43rd Annual Convention, CINCINNATI, February 24-26, 1947

JOURNAL
of the
AMERICAN CONCRETE INSTITUTE

(ACI PROCEEDINGS Vol. 43)

Vol. 18 November 1946 No. 3

CONTENTS

to provide a comradeship in finding the best ways to do concrete work of all kinds and in spreading that knowledge

ADDRESS: NEW CENTER BUILDING, DETROIT 2, MICH.

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Resuming, with this volume year, the former JOURNAL publication schedule of 10 issues instead of 6 for the year, the Supplement, issued in recent years with the November issue, will be mailed with the December JOURNAL. It will contain Title Page, Table of Contents, Closing Discussion and Indexes, concluding the volume otherwise completed in the issue of the previous June.

Vol. 18—No. 3 November 1946 (Proceedings Vol. 43)

JOURNAL
of the
AMERICAN CONCRETE INSTITUTE

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Papers and other contributions prepared with a view to Journal publication should be submitted in triplicate, addressed Secretary, Publications Committee, American Concrete Institute, 7400 Second Boulevard, Detroit 2, Michigan. Publication of a contribution does not imply the acquiescence of critics (whose advice is sought by the Committee, prior to acceptance) or of the Institute in the opinions which it expresses nor the approval of data or practice which the contribution records. Institute authority attaches only to Standards formally adopted as provided in the By-Laws. A committee report implies merely the joint contribution of an appointed group.

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It is the policy of the American Concrete Institute to encourage participation by its members and others in the work of extending the knowledge of concrete and reinforced concrete as a basis for improved products and structures.

To this end the Board of Direction has assigned to the Publications Committee the responsibility of selecting for publication such papers, committee reports, discussions and other contributions or parts of such contributions, as in the judgment of the Committee, seem to offer most of value in attaining Institute objectives within space requirements consistent with budget limitations.

AMERICAN CONCRETE INSTITUTE

NEW CENTER BUILDING
DETROIT 2, MICHIGAN

● With the September 1946 issue of the Journal, ACI resumed its pre-depression publication schedule of ten issues a year—monthly, September to June—instead of six issues as in recent years.

● The annual Supplement, usually issued with the November Journal, will be mailed this year with the December number. The Supplement will contain Title page, Table of Contents, Closing discussion and Indexes for Proceedings volume 42, otherwise completed with the previous June Journal.

● Have **you** proposed one or more of the 591 new members since May first?

● Discussion of the papers and reports in this issue is invited. As with all contributions submitted for the consideration of the Publications Committee with a view to publication, triplicate copies of discussion should be addressed to Secretary, ACI Publications Committee, New Center Building, Detroit 2, Mich. Closing date for discussion of November contents is March 1, 1947.

● 43rd Annual ACI Convention, Cincinnati, Ohio, February 24, 25, 26, 1947. Circle those dates on your calendar.

[To facilitate selective distribution, **separate prints** of this title (43-10) are currently available from ACI at 50 cents each—quantity quotations on request. **Discussion** of this paper (copies in triplicate) should reach the Institute not later than March 1, 1947]

Title 43-10 —a part of PROCEEDINGS, AMERICAN CONCRETE INSTITUTE **Vol. 43**

JOURNAL
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Vol. 18 No. 3 7400 SECOND BOULEVARD, DETROIT 2, MICHIGAN **November 1946**

Lining of the Alva B. Adams Tunnel*

By RICHARD J. WILLSON†
Member American Concrete Institute

SYNOPSIS

The 13.03 mile Alva B. Adams Tunnel, excavated under the Continental Divide, as a part of the transmountain water diversion plan of the Colorado-Big Thompson Project, United States Department of the Interior, Bureau of Reclamation, has now been lined with concrete. Lining equipment and methods are described.

INTRODUCTION

The Alva B. Adams Tunnel, excavated under the Continental Divide of the Rocky Mountains in Northern Colorado, now lined with concrete, is capable of diverting 550 sec. ft. of water from the watershed of the Colorado River, west of the Continental Divide, to the eastern slope of the Divide. The tunnel, which was previously known as the "Continental Divide Tunnel," is one of the principal features of the Colorado-Big Thompson Project designed by, and constructed under the supervision of, the United States Bureau of Reclamation. The transmountain diversion of water for irrigation of northeastern Colorado prairie lands, is the prime objective of the project and the diverted water will provide 320,000 acre-feet of supplemental water annually for irrigation of 615,000 acres of land. Power structures will make use of the natural fall of the diverted water for generation of 900,000,000 kwh. of electrical energy annually for project operation and general consumption.

When completed the project will include, in addition to the transmountain tunnel, several major structures on the eastern and western slopes of the Continental Divide.

Green Mountain Dam, an earth fill structure on the western slope, is now completed and in operation. It is located on the Blue River, a

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*Received by the Institute Oct. 12, 1945.
†Area Field Engineer, U. S. Bureau of Reclamation, Grand Lake, Colo.

tributary of the Colorado River. This dam was constructed for the purpose of impounding water on the western slope to replace that diverted to the eastern slope by the Colorado-Big Thompson diversion project. Two 12,000 kva. generators installed in an adjoining powerhouse have a capacity of 15,000,000 kwh. of electrical energy monthly.

Shadow Mountain Dam is another earth fill structure on the western slope. It's reservoir will be connected by channel with Grand Lake, the headwater of the Colorado River, and together they will serve as a regulating reservoir for water to be diverted through the tunnel.

Granby Dam, located some 8 miles downstream from Shadow Mountain Dam, is the third major structure on the western slope, and has not yet been completed. It also will be an earth fill structure and will function as the storage reservoir for water to be diverted to the eastern slope. Being 85 feet lower than the Shadow Mountain-Grand Lake diversion reservoir, water will have to be pumped from the storage reservoir to the diversion reservoir.

Water, after passing through the Alva B. Adams Tunnel to the eastern slope of the Divide, will be handled in closed conduit, siphons, open canals, and other tunnels on its way to the foothill reservoirs. The fall will be utilized in the generation of power.

THE TUNNEL

Excavation of the perfectly straight 13.03 mile Alva B. Adams Tunnel was begun in June 1940 and completed in June 1944, after nine months delay due to lack of materials as a result of the war. The tunnel as drilled, has a min. dia. of 11.75 ft. in unsupported ground and 12.75 ft. in supported ground. It slopes from west to east 0.155 ft. per hundred ft., making the east portal 107 ft. lower than the west portal. The tunnel was excavated from the two portals, without intermediate shafts or adits; the longest tunnel in the United States to be excavated in this manner. Upon being "holed through" it was found that the tunnel grade and line were off only ¾-in. and 7/16-in. respectively, after having been extended five miles from the west portal and eight miles from the east portal.

The tunnel was lined with concrete to a finished circular section having an internal diameter of 9.75 ft. Lining was started November 16, 1944, discontinued for 3 months in 1945 due to manpower shortages, and completed February 28, 1946.

LINING OPERATION

Concrete lining of the tunnel was done by contract under the supervision of the Bureau of Reclamation. The western half of the work was done by the Stiers Bros. Construction Co. of St. Louis, Mo.; the eastern half by the S. S. Magoffin Company of Englewood, Colo. These contractors had previously completed the excavation of the tunnel.

The major portion of the equipment employed by the two contractors in the lining work was identical and lining procedures were correspondingly similar. Cement and aggregates were delivered to batching plants at the tunnel portals where they were proportioned in one-cubic yard dry batches. The batches were placed in 24-in. gage specially constructed cars and transported to handling and mixing equipment in the tunnel. Water was added at the mixer and concrete pumped into forms by Rex pumpcrete equipment.

The batch cars and the handling, mixing and placing equipment were specially designed for the work, clearance inside the tunnel being the controlling feature of the design. The equipment, or so-called "string," was interconnected and movable as a unit on the 24-in. gage tunnel track. In Fig. 1, there can be seen, from left to right; a batch car; the transfer conveyor and transfer hopper; the mixer conveyor and mixer; the pumpcrete conveyor and pumpcrete machine, with 2-cubic yard horizontal remixing drum; and an air winch mounted on trucks ahead of and attached to the front of the pumpcrete machine carriage.

On the east end of the work, batch cars were pushed to the foot of the incline track leading to the receiving hopper. From this point they were pulled up the incline and spotted over the receiving hopper by cable and electric hoist. On the west end of the work, batch cars were pushed up the incline and spotted over the batch receiving hopper by electric locomotive. The batch, on being dumped from the batch car into the receiving hopper, fell onto the transfer conveyor and was elevated to the transfer hopper. From the transfer hopper it fell onto the mixer conveyor and was elevated to the mixer. The mixed concrete was discharged from the mixer onto the pumpcrete conveyor and elevated to the remixing drum of the pumpcrete machine. The action of the re-

Fig. 1—The "string." Handling, mixing, and placing equipment was interconnected and traveled as a unit on the 24-in. gage tunnel track.

mixing drum forced concrete into the pump, which in turn forced it through 7-in.pipe to the forms.

The lining was placed in two operations: first the lower 66 degrees of the circular section, comprising the invert (Fig. 2) and second, the lining of the arch and sidewalls. Concreting on the east end of the tunnel began November 16, 1944 and was completed February 15, 1946. Placement of concrete on the west end of the tunnel began April 1, 1945 and was completed February 28, 1946. Some 130,000 cu. yd. of concrete were required for the entire lining.

SCHEDULE OF OPERATIONS

Confined working space in the tunnel controlled, to a large degree, the progress of the lining work. The setting of forms, transportation of concrete materials to the mixing equipment, and rate at which concrete could be placed, were also controlling factors.

Both contractors worked on a three-shift per day, six-day per week basis. Invert concrete placement, however, was actually accomplished on a one-shift basis; the other two shifts being utilized for form work, cleanup, movement of equipment, etc. Arch and sidewall lining was handled on a similar schedule at first because of a manpower shortage. However, concrete placement was later accomplished on two shifts and a three-shift basis appeared possible had manpower been available.

AGGREGATES

Aggregate for the west end of the tunnel was obtained from a river deposit some two miles downstream from Grand Lake. The material consisted of durable semi-angular sand and well rounded gravel. Overburden was not excessive and was removed from the deposit by stripping. The aggregates were washed and separated by screening into three sizes: sand, No. 4- to ¾-in. gravel, and ¾- to 1½-in. gravel, all of which were very satisfactory. The average fineness modulus of the sand was 2.90. Rock larger than 1½-in. was present only in small quantities and was wasted. Aggregates were stockpiled near the tunnel portal.

For the east portion of the tunnel lining, and other project features in the vicinity, a deposit of material on the Big Thompson River, three-quarters of a mile east of Estes Park, was utilized. Procurement of aggregate for project features on the east side of the Continental Divide was something of a problem. Suitable deposits near the sites of the work, were few, and the deposit east of Estes Park was far from ideal. It was spotty in character and contained clay strata, generally coarse sand, and large cobbles and boulders. Sand of satisfactory fineness and grading could only be produced by utilization of a part of the overburden of fine

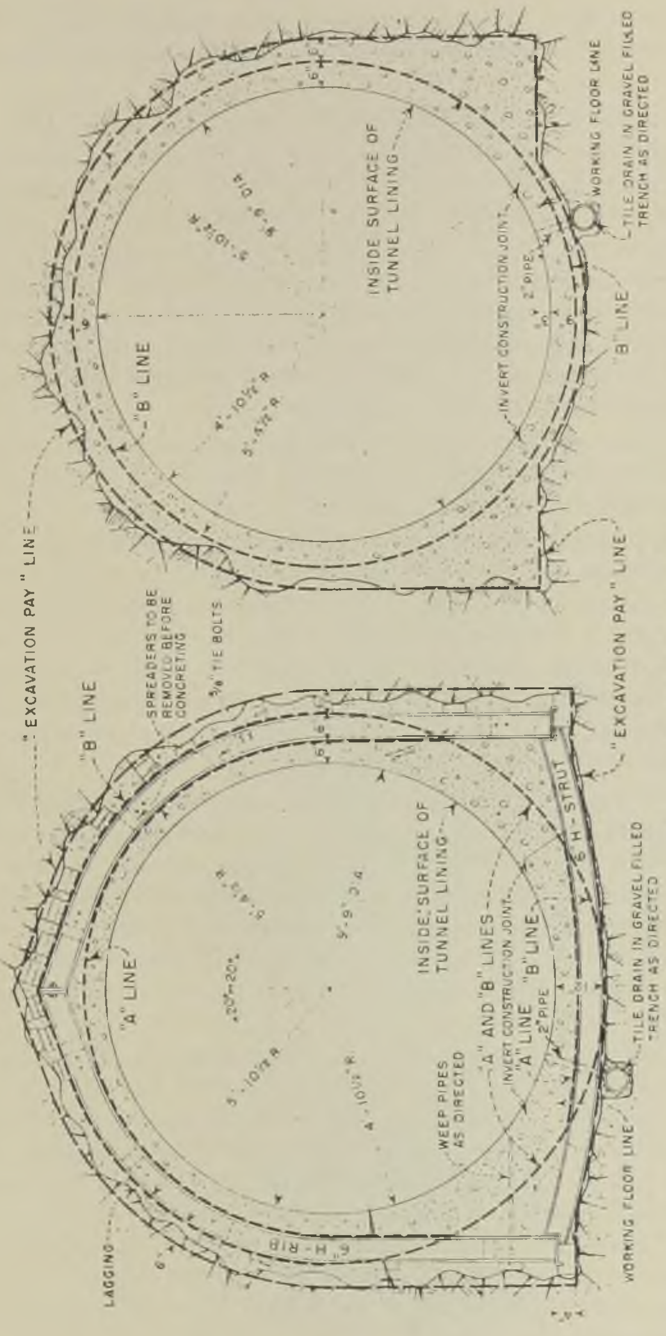


Fig. 2—Typical tunnel sections.
(Left)—Supported
(Right)—Unsupported

sand, silt, and clay. Thorough washing was necessary and, in order to utilize as much of the pit material as practicable, large rock had to be crushed.

Specifications provided that aggregates from the deposit near Estes Park be processed into sand and two fractions of coarse aggregate having nominal sizes of 3/16- to ¾-in. and ¾- to 1½-in. The processing plant as originally erected by the contractor, is shown in Fig. 3. It embodied an 18 x 36-in. primary jaw crusher set to a jaw opening of 3½ in.; a 9 x 36-in. secondary jaw crusher set to a 1-in. opening; a fixed gravity screen having 3/16-in. elongated openings for initial separation of sand from the coarse aggregate; and a triple-deck gyratory screen with screens having 1¾-in. square, 1-in. round and 3/16-in. elongated openings on the top, middle and bottom decks, respectively.

Spray nozzles above the screens proved inadequate for removing clay balls from the coarse aggregate and it was necessary to install a spiral washer for each size of coarse aggregate.

Sand fell from the gravity screen directly into a bin under the screening tower. From the bin the sand flowed by gravity to a centrifugal pump and was pumped, through a 6-in. pipe line 1,200 feet in length, to the stock pile. All or any part of sand passing the 3/16-in. mesh bottom deck of the vibrating screen could be diverted to the sand bin or to waste. Generally the coarse portion passing through the lower part of the screen only was wasted. The quantity and velocity of the water in the sand bin was utilized in control of silt and clay content.

The use of jaw crushers in crushing the hard cobbles resulted in production of a relatively high percentage of flat and elongated particles, many of which would just pass a 1¾-in. square opening. As this condition was thought to detract from the pumpability of concrete produced with the aggregate, a series of trial concrete mixes was made. The aggregate, then being produced and employed in the trial mixes, was graded 24 percent, No. 4 to ⅜-in.; 16 percent, ⅜- to ¾-in.; and 60 percent, ¾- to 1½-in.

The trial mixes indicated that it was not possible to obtain an entirely satisfactory concrete, even with as much as 46 percent sand or by use of admixtures in reasonable amounts. Characteristic mixes illustrating the problem are given in Table 1, mixes A and B. Elimination of the oversize in the ¾- to 1½-in. aggregate size, mix C, improved the concrete characteristics somewhat, and a reduction in the quantity of No. 4 to ⅜-in. fraction in the No. 4 to ¾-in. aggregate size, mix D, added to the improvement. However, best results were obtained in mix E, by increasing the −100 mesh fraction of the sand 4.2 percent, along with the previous corrections incorporated in mixes C and D.

Fig. 3—The plant erected for processing of aggregate from the Meadows Deposit.

TABLE 1—EFFECT OF AGGREGATE ON CONCRETE CHARACTERISTICS

Mix no.	Aggregate data				Mix data					Characteristics of fresh concrete				
	Sand FM	Coarse aggr. grading			a/c ratio	per-cent sand	Water lb. /C.Y.	Cement content bbl./C.Y.	w/c ratio	Slump in.	Remolding effort jigs*	Bleeding†	Comp. str. psi. 28 Da.	Remarks
		no. 4-⅜ in.	⅜ in. ¾ in.	¾ in. 1½ in.										
A	2.97	24	16	60	6.40	43	276	1.36	0.54	1¾	48	8.4	4690	Concrete harsh and rocky fair finish; some segregation.
B	2.97	24	16	60	6.46	46	290	1.35	0.57	2¾	47	12.4	4620	Rocky and sticky, good finish; little segregation.
C	2.97	24	16	60	6.59	43	286	1.33	0.57	3	51	10.2	3860	(Eliminated +1½") Fair concrete, good finish, slight segregation.
D	2.97	20	30	50	6.59	43	287	1.34	0.57	3¼	23	11.6	3980	(Eliminated +1½") Fair concrete, fair finish, very slight segregation.
E	2.84	20	30	50	6.59	43	284	1.32	0.57	3¼	38	8.7	4100	(Eliminated +1½" and increased −100 mesh sand). Good concrete, good finish, and no segregation.
‡F	2.94	17.3	27.7	55	6.13	43	285	1.43	0.53	2	—	—	5510	Invert lining mix.
‡G	2.88	18	27	55	5.43	41	311	1.56	0.53	4	—	4.5	5370	Arch and sidewall lining mix.

