panels was to be treated with flexible vacuum panels as in test No. 4. After the concrete was placed in the forms and vibration started, it was apparent that the rigid panels were insecurely attached to the test form. Attempts to secure them were unsuccessful and the rigid panels had to be removed. Attempts to vacuum-treat the surface with flexible panel were no more successful than in test No. 4.

Test No. 6

41. Test form. Same test form as in test No. 4.

42. Vacuum mat. Same Blaw-Knox rigid vacuum mat as in test No. 1.

43. Vacuum surface. Same as in test No. 1.

44. Concrete. Same as in test No. 1.

45. Procedure. In spite of the results of test No. 1, Mr. Creskoff was of the opinion that the Blaw-Knox rigid vacuum panel could be made to work. Before placement of concrete, the curvature of the rigid mat was checked with the curvature of the form and made to agree within 1/8 in. Concrete was placed, vibrated and screeded as accurately as was possible. Even with this extreme care, which would be impracticable in actual use, it was impossible to seal the edges of the rigid vacuum mat and this test was no more successful than test No. 1. Some thought was given to the

use of the rigid vacuum mats as fixed vacuum invert forms. This idea was abandoned as impracticable because of the difficulty in placing the concrete under the form through the congestion of steel in the invert without air pockets under the rigid form.

Test No. 7

46. Test form. Same form used as in test No. 4.

47. Vacuum mat. Fixed rigid vacuum mats securely attached this time to test form were constructed of tongue-and-groove lumber and lined with vacuum surfacing, 6 ft 2 in. long and 4 ft wide. Flexible mats were used in the center between the rigid forms constructed of 22-gauge metal, size 3 ft by 4 ft.

48. Vacuum surface. Two layers of 16-mesh fly screen, first layer extending to within 2 in. of edge of mat, second layer extending to 1 in. from edge of mat. Cloth covering extended over edge of mat and was glued to backside. No rubber seal was used at edge.

49. Concrete. Same as in test No. 1.

50. Procedure. The fixed forms were fastened as in test No. 5 leaving a 12-in. space at either 6-ft edge of test form. Concrete was placed and thoroughly vibrated to fill the space under the fixed form and in the 4-ft space between the fixed forms. Vacuuming was applied for 30 min to the fixed forms and to the flexible forms placed in the 4-ft space. After 30 min the fixed forms and flexible panels were removed. Voids were found under the lower edge of the fixed form and vacuuming under the flexible mats was unsuccessful, except immediately under the vacuum nipple at the center of the mat. It was decided that the flexible mat was too flexible to permit the entire surface under the

mat to be vacuumed. This test was unsuccessful. An offset of about 1/2 in. occurred between the edge of the flexible panel and the rigid form and it was decided that some form of edging was necessary on the lower edge of the rigid form to hold the flexible mat and prevent this offset.

Test No. 8

51. Test form. Same as in test No. 4.

52. Vacuum mat. Fixed form used as in test No. 7 but with 1-in. rubber flap fastened to lower edge to prevent offset which occurred in test No. 7. A flexible panel was used, constructed of 20-gauge metal instead of 22 as in test No. 7, size 4 ft by 6 ft.

53. Vacuum surface. One layer of expanded metal extending to 2 in. from edge of form; one layer of fly screen extending to 1 in. from edge of form; cloth extending to edge of form and glued to back.

54. Concrete. Same as in test No. 1.

55. Procedure. Concrete was placed in this test installation as in test No. 7 except that at the start of vacuuming, concrete was vibrated for about two minutes of the vacuum period on each side. This was done in an attempt to fill the voids which occurred under the fixed form in test No. 7. Vacuum was applied for 30 min presumably using 20 in. of vacuum as indicated by the gauge at the pump. However, after fixed form and panels were removed, it was apparent that vacuuming was not effective and it was found that the line to the vacuum pump was completely filled with ice. This occurred even though the air temperature was 36 F. Vacuuming, however, was sufficiently effective to determine that the 2-min vibration period at the start of the vacuuming period

would successfully fill the voids under the fixed form. Vacuuming was not effective under the flexible mats placed in the center.

Test No. 9

56. Test form. Three-ft by six-ft section in the center of form used in test No. 4.

57. Vacuum mat. Same flexible vacuum mat as in test No. 8.

58. Vacuum surface. Same as in test No. 8.

59. Concrete. Same as in test No. 1.

60. Procedure. This test was performed in an attempt to determine the efficiency of the flexible mats which were unsuccessfully used in test No. 8 because of freezing of the line. Vacuuming was applied for 30 min, using 20 in. of vacuum, and the results were satisfactory.

Test No. 10

61. Test form. Invert of the portal to tunnel 8, 15 ft long.

62. Vacuum mat. Fixed form lined with vacuum surfacing constructed as in test No. 8 but extending 1 ft beyond the bulkhead at either end of the invert. Flexible mats for the 6-ft space in the center between the rigid form were used, constructed as in test No. 9.