Notes: All mix and aggregate data on a weight basis.
*Remolding apparatus patterned after Powers Remolding apparatus.
†Percent by weight at 2 hours and 20 minutes. U. S. B.R. Design: 25. (Concrete Manual).
‡All but mixes F and G employed aggregate produced prior to installation of the roll crusher.

With the trial mix data as a guide, an effort was made to improve the grading of the aggregate being processed by securing a finer sand, changing the grading of the coarse aggregate, and reducing the quantity of long and flat particles.

A finer sand was produced by wasting portions of the 4, 8, and 16 mesh fractions of the sand and by inclusion in the aggregate deposit excavation, a layer of fine sand, silt and clay overlying the main deposit. This layer had previously been removed as stripping and wasted. Use of the layer called for more thorough washing of the coarse aggregate for removal of silt and clay and was accomplished by the spiral washers mentioned previously.

To eliminate the oversize in the coarse aggregate, the contractor was permitted to reduce the nominal maximum size to 1¼ in. with the understanding that all of the larger sizes of the coarse aggregate would pass a 1½ in. square opening. The contractor also replaced the 9- x 26-in. secondary jaw crusher with a 22- x 40-in. corrugated roll crusher. These changes brought about a material improvement in the grading and in the particle shape of the aggregate. Studies made of the roll crusher product, and discussed below, showed the coarse aggregate to have fewer flakes and elongated particles with rollers set to provide a ½- to 1-in. space between rolls. Further, at this particular setting, the coarse aggregate was being produced in the proportions of 18.1 percent No. 4 to ⅜-in.; 31.2 percent, ⅜- to ¾-in.; and 50.7 percent, ¾- to 1¼-in. very close to the desired grading.

Resulting aggregate produced mixes which were exceptionally workable and it was possible to employ less sand than was anticipated. Both invert and arch and sidewall mixes, adjusted to meet job conditions are given in Table 1. Mix F was used in the invert lining and was placed and finished without difficulty at slumps as low as 1 in. Concrete for arch and sidewall lining was normally placed at a slump of 3¾- to 4¼-in. and was easily handled, placed, and consolidated. Best results on the job, with the roll crushed aggregate, were obtained with a coarse aggregate grading of 45 percent No. 4 to ¾-in. and 55 percent ¾- to 1¼-in. The improved workability of the concrete would probably have enabled return to the larger maximum size for pumpcrete work, but it was decided to adhere to the contract commitments, which provided for the 1¼-in. nominal maximum size.

Test data included in this paper should not be misconstrued to indicate roll crushers were the only solution to our problem, but they did fortunately provide satisfactory results on this particular job with local aggregates, the coarser portion being essentially composed of slightly to moderately weathered gneisses and granitic rocks.

The aggregate plant produced a clean and fairly well graded sand, having an average fineness modulus of 2.80, and a clean coarse aggregate, containing 50 to 75 percent of crushed material in the 3/16- to ¾-in. size and 50 to 60 percent in the ¾- to 1¼-in. size.

To evaluate the improvement in particle shape, due to use of the roll crusher, the relative quantities of flaky and long particles present in the coarse aggregate produced prior to and after installation of the roll crusher, were analyzed by the method presented in Road Research Bulletin No. 2, "The Shape of Road Aggregate and Its Measurement." The bulletin was published by the British Department of Scientific and

TABLE 2—A STUDY OF PARTICLE SHAPE OF COARSE AGGREGATE

(Percent of total finished product)

Description of aggregate			Pior to installation of roll crusher	After installation of roll crusher	
Size	Type	Shape		Roll set at ½"	Roll set at 1"
1"–1½"	Uncrushed	All	59.5	76.8	27.8
		Flakes	4.4	4.6	0.6
		Longs	8.7	4.4	0.8
	Crushed	Crushed	40.5	23.2	72.2
		Flakes	6.3	2.8	6.9
		Longs	15.0	1.3	2.8
	Total	All	100.0	100.0	100.0
		Flakes	10.7	7.4	7.5
		Longs	23.7	5.7	3.6
¾"–1"	Uncrushed	All	61.1	57.2	19.4
		Flakes	1.8	1.3	0.8
		Longs	15.4	12.9	3.0
	Crushed	All	38.9	42.8	80.6
		Flakes	4.8	2.8	5.5
		Longs	20.5	11.0	18.4
	Total	All	100.0	100.0	100.0
		Flakes	6.6	4.1	6.3
		Longs	35.9	23.9	21.4
½"– ¾"	Uncrushed	All	72.5	28.9	37.8
		Flakes	5.2	1.0	2.3
		Longs	17.7	8.3	7.4
	Crushed	All	27.5	71.1	62.2
		Flakes	4.3	5.7	6.2
		Longs	13.2	18.3	4.1
	Total	All	100.0	100.0	100.0
		Flakes	9.5	6.7	8.5
		Longs	30.9	26.6	11.5

Industrial Research and Ministry of Transport. A summary of the results of the study is given in Table 2.

CEMENT

A Type II (modified) cement was used. That for the east portion was purchased from the Colorado Portland Cement Company and transported in bulk by truck directly to the east portal batching plant from the mill storage silos near LaPorte, Colo. Cement for the west portion was furnished by the Monolith Portland Cement Company from a plant near Laramie, Wyo. and was shipped by rail in bulk from the plant to a 1500 bbl. storage silo at Granby, Colo. From Granby the cement was trucked 12 miles to the west portal batching plant. The trucks (Fig. 4) consisted of a standard dump bed with special water tight cover. Similar trucks were employed on both sides of the divide in transporting cement and functioned very satisfactorily.

BATCHING

Cement and aggregate for concrete were proportioned by weight in manually operated equipment installed in plants erected at each tunnel portal, (Fig. 5 and 6).

Fig. 4—Cement was transported in standard dump trucks fitted with a specially constructed water tight cover.

Cumulative batching hoppers were employed in proportioning the aggregates and separate hoppers in weighing the cement. The batching plant at the west portal consisted of a circular cement storage bin of 600 bbl. capacity, surrounded by the three aggregate supply bins and had an

Fig. 5 (top)—The east portal batching plant was in reality two independent structures, one for the batching of aggregates and the other for the storage and batching of cement.

Fig. 6 (bottom)—The west portal batching plant was erected over the tunnel portal.

added feature in that it had been erected directly over the tunnel portal. All batched materials were therefore protected from rain and snow at all times, a distinct advantage in this climate. The batching plant at the east portal was in reality two structures. One housed the aggregate supply bins and batching equipment and the other, a circular cement storage bin of 1,500 bbl. capacity and cement batching equipment.

TRANSPORTATION OF CONCRETE MATERIALS

The weighed concrete materials were manually dumped from batching hoppers into the specially constructed 24-inch gauge bottom dump rail cars (Fig. 7). The cars were divided into two compartments each capable of holding cement and aggregate for one-cu. yd. of concrete. In each compartment a special open bottom container was built for the cement to keep it separate from the damp aggregate and lids were provided to protect it from moisture in the tunnel. The containers were deepened 4-in. more than shown in Fig. 7, to accommodate the cement, which was bulked due to batching. To avoid loss in transfer of cement from batcher to cars, a canvas tube attached to the bottom of the cement batching hopper was employed.

On the east portion of the work, six car trains, pulled by 8-ton battery electric locomotives, transported dry-batched materials for 12 cu. yd. of concrete into the tunnel. Six such trains were kept in service during concrete placement operations. On the west portion of the work, both electric and diesel locomotives were used. Diesel locomotives hauled 10 cars (20 cu. yd. batches) into the tunnel. Two such trains on the west side were in service during placement. In using the electric locomotives, 4 eight-car (16 cu. yd.) trains were required. Sidings, or passing tracks, at intervals throughout the tunnel, permited passing of loaded and empty trains. A movable siding or "California Switch," located just to the rear of the receiving, mixing, and placing equipment, was employed in switching empties from the equipment and loads to the equipment. Switching in both ends of the tunnel was accomplished by battery electric locomotives.

CLEANUP OPERATION

The major portion of the cleanup work was completed before placing operations in the tunnel invert began and consisted of removing loose rock, mud, and debris. However, such materials and water that accumulated after the original cleanup, were removed just prior to the placement of the invert concrete by hand shovel, brooms and pumps.

Material in the shoulders at the sides of the invert (Fig. 2) was broken tunnel rock composed of coarse fragments embedded in finer material.

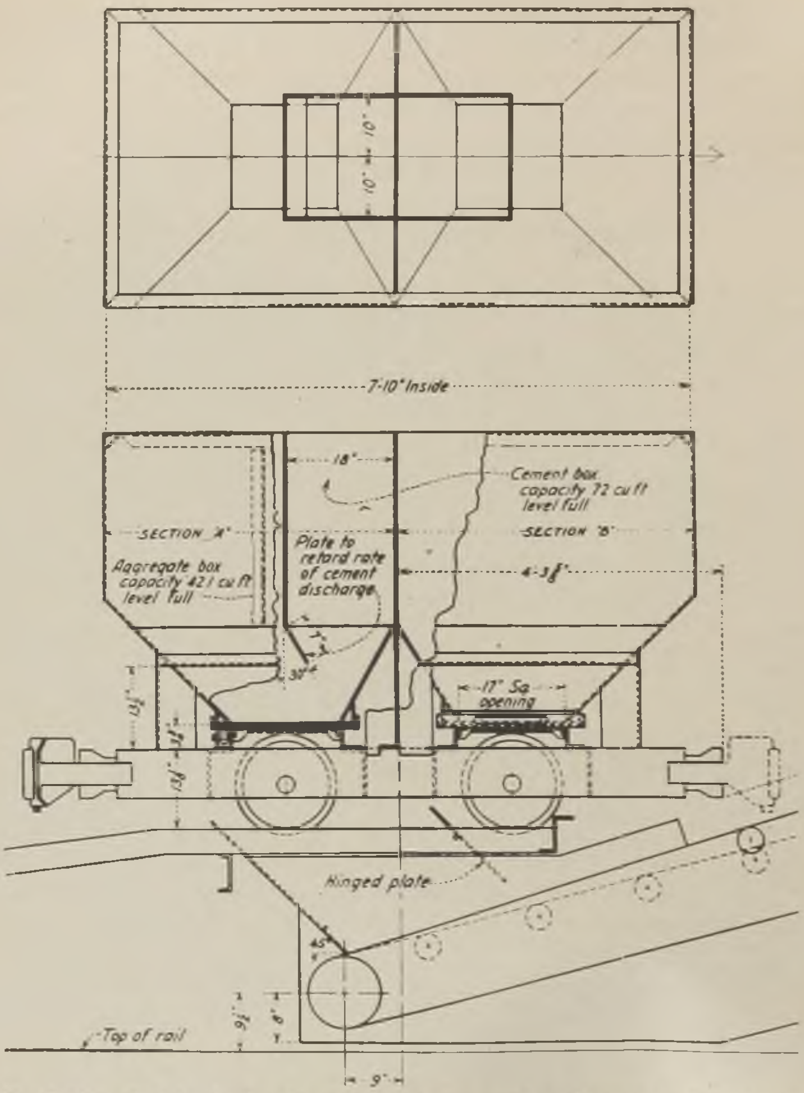


Fig. 7—Detail of the dry-batch cars used in transportation of cement and aggregate to site of mixing and placing.

It was densely compacted, and as attempts at further consolidation by mechanical means resulted more in loosening of the material than in its consolidation, this corner fill was allowed to remain in place.

The invert lining was placed in advance of the arch and sidewall lining, consequently some accumulation of debris, rock, etc., occurred before the arch and sidewall lining was placed. Just prior to the placement of arch and sidewalls, loose rock was barred down, and debris, mud, water and the scale or encrusted mortar on steel supports, were removed. In supported ground, all collar braces were removed, lagging was removed insofar as practicable, and the remaining lagging was tightened.

TUNNEL DRAINAGE

Flow of water into the tunnel from surrounding rock was considerably less than was originally anticipated. Grouting of the rock, as the heading advanced during excavation, was successful in reducing the flow so that drainage was not a major problem. However, there were some areas that needed attention in this respect and they were handled by various methods. Where flow from shattered rock or numerous fissures was encountered, tile drains (Fig. 2), parallel to the center line of the tunnel, were laid in gravel filled trenches prior to placement of the invert. Drainage from the trenches was accomplished by 2-inch pipe extending from trench through lining into tunnel invert. In areas more or less confined to flow from a continuous fissure, a box filled with gravel was used to cover the main flow from the fissure, and a pipe from the box through concrete lining served as a drain from the lined tunnel. In other cases, where flow was from a spring or from a single fissure, a hole drilled into the water course served for installation of a 2-inch pipe which extended through the concrete lining.

In all of the above instances pipe was set prior to the placement of concrete. Areas in the tunnel showing little flow, but some dampness, were provided with drainage by drilling 2-in. weep holes through the completed lining.

INVERT FORMS

On the east end of the tunnel, wooden invert forms (Fig. 8) were employed. They consisted of 20-foot longitudinal sections, constructed of 3-in. lumber, nine or twelve in. in width, depending upon the depth of the excavated tunnel bottom.

Each end of the twenty-foot sections was notched and steel plates were provided on the outside of the form for assuring a tight fit between sections and for maintaining adjoining sections on line and grade. A spreader, either 2- x 8- or 2- x 10-in., depending upon use of 3- x 9-in. or 3- x 12-in. longitudinal form sections, was set between the parallel sections of the forms and the forms were then pulled together with a Coffin jack. Wedges under the forms provided adjustment for grade and shores braced against tunnel walls provided adjustment for line and prevented the forms from floating. After forms had been set and shores placed, the Coffin jacks were removed. The spreaders between parallel

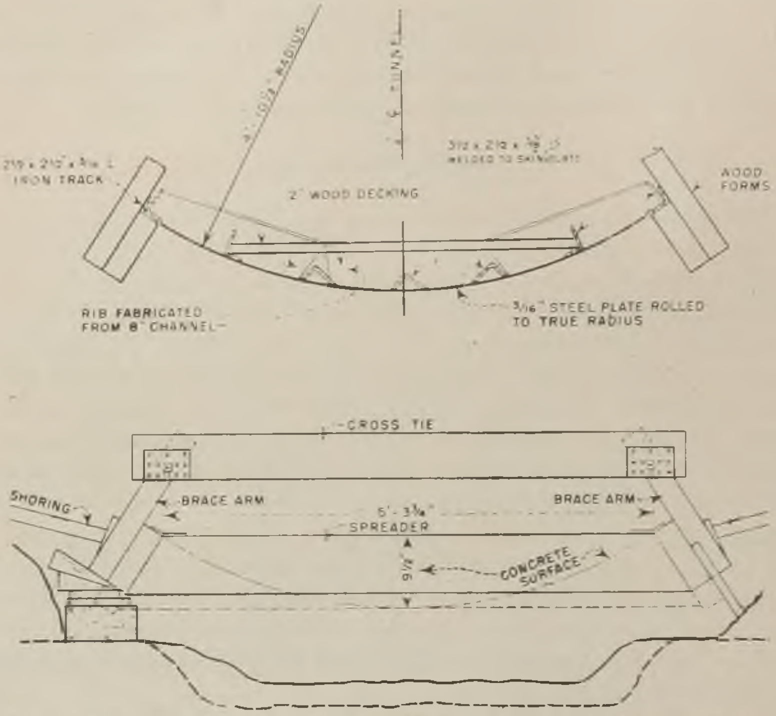


Fig. 8—Invert forms (bottom) and slip form (top) for invert lining on the east end of tunnel.

sections of forms were removed just ahead of concrete placement operations.

Invert forms in the west portion of the tunnel consisted of standard 9-in. paving forms and were held in place by anchor bars drilled into the tunnel walls as shown in Fig. 9. Setting of forms, spacers, blocking, etc., was similar to that employed in the east portion of the tunnel.

Invert forms were generally left in place 24 to 48 hours, depending on the amount of invert placed during a day and the need for forms for the following day's work.

ARCH AND SIDEWALL FORMS

Steel forms manufactured by the Blaw-Knox Co. were employed in lining the arch and sidewall sections of the tunnel. Forms were furnished the contractors "knocked down" into five parts; the arch, the two sidewalls, and the two aprons. When assembled, the sections were 5 feet in length, and in turn were assembled into a 25-ft. form section. Details of the form construction are shown in Fig. 10. The contractor on the east portion of the tunnel lining work had 14 such 25-ft. sections

Fig. 9—9-inch steel paving forms used for the west end of tunnel invert lining.

Fig. 10—An assembled arch and sidewall form.

or 350 lin. ft. of form. The contractor on the west portion had 15 25-ft. sections, or 375 lin. ft.

Hatchways were provided in the forms at 5-ft. intervals in the arch and at 10-ft. intervals just below the spring line.