63. Vacuum surface. Same as test No. 9.

64. Concrete. Same as test No. 1.

65. Procedure. Considerable difficulty was encountered in vibrating the concrete at the upper edge of the invert because of lack of restraint in the form at the back. The form at the back was constructed of an I-beam with 10-inch flange used as the form. It was decided that more forming would be required at the back in order to restrain the concrete and force it to flow under the fixed form. During vacuuming it was not

possible to maintain more than 7 in. of vacuum as measured by gauge on the manifold at the invert. This indicated leakage either in the fixed mat or flexible mat or both. Investigation of the fixed vacuum mat indicated that the seal at either end had not been placed at the bulkhead. This allowed air to enter between the rigid form and the bulkhead, which was the probable reason for failure to maintain a vacuum. Because of the considerable delay in vibrating the concrete, sealing the panels, checking vacuum, etc., it was not possible to vacuum the center of the invert. After the removal of the fixed forms, a large number of voids was found under the lower edge. This test was unsuccessful because of difficulty in vibration and inaccuracy in construction of the vacuum panel. However, because of the difficulties encountered in this test and in preceding tests using the fixed form, it was decided that the use of the fixed vacuum form would be impracticable. Too many items could cause failure of this method. Mr. Creskoff did not remain to witness this test and was not present thereafter.

Test No. 11

66. Test form. The invert of portal to tunnel 7. Two 8-in. steel channels were used at either side of the invert, placed parallel to the invert axis and leaving a 6-in. space at each upper edge. These were used partly to restrain the flow of concrete from the haunches during vibration and to fasten the anchor bolts which will be used to anchor the form for the arch pour.

67. Vacuum mat. Same as in test No. 9 but of various sizes to cover the invert.

68. Vacuum surface. One layer of expanded metal and one layer of

16-mesh fly screen extending to 2 in. from the edge of the flexible mat; rubber seal 2 in. wide and 1/32 in. thick from edge of expanded metal to edge of mat; cloth covering extending over rubber seal and glued to back of flexible mat.

69. Concrete. Same as in test No. 1.

70. Procedure. Considerable difficulty was encountered in screeding this invert. In this respect, screeding operations were not improved since the first invert had been place. This meant that the vacuum treatment could not be applied until three or four hours after the concrete had been placed. Because of low temperature (concrete temperature 54 F, air temperature 34 F) the concrete did not reach initial set during this period and was still plastic when vacuum process was applied. Considerable difficulty was encountered in sealing the vacuum mats which were placed with the long dimension parallel with the axis of the tunnel. Vacuuming was partly successful, but it was decided as a result of this test that the vacuum panel should be placed with the long dimension perpendicular to the axis of the tunnel and with rubber flaps along the edge as in test No. 2.

Test No. 12

71. Test form. The invert to tunnel 6.

72. Vacuum mats. Flexible panels were constructed of 20-gauge metal, size about 3 ft by 6 ft.

73. Vacuum surface. One layer of expanded metal and one layer of 16-mesh fly screen extending to 2 in. from edge of mat, rubber seal 3-1/4 in. by 1/16 in. thick placed from edge of expanding metal to 1-1/4 in. beyond edge of mat, cloth covering extended to within 1/2 in. of edge of

rubber seal and was fastened to it with staples and glue.

74. Concrete for invert surface only. Maximum size aggregate, 3/4 in.

Cement factor, 5.5 sacks per cu yd.

Water-cement ratio, 5.5 gal per sack.

Sand-aggregate ratio, 38 per cent.

Slump, 2-1/2 in.

75. Procedure. The same difficulty in screeding was encountered in this test as in all other tests except that this time screeding operations were so delayed that it was not safe to take extra time to use the vacuum process because of danger of concrete setting up. The vacuum process was therefore not used except under one flexible mat. This flexible mat was placed with the long dimension perpendicular to the axis of the tunnel and vacuumed for 20 minutes with 20 in. of vacuum. After vacuuming, the surface appeared satisfactory.

Conclusions

76. Conclusions reached as a result of this series of experiments were as follows:

a. It is much more difficult to obtain satisfactory seal on a curved invert than on a flat surface.

b. The use of rigid vacuum panels presented too many difficulties and was therefore not practicable.

c. Flexible panels constructed of 20-gauge metal using one layer of expanded metal, one layer of fly screen and cloth with a rubber seal and rubber flap at the edge, would be satisfactory. The rubber seal and the rubber flap at the edge are believed to be necessary to obtain a satisfactory seal. This mat should be used with the long dimension perpendicular to the axis of the tunnel.

d. At temperatures just above freezing, the air lines must be constantly watched to prevent freezing.

e. Steel-troweling of the vacuum-treated surface can be successfully accomplished, however, with difficulty if vacuum treatment is applied for too long a period.

f. The type of vacuum mats and construction methods found satisfactory for use on curved surfaces are described below:

(1) The invert is prepared and screeded by standard methods with as little delay as possible between final placement of concrete and the finish of screeding operations. Screeding should be fairly accurate with no holes caused by lack of grout remaining in the surface. Vacuuming compresses the surface about 1/8 in. and the surface should therefore be screeded 1/8 in. high. The vacuum mats used should be 3 to 4 ft wide and long enough to span the entire width of the invert. They are constructed of 20-gauge galvanized iron with the vacuum surfacing consisting of one layer of expanded metal placed next to the galvanized iron and one layer of 16-mesh fly screen over this extending to about 2 in. from the edge of the galvanized metal. A rubber seal, 1/16 in. thick and 3-1/2 in. wide, extends from the edge of the fly screen and expanded metal to 1-1/2 in. beyond the edge of the galvanized iron. Cloth covering over the fly screen extends to about 1/2 in. from the edge of the rubber seal and is fastened to it by staples and glue. Sufficient vacuum mats are on hand to cover half the invert. These are placed on the fresh screeded concrete with the rubber seal extending to the edge of the rubber seal of the adjacent mat. One 1-in. vacuum connection is used for each 12 sq ft of vacuum surface. Two handles are welded to each end of the vacuum mat to facilitate handling. An air gauge, which measures the vacuum pressure in inches, is attached to the vacuum manifold at the form. This is necessary in order to get an accurate reading of the vacuum actually used. The gauge at the vacuum pump may not be indicative of the vacuum at the form because of stoppage in the vacuum line. It is necessary that the air line from the manifold to the vacuum line, as well as the air lines from the vacuum panel to the manifold, be kept warm during cold weather, otherwise they will freeze.

(2) After the vacuum panels are in place, 18 in. of vacuum is applied for 15 min after which the mats are moved to the other half of the invert and the vacuum

applied similarly. Previous experience has indicated that longer vacuum periods resulted in concrete which was difficult to finish with a steel trowel. Steel-troweling or some other surface treatment is necessary to remove the ridges left between the vacuum mats.

Fort Randall Dam

Conditions and limits of experience to date

77. Vacuum treatment of concrete at Fort Randall Dam has so far been applied only to the floors of water passages in the intake structure. All of this processing has been done in cool weather, the first slab having been treated on 30 September of this year.

78. The treated pours range from approximately 13 to 26 sq yd in area and were in most cases 2 ft thick. These pours were units in the third or top lift of a large slab 8 ft thick. Approximately 30 pours have been vacuum-processed to date.

Properties of concrete mixes

79. The coarse aggregate was crushed Sioux quartzite. Natural sand was used as fine aggregate. Cement was Type II. An air-entraining agent, Protex, was added at the mixer.

80. Two different mix designs were used. One mix used aggregate graded up to 3 in. The maximum size of aggregate was reduced to 1-1/2 in. where the close spacing of reinforcing steel near the top of the lift precluded the use of 3-in. aggregate. These mixes had the following composition and properties:

	3-in. Mix	1-1/2-in. Mix
Coarse aggregate grading		
1-1/2 in. - 3 in.	38%	0
3/4 in. - 1-1/2 in.	33%	55%
No. 4 - 3/4 in.	29%	45%
Sand/total aggregate	27%	35%
Cement content, per cu yd	4.1 sk	5.1 sk
Water content, per cu yd	195 lb	225 lb
W/C	0.50	0.47
Air, % of total mix volume	4.0	4.5
Slump	1 in.	2 in.

81. Nearly all of the concrete processed to date was placed at about 50 F; ice was added to the mix when necessary to obtain this temperature. Because of the low placing and ambient temperatures the concrete was quite slow in hardening, the time of initial set being estimated at about 6 hours.

Equipment used

82. The main items of equipment used in vacuum processing at Fort Randall Dam were as follows:

12 vacuum mats 3 ft x 4 ft

2 vacuum mats 1 ft x 4 ft

1 vacuum mat 2 ft x 2 ft

1 Chicago Pneumatic Compressor, 315 CFM, capable of producing up to 20 in. of vacuum

2 vacuum tanks, 50 gal capacity (for collecting water).

Other items included hose lines, manifold, valves and gages.

Vacuum process procedure and results obtained

83. Immediately after the concrete was placed, it was shaped to line and grade by screeding and floating.

84. For the first pours the vacuum was applied immediately after the concrete had been floated, and it was found that some bleeding took place after the mats were removed. The practice was then changed to delay the application of the vacuum until the moderately heavy bleeding exhibited by these mixes was well under way, 1-1/2 to 2 hours after placing; using this procedure no bleeding took place after the mats were removed. It was believed logical to suppose that by delaying the application of the vacuum a greater quantity of water was removed and a more durable surface obtained.

85. Practically all of the vacuum processing was done by the 3-ft by 4-ft mats. A minimum suction pressure of 15 in. of mercury was required and 17 in. was the average actually obtained. Generally 6 to 8 mats were placed at a time, this being the maximum number for which the compressor could maintain satisfactory suction pressures. This means that one to two changes of mats were required to process the entire top surface of a pour. It was expected that the compressor capacity, and possibly the number of the mats also, would need to be increased for warm-weather processing when sizeable delays between placing and processing would probably not be permissible.