All forms were wired for 110 volt electric current, with wiring enclosed in rigid and flexible conduit. Outlets were provided for lights at 5-ft. intervals on each side of the forms and there was a convenience outlet box on each side at each end of a 25-ft. form section. Rapid connection of electric cables between forms was readily accomplished.

Fig. 11 shows an arch and sidewall form in place. In the figure, form aprons are bolted to anchor bolts that have been set in the invert at 5-ft. intervals while the concrete was still plastic. The needle beam of the form shifting "Jumbo" has been raised by four hydraulic jacks to contact the arch. Screw jacks are extended to hold sidewall portions of the form against the lining. To strip forms, bolts between adjacent 25-ft. form sections are first removed. Invert anchor bolts and bolts between aprons and sidewall portions are next removed and aprons are raised. The screw jacks pull the apron and sidewall forms inward until opposite sides are against the "Jumbo." The needle beam is then lowered and

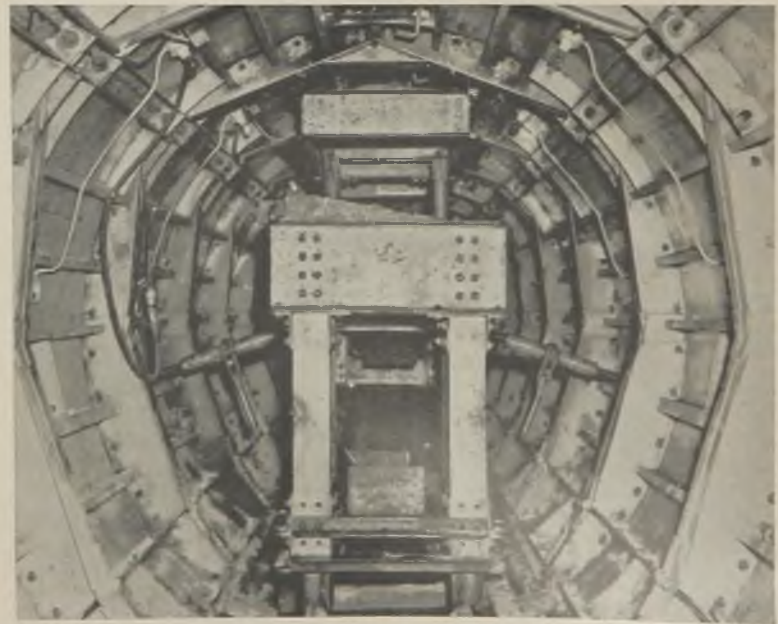


Fig. 11—An arch and sidewall form in place and traveler or "Jumbo" in position for removal of form.

the form folds into position for transportation through other forms in place, to a new location.

Form setting was exactly the reverse of stripping. A form could be stripped, moved ahead, cleaned, oiled, and reset in less than 2 hours. Forms were left in place a minimum of 24 hours after concrete placement.

At the end of placing operations for the day, a vertical construction joint was provided by placing a wooden bulkhead at the end of the last 25-foot steel form filled during the day. Bulkheads were left in place for six to eight hours before being stripped.

CONCRETE MIXING

Procurement of a suitable mixer for use in the tunnel work presented some problems because standard mixers of sufficient capacity were too large for a tunnel of this size. It was necessary, therefore, to remodel the mixer frame and either lower the water batching tanks or provide for water batching by meter. On the east end of the work, a Ransome mixer was selected by the contractor and water was batched by meter. On the west end, a Rex mixer was employed with the water batching tanks lowered to provide clearance between the tanks and tunnel roof. The small clearance between mixer and tunnel arch and walls can be seen in Fig. 12 and 13. Both mixers had a capacity of 1 cubic yard.

In feeding the batching water, a portion preceded the aggregate into the mixer, the main portion was fed with the cement and aggregate, and the balance was added after aggregate and cement. On being discharged from the mixer, as shown in Fig. 13, concrete fell onto the pumpcrete charging conveyor for delivery to the 2-cu. yd. remixing drum of the pumpcrete machine. The remixing produced a more uniform concrete and resulted in less delay in placing progress. The original mixing period of 1½ minutes was reduced to 1 minute because of the remixing.

TRANSPORTATION OF FRESH CONCRETE

Movement of concrete to forms was accomplished by the pumpcrete machines, of which the horizontal remixer drum was a part. In both portions of the tunnel No. 200 pumpcrete machines pumped the concrete through 7-in. external diameter (6⅞-in. i.d.) steel pipe to the forms. The pump on the western portion of the lining work was a conventional double-valve machine. That on the east portion was of new design, having a single valve. Both machines functioned well. The principal feature of the single valve machine was its simplification. It had fewer working parts, was more quickly repaired, required less servicing, and was more easily cleaned at the end of a day's work. Some difficulty was encountered in pumping concrete with the experimental type single

Fig. 12 (top)—A Rex mixer was used on the west end of the work. Water batching tanks were lowered to provide clearance between mixer and tunnel roof.

Fig. 13 (bottom)—A Ransome mixer was used on the east end of the work. Water batching tanks were removed completely to provide clearance and batching performed by meter.

valve machine during early operations, but the problems were largely corrected by the manufacturer and concrete with slumps as low as 1-in. were placed without difficulty through 600 ft. of pipe.

The location of the pumpcrete pipe line in transporting invert concrete to forms differed on the east and west ends. On the eastern work, the pipe line was supported on tripods and 10-ft. sections of the line were removed from the discharge end as placement progressed. On the western work, a 300-ft. "slick" line, that is, a 300-foot section of pipe without couplings, was suspended on rollers from the roof of the tunnel by anchor bars set into the rock or welded to the steel tunnel supports. The 300-foot "slick" and "string" of equipment were moved backward as placing progressed. The installations are shown in Figs. 9, 14, and 15.

PLACING

Invert concrete, delivered at the forms on the eastern work from the pipe line located approximately in the center of the invert section (Fig. 14) fell a maximum distance of 4 ft. to the tunnel floor. General practice allowed concrete to pile up as it flowed from the pipe line. It was then shoveled and vibrated into place. Little segregation occurred during the handling of the 1¾ in. slump concrete in this manner but care was exercised to avoid over-vibration and movement by vibration in a horizontal direction was held to a minimum.

The invert form was filled until it was approximately level full. A slip-form, which rode on the edges of the invert form (Fig. 8) was then pulled ahead by a cable attached to an air winch located on the front of the pumpcrete machine. Internal type vibrators consolidated the concrete immediately ahead of the slip form as it moved forward.

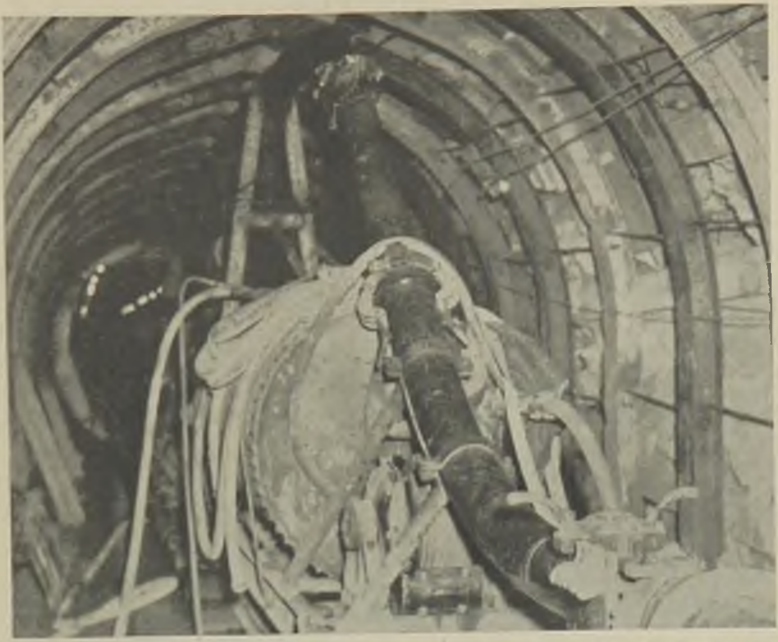
The pumpcrete line on the west end was 6 to 7 feet above the tunnel floor and the chute (Fig. 15) which rode on invert forms, prevented excessive uncontrolled drop. Otherwise placing procedure was similar to that on the east end.

Sagging of the plastic concrete, which was aggravated by vibration, caused some difficulty in filling the invert adjacent to the sloping longitudinal side forms. For this reason vibration had to be done with care and the slump held at not more than 1½ to 2 in.

In placing arch and sidewall lining a total of approximately 150 ft. of pipe was employed. 130 ft. of this pipe was "flattened-slick," made by welding 7-in. standard pumpcrete pipe, without couplings, and flattened in the vertical direction to 6 in. This was done to provide extra clearance between arch forms and tunnel back which was nominally about 9 to 12 in. In beginning operations 75 to 100 ft. of forms were set and the "slick" passed over the forms at the crown of the arch (Fig. 16).

Fig. 14 (top)—Placement of invert lining on the east end.

Fig. 15 (bottom)—Placement of invert lining on the west end was accomplished by use of a "slick" suspended from tunnel roof. Discharge end of "slick" was supported by traveller running on paving form.



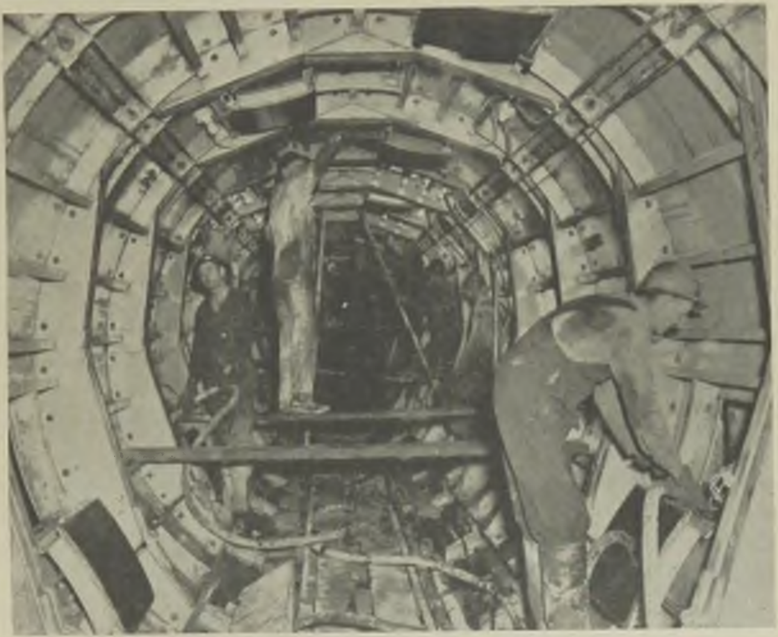


Fig. 16 (top)—Placement of arch and sidewall lining. The pump line "slick" passes over the arch form.

Fig. 17 (bottom)—Activities at site of arch and sidewall placement.

In placing concrete in the arch and sidewall forms the end of the "slick" line was set 2 ft. from the previously formed construction joint. Two batches of sand-cement mortar were first pumped into the forms and distributed equally on each side. Concrete of 4½-in. slump was then pumped into the form until the area adjacant to the previously placed arch and sidewall lining had been filled. The slump was then reduced to 4 in. and the concrete assumed a slope of 4 or 5 to 1 in the sidewalls from the crown of the tunnel to the invert. Pumping continued until the arch was filled and the end of the "slick" buried 5 to 10 ft. The "slick" was then withdrawn 2 to 3 ft. by moving the "string" of equipment by air winch and cable anchored to the track behind the equipment. When pump pressure was insufficient, compressed air was used to fill cavities in the arch and hips adjacent to the arch or to fill the arch in areas where lagging was in place. Air was supplied to the "slick" through a 1½-in. valve located 20 ft. from the discharge end of the pipe. The pumpcrete machine did an excellent job and thereby minimized the amount of air "slugging" necessary.

Internal vibration by flexible shaft "wiggle-tail" vibrators, was performed where possible, through hatches in the sidewall forms. It was of special benefit in the consolidation of concrete adjacent to the invert concrete. Space behind the forms was constricted, however, and there was not sufficient space for workmen. Therefore, external vibration was necessary. This was accomplished by chipping hammers operated against the ¼-in. skin plate of the forms, and by electric vibrators clamped to members of the forms.

A view of concrete placement in arch and sidewall is shown in Fig. 17. Two internal vibrator operators can be seen in the foreground with flexible shafts of the vibrators extending through the hatchways of the sidewall forms. Hatches along the crown of the form are open in the immediate foreground and a workman with arm extended through the third hatchway is operating the "air-slugger" valve. The inspector with head extended through the seventh arch hatchway is examining the concrete being placed in the arch. The placing foreman also observed placement in this manner. Other men in the background are operators of the external vibrators or chipping hammers.

A day's placement of arch and sidewall lining was completed against a vertical wooden bulkhead, at the end of a 25-ft. form section. It was required that joints be either vertical or radial. There was only one departure from the requirement for vertical construction joints. In this instance, equipment failure resulted in the abandonment of placement midway in a 25-ft. section. A radial joint was constructed, without removing forms, by trowelling the joint while concrete was still plastic. After initial set had taken place, the joint was thoroughly broomed and cleaned by air and water under pressure. Before resumption of placement the joint was covered with a layer of mortar.

FINISHING

The finishing of the concrete surface of the invert was performed in four steps. First, anchor bolts for holding the sidewall and arch forms in position were set as soon as possible behind the slip form. Anchor bolts (Fig. 18) consisted of a helical spring into which a 1¼-in. x 14-in. bolt was screwed. The bolt-spring assembly was set in place and the bolt removed after the concrete had attained its initial set. Second, the surface was wood floated to general shape, pulling any sag back to the form and consolidating the concrete adjacent to the form. Third, surface irregularities were removed ½ hour to an hour after placement by Fresno type long-handled finishing blades or long wooden floats. Fourth, final steel trowelling, 4 to 6 hours after concrete had been placed, completed the work.

Finishing of arch and sidewall lining was more a matter of patching or trimming poorly formed construction joints. Such patching was minor. Some of the usual small air voids that occur with sloping steel forms were present below the spring line and increased in frequency toward the bottom of the sidewalls. These voids were ¼-in., or less, in dia. and of similar depth. No treatment was given them. Few rock pockets resulted but some holes occasioned by leakage of mortar through form joints were repaired by chipping and dry-packing. Anchor bolt holes in the invert were also dry-packed after they had served their purpose.

The longitudinal joints between sidewall and invert lining required attention because of the overlap of sidewall form apron onto the invert concrete. Overlapping concrete was removed by bush hammer. A view of the completed lining is shown in Fig. 19. Some flow lines or sand streaks developed, as shown in the photographs, unless care was exercised in keeping concrete flowing uniformly into each sidewall section.

CURING

Tunnel lining concrete was cured by a clear sealing compound produced by the Dewey and Almy Chemical Company and marketed under the trade name of "Daraseal No. 77." The compound was applied by air-spray to the finished surface in a single coat. Good coverage was obtained by using 1 gal. of the compound for each 180 sq. ft. of surface. The compound was applied to invert concrete surfaces about 12 hours after the concrete was placed. Application to sidewall and arch lining took place after steel forms had been stripped, usually in 24 to 48 hours.

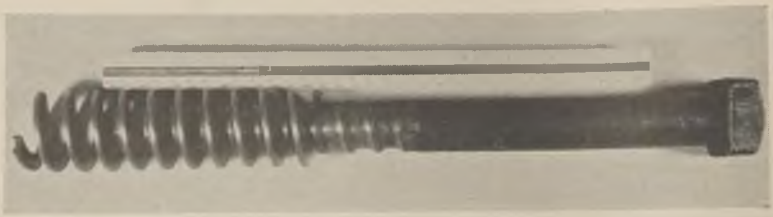


Fig. 18—Anchors.

During excavation, the tunnel was ventilated by blowers which furnished air through a 20-in. steel fan line to the workmen in the heading. The line was suspended from anchor bolts set in the right arch of the tunnel and was extended as necessary as the heading advanced. On the west side, 2 Roots-Connersville blowers, each capable of furnishing 12,000 cfm. of air, were employed. One blower was located at the west tunnel portal and the other, 20,700 ft. in from the west portal, functioned as a booster. On the east end of the tunnel 4 smaller, but similar Roots-Connersville blowers were used. Each of the smaller blowers had a capacity of 7,000 cfm. of air. One of the 4 blowers on the east end was located at the tunnel portal, and the other three, functioning as boosters,

Fig. 19—The completed lining is relatively free from imperfections and a glossy finished surface is produced by the form oil.

at 9,000- to 12,000- ft. intervals throughout the tunnel. The blowers were reversible and could readily be changed from "blow" to "draw" or vice-versa.

Because of the limited clearance in the tunnel, it was necessary to remove the 20-in. fan line before beginning concrete placement. All blowers were then moved to the portals. The two 12,000 cfm. blowers were installed at the west tunnel portal and the four 7,000 cfm. blowers were installed at the east portal. Bulkheads were constructed at the portals and doors provided for passage of equipment and materials. The blowers furnished air through the bulkheads with blowers at one end of the tunnel "blowing" while those at the other end were "drawing." The operation was balanced weekly by reversing the direction of the blowers. For this reason variation occurred in curing conditions.