86. The vacuum was generally maintained for 25 to 30 minutes, or as long as an appreciable flow of water was observed through a lucite tube inserted in a hose line leading away from one of the mats. The

total water extracted by the vacuum process ranged from .06 to .08 gal per sq ft of area, the average being .07 gal.

87. Immediately after the mats were removed, the entire surface was gone over lightly with a steel trowel to remove irregularities.

88. From visual inspection of hardened concrete chipped from a processed slab it was indicated that the vacuum penetrated 1 in. to 1-1/2 in.

Whitney Dam

89. Vacuum treatment of concrete on Whitney Dam was specified for the unformed portions of the overflow section of the spillway and for the sluiceway floors. Suction mats, both rigid and flexible, manufactured by the Vacuum Concrete, Inc., Philadelphia, Pa., were used. A vacuum pump recommended by that company was used throughout the work.

90. The following field data were obtained from tests and observation by the project personnel:

a. A test on vacuum treatment of battered mass concrete surfaces was conducted on 9 June 1949. The test section was on the downstream face of block 30, lift 20. A steel form was converted to vacuum treatment by placing 1/4-in. plywood on the form, then stapling one layer of fly screen to the plywood. One layer of unbleached muslin was then stretched over the form and stapled to cleats fastened to the outside of the form for this purpose. Two rows of seven 3/4-in. nipples were welded to the form at the 1/3 points. No external or internal rubber strips were used on the form. By stopping the screen wire approximately 1 in. from the edges, mortar against the cloth and plywood effected the seal. Two panels 19.75 ft in length and 6.10 ft in width were used. Four-bag exterior concrete was placed against the form for the entire 5-ft lift before vacuum treatment was applied. The 5-ft lift was placed against the form in approximately 45 min; 26 in. of vacuum was applied for 30 min. The top 2-1/2 ft of the lift was revibrated after the vacuum had been applied for

15 min. The amount of water extracted from the test section was 0.26 lb per sq ft. After 48 hr the form was removed presenting a surface of fine texture with no air pockets. Four 6-in. cores were taken from the test section and delivered on 4 August 1949 to the Concrete Research Division of the Waterways Experiment Station for observation and test. (Examination of these cores is covered in the description of the petrographic examination of cores, paragraphs 55-61 of the main report.) Visual observation of the cores indicated that air pockets existed approximately 1/8 in. under the surface and that the effective depth of vacuum treatment was shallow.

b. Vacuum process was used on the bucket section of the spillway and on the sluiceway floor of Whitney Dam. It was found that a tight wood-float finish could not be obtained after the application of vacuum process. It was necessary to use a steel trowel and brush to obtain the desired finish.

c. The amount of water extracted from unformed surfaces varied from 0.04 lb per sq ft to 0.30 lb per sq ft. The length of time vacuum process was applied was varied from 10 min to 30 min with no appreciable difference in finishing noted.

d. It was the opinion of the field office that vacuum process greatly reduced finishing time.

91. Observations made by representatives of this office indicated that vacuum treatment of a formed surface on mass concrete has about the same effect as absorptive form lining, but the degree and thickness of "case hardening" are greater. When absorptive form lining is used, the thickness of the "case hardened" film is between 1/16 in. and 1/8 in., while with vacuum treatment it is between 1/8 in. and 1/4 in. in thickness. However, on formed surfaces and specifically on battered formed surfaces the air and water voids which normally show on a concrete surface which has not been treated, are still present under the "case hardened" skin of vacuum-processed concrete. As these voids are not visible and their size, number and distribution not determinable, no corrective action to minimize or eliminate them can be taken nor can any

remedial action be initiated to fill them.

92. The limited experience with vacuum treatment of mass concrete on formed surfaces by this office leaves much to be desired. It is believed, however, that proper use of vacuum treatment of unformed surfaces is beneficial, especially on slightly sloping sections.

Fort Gibson Dam

Purpose of vacuum-processed concrete

93. The purpose of using vacuum-processed concrete is to secure a surface highly resistant to wear by removing excess water and entrapped air with vacuum suction, after the concrete is placed.

Equipment used

94. A Chicago Pneumatic 315-cu-ft compressor was used to produce the vacuum, by connecting to the suction side of the compressor. The only change necessary on the compressor was to replace the two air cleaners on the suction side of the compressor with a manifold to which the 2-in. vacuum hose was attached.

95. Two water receiver tanks of 60-gal capacity were used. A manifold between the tanks allowed alternate use, so that one tank could be emptied while the other was in use. Two-inch hose led from the compressor to the receiver tanks with 2-in. hose from the tanks to the manifold.

96. Flexible hose of 1-in. inside diameter was used for connecting the mats to a 2-in. pipe manifold with 1-in. nipples.

Placing

97. The upstream section used in this description referred to the section that was located on the upstream side of the gate seat recess

and the downstream section was the part located on the downstream side of the gate seat recess. Placing procedure was as follows:

a. Placing the regular Class-C exterior concrete started on the upstream side of the form wall and was continued to within 2 ft of the small form that was on the downstream construction joint at elevation 540.27. The second lift was started on the upstream side and continued to the downstream side again, to within 4 ft of the finished grade line. Each lift was treated in this manner with each separate lift stepped back from the downstream grade line. When the regular Class-C exterior concrete (6 in. top size) was within 12 in. of grade, the Class-C special concrete (3 in. top size) was ordered and placing was started on the downstream side and the entire downstream section was covered with concrete, vibrated, screeded and bullfloated. The concrete had to be screeded and floated to the true grade and contour before the mats were placed.

b. Operations on the upstream side were suspended until vacuum-processing was practically completed on the downstream side. This allowed the finishers to keep rather close to the vacuum-processing with the final finish. Too much area should not be vacuum-processed at one time because cracking will occur before the finishers can seal the surface.

c. Vacuum mats were placed on the surface and allowed to stay on 15 min with an average of 20-in. vacuum. The finishers started to work on the surface with a wood float and steel trowel as soon as the mats were removed. Two finishers were used on each pour. When finishers were unable to keep up, the mats were left on the surface but the vacuum was turned off. This prevented excess drying until the finishers were ready to work the surface. It was found by trial that mats placed normal to the dam axis were more successful than those placed parallel to the axis.

Makeup of mats

98. Mats were made of sheet metal with a regular size of 3 ft by 4 ft and a few 1-ft-by-4-ft sections to fit in required form widths. The mats had 1-in. elbows in the center of the back side attached to floor flanges, with a quick-opening valve for opening and closing the vacuum

line. The face of the mats consisted of heavy muslin cloth, 128 thread, backed by two layers of 14-mesh insect screen. It was necessary to wash the cloth off immediately after use to prevent clogging on the next pour. Six 3-ft-by-4-ft mats and one 1-ft-by-4-ft mat were used to process each layer. The total surface processed on each pour was 684 sq ft requiring nine applications of the seven mats listed above. The outside edges of the mats had 2-in. strips of rubber all around (trade name "C. I. Sheeting"). Three-inch strips of surgical rubber were cemented to the CI Sheeting with Plasticon cement. The surgical rubber extended an average of 1-1/2 in. beyond the mat frame. The surgical rubber cost 16 cents per sq ft and the CI Sheeting cost 79 cents per sq ft.

99. Experienced operators could tell whether the mats were sealing properly and maintaining the proper vacuum. The mats would visibly flatten when working properly. If the mat simply lay on top and could be moved or raised easily, the vacuum was too low (below 20 in.) or there was a leak in the gaskets. If a mat was loose and slipped around, it was not working properly.

Difficulties encountered
and remedial measures

100. a. The mats, as made up at the factory, did not have the proper kind of rubber to seal the edges. The gasket rubber, which came with the mats, was later overlaid with surgical rubber which is much softer and sealed more readily.

b. The floor flange attached to the back of the mat did not seal properly and it was necessary to replace the rubber gasket and use sealing compound to stop the leaks at this point.

c. When a hot dry wind was blowing over the surface to be finished, large cracks opened up after the mats had been removed if too large an area was exposed before final finish was accomplished. This was overcome by placing shorter lifts and following very closely with the final troweling.

d. The same personnel should be used to operate the mats at all times to avoid changes in procedure of applying the mats and other details of the process.

e. The mats should be placed as soon as screeding and bull-floating is completed. It is not necessary to trowel the finish prior to the placing of the mats.

f. Cracking of the processed surface by knee boards of the finishers was overcome by using 3-in. top size aggregate in the mix for the top foot. It is believed that use of this larger size aggregate helped support the weight of the finishers.

g. Some difficulty resulted from over-processing during the first pours, caused by leaving the mats on vacuum longer than 15 to 20 min. This resulted in a dry surface which could not be finished readily. The condition was remedied by lightly sprinkling the surface, although it is recommended that the mats be left in place and the vacuum shut off to preserve the necessary moisture in the surface for final finish.

h. When mats were not placed close enough together, the unprocessed space between them cracks and weakens the surface. Rubber gaskets along the edge of the mats should be placed flush with each other.

i. Finishing operations were expedited by building a set of movable steps curved to the downstream slope of the pour, which permited the finishers to work without getting on the fresh concrete. The top of the steps rested on the gate seat box and the bottom on the catwalk.

j. When replacing the muslin on mats it was found that if drawn up too tight it would shrink and wrinkle up on application to the surface. The cloth should be left loose enough to allow for shrinkage.

k. Some difficulty was experienced when using mats during a rain owing to the excess water on the surface.

l. Dirty cloth on the mats causes the resulting surface to be spotted.