During the invert placement, atmospheric conditions within the tunnel were fairly stable. The tunnel air temperature varied from 55 to 70 F. and the relative humidity from 90 to 100 percent. In arch and sidewall lining, more variation occurred due to the method of ventilation and the heat generated by the concrete placed.

The first curing tests were made while invert lining was being placed on the east portion of the tunnel. The tests consisted of four sets of standard 6 x 12-in. cylindrical test specimens fabricated from concrete being placed in the invert. The cylinders were tested for compressive strength at ages of 7 and 28 days. Each test set consisted of 8 cylinders. Two cylinders were water cured at 70 F in the materials testing laboratory, after removal from molds at the age of 24 hr. The other six cylinders were stored in the tunnel after removal from the molds at the age of 24 hr. Two of the tunnel specimens were sprayed with "Daraseal No. 77" curing compound; two were cured in water in the tunnel; and two were exposed to tunnel atmosphere. Data obtained (Table 3), was uniform, insofar as tunnel curing of invert concrete was concerned. Water curing showed best results, with atmospheric curing next, and compound curing the lowest. On the basis of laboratory cured specimens, the relationship of compressive strength for the various types of curing is shown in Table 4.

With the test data available, curing of invert concrete by compound was abandoned. Similar tests were made on the east side in connection with concrete placed in the arch and sidewall lining. Results were variable and compound curing was resumed.

CONCRETE CONTROL

Rigid control of aggregate processing, concrete manufacturing, and concrete placement, was exercised by inspection personnel of the Bureau

TABLE 3—CURING TESTS

Test series	Mix data					Curing data					Compressive strength data							
							Average Temperature—F.				7-day				28-day			
											Curing method				Curing method			
	a/c ratio by wt.	per-cent sand by wt.	Cement content bbl. /cy	w/c ratio by wt.	Slump in.	Rel. hum. percent	Fresh conc.	Tunnel		Lab. water	Dara-seal	Tunnel		Lab. water	Dara-seal	Tunnel		Lab. water
								Air	Water			Atmos	Water			Atmos.	Water	
I	5.37	45	1.59	0.49	2¼	96	60	64	64	70	2050	2370	2440	2600	3930	4620	4620	5060
II	6.13	43	1.43	0.51	2	96	54	64	64	70	2480	2550	2550	2780	4970	5240	5060	5500
III	6.13	43	1.43	0.53	2	95	50	64	64	70	*1820	*1960	*1890	*2180	4000	4030	4490	4740
IV	6.13	43	1.43	0.50	1¾	95	57	64	64	70	2210	2410	2530	2580	4780	5130	5020	5450
Average											2140	2320	2350	2540	4420	4760	4800	5190

*Tested at age of 6 days.

TABLE 4—RELATION OF COMPRESSIVE STRENGTH FOR VARIOUS TYPES OF CURING

Curing methods	Invert tests*	
	7-day	28-day
Daraseal No. 77	84.3	85.2
Tunnel Atmosphere	91.3	91.7
Tunnel Water	92.5	92.5
Laboratory Water	100.0	100.0

*Percentages of strength of laboratory water-cured specimens.

of Reclamation. Mixes were adjusted daily to compensate for oversize and undersize in the aggregates employed and each train of concrete material batched was sampled and the aggregate moistures determined for adjustment of mixing water to be added at the mixer in the tunnel. Aggregate was produced and mixes adjusted for significant oversize and undersize, following the method outlined by L. H. Tuthill in "Developments in Methods of Testing and Specifying Coarse Aggregates"*. Mix uniformity was very good.

Slump tests of freshly mixed concrete were made from samples of concrete obtained as the mixer was discharged. Concrete from each train of material mixed was so tested.

Special tests of the concrete were made to determine the loss of slump between mixer and forms. In invert placement, concrete normally had a slump of 1¾-in. at the mixer. No loss in slump was noted between mixer and forms. Arch and sidewall concrete normally had a slump of 4 in. at the mixer, a loss of ¼ to ½ in. in slump was usual in this operation. In the latter case, however, tunnel temperatures generally exceeded the concrete temperature by 10 to 20 degrees and accounted for some of the loss that occurred.

Bleeding tests also were made at frequent intervals and were expressed as a percentage of water gain based upon total mixing water. The percentage encountered varied from 2 to 8 percent and was not a serious problem. The bleeding appeared to be a function of the sand fineness.

Test specimens of concrete, fabricated in the tunnel from samples obtained at the mixer, were made in cylindrical 6 x 12-in. cast iron molds. Specimens, in molds, remained in the tunnel for 24 hr. and were then removed to the project laboratory where the mold was removed and specimens cured in water at 70 F until tested for unit weight and compressive strength.

In making contract payments, the volume of concrete placed was computed from batch weights of cement and aggregate, from water added at the mixer, and from water contained in the aggregates as determined by aggregate moisture tests. Entrapped air was neglected. The computed value was compared with the concrete yield determined from unit weight tests made of the fresh concrete and also from the unit weight of compressive strength test specimens. A variation of 1½ percent was the maximum.

CONSTRUCTION AND SUPERVISORY PERSONNEL

All features of the project were designed by the Bureau of Reclamation with main offices in Denver, Colo., Walker R. Young, Chief Engineer.

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*ACI JOURNAL, Sept. 1942, *Proceedings* V. 39, P. 21.

Project activities were supervised in the field by C. H. Howell, Project Engineer. Engineers F. K. Matejka and G. R. Highley were responsible for tunnel work on the east and west portions respectively. R. P. Blackwell, engineer, was responsible for concrete control and A. C. Link, engineer, for construction of the west portion of the tunnel. Work on the east end and coordination of all lining work was the duty of the writer.

F. R. Purvis was general superintendent for the S. S. Magoffin Company on the east portion of the tunnel and George England was concrete superintendent. John R. Austin was superintendent and general manager for the Stiers Bros. Construction Company on the west portion of the tunnel, with Ray Blasongame in charge of the lining work.

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To facilitate selective distribution, **separate prints** of this title (43-11) are currently available from ACI at 25 cents each—quantity quotations on request. **Discussion** of this paper (copies in triplicate) should reach the Institute not later than March 1, 1947

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Repairs to Spruce Street Bridge, Scranton, Pennsylvania*

By A. BURTON COHEN†
Member American Concrete Institute

SYNOPSIS

Repairs and reinforcements of the Spruce Street Bridge built in 1893 over the Lackawanna Railroad and Roaring Brook in Scranton, Pa. are described. The effective application of the "Alpha System-Composite Floor Design" reinforced the floor system at the same time a new concrete floor slab was laid. Contract prices are included and ten illustrations supplement the text of the paper.

The Spruce Street Bridge, built in 1893 over the Lackawanna Railroad and Roaring Brook, carries a main highway leading from New York City into the near-by central-city business section of Scranton, Pa. It consists of six through Pratt truss spans averaging about 106 ft. in length and one 210-ft. deck span over Roaring Brook. (Fig. 1) They are supported on steel towers 8 to 10 ft. in width. The roadway, 37 ft. in width, includes a single-track street car line placed along the easterly curb. Two 8-ft. sidewalks are cantilevered from the trusses. The floor beams, at panel points, are spaced 17-to 21-ft. centers, excepting on the deck span over the brook, where the spacing is 10 ft. Longitudinal I-beam stringers, 3 ft. 11½ in. on centers, rest directly on the floor beams.

The bridge had been posted for load restriction due to the apparent weakness of the floor system. There was a noticeable vibration of the trusses even as restricted loads passed over the bridge. It was evident that this was caused by the corrugated roughness and large scale disintegration of the pavement composed of 3 in. of asphalt laid on a dry concrete cushion. This pavement was laid directly on ⅜-in. buckle plates which were bolted to the stringers. Many of the bolts were loose and some were missing.

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*Presented at the 42nd Annual ACI Convention, Buffalo, N. Y., February 20, 1946.
†Consulting Engineer, New York, N. Y.

Fig. 1—General view of Spruce Street Bridge

Repairs and reinforcement

The general lack of rigidity of the floor system was the cause of the vibrations that completely disintegrated the pavement. It was impossible to maintain the pavement in good condition. The span over the railroad was replaced in 1937 due to major deterioration caused by locomotive fumes. The original structural members of the remaining 6 spans, 792 ft. in length, were in good condition showing no sign of section diminution. The buckle plates were well preserved, minor repairs had been made from time to time, but structural reinforcement had been given no consideration.

Assuming that the bridge had the proper strength, the city was faced primarily with the expense of replacing the pavement. A preliminary analysis showed the stringers to have the precariously low carrying capacity of 6- to 8-ton vehicular loading. This condition did not warrant stiffening repairs to the buckle plates in order to replace the pavement. Then followed the imperative consideration of structural reinforcement of the bridge.

Application of the "Alpha System-Composite Floor Design"

The old pavement was removed to the street car rail and replaced by a concrete paving slab of like thickness, about 6 in., to become the flange of a composite T-beam with the I-beam stringers (Fig. 2). A ½-in. slot separated the buckle plates along the center line of the stringers adjacent to the bolt lines. The buckle plates were welded to the stringers in the slot, and the spirals to the buckle plates, to effect the shear or bonding medium between the concrete slab and the I-beam stringer. The strength of the floor system was thus increased from a 6-to 8-ton

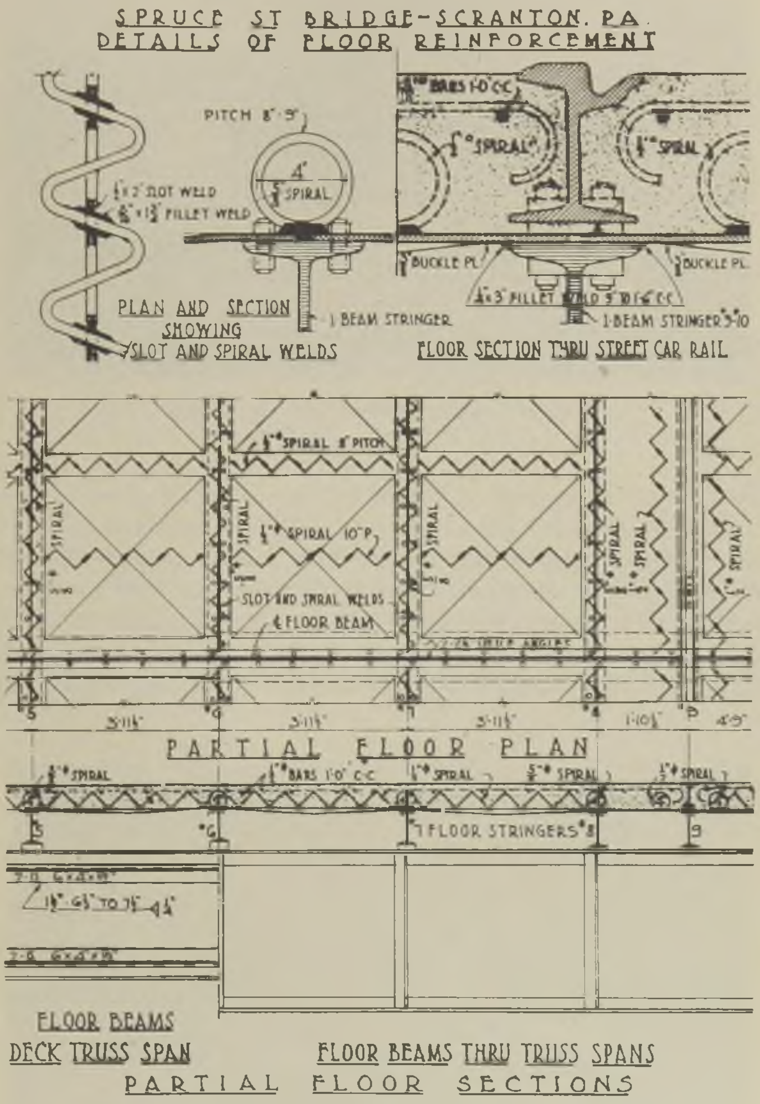

Fig. 2—Details of reinforcement, floor plan and floor sections

Fig. 3—Looking north across the deck span

loading to a 15-ton loading. This did not exceed the effect on the trusses of a uniform live load of 100 lb. per sq. ft. over the entire floor, for which trusses were originally designed. The floor beams, spaced 17 to 21 ft. apart, were also of sufficient strength to carry two 15-ton truck concentrations and a street car loading in line. The floor beams of the deck span, 10 ft. apart, were over-stressed. These were reinforced by welding a pair of 4-in. x 6-in. angles in both top and bottom flanges. (Fig. 2)

Fig. 4—Looking south through two end spans

In addition to the spirals, ½-in. round transverse and longitudinal bar reinforcement provided for shrinkage and thermal changes. Transverse spirals joined the buckle plates to the slab for transverse composite action. The longitudinal spirals were ⅝-in. plain round bars with 8-in. pitch; transverse spirals were ½-in. round bars with 8- and 10-in. pitch. (Fig. 5). The street car rails were directly over two stringers. In order to maintain street car traffic during construction operations, the buckle plates were welded to the stringers under the plates and each rail flanked by a pair of spirals parallel and immediately adjacent thereto.

The slot weld (½-in. fillet 2 in. in length) and the spiral weld (¼-in. and ⁵⁄₁₆-in. fillets 1¾-in. in length) coincide in position at the point of contact of the spiral, so that both welds could be made simultaneously. (Fig. 2 and 5). Some of the buckle plate bolts were knocked out in the operation of removing the old pavement. No shear value was assessed for these bolts in design of the composite section. There were 19,000 in. of slot welding, 11,600 in. of overhead welding under the street car tracks and 96,500 in. of spiral welding. The weight of the spirals amounted to 29,000 lb.

Pouring

A sectional platform which was readily removed by hand was placed on wooden horses to form a stage over which the concrete was hauled in buggies. Alternate sections of the slab were poured to facilitate longitudinal screeding. These sections were bounded by transverse construction joints over each floor beam. The bulkheads rested against a pair of 2½-in. angles, which joined and supported the buckle plates transversely. Since the concrete slab section was pierced by these angles, they were found to be a favorable line for a construction joint. (Fig. 6 and 7).

Fig. 5—Spiral reinforcement

Fig. 6—A typical panel

The concrete was delivered in 3-yd. transit trucks from a ready mix plant located about a mile from the bridge site. 5½ bags of portland and 1 bag of natural cement per cu. yd. resulted in an excellent mobile concrete. Other characteristics of the mix were: sand, 1200 lbs.; stone (1½-in.), 1870 lb.; water, 35 gal. plus aggregate absorption; slump, 3-in. The concrete had practically no movement by its own weight, but it moved very sluggishly en masse with little vibration. About 4 to 6 sections, averaging 19 ft. in length, were poured daily. Transversely,

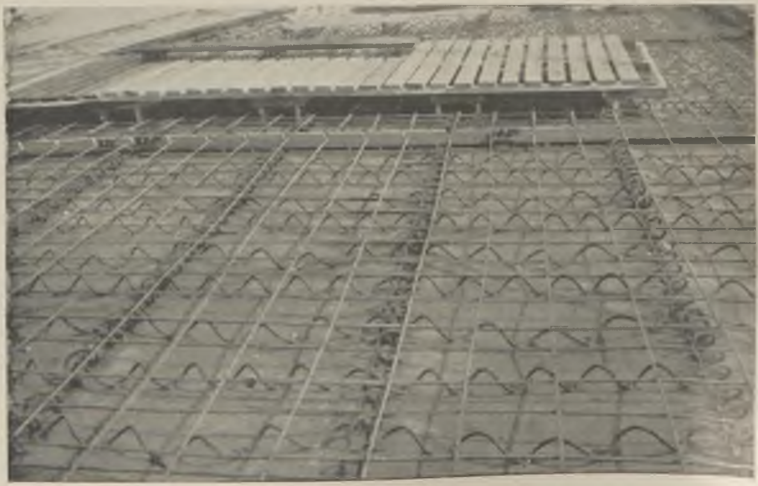

Fig. 7—Slab section ready for concreting

Fig. 8—Placing concrete slab

the slab was poured in two sections: 1) the roadway to inside rail of track, 28 ft. 4 in. in width; and 2) track section to curb, 8 ft. 8 in. in width. The roadway sections for the full length of the bridge were poured first from trucks operating over the old pavement of the track section.

The concrete was screeded from the transverse bulkhead, a 2 x 6 in. plank on edge, bolted to clamps with slotted holes for adjusting plank to the crown of road. The clamps were welded to the floor plates. The

Fig. 9—Screeding

Fig. 10—Curing by oil spray

bulkheads were easily bowed to crown of the pavement (Fig. 8). The concrete surface was wood floated after screeding from a wooden bridge spanning the panel section, after which it was carefully broomed. The concrete was cured by an oil spray with the trade name of "Rite-Cure."

Contract prices for the job were:

(1)	Old pavement removed	$ 6,800
(2)	New expansion joint assemblies	1,800
(3)	Floor beam angle reinforcement	3,000
(4)	Painting, new drains, misc.	1,500
(5)	Concrete paving slab	10,000
(6)	Spiral, slot, overhead welding, bar reinforcement	20,400
	Total	$43,500

The area of the bridge floor (37 ft. x 792 ft.) was 29,304 sq. ft. The cost of floor reinforcement, items (3) and (6), was $23,400, a unit cost of 80 cents per sq. ft.

To facilitate selective distribution, **separate prints** of this title (43-5b) are currently available from ACI at 75 cents each—quantity quotations on request. **Discussion** of this paper (copies in triplicate) will be considered only on the basis of the **entire contribution** and should reach the Institute not later than July 1, 1947

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Studies of the Physical Properties of Hardened Portland Cement Paste*

By T. C. POWERS†
Member American Concrete Institute
and T. L. BROWNYARD‡

PART 2. STUDIES OF WATER FIXATION

CONTENTS

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†Manager of Basic Research, Portland Cement Assn. Research Laboratory, Chicago 10, Ill.

‡Navy Dept., Washington, D. C., formerly Research Chemist, Portland Cement Assn. Research Laboratory. Chicago 10, Ill.

INTRODUCTION

In the preceding part of this paper some of the methods of studying hydrated portland cement paste were reviewed and the principal results obtained by previous investigators were presented. In this part of the paper the studies of water fixation carried out in this laboratory will be described.*

As shown in the first section, water fixation has claimed the interest of several investigators. The reason for such interest is not hard to find. Some of the water associated with hardened cement paste is obviously a constituent of the new solids produced by chemical reactions. If all such water is driven from the paste, the cohesion of the paste is destroyed. Another part of the water, amounting in saturated paste to as much as 50 percent of the volume of the paste, or even more, is free to leave the hardened paste without destroying the cementing value of the material. It does, however, have important effects on the hardened paste: the paste shrinks as water is lost and swells as it is gained; the strength and hardness of the hardened paste vary with its degree of saturation; some of this water is freezable and is thus a source of disruptive pressures that tend to disintegrate concrete exposed to weather. Furthermore, the amount of water that is free to come and go in response to changes in ambient conditions is an index to the degree of porosity of

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*The characteristics of the cements mentioned in this part may be found in the Appendix to Part 2.

the hardened paste. The porosity is obviously an important property of the material related directly to its quality.

One incentive for studying the fixation of water in hardened paste was the possibility that suitable measurements of the manner in which the water is associated with the solids would provide the means of estimating the nature and size of the pores in the paste. It was hoped that such knowledge would simplify the problem of relating the chemical and physical characteristics of the cement to its quality. This hope arose rather directly from the hypothesis of Freyssinet(1)* which had a major influence on our choice of experimental procedure. The chosen procedure was intended to yield information on the porosity and pore-size distribution of the hardened paste and other information that might bear on the questions of volume change, durability, plastic flow, etc.

Porosity. To speak, as above, of the porosity of hardened paste is likely to be misleading unless the term is properly qualified. The word "porosity" can be interpreted differently according to past experience or to the chosen criterion as to what constitutes porosity. Certainly, the term is misleading here if it calls to mind such materials as felt or sponge.

Whether or not a material is considered to be porous depends in part on the means employed for detecting its porosity. If a material were judged by its perviousness alone, the decision would rest primarily on the choice of medium used for testing its perviousness. For example, vulcanized rubber would be found impervious, and hence, non-porous, if tested with mercury, but if tested with hydrogen it would be found highly porous. The perviousness of hardened cement paste to water and other fluids is direct evidence of the porosity of the paste.

Regardless of the size of the pore, a substance near enough to the boundary of the pore is attracted toward the boundary by one or more types of force known collectively as forces of adsorption. These forces are sufficiently intense to compress a fluid that comes within their range. If the fluid is a vapor, the degree of compression may be very great; the vapor may be liquefied or solidified; if the fluid is already a liquid, it may undergo further densification on making contact with the solid surface. Since the range of the forces causing such effects is very small—a few hundredths or thousandths of a micron—only a negligible part of the enclosed space in pores of microscopic or macroscopic dimensions is within the range of surface forces. However, when the pores are of the same order of magnitude as the range of surface-forces, it follows that a large portion, or all, of the enclosed space is within the range of surface forces. For this reason, substances containing a large volume of sub-

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*See references, end of Part 2.

microscopic pores exhibit properties and behavior not noticeable in ordinary porous bodies. For example, porous bodies of submicroscopic (colloidal) texture shrink and swell markedly on changing the liquid content of the pores, the magnitude of the effect being controlled by the intensity of attraction between the solid and the liquid. Moreover, changes in liquid content alter such properties as strength, elasticity, heat content, and other properties that in non-colloidal solids are virtually constant at a given temperature. Some of these effects will be the subject of discussion farther on.

CLASSIFICATION OF WATER IN HARDENED PASTE

The present discussion aims to elucidate those features of a hardened paste that are revealed by the relative proportions of the total water content that fall in three different categories, as follows:

(*1*) *Water of constitution.*

As used here, this term refers to water of crystallization or water otherwise chemically combined; it refers to water that is a part of the solid matter in a hardened paste.

(*2*) *Water bound by surface-forces—adsorbed water.*

(*3*) *Capillary water.*

This is that water which occupies space beyond the range of the surface-forces of the solid phase.

The above classification is of little practical use, for as yet no way has been devised for actually separating the total water content into such divisions. On drying, water of category (2) and of category (3) are lost simultaneously. Furthermore, not all the water in these two categories can be removed without removing also some of the water of constitution (category (1)). Nevertheless, since evaporation or condensation is the most feasible means of manipulating it, the total water must be studied first with respect to the relative volatilities exhibited by different portions of it. From such data, means of estimating the amounts of water in the three categories given above have been developed, as will be shown.

The water in a saturated, hardened paste is classified in this paper according to its volatility as follows: The water that is retained by a sample of cement paste after it has been dried at 23 C to constant weight in an evacuated desiccator over the system $Mg(ClO_4)_2.2H_2O$ + $Mg(ClO_4)_2.4H_2O$ as a desiccant* is regarded, in this discussion, as "fixed" or "combined" water. To avoid any unintentional commitments as to the state of combination of this part of the water, it is called *non-evaporable water.* The rest of the water in a saturated specimen is called the *evapor-*

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*The material is purchased as "Dehydrite"—$Mg(ClO_4)_2$. The two molecules of water are added at the time of use. See Drying of Samples.

able water. The non-evaporable water probably includes most of the water of constitution, but not all of it, for at least one of the hydrates, calcium sulfoaluminate, is partially decomposed when the evaporable water is removed. On the other hand, it is not certain that all the non-evaporable water is water of constitution, for it is possible that some of it can be removed (by slightly raising the temperature) without decomposing any compound present. (See Part 1, Isobars from Portland Cement Paste.) In this connection, a reading of Lea's paper "Water in Set Cement" is recommended.[2]

MATERIALS AND EXPERIMENTAL PROCEDURES

The materials used for these studies were hardened neat cement pastes, pastes of cement and pulverized silica, or cement-sand mortars made with a wide variety of commercial and laboratory-prepared cements. The experimental procedures differed somewhat from time to time and with the type of specimen employed. The general features of the procedures will be described here, and certain other details will be given at appropriate points in other sections of this paper. A detailed description of the materials and methods of the various projects will be found in the Appendix to Part 2.

PREPARATION OF SPECIMENS

Neat cement cylinders

(Series 254-K4B and 254-MRB). Neat cement specimens were prepared, usually at a water-cement ratio of 0.5 by weight, by molding the mixed paste in cylindrical wax-impregnated paper molds ⅞-in. by 6-in. long. In some investigations cylindrical molds of other types were used. The molds were stoppered and laid in water horizontally as soon as they were filled, and the stoppers were removed after about 24 hours so that the curing water might have ready access to the cement paste.

In mixing the pastes, 200 g of cement was mixed with the desired amount of water in a kitchen-type mixer. The mixer was operated at top speed for two minutes and then the paste was allowed to rest for three minutes, and finally mixed again for two minutes. This procedure was followed to avoid the effects of certain types of premature stiffening, whether or not the cements showed any such tendency.

Mortar specimens

The majority of the mortar specimens were made from the mixes shown in Table 1.

As indicated in the Table 1, the aggregate consisted of standard Ottawa sand (20-30 mesh) and pulverized silica, the latter being of about the same specific surface as the cement. The quantity of silica was

TABLE 1—MIXES FOR MORTAR SPECIMENS
(Series 254-8-9-10-11)

Mix	Proportion by weight			Batch quantities in grams		
	Cement	Pulverized silica	Standard sand	Cement	Pulverized silica	Standard sand
A	1.00	—	1.64	1400	—	2300
B	1.00	0.33	2.30	1000	330	2300
C	1.00	0.71	3.65	750	530	2300

such as to give all the mixes about the same total (absolute) volume of cement + silica + water.

The water-cement ratios were adjusted to give a 1½-2-in. slump (6-inch cone) and varied through a small range with the different cements used. The values (after bleeding) were about 0.33, 0.45, and 0.58 for mixes A, B, and C, respectively.

The batches were mixed in a small power-driven, open-tub mixer. Each batch was first mixed 30 seconds dry and then for 2 minutes after the water was added. Two operators working simultaneously then made duplicate slump tests and returned the slump samples to the mixing tub. After remixing the material for 30 seconds, 2x2-in. cubes and 2x2x9½-in. prisms were cast in watertight, three-gang molds which had been previously weighed.

Measurements were made from which the air contents and the loss of water due to bleeding could be computed. This procedure was as follows: Before each cube mold was filled, its outside surface was carefully cleaned and, after filling, the mold and contents were weighed. Then the mold was placed in saturated air. After two hours, water that had accumulated at the top through settlement was carefully removed with absorbent paper and the mold again was weighed. The molds were then immersed in water at 70 F where they remained for at least 12 hours. They were then removed from the water, dried with paper and again weighed. Following this the specimens were removed from the molds, weighed in air surface-dry, and then in water so as to obtain the weight and volume of the material. The cubes were then stored in a fresh supply of water at 70 F where they remained until test or until they were 28 days old. Those that were scheduled for tests beyond 28 days were then stored in the fog room at 70 F.

During the water storage the water was changed periodically to prevent the building up of high alkali concentration.

At the scheduled time of test the cubes were again weighed in the surface-dry condition and under water. Those that had had a period of storage in moist air were placed in water one day before the scheduled test date to allow them to absorb water if they could.

The data obtained in this manner made it possible to ascertain the average amount of original unhydrated cement, silica, sand, water, and air in each group of companion hardened specimens.

The prisms were treated in the same way as the cubes except that the measurements of settlement (bleeding) were not made.

Truncated cones

In one of the earlier investigations (Series 254-7) mortar specimens were cast in watertight, truncated cones of 4-in. base, 2-in. top diameter, and 6-in. height. Measurements similar to those made on the cubes were made on these cones before and after removing the molds. This gave accurate data on the settlement and the final proportions of the ingredients of the mixtures.

TESTING OF MORTAR SPECIMENS

At the scheduled test ages, which usually ranged from 7 days to 6 months, two cubes of a kind were tested for compressive strength. Throughout these procedures the cubes were carefully kept wet and, after being tested, cubes of a kind were placed immediately in airtight containers.

PREPARATION OF SAMPLES FOR STUDIES OF HARDENED PASTE

Mortar specimens

The tested mortar cubes in airtight containers, mentioned above, were taken from the containers as soon after the strength test as possible and passed quickly through a small jaw crusher. The crushed material was immediately transferred to a nest of sieves (No. 4-8-14-28-35-100-150) already cleaned, assembled, and sealed at the joints with wide rubber bands. The sieves were shaken on a sieving machine for 5 or 10 minutes and then, to prevent losses of water by evaporation, the nest of sieves was opened in the moist room and the material caught between the 35- and 100-mesh or, in some series, between the 48- and 100-mesh sieves, was transferred to a screw-top sample bottle. This material, which consisted of granules of hardened cement paste or hardened paste and pulverized silica, was used for the studies to be described.

Neat cement cylinders and mortar cones

The neat cement cylinders and mortar cones were weighed in air and in water by procedures somewhat like that described for the mortar cubes. Then, since no physical tests were made on these specimens, they were immediately passed through the jaw crusher and a granular sample was obtained by the procedure described above. In some of the earliest tests the crushing was done with mortar and pestle, but this procedure permitted too much drying and carbonation of the material.

Neat cement slabs

For the most recent project of this study (Series 254-18) the test samples were very thin, neat-cement slabs. These were prepared from cylinders by sawing off slices and then grinding the slices on a glass plate with carborundum dust and water. By this method the slabs were reduced to an average thickness of about 0.3 mm. When saturated, they were translucent.

DRYING OF SAMPLES

The granular samples described above, in quantities not exceeding 15 g, were placed in wide-mouthed weighing bottles and stored in vacuum desiccators with anhydrous magnesium perchlorate (Dehydrite). (The desiccators were exhausted with a Cenco Hyvac pump.) When an excess of the anhydrous desiccant was used, the effective drying agent was a mixture of $Mg(ClO_4)_2$ and $Mg(ClO_4)_2.2H_2O$. With the thought of avoiding the dehydration of the calcium hydroxide, we used a quantity of anhydrous magnesium perchlorate in each desiccator such that when the original compound had combined with all the water given up by the samples the desiccant had become a mixture of $Mg(ClO_4)_2.2H_2O$ and $Mg(ClO_4)_2.4H_2O$; that is, this was the mixture that determined the final water vapor pressure in the desiccator. (Although this was the intention, there is some evidence in the data that the desired result was not always realized. In some cases the final desiccant was probably the mixture $Mg(ClO_4)_2 + Mg(ClO_4)_2.2H_2O$. Some of these cases are mentioned in later discussions, but it was impossible to identify all cases with certainty.)

In some of the earlier projects other desiccants were used, namely, P_2O_5, H_2SO_4, and CaO. In some the drying was done in desiccators containing air instead of in vacuum desiccators. However, most of the data reported here were obtained by the procedure described above.

Reproducibility of results

To test the reproducibility of results obtained by the drying procedure used for the greater part of this investigation, four sets of samples, each comprising 11 companion portions, were prepared from a single neat paste specimen 3½ months old. The results are given in Table 2.

The differences among the figures in any one column indicate the degree of variation among the samples in a given desiccator. The figures for the average loss for the different sets indicate the variations, if any, between conditions in different desiccators. The average losses for sets A and B are slightly higher than for sets C and D. Sets A and B were

TABLE 2—REPRODUCIBILITY OF DRYING LOSSES

Cement: Laboratory blend of 4 commercial brands, Lot 13495
Nominal $w/c = 0.50$ by wt.
Curing: 3½ months in water

Sample No.	Loss of water—% by wt.			
	A	B	C	D
1	19.81	20.14	19.75	19.87
2	20.06	20.01	19.84	19.80
3	19.93	20.10	19.85	19.96
4	19.99	20.13	19.66	19.89
5	20.06	20.10	19.67	19.82
6	20.09	20.07	19.86	19.84
7	19.98	20.04	19.93	19.87
8	20.00	20.09	19.63	19.87
9	20.13	20.03	19.84	19.84
10	20.00	20.04	19.74	19.79
11	19.72	20.20	19.58	19.90
Average	19.98	20.09	19.76	19.86

dried immediately after they were prepared. Sets C and D were stored in screw-top sample bottles for about one week before they were dried. It seems, therefore, that the smaller loss from sets C and D was probably due to the additional hydration of these two sets during the one-week waiting period.

DETERMINATION OF NON-EVAPORABLE WATER

One-gram portions of the samples dried as described above were heated at about 1000 C for about 15 minutes. The samples were cooled and weighed and then given a 5-minute reheat to check the completeness of ignition. The amount of loss minus the ignition loss of the original cement is called the non-evaporable water content of the sample.

The computation involves the assumption that the weight of the non-evaporable water is exactly equal to the increase in ignition loss. Such an assumption introduces some error. In the first place the original cement was not pre-dried as were the hydrated samples before determining loss on ignition. Hence, the ignition loss as reported for the original cement might be slightly above the value correct for this computation. A second, more serious, source of error arises from ignoring the increase in the amount of combined carbon dioxide. Although precautions against exposure of the granular samples of hardened paste to carbon dioxide were taken, some carbonation did occur. Tests made on 15 different samples showed that in 60 percent of the cases carbonation amounted to less than 0.5 percent of the weight of the original cement. However, carbonation as high as 1.9 percent was found. When carbonation has occurred, the loss on ignition of the carbonated sample will be greater than the non-evaporable water content before carbonation occurred. The increase is about 0.59 times the weight of CO_2 combined. For example, if the loss on ignition is 0.2 g per g of cement greater than the original loss on ignition, and if the CO_2 content has increased by 0.005 g per g of cement, the non-evaporable water would be 0.2 minus the quantity $(0.005 \times 0.59) = 0.197$. Thus, in this example, the assumption that the increase in loss on ignition is equal to the non-evaporable water results in an error of about 1.5 percent. At earlier stages of hydration, when the loss on ignition is smaller, the relative error would be considerably greater for the same amount of carbonation.

Since the necessary data are available on only a few of the samples and since also there is some question as to the accuracy of the figures for amount of carbonation, no attempt to correct loss on ignition for CO_2 was made in preparing the data for this report. Variations in the amount of carbonation among the various samples undoubtedly contributes to the random variations that will be noted.

Degree of desiccation of dried samples

The degree of desiccation obtained by the drying procedure described above is indicated by the data given in Table 3, which gives also the results obtained with other desiccants. For brevity, only one of the two components of the desiccating mixture is given. The samples tested were neat cement pastes (original w/c (by wt.) = 0.5), that had been cured 1 year in water. Each paste was made with a different cement, the group representing a wide range in chemical composition.