m. Leaks which develop around the rubber gasket on the edge of the mats can be stopped by applying a small amount of grout picked up from the unprocessed surface and applied over the leak.

n. Mats should be closely inspected for cleanliness before being placed on the concrete surface. Clogged screens or crusted muslin will cause a loss of several inches of vacuum.

o. Carelessness in closing the valve, so that the vacuum is not entirely cut off when the mat is lifted, will result in damage to the surface. Sections of the surface mortar will come off with the mat unless the valve is entirely closed.

p. The concrete showed a tendency to slump below grade at the crown of the ogee section, elevation 547.0. It was determined that this was caused when the mix had too high a slump and was over-vibrated. This was remedied by controlling the vibration.

q. Mats can be kept in better condition if a rack is constructed in which to store them when not in use.

r. Valves and nipples attached to the mat sometimes freeze owing to condensation. This can be remedied by applying the heat from a large floodlight with 1000-watt bulb to the frozen connection.

s. The mats, as received from the factory, had two handles placed across opposite corners to facilitate placing and removing. It was found that handles placed in this location stiffened the corners and prevented sealing at this point. The handles were placed in the center of the top and bottom of the mat and no further trouble ensued.

Concrete mixes used

101. Class-C exterior concrete was required for the entire lift of the crest of the ogee section. The manufacturer advised using a rather harsh mix since the water could be more readily removed from such a mix. It was also recommended that the large size aggregate be removed from the mix. Accordingly, a mix of the following proportions was used on the top foot of the first pour. All weights based on a 1-cu-yd mix:

Cement	423 lb
Water	250 lb
Sand	958 lb
3/4-in. stone	1000 lb
1-1/2-in. stone	1526 lb

102. The vacuum process did not prove successful on this mix in that not enough water could be removed. Accordingly the mix for the top foot was changed as follows:

Cement	423 lb
Water	250 lb
Sand	961 lb
3/4-in. stone	624 lb
1-1/2-in. stone	800 lb
3-in. stone	1098 lb

103. This mix proved satisfactory and was used on the remainder of the pours. Several slight variations in aggregate proportions were used in the above mix as an experiment, but the original mix using 3-in. top size aggregate was found most satisfactory.

Results

104. The total area processed was 14,424 sq ft, from which an average of .045 gal of water was removed per sq ft. The average processing time was 17.4 min, and the average vacuum was 19.4 in. The average effective depth of the processing determined by digging out small pockets here and there in the processed surface was 2 in. The average slump of the concrete treated was 2 in.

Cost of using process

105. The cost of using the vacuum process on the crest of the ogee section at Fort Gibson Dam was between $0.10 and $0.12 per sq ft, plus a royalty of $0.035 per sq ft for the use of the mats.

Conclusions

106. The following observations and conclusions are submitted as a result of the experience with vacuum-processed concrete finishing at Fort Gibson Dam:

a. It is necessary that the equipment used, especially the mats, be kept in first-class condition. Some changes may be necessary in the equipment as received from the manufacturer, such as the addition of a softer rubber gasket around the edges.

b. The crew of men placing the mats and the finishers should be drilled on the procedure for applying the mats, maintaining the vacuum and finishing, before and after placing the mats. A small, efficient crew should be used on this operation, using the same men for the same operation each time. As they become experienced, very little difficulty will be experienced with the process.

c. The operation is advantageous to the contractor in that it allows the finishers to get on the surface for final finish several hours sooner than if regular methods of finishing were used. As noted previously, the cost is not excessive for this type finish.

d. The final surface is very desirable from the standpoint of appearance and density. No air and water voids, either visible or crust-covered, are to be found on the finished surface and from cores drilled in vacuum-finished lifts, the top 2 in. appear to be well consolidated. Several beams, made at the Fort Gibson project, which were vacuum-processed showed equal or better results under 300 cycles of freeze-thaw than beams made of the same concrete without vacuum-processing.

e. Tests of the air content of the vacuum-processed concrete before and after processing showed the usual loss of entrained air due to vibrating of about .8 per cent to 1.0

per cent, indicating that the final entrained-air content is approximately the same as for ordinary vibrated concrete.

f. It is the opinion of this office that vacuum-processing is satisfactory whenever a hard, void-free surface requiring durability is required. The experience at Fort Gibson Dam was confined to the crest of the ogee spillway but any horizontal surface could be finished by the same methods. It can be stated that the vacuum process was highly successful at this project.

Buggs Island

107. The following is a summary of experience with vacuum-processing of the spillway apron at Buggs Island Dam.

Dimensions

108. Each monolith was roughly 37 ft x 50 ft, with the 50-ft dimension parallel to the axis of the dam. The surface of the bucket section was a circular arc of 40-ft radius with a chord of approximately 23 ft joined at the downstream end by a tangential flat surface approximately 13 ft long on a 20-degree slope. Two lifts were required to complete the bucket section in each monolith, the first included the entire curved portion of the surface and the second included the entire flat sloping portion of the surface, tangent to the downstream edge of the curved portion. Depth of concrete in the bucket section varied from 1.4 ft to 5 ft. Screeding templates were set on 10-ft spacing.