It will be noted that with any given desiccant, the percentages of non-evaporable water for the different pastes differ over a considerable range. However, it is significant that all the results obtained with one desiccant bear a virtually constant ratio to the results obtained with another. This is shown in Table 4, where the results are expressed as

TABLE 3
(Data from Series 254-K4B)

Paste No.	Water retained at equilibrium with the desiccant indicated, % by wt. of cement in specimen			
	P_2O_5	$Mg(ClO_4)_2$	$Mg(ClO_4)_2.2H_2O$	H_2SO_4 conc.
4S	18.3	21.4	22.8	22.3
5S	17.4	20.6	22.0	22.7
7Q	21.4	25.4	26.6	27.1
7P	21.1	25.2	26.5	27.1
7S	20.6	24.6	25.9	26.5
11S	17.6	20.9	22.2	22.5

TABLE 4

Paste No.	Amount of water retained relative to that retained by $Mg(ClO_4)_2.2H_2O$			
	P_2O_5	$Mg(ClO_4)_2$	$Mg(ClO_4)_2.2H_2O$	H_2SO_4, conc.
4S	0.80	0.94	1.00	0.98*
5S	0.79	0.94	1.00	1.03
7Q	0.80	0.95	1.00	1.02
7P	0.80	0.95	1.00	1.02
7S	0.79	0.95	1.00	1.02
11S	0.79	0.94	1.00	1.02

*This value is probably in error—too low. In another group of tests, the ratio for conc. H_2SO_4 was found to be 1.08. Possibly the sulfuric acid used in this second group had a slightly higher water vapor pressure than the acid represented in the table.

ratios to the quantity retained over a mixture of magnesium perchlorate dihydrate and magnesium perchlorate tetrahydrate.

The published information on the actual water vapor pressures maintained by these desiccants is not entirely satisfactory. The values given in Table 5, below, are the most reliable that can be found. Note that these values are upper limits; the actual water vapor pressures may be much lower.

TABLE 5

Drying agent	Residual water at 25 C		Reference
	Mg. per liter	Relative vapor pressure, p/p_s*	
P_2O_5	$<2.5 \times 10^{-5}$	$<1 \times 10^{-6}$	(1)
$Mg(ClO_4)_2$(anhyd.)	$<3 \times 10^{-3}$	$<130 \times 10^{-6}$	(3)
H_2SO_4	$<3 \times 10^{-3}$	$<130 \times 10^{-6}$	(2)
CaO	$<3 \times 10^{-3}$	$<130 \times 10^{-6}$	(3)

*p = existing water vapor pressure. p_s = water vapor pressure over a plane surface of pure water—the "saturation pressure" at a given temperature.
(1) Morley, *J. Am. Chem. Soc.* v. 26, p. 1171 (1904).
(2) Morley, *Am. J. Sci.* v. 30, p. 141 (1885).
(3) Bower, Bureau Stds. J. Research v. 12, p. 246 (1934).

The data for CaO are open to question. Evidence to be presented in Part 4 indicates that the equilibrium relative vapor pressure of water over CaO may be much less than the value given.

The data for P_2O_5 and H_2SO_4 are the result of very painstaking measurements and are probably close to the correct ones. The results in Table 4 bear this out. The amount of water retained by pastes dried over P_2O_5 is less than that retained over any other desiccant; that retained over H_2SO_4, conc., is more. With respect to $Mg(ClO_4)_2$(anhyd.), the water vapor pressure maintained by this desiccant is certainly far less than the upper limit given in Table 5. The data in Table 4, together with the data given on page 286, indicate that the relative vapor pressure is well below 24 x 10^{-6}, the vapor pressure of water at dry ice temperature (-78 C) relative to "saturation pressure" at 25 C.

Data on the vapor pressure over $Mg(ClO_4)_2.2H_2O$ are not available in the literature. However, the data on page 286, indicate that it is about 24 millionths of the "saturation pressure."

A method of drying more commonly used than the isothermal procedures just discussed is that of oven-drying at a temperature at or slightly above the normal boiling point of water. To compare the degree of desiccation obtained from such oven-drying with that obtained isothermally over $Mg(ClO_4)_2.2H_2O + Mg(ClO_4)_2.4H_2O$, four samples that had previously been dried by the latter procedure were placed in an oven at 105 C and allowed to come to constant weight. The results are shown in Table 6.*

TABLE 6

No. of Sample	Loss in weight in oven—% of non-evaporable water content as found by isothermal drying over $Mg(ClO_4)_2.2H_2O$ + $Mg(ClO_4)_2.4H_2O$
16213	10
16214	11
16198	10
15669	13

Stability of hydrates

The figures given in the foregoing paragraphs indicate the "degree of dryness" produced by the method adopted for this investigation in terms of the amount of water retained by the paste and the relative vapor pressure of this residual water, called non-evaporable water. An attempt will now be made to indicate the amount of water retained by the hydrated compounds of portland cement when dried by this procedure.

The microscope reveals that both microcrystalline and colloidal materials occur in hardened paste, the colloidal material appearing as an amorphous mass enclosing microcrystalline $Ca(OH)_2$ and unhydrated residues of the original cement grains. Any such microcrystalline hy-

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*In this test no attempt was made to control the water vapor pressure in the oven. This is the incorrect procedure that has frequently been used in studies of this kind.

drate will remain unaltered during the process of drying if its dissociation pressure is lower than the vapor pressure maintained by the drying agent. If the dissociation pressure of the hydrate is higher than the vapor pressure maintained by the drying agent, dehydration is possible but not certain; only direct trial will tell whether it will occur under the conditions of the experiment. Under suitable experimental conditions, the hydrate will lose one or more gram-molecular weights of water per mole of hydrate without appreciable change in vapor pressure, the amount lost being determined by the nature of the hydrate.

As was shown in Part 1, the water content of *colloidal* hydrates bears no small-whole-number, molar ratio to the anhydrous material (except perhaps by chance) and none of it can be removed without a corresponding change in the equilibrium water vapor pressure. That is, the water content of a colloidal hydrate varies continuously with changes in ambient conditions. The colloidal material in hardened cement pastes predominates over non-colloidal constituents to such a degree that the dehydration process shows only the characteristics associated with colloidal material and therefore the dehydration curves do not indicate directly the extent to which the microcrystalline material becomes decomposed.

The extent to which the hydrates of the major compounds of portland cement are dehydrated under the drying conditions described can be estimated from the data given in Table 7. The data pertain to products obtained by hydrating the compounds separately. The first eight lines of data show the amounts of water retained by C_3S (under the drying conditions described) after various periods of hydration. They show that the amount is greater the longer the period of hydration. However, a maximum would be expected, though it is not clearly indicated by these data.

As brought out in Part 1, the figures given in Table 7 should be regarded as single points on smooth isobars and therefore have no unique significance. Had the temperature of drying been higher, the amount of water retained at any given age would have been less, and vice versa. On the other hand, if the hydration products were microcrystalline hydrates, each hydrate would probably be stable over a considerable temperature range, with pressure constant, or over a pressure range with temperature constant.

The alumina-bearing compounds that occur in portland cement clinker, *when hydrated separately*, produce microcrystalline hydrates having definite amounts of water of crystallization. A list of several compounds is given in Table 8, together with information as to their stability in the presence of $Mg(ClO_4)_2.2H_2O$, CaO, or P_2O_5.

TABLE 7—FIXED WATER IN HYDRATED C_2S AND C_3S AS REPORTED BY SEVERAL INVESTIGATORS

Compound	Nominal w/c by wt.	"Fixed water" at age indicated, grams per gram of original anhydrous material					
		3 days	7 days	28 days	6 mo.	1 year	3 years
C_3S^a	0.35	0.103	—	0.146	0.150	0.190	—
C_3S^b	0.40	0.198	—	—	—	0.213	—
C_3S^c	0.78	—	—	—	—	—	0.31
C_3S^d	0.33	—	0.103	0.143	0.207	—	—
“	0.45	—	0.102	0.147	0.224	—	—
“	0.60	—	0.104	0.150	0.238	—	—
“	1.00	—	0.110	0.161	0.254	—	—
C_2S^a	0.30	0.013	—	0.034	0.108	0.122	—
C_2S^b	0.40	0.019	—	0.043	—	0.138	—
C_2S^c	0.33	—	—	—	—	—	0.09
C_2S^d	0.33	—	0.020	0.036	0.134	—	—
“	0.45	—	0.020	0.032	0.142	—	—
“	0.60	—	0.016	0.025	0.120	—	—
“	1.00	—	0.017	0.026	0.130	—	—

a — R. H. Bogue and Wm. Lerch, PCAF Paper, No. 27.
The specimens were cured in vials with excess water present. Material ground to pass 100 mesh, 90 percent to pass 200. "Fixed water" is the loss on heating at 1000 C from samples pulverized and dried in an oven at 105 C with no control of the water vapor pressure in the oven.

b — R. H. Bogue, Effects of Phase Composition on the Volume Stability of Portland Cement, PCAF (1940) (mimeographed)
The specimens were cured in vials with no extra water. The material was "ground to approximately 2200 cm^2/gm." "Fixed water" as in *a*.

c — This laboratory
The specimens were molded and cured in extraction-thimbles surrounded with water. The silicates were each ground to give 85 percent passing the No. 200 sieve, but the trisilicate was nevertheless the finer. p/p_s at equilibrium was about 0.5×10^{-6}. The amount of water was determined by heating at 1000 C.

d — F. P. Lasseter, Chemical Reactions in the Setting of Portland Cement—Dissertation, Columbia University, 1939.
The specimens were cured in vials with extra water present. Samples of -100 mesh material were dried 3 hr. at 105 C in "dry CO_2-free air."

The first compound listed, the high-sulfate form of calcium sulfoaluminate, may occur in hardened paste to the extent that gypsum is present for its formation (assuming an excess of C_3A). The data indicate that all but 9 of the 32 molecules of water of crystallization may be lost. In an average cement containing 1.7 percent SO_3, all of which reacted to form the calcium sulfoaluminate, the amount of hydrated sulfoaluminate per gram of cement would be about 0.09 g. About 0.03 g of this would be lost on drying.

The second item in Table 8 refers to the low sulfate form of calcium sulfoaluminate, a compound which probably does not form under the conditions prevailing in the hardening of the pastes used here. If it did occur, the data indicate that 2 of the 12 molecules of water of crystallization might be lost on drying over $Mg(ClO_4)_2.2H_2O$.

The hexahydrate of C_3A evidently would not be dehydrated by $Mg(ClO_4)_2.2H_2O$. The 12-hydrate of C_3A is reduced to about the 8-hydrate on drying over $Mg(ClO_4)_2.2H_2O$. $C_4A.12H_2O$ is not dehydrated by the conditions used for this study.

TABLE 8

Compound	Number of molecules of water retained in the presence of the desiccant indicated		
	$Mg(ClO_4)_2.2H_2O$	CaO	P_2O_5
$C_3A.3CaSO_4.32H_2O$	9(a)	8(b)	7.5(c,d)
$C_3A.CaSO_4.12H_2O$	10(a)	—	8 (c,d)
$C_3A.6H_2O$ (cubic)	—	6(e)	—
$C_3A.12H_2O$ (hex)	—	8(e)	—
$C_4A.12H_2O$	—	—	12(f)

a — This laboratory.
b — Jones: Symposium on the Chemistry of Cements (Stockholm, 1938), p. 237.
c — Forsen: *Zement* v. 19, pp. 1130, 1255 (1930); v. 22, pp. 73, 87, 100 (1933).
d — Mylius: *Acta Acad. Aboensis* v. 7, p. 3 (1933); see *b*.
e — Thorvaldson, Grace & Vigfusson: *Can. J. Res.* v. 1, p. 201 (1929).
f — Assarsson: Symposium on the Chemistry of Cements (Stockholm, 1938), p. 213.

It thus appears that of the various microcrystalline hydrates that can be formed from the constituents of portland cement only the calcium sulfoaluminate would be decomposed to an appreciable extent; it would lose 72 percent of its water of crystallization. After a long period of hydration, the water held by the hydration products of C_3S and C_2S amounts to 20 to 30 percent and 10 to 14 percent of the weight of the original material, respectively.

Before this subject is closed it should be said that the occurrence of the microcrystalline hydrates of C_3A in hardened paste, particulary $C_3A.6H_2O$, is very doubtful. Several observations indicate this. One is the fact that drying-shrinkage is greater for cements of high C_3A content. This cannot be explained on the basis that C_3A combines with water to form the hexahydrate $C_3A.6H_2O$, since that crystal does not lose water under the conditions of ordinary shrinkage tests.

DETERMINATION OF TOTAL EVAPORABLE WATER

The water that a sample is capable of holding in addition to the non-evaporable water is called the *evaporable water*, as defined before. The procedure for determining the evaporable water content of granulated samples is as follows: About 5 grams of the sample to be saturated is placed in a 50-ml Erlenmeyer flask fitted with a special stopper that permits either the introduction of water from a burette or a stream of dried air free from CO_2. At the start, water is slowly dropped onto the sample from the burette until the sample, upon being shaken, gathers into a lump and clings to the flask. Dry air is then passed over the sample while it is vigorously shaken by hand. After 2 minutes of this treatment, the flow of air is stopped and the shaking of the flask is continued. If the sample persists in gathering into a lump, the drying is continued for 2 more minutes. This procedure is continued until the particles just fail to cling to each other and to the flask. The total water

TABLE 9—DATA ON TOTAL WATER CONTENT OF SATURATED SAMPLES

Series 254-MRB

Cement No.	Age at test, days	$\frac{w_o}{c}$	Total water at test, w_t/c				$\frac{w_n}{c}$
			Original specimen	Granules			
				SSD 1	*SSD 2*	*SSDO*	
1	2	3	4	5	6	7	8
14900	126	0.45	0.526	0.508	0.515	0.527	0.227
14901	126	0.39	0.498	0.491	0.493	0.503	0.223
14902	133	0.39	0.515	0.501	0.495	0.511	0.227
14903	133	0.42	0.527	0.511	0.516	0.526	0.227
14904	162	0.42	0.489	0.490	0.481	0.499	0.228
14905	162	0.41	0.493	0.490	0.482	0.502	0.230
14906	173	0.48	0.551	0.550	0.541	0.567	0.236
14907	173	0.41	0.464	0.461	0.458	0.474	0.219
14908	200	0.39	0.487	0.479	0.475	0.492	0.225
14909	200	0.48	0.562	0.548	0.546	0.572	0.226
14910	204	0.46	0.521	0.513	0.510	0.535	0.228
14911	204	0.46	0.536	0.526	0.521	0.546	0.229
14912	212	0.49	0.551	0.547	0.541	0.568	0.225
14913	212	0.41	0.478	0.477	0.476	0.493	0.221
14914	222	0.42	0.495	0.487	0.499	—	0.225
14915	222	0.44	0.518	0.520	0.517	0.530	0.224
Average			0.513	0.506	0.504	0.523	0.226

SSD = Saturated, surface-dry.
SSD1 = Granulated sample (100-48 mesh) dried in vacuo over $(MgClO_4)_2.2H_2O$ and then resaturated in the presence of air
SSD2 = Granulated sample dried in the same way as *SSD1*, and resaturated in a vacuum.
SSDO = Granulated sample of original, undried material brought to the *SSD* condition by adding water in the presence of air
w_n/c = Non-evaporable water, g per g of cement.
w_o/c = Original water-cement ratio by wt., corrected for bleeding
w_t/c = Total water-cement ratio at time of test

held by the sample in this condition, minus the non-evaporable water, is the total evaporable water as defined above.

Data from 40 such determinations showed that the average difference in the values obtained in duplicate determinations by a given operator was 0.36 percent of the dry weight. In three cases out of 40, the difference in values was more than 1 percent. Other experiments showed that the results obtained by two operators working independently did not differ more than did duplicate determinations made by a given operator.

The procedure just described permits water to enter previously dried granules from all sides simultaneously. Since the dried grains are known to contain a considerable amount of adsorbed air, the question arises as to how completely the air is displaced by the water. To answer this question, some dried samples were evacuated, so as to remove most of the adsorbed air, and then the water for saturation was introduced in the absence of air. Companion samples were treated in the presence of air in the usual manner.

TABLE 10—DATA ON TOTAL WATER CONTENT OF SATURATED SAMPLES

Series 254-K4B

Ref. No.	Age at test, days	$\frac{w_o}{c}$	Total water at test, w_t/c			$\frac{w_n}{c}$
			Original specimen	Granules		
				SSD	*SSDO*	
1	2	3	4	5	6	7
1-S	180	0.470	0.556	0.543	0.557	0.223
1-P	180	0.473	0.577	0.559	0.576	0.233
1-Q	180	0.425	0.521	0.502	0.515	0.229
4-S	144	0.463	0.522	0.510	0.525	0.179
4-P	138	0.460	0.548	0.512	0.535	0.177
4-Q	138	0.450	0.518	0.495	0.515	0.177
5-S	150	0.427	0.502	0.498	0.510	0.165
5-P	146	0.453	0.542	0.509	0.519	0.159
5-Q	150	0.456	0.533	0.514	0.527	0.165
6-S	196	0.471	0.529	0.508	0.530	0.215
6-Q	191	0.447	0.532	0.512	0.536	0.222
7-P	164	0.473	0.570	0.556	0.575	0.240
7-Q	171	0.480	0.548	0.549	0.564	0.239
11-P	164	0.445	0.521	0.516	0.532	0.186
11-Q	172	0.440	0.515	0.509	0.516	0.190
15-S	202	0.485	0.558	0.536	0.561	0.217
15-Q	202	0.445	0.555	0.529	0.544	0.220
16-P	223	0.464	0.540	0.525	0.541	0.226
16-Q	223	0.456	0.516	0.502	0.520	0.225
20-S	170	0.472	0.549	0.543	0.554	0.231
20-P	167	0.462	0.551	0.542	0.555	0.233
20-Q	176	0.436	0.520	0.508	0.519	0.226
Average		0.455	0.537	0.520	0.540	0.208

SSD = Saturated, surface-dry.
SSDO = Granulated sample of original, undried material brought to the *SSD* condition by adding water in the presence of air
w_n/c = Non-evaporable water, g per g of cement
w_o/c = Original water-cement ratio by wt., corrected for bleeding
w_t/c = Total water-cement ratio at time of test

Results are given in columns 5 and 6 of Table 9. (Table 9 gives also other data confirming those in Table 10. The averages 0.506 and 0.504 for the ordinary and vacuum procedures, respectively, show that the air has no appreciable influence on the results.

DISCUSSION OF GRANULAR SAMPLES

Since most of the experiments to be described were made with granular samples of the original specimens, it is necessary to consider the extent to which the granules differ from the original material.

Neat cement—effect of granulation on porosity

Table 10 gives water content data for a group of neat cement specimens and the granular samples prepared from them. The original specimens were 1x7-in. neat cement cylinders that had been stored under water for the periods shown in column 2. During the curing period, they gained in weight, the average gain being 0.082 gram per gram of cement (0.537-0.455).

From each specimen one granular sample (100-48 mesh) was prepared and then saturated by adding excess water to the granules. The excess was evaporated until the saturated surface-dry condition was reached. The results are given in column 6. A comparison of columns 4 and 6 will show that if the difference shown is significant, we may conclude that the saturated granules held slightly more water than the original specimen did at time of test. This indication is somewhat more definite in Table 9. Compare columns 4 and 7. This proves that in specimens of this kind the small granules have very nearly the same porosity as the original specimen, and it indicates that even though the original specimens were stored continuously under water, they did not remain fully saturated. This indication was supported by the dry appearance of the freshly crushed cylinders.

Neat cement—effect of drying on porosity of granules

Other samples of each specimen were dried over $Mg(ClO_4)_2.2H_2O$ and then brought to the saturated surface-dry condition. The results, given in column 5 of Table 9, should be compared with those in column 6. Also in Table 9 compare columns 5 and 6 with column 7. The average water content of the dried and resaturated granules is about 96 percent of that of the saturated granule that had not been dried.

This shows that the drying of the granules produced a permanent shrinkage that reduced the porosity of the granules below that of the paste in the original specimen. In samples of this kind (moderately low w/c, well cured) the effect is small. In specimens of higher w/c and lesser degree of hydration, the effect should be larger.

Mortar specimens—effect of granulation on porosity of paste

The mortar specimens used in these studies were made with non-absorptive, quartz sand. Consequently, all water originally in the specimen (after bleeding) as well as that absorbed during curing is held in the paste, and data showing differences between the total water contents of the original specimens and that of the granular samples represent differences in the degree of saturation, or in the porosity, of the hardened paste, just as they do with neat specimens.

Data of this kind were obtained from mortar cubes for specimens of different ages and different water-cement ratios. Typical results are given in Fig. 2-1, A and B.

The cement represented in A is a slow hardening type; that in B is normal.

In each diagram the circled dots represent the total water content of the original specimen; the crosses, the total water content of the dried-and-resaturated granules; and the triangles, the granules that were saturated without preliminary drying.

It is apparent that for specimens cured 28 days or more, the relationships are about as were found for the neat pastes described above. However, at earlier ages, especially for the slow hardening cement, the granules show less porosity than the pastes of the original specimens, the difference being greater, the higher the original water-cement ratio.

These results seem to indicate that during the early stages of hydration the paste contains voids nearly as large as the granules of the samples and that as hydration proceeds, these larger voids disappear.

On the whole, these results show that the porosity of a granular sample is about the same as that of the pastes in the original specimen except for specimens having pastes of very high porosity. A granular sample that has been dried has a smaller total pore volume than the original paste. From other data it is known that this effect, in well cured specimens, diminishes with decrease in the original water-cement ratio and probably becomes negligible at about $w_o/c = 0.3$ by weight.

METHODS OF STUDYING THE EVAPORABLE WATER

As shown by the earlier work reviewed in Part 1, when a specimen of hardened paste at room temperature is exposed to water vapor or to air containing water vapor, its water content spontaneously changes until equilibrium between the water held in the specimen and the outside water vapor is established. The establishment of equilibrium involves a change in moisture content of the sample, for the nature of the hardened paste is such that at a given temperature the relationship between vapor pressure of the water in the hardened specimen and the water content is represented by a smooth curve. Moreover, the nature of the paste is such that a specimen can remain saturated only when it is in contact with saturated water vapor or with liquid water.

Much of the work to be reported here consisted in determining the relationships between the evaporable water content and the vapor pressure for various samples of hardened cement paste. The taking up of moisture from the atmosphere will be referred to as *adsorption*, and the reverse will be called *desorption*, even though other processes might be involved. The plotted results will be called *adsorption* and *desorption isotherms*, respectively. When speaking of both processes collectively or of the processes in general without specifying the direction of moisture change, the term *sorption* will be used.

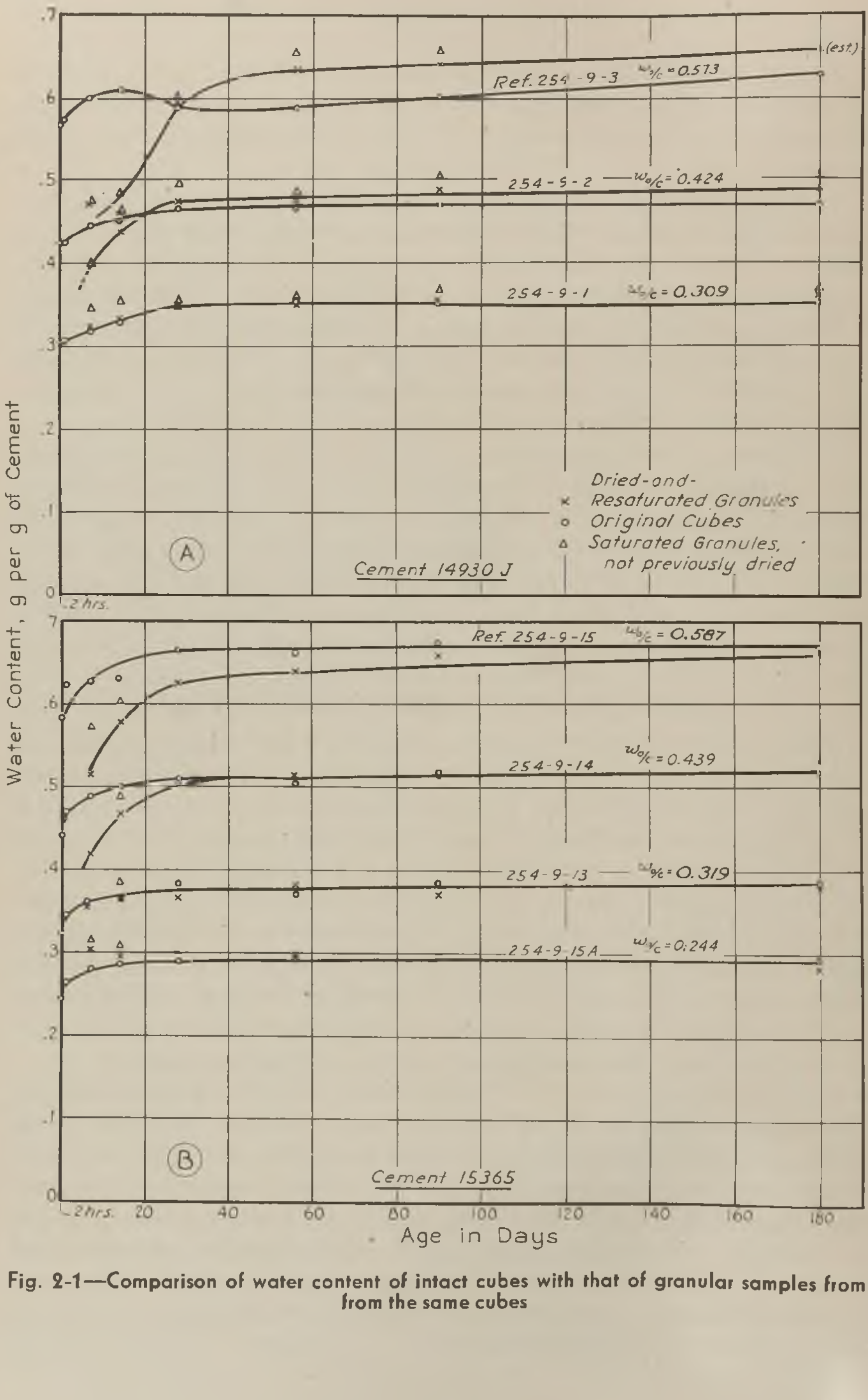

Fig. 2-1—Comparison of water content of intact cubes with that of granular samples from from the same cubes

THE APPARATUS FOR SORPTION MEASUREMENTS

Two types of apparatus were used for sorption measurements. In one the samples were exposed to water vapor only and in the other the samples were exposed to CO_2-free air containing controlled amounts of water vapor. The first is referred to as the *high-vacuum apparatus* and the second as the *air-stream apparatus.*

High-vacuum apparatus

The high-vacuum apparatus used for these studies is illustrated schematically in Fig. 2-2. As shown, two samples may be kept under test simultaneously. The samples may be either small granules or thin wafers. If granules, they are contained in small buckets made of platinum foil which are suspended on helical springs made of quartz in the two chambers marked C. If the samples are wafers, they are suspended from the springs by platinum hooks.

After the air has been pumped out, water vapor of known pressure is admitted to chamber C. The pressure of the vapor is indicated directly by the oil in manometer D. The arrangement is such that during the adsorption process the sample is never subjected to a higher vapor pressure than that with which it will finally be in equilibrium. This is an important feature of the method, for experience has shown that if the ambient vapor pressure is allowed to change as the samples approach equilibrium, the equilibrium-weight is different from what it would have been had the vapor pressure been maintained constant. This is due to the phenomenon of hysteresis, discussed later on.

The changes in weight of the sample are observed by measuring the changes in length of the quartz springs by means of a cathetometer. The spring-cathetometer combination has a sensitivity of about 0.2 mg. With a live load of about 400 mg this gives adequate accuracy.

The water vapor pressure is generated by the water (or ice) in bulb A or bulb B. Bulb B is used for the lowest pressure of the range employed which is that of water at the temperature of dry ice wetted with alcohol, -78 C. For all higher vapor pressures cock 2 is closed and 1 is open, thus utilizing bulb A. The temperature of the water (or ice) in A is controlled by a cryostat, which is maintained at any desired temperature down to -25 C within about ± 0.05 C.

For the highest pressure used, a small amount of water is distilled from A into the bottom of C and stopcock 1 is then closed. By maintaining the temperature of the tube outside the 25 C air-bath above 25 C, the water vapor pressure in C is, theoretically, maintained at 23.756 mm of *Hg*, the saturation pressure of water at 25 C. Accurate measurements at this vapor pressure, or at any vapor pressure above about 95 percent of the saturation pressure, cannot be obtained by this method because of condensation on the springs.

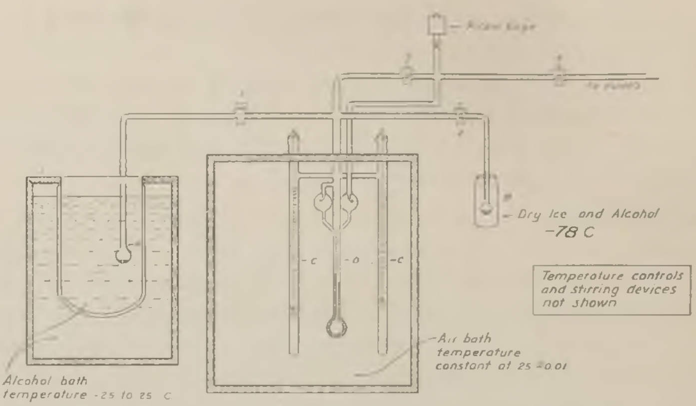

Fig. 2-2—High vacuum sorption apparatus

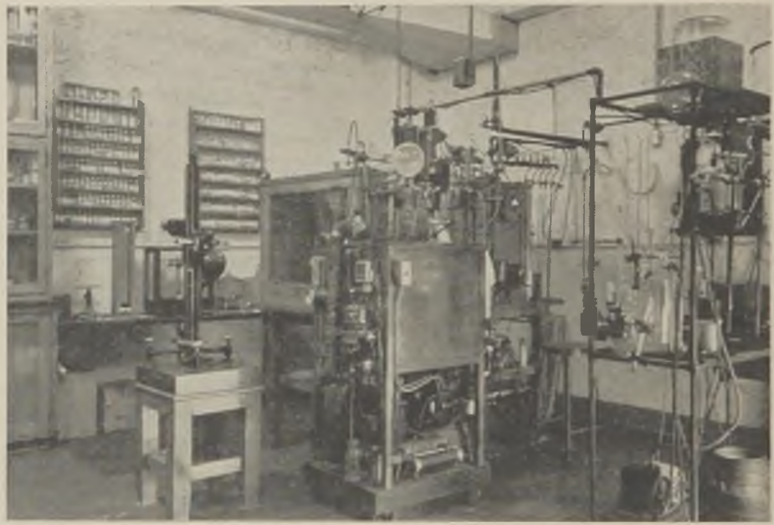

Fig. 2-3—General view of apparatus

Between cocks 3 and 4 a Pirani-type vacuum gage is attached so as to indicate the pressure on the "zero" side of the manometer. This is to make certain that the readings on the manometer are not vitiated by slow leaks on the zero side.

To check against leaks on the other "pressure" side of stopcock 3, the temperature of the bath surrounding A is measured by means of an eight-junction thermocouple and a type-K potentiometer. The vapor pressure of the ice or water in bulb A can then be ascertained from handbook data. Any discrepancies between the pressure shown at D and the pressure indicated by the temperature at A that are greater than the inaccuracy of measurement would be indicative of pressure from gas other than water vapor.

A general view of the apparatus is given in Fig. 2-3. The cabinet in the foreground contains the controlled bath for bulb A. The large cabinet in the middle background is the 25 C air-bath. This cabinet is the same as that used for the air-stream apparatus to be described below. It can be used for both methods simultaneously, although that has not been done as yet.

The cabinet in the foreground is the cryostat. It contains a cylindrical vessel of about 10-gallon capacity filled with alcohol. This is cooled by the refrigeration unit mounted under the cabinet. A one-gallon container is mounted, submerged to its upper rim, in this alcohol bath. The container is a double-walled glass vessel with air between the walls. It contains the alcohol in which bulb A, Fig. 2-2, is immersed. By means of an electrical heater and thermoregulator, the temperature of this one-gallon bath is maintained at whatever level is desired. The thermoregulator is a laboratory-made, toluene-mercury type. It operates through an electronic switch and Mercoid relay.

The air in the large cabinet is kept in rapid circulation by means of two electric fans and two air-driven windshield fans. The cabinet is cooled by continuously circulating cold alcohol through a copper coil inside the cabinet. The circulated alcohol is cooled by means of another coil dipping into the outer alcohol bath of the cryostat described in the foregoing paragraph.* The cabinet is heated by an electric heater (about 200 watts). The input to the electric heater is controlled by a laboratory-made, toluene-mercury thermoregulator that operates through an electronic switch and Mercoid relay. The sensitivity of the regulator is about 0.005 C. The variation in temperature at any given point does not exceed 0.01 C, and the average temperatures at different points do not differ more than 0.02 C.

Air-stream apparatus

The air-stream apparatus is built in and around the large cabinet just described. It was designed to deliver 11 streams of air simultaneously, each stream having a different water content and hence different water vapor pressure. The following description pertaining to one of the air streams is applicable also to the rest.

The air to be conditioned is taken from the compressed air supply of the laboratory. The air pressure is reduced to 3 lb. per sq. in. by means of two diaphragm-type pressure-reduction valves connected in series. The low-pressure air is then delivered to a train of one-gallon bottles such as is illustrated in the lower part of Fig. 2-4. The first bottle

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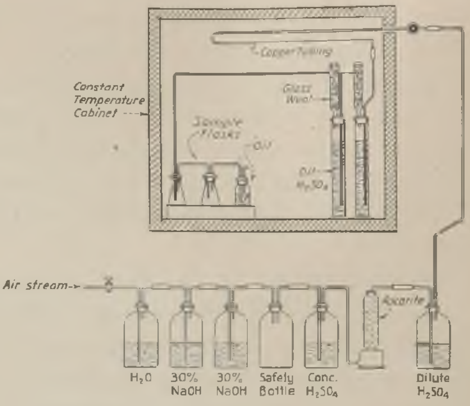
*This arrangement is used at present. For most of the period covered by this paper cold tap water from the building supply was used, but this often failed its purpose during the summer.