Placing procedure

109. Concrete was placed in approximately 18-in. layers to bring one end of the form to grade rapidly in order to allow the finishers to get started as soon as practicable. As soon as the 10-ft space between screeding templates was full, the finishers brought the concrete to

final grade by screeding. The screeds used on initial pours were ordinary straight-edge, 2-in.-by-6-in. boards, but an I-beam with a vibrating attachment was soon adopted. Flexible steel vacuum mats were used. (It was found that sealing these airtight was difficult. The solution obtained was to remove irregularities in the concrete surface by hand floating and to cement a thin rubber flap about 2 in. wide around the edges of the mat.) The mats were placed as rapidly as completion of the finishing process would permit. Finishing with hand floats following the vacuum process was limited to dressing down a slight ridge left between the mats.

Concrete mixes used

110. Since the finish grade was on a slope, a fairly stiff mix was used. It was found that a slightly under-sanded mix (recommended by the Vacuum Process Corporation's agent) was difficult to place and bled freely, both before and after vacuum-processing. A mix that gave a smooth finish was finally adopted as the most practicable because the smooth finish allowed the rubber flaps to seal the mats airtight against the concrete. Vacuum was maintained usually for 15 min. No appreciable amount of water was removed after the first 10 min. It was observed a few weeks after placing the concrete that it rang hard and true when struck with an iron bar.

111. The following sub-paragraphs contain information abstracted from a report entitled, "Vacuum Processed Concrete," covering examination of cores from Buggs Island Dam project.

Laboratory examination

a. Examination was made of thirteen 3-3/8-in.-diameter cores varying in length between 20 and 25 in. All cores were taken from the spillway apron and 11 of the 13 were of vacuum-processed concrete.

b. The cores were examined megascopically and by microscope to determine the effect of vacuum-processing on particle arrangement within the concrete, size and shape of void spaces and relative void content and change in density with increasing depth.

c. It was noted that the entrained-air content varied considerably throughout each core and from core to core, with no evidence of sponginess in any of the specimens. The variation in air content does not appear to follow any definite pattern. If results on three cores which had quite high air content immediately adjacent to the surface were excluded it was found that the average density ranged from 147.8 to 149.8 lb per cu ft with the greatest density at 5 to 7 in. in from the surface and the least density in immediate contact with the processed surface. Three of the processed cores had air contents in the mortar surface ranging from 6.6 to 8.0 while the air content for this region in the other cores averaged 3.4. The reason for this high air content is not known. There appeared to be little or no evidence that vacuum-processing affected the size, shape or distribution of the entrapped air voids.

112. The coarse aggregate distribution and particle arrangement did not appear to be affected by the vacuum treatment.

Clark Hill Dam

113. A discussion of experiences with vacuum treatment of mass concrete surfaces at Clark Hill Dam may be divided into two parts: (1) formed surfaces, and (2) unformed surfaces.

114. Difficulty in obtaining entirely satisfactory results with the vacuum-processing of formed concrete surfaces resulted in an order by the Office of the Chief of Engineers to discontinue the application of the process on both formed and unformed surfaces after 26,000 sq ft of a contract total of 131,000 sq ft was completed. One difficulty

encountered from the start was the fastening of the fly screen to the cantilever wood form panels in a manner to prevent its curling at the junction with the rubber sealing strips. This condition resulted in slight depressions in the formed surface at either side of the seal strips. This difficulty was largely overcome by cutting the top layer of the fly screen oversize and folding the surplus under the bottom layer and by tight stretching and close stapling along the edges.

115. After about 26,000 sq ft of surface was treated, a second difficulty was noted in the surface of the concrete. A veneer of hard mortar 1/16 in. to 1/8 in. in thickness was found to overlie a strata of highly air-entrained or frothy mortar in some of the concrete surfaces. This mortar veneer had spalled off in a few spots and the extent to which the condition existed could not be determined readily. After investigation and discussion concerning the probable cause of this condition the consensus was that the concrete next to the form probably had not been revibrated during and after evacuation of the surplus mixing water to rearrange the concrete mix particles to give maximum density. The resulting void was at least partially filled with enlarged entrained air bubbles caused by reducing their atmospheric pressure during the evacuation. Failure to find a similar condition in cores taken from the surface of one monolith known to have been revibrated during and after evacuation tended to support this conclusion. Further examination of the vacuum-treated formed areas showed this frothy condition to be confined entirely to the flattest sloped forms and the bad areas presented only a small percentage of the total formed area treated.

116. This trouble was not corrected by the substitution of absorptive

form lining in lieu of the vacuum process. A similar condition was subsequently observed on several placements formed against lining, particularly some of those placed against the flattest sloping forms. A review of the records of weather conditions usually indicated showers during the period of placement.

117. It is now believed that earlier conclusions drawn as to the probable cause of this frothy condition in connection with the vacuum process may have been largely erroneous and that the chief cause was overwet* and highly air-entrained grout coming in contact with the form. It is very difficult to prevent the concrete from falling away from the flat-sloping overhanging form and to prevent free water or diluted grout from rising and coming in contact with the surface of the form. More than the normal amount of vibration required to assure proper consolidation tends to cause the lighter ingredients, namely, air and water, to rise and accumulate under the form. The water is absorbed or evacuated but surplus air becomes entrapped, possibly to a greater extent within the very stiff grout immediately next to a lined form than it would in a more fluid grout where a liner is not used. It becomes increasingly evident that in placing air-entrained concrete under a flat sloped form having an absorptive or vacuum liner great care must be exercised to prevent concentration of highly air-entrained concrete next to the formed surface. Not only does the concrete slope need to be maintained to prevent any free water from accumulating next to the form, but there is an ever-present danger of over-vibration in consolidating the concrete.

* Wet mixes segregate allowing coarse aggregate to sink and mortar to come to the surface.

118. One of the contributing factors to the unsatisfactory results obtained with the vacuum process against formed surfaces at the Clark Hill project is a rather incomplete specification quoted in its entirety as follows:

> "The surfaces as shown on the drawings shall be treated by the Vacuum Concrete Process in accordance with the practice recommended by the Vacuum Concrete, Incorporated, 4210 Sanson Street, Philadelphia 4, Pennsylvania. No payment will be made for vacuum treatment of the concrete surfaces, the cost therefor shall be included in the unit contract price for the concrete."

119. Despite repeated requests by this office, both through the contractor and directly to Vacuum Concrete, Incorporated, for specific and detailed instructions and recommendations that would constitute a specification, the only information received was vague and of a general nature. A representative of Vacuum Concrete, Incorporated, remained on the job only through the first placement. No representative appeared thereafter until after the work was stopped.

120. No major difficulties other than ridges caused by irregularities in the vacuum mat were experienced with the vacuum process on unformed surfaces where the flexible mats were used. It was found that screeding and floating of the dry mix (1 in. $\pm$ slump) used in the spillway bucket invert (50-in.-radius curve) had to be expedited in order to place mats while the concrete was still plastic enough to effect a seal at the edges. No more than about one hour should elapse, even on relatively cool days, between dumping the concrete and placing the mats, otherwise a seal cannot be held. It is believed that more difficulty would have been experienced in sealing the flat mats to an outside curve such as occurs on the spillway crest of the Clark Hill Dam.

121. The job was started using a 360 C.F.M. compressor converted to a vacuum pump. This proved to be inadequate in capacity to maintain a minimum 15-in. vacuum on a single panel form, or on more than 6 mats. An 850 C.F.M. rotary pump was then obtained which would hold about 20 in. of vacuum on a panel form and 15 in. to 20 in. on as many as 10 mats. Average water evacuated was about 0.25 lb per sq ft from unformed surfaces and 0.35 lb per sq ft from formed surfaces, after 20 min of processing.

122. No physical tests were made on vacuum-processed concrete at Clark Hill other than sounding the surface with a ball peen hammer to locate the areas previously described. From field experience with vacuum treatment of mass concrete at Clark Hill, and from visual observations of the large scale tests conducted at the Waterways Experiment Station, it is concluded that satisfactory results can be achieved only with a great deal of attention devoted to each one of the numerous small details involved. With any one of the following details slighted, results are unsatisfactory:

- a. Extreme care must be exercised in securing the wire and the muslin to prevent wrinkling or curling.
- b. The muslin must be stretched along the joint line to be sure that no sandblast sand or other foreign material has penetrated to form a bulge in the form surface resulting in a depression in the concrete.
- c. The forms must be secured with enough ties to prevent deflection so that no loss of vacuum through the construction joints will result.
- d. Rubber seals must be maintained airtight with wire mesh and muslin must be kept clean and free of splashed grout.
- e. Extreme care must be used in fabricating forms, especially wood forms. Steel forms are superior to wood for the process.
- f. Air-entrained concrete must be placed very carefully to avoid

entrapment of any diluted or frothy mortar against the muslin.

g. Initial over-vibration of air-entrained concrete should be avoided, especially under the flat sloping forms. Only the amount necessary for proper consolidation after the concrete has been placed against the form should be used. (Not flowed with the vibrators.)

h. Revibration along the forms after evacuation is necessary to rearrange concrete mix particles to occupy the void left by extracted water.

i. Equipment must be maintained in good order and ample capacity to hold 15-in. to 20-in. minimum vacuum assured.

j. Placements should be scheduled so that at no time will available equipment be overtaxed. (Twenty minutes evacuation time for each cell.)

k. Screeding and floating of unformed surfaces should be expedited so that processing may be started as quickly as possible after placement.

123. Where the proper attention is given to these details, results will be good but the cost will be high. Whether the benefits to be obtained justify the cost of vacuum-processing is the question to be decided.