Fig. 2-4—Schematic diagram of one of the air conditioning trains for adsorption tests



contains water, and the next two sodium hydroxide solutions. The water bottle at the head of the train prevents the formation of sodium carbonate in the inlet tube of the caustic-soda bottles. Next in line is an empty bottle for safety and this is followed by a bottle of concentrated sulfuric acid (specific gravity 1.84) to dry the air. The dry air is then delivered to a tower of Ascarite to remove any traces of carbon dioxide that might have escaped the caustic-soda solutions. The air stream then passes through a 3-gallon bottle containing dilute sulfuric acid. The output of this bottle is divided into two streams, one of which is shown in Fig. 2-4. The strength of the acid in the large bottle just mentioned is so regulated that it gives the air passing through it a water content somewhat below that desired for either of the two streams taken from the bottle. This slightly-too-dry air then is piped into the constant temperature cabinet where it circulates, first through a length of copper tubing to permit the temperature to reach 25 C and then through two towers of sulfuric acid connected in series as shown in the upper part of Fig. 2-4. The second stream taken from the bottle is led similarly to another pair of acid-towers, regulated to give a different vapor pressure. The strength of the acid in the towers is carefully regulated to have exactly the vapor pressure desired in the outgoing stream of air. To insure equilibrium between the stream of air and the acid the air is dispersed as fine bubbles by means of porous plugs fastened to the ends of the inlet tubes. (These porous plugs were made in the laboratory by sintering granulated glass in a crucible.) To remove entrained droplets of acid, each tower is equipped with a glass-wool filter as shown.

The outgoing stream of air is led through rubber connections to an Erlenmeyer flask containing the sample under test. As the air passes the dry granules, they absorb some of the water vapor. This continues until the vapor pressure of the water in the sample becomes equal to that of the water vapor in the air stream.

Two samples are run simultaneously by connecting sample-flasks in tandem as shown. The outgoing stream of air from the second flask bubbles through a mineral oil contained in a 6-oz. bottle and then escapes to the interior of the cabinet. The mineral-oil trap prevents back-diffusion of moisture and carbon dioxide from the air in the cabinet to the sample.

Eleven such pairs of sample-bottles in the cabinet make it possible to obtain simultaneously 11 points on the adsorption curves for each of two materials.

Because the air delivered to the acid towers inside the cabinet is in each case slightly drier than the output from the towers, the level of the acid in the towers gradually subsides during the continuous flow of the air streams. About once a month it is necessary to replenish the towers by adding distilled water. This is done by means of glass tubes (not shown in sketch) leading from the stoppers in the tops of the acid towers through the top of the cabinet. Similarly, the acid in the large bottles outside (under) the cabinet and the caustic-soda solutions are renewed about once a month.

During the development period, the water content of each air stream was measured by passing a measured volume of the air through weighing tubes filled with P_2O_5. The relative vapor pressure of each stream was then computed from the law for perfect gases. A number of such measurements showed that the water vapor pressure in the air streams differed from that which could be computed from the strength of the acid by less than 0.025 mm of mercury or a difference in p/p_s* of less than 0.001. When this was learned, the air streams were considered always to be at equilibrium with the acids in the towers.

The sample flasks were removed from the cabinet once daily and weighed on a chemical balance, care being taken to minimize the exposure of the granules. A typical record of the results of such weighings is shown in Fig. 2-5. This diagram shows that for those samples exposed to water vapor of relatively low pressure the weights reached a maximum and thereafter declined. At vapor pressures of 0.8 p_s or higher the weight either remained constant after one or two days or else continued to increase steadily, though very slightly, with time, this tendency being more pronounced the higher the vapor pressure. The increase in weight just mentioned is believed to be due to hydration of fresh surfaces of clinker residues exposed on crushing the original sample.

The behavior of the specimens exposed to the drier atmospheres is not understood. The phenomenon was not observed when using the high-vacuum apparatus. From this it may be inferred that the presence of air

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*p = vapor pressure of air steam
p_s = saturation vapor pressure of water

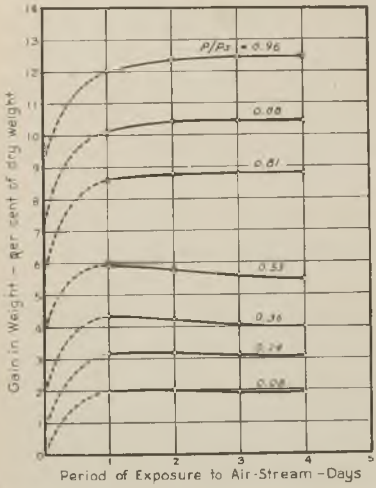


Fig. 2-5—Typical relationship between gain in weight and period of exposure

may have something to do with the result. However, as will be shown later, the major aspects of the results obtained in the presence of air are essentially the same as those obtained in the absence of air.

Inasmuch as the decrease in weight shown by the lower curves in Fig. 2-5 continued for as long as two weeks, it was decided to use maximum rather than final weights. There was some question as to whether the final weight was any more significant than the maximum weight; also, since the decline from the maximum represented but a small percentage of the total gain, it did not seem justifiable to retard the experimental work to the extent necessary to get final weights.

Reproducibility of results

The reproducibility of the data obtained in the manner just described is illustrated in Table 11. These are results from two sets of samples made from the same specimen, each set being tested independently. The corresponding figures are in very good agreement except at the two highest pressures. Such differences were commonly observed and were probably due to different degrees of proximity to equilibrium.

Comparisons such as those that are given in Table 11 were made at other times during the course of these experiments, with similar results. Nevertheless, there is reason to believe that in some groups of tests the variability was considerably greater than would be expected from such data as those presented above. Possibly such variations are due not so much to variations in the adsorption measurements themselves as to variations in auxiliary tests as when the samples contained pulverized silica and therefore required a chemical analysis for the estimation of cement content. The discrepancies that will be noted among the various

TABLE 11—REPRODUCIBILITY OF THE ISOTHERMS

Cement: 16189
Initial w/c: 0.50
Curing: 6 weeks in water

Relative vapor pressure p/p_s	Total water-content of sample indicated, % by weight of cement	
	A	B
0.0 (non-evap. H_2O)	15.47	15.42
0.08	17.98	18.03
0.16	18.87	18.94
0.32	20.10	20.28
0.39	20.82	20.98
0.46	21.44	21.65
0.53	22.02	22.09
0.60	22.82	22.90
0.70	24.82	24.76
0.81	27.52	27.53
0.88	30.43	29.69
0.96	35.31	34.60

data yet to be presented are often such as would result from errors in the determination of the cement content of the sample. The data obtained from samples of neat cement were less erratic.

Use of ordinary desiccators

In some auxiliary work, neither the air-stream nor high-vacuum apparatus was used. Instead, samples were placed in ordinary air-filled desiccators in the presence of a suitable desiccating agent. The samples were weighed from time to time until the results indicated equilibrium to have been reached.

Theoretically, the results obtained in this way should, in most respects, be the same as those obtained by the methods already described. Actually, the results from the samples dried in desiccators did not agree very well with the results obtained by the other two methods. The cause of the discrepancy is not known. It was observed, however, that the rate of absorption in an air-filled desiccator is very much less than that in vacuum or air stream. This suggests the possibility that the exposure of samples was terminated too soon, that is, that they did not approach equilibrium as closely in the air-filled desiccators as they did when tested by either of the other two methods. Another possibility is that, owing to the longer exposure and to the continued presence of air, samples tested in desiccators might have become carbonated sufficiently to influence the final results. At any rate this method is not recommended.

RESULTS OF THE SORPTION MEASUREMENTS—EMPIRICAL ASPECTS OF THE DATA

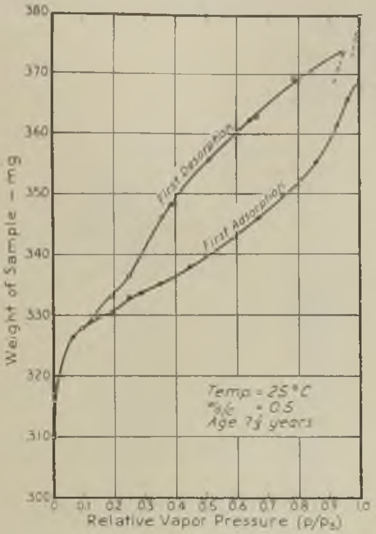
General features

Fig. 2-6 and Tables 12 to 17 record a run made with the high-vacuum apparatus illustrated in Fig. 2-2. In this case the sample was a very thin wafer of hardened neat cement paste described in Table 12, w_o/c = 0.5 by weight. In its initial, saturated state it weighed 380.5 mg, as indicated by the uppermost point in Fig. 2-6. After the sample was installed, the air was pumped out of the apparatus. The initial pumping period was made brief to avoid overdrying the sample. The object was to remove the air from the chamber without removing water from the sample, if possible. To maintain the water vapor pressure as high as possible during the pumping a small amount of water was introduced into the sample chamber before the pumping began. The desired result was not obtained; the pump removed the water vapor so rapidly that nearly half the evaporable water in the sample was removed during only 6 minutes of pumping.

As soon as the initial pumping was finished, the sample was subjected to a vapor pressure of 0.94 p_s. Owing to the losses suffered during the initial pumping, the sample gained in weight at this pressure until it reached equilibrium at a weight of 374.4 mg. Then the pressure was lowered step by step and the rest of the points appearing on the desorption curve were obtained. At the final weight, 309.8 mg, the sample was at equilibrium with the vapor pressure of the ice at -78 C, the temperature of dry ice.

As soon as the evaporable water had been removed, the vacuum pumps were operated for many hours so as to remove as much air from the system as possible. Then the vapor pressure was increased stepwise, thus establishing the adsorption curve shown.

As shown in Fig. 2-6, the adsorption and desorption curves coincided only at pressures below 0.1 p_s. (As a matter of fact, it is not certain that the curves coincided over this range, but it seems probable that they did so.) Studies of other materials(3) show that in the range of pressures where the curves form a loop, innumerable curves within the loop can be produced under suitable experimental conditions. If the process of adsorption or desorption is reversed at any point short of the horizontal extremes of the loop, the part of the curve that had previously been generated will not be retraced but instead the points will cut across the loop. If at any stage of adsorption in this range the process is reversed, the resulting downward curve will cross over from the adsorption to the desorption curve. If the desorption curve is reversed, then a new rising curve will cross over toward the adsorption curve, but instead of joining the adsorption curve the new curve will rise more or less parallel to the adsorption curve, the loop being closed only at the saturation point. Thus, it is possible to obtain points representing thermodynamic equilib-



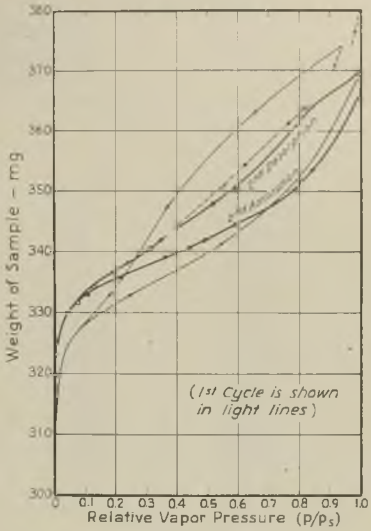
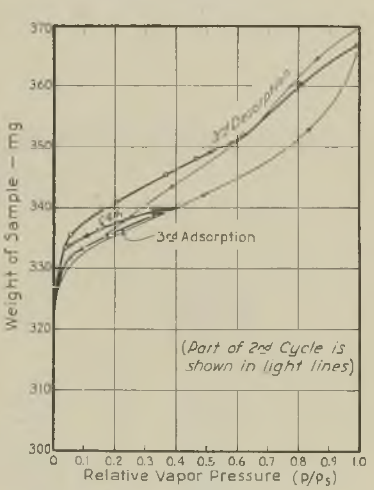


Fig. 2-6A (upper left)—Data from Tables 12 and 13

Fig. 2-6B (upper right)—Data from Tables 14 and 15

Fig. 2-6C (lower right)—Sorption isotherms for cement slab made from cement 13495

High vacuum apparatus. Data from Tables 16 and 17



rium* between the evaporable water in the sample and the ambient water vapor anywhere between the desorption and adsorption curves.

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*Chemists tend to question whether or not these should be called equilibrium points. They feel that, like points representing chemical equilibrium, a given point should be attainable from either side.

However, the requirement that a state of equilibrium must be approachable from either side with the same result does not properly apply to all physical equilibria. See for example the "ink bottle theory" of sorption hysteresis (Brunauer, p. 398). This theory shows that different amounts of water could be in equilibrium with the same vapor pressure. This is not to say that the conditions pictured in developing the ink bottle theory actually exist in hardened paste. It merely refutes the idea that equilibrium between water content and vapor pressure requires that only one water content can be associated with a given vapor pressure.

A paper by W. O. Smith (Sorption in an Ideal Soil, Soil Sci. v. 41, p. 209, (1936)) is especially pertinent. He showed by geometrical analysis that in an assemblage of spheres holding water by capillary condensation, different amounts of water can be in thermodynamic equilibrium with the same vapor pressure. Such equilibrium is reversible in the sense that the same *surface curvature* should be established at a given vapor pressure, regardless of the direction of approach. See Part 3, Capillary Condensation.

TABLE 12—FIRST DESORPTION CURVE FOR SLAB PREPARED FROM CEMENT 13495

High-vacuum apparatus
Age 7 years, 116 days
Original w/c = 0.50 by wt.

p/p_s (p_s = 23.756 mm of *Hg*)	Wt. of sample, mg	Evaporable water in the sample	
		mg	Fraction of dry wt. of sample (= w)
1.000	380.5	70.7	.2485
?	346.8 (a)	37.0	.1194
0.942	374.4	64.6	.2085
0.780	369.3	59.5	.1921
0.663	363.1	53.3	.1720
0.509	355.8	46.0	.1485
0.351	346.1	36.3	.1139
0.250	336.5	26.7	.0862
0.193	333.4	23.6	.0762
0.099	328.0	18.2	.0587
0.000	309.8	00.0	.0000

(a) Weight after 6 minutes of pumping—vapor pressure unknown.

TABLE 13—FIRST ADSORPTION DATA FOR SLAB PREPARED FROM CEMENT 13495

High-vacuum apparatus

p/p_s (p_s = 23.756 mm of *Hg*)	Wt. of sample, mg	Evaporable water in the sample	
		mg	Fraction of dry wt. of sample (= w)
0.000	309.8	00.0	.0000
0.064	326.7	16.9	.0545
0.155	329.8	20.0	.0646
0.193	330.7	20.9	.0675
0.249	332.1	22.3	.0720
0.350	335.1	25.3	.0817
0.446	338.0	28.2	.0910
0.598	343.0	33.2	.1072
0.745	351.0	41.2	.1330
0.855	356.6	46.8	.1511
0.959	366.4	56.6	.1827
0.995	369.6	59.8	.1930
1.000		67.0 (est.)	.2162 (est.)

TABLE 14—SECOND DESORPTION CURVE FOR SLAB PREPARED FROM CEMENT 13495

High-vacuum apparatus

p/p_s ($p_s=23.756$ mm of Hg)	Wt. of sample, mg	Evaporable water in the sample	
		mg	Fraction of dry wt. of sample ($=w$)
0.995	369.6	50.0	.1565
0.848	364.1	44.5	.1392
0.594	350.7	31.1	.0973
0.397	344.0	24.4	.0763
0.82*	364.3	44.7	.1399
0.314	340.5	20.9	.0654
0.194	336.7	17.1	.0535
0.128	334.2	14.6	.0457
0.078	331.7	12.1	.0379
0.004	323.4	3.8	.0119
0.000	319.6	0.0	.0000

*Temperature controls failed and caused unintentional rise in pressure.

TABLE 15—SECOND ADSORPTION CURVE FOR SLAB PREPARED FROM CEMENT 13495

High-vacuum apparatus

p/p_s ($p_s=23.756$ mm of Hg)	Wt. of sample, mg	Evaporable water in the sample	
		mg	Fraction of dry wt. of sample ($=w$)
0.000	319.6	0.0	.0000
0.042	330.4	10.8	.0338
0.112	333.2	13.6	.0426
0.220	335.7	16.1	.0504
0.364	339.0	19.4	.0607
0.450	340.7	21.1	.0660
0.596	344.7	25.1	.0785
0.806	351.4	31.8	.0995
1.00 (?)	366.8	47.2	.1477

TABLE 16—THIRD DESORPTION OF SLAB PREPARED FROM CEMENT 13495

High-vacuum apparatus

p/p_s ($p_s = 23.756$ mm of *Hg*)	Wt. of sample, mg	Evaporable water in the sample	
		mg	Fraction of dry wt. of sample ($=w$)
1.00 (?)	366.8	45.8	.1427
0.807	360.8	39.8	.1240
0.624	352.0	31.0	.0966
0.467	348.0	27.0	.0841
0.370	345.3	24.3	.0757
0.202	340.9	19.9	.0620
0.052	335.3	14.3	.0445
0.043	334.2	13.2	.0411
0.000	321.0	00.0	.0000

TABLE 17—THIRD PARTIAL ADSORPTION AND PARTIAL DESORPTION DATA FROM SLAB PREPARED FROM CEMENT 13495

High-vacuum apparatus

p/p_s ($p_s = 23.756$ mm of *Hg*)	Wt. of sample, mg	Evaporable water in the sample	
		mg	Fraction of dry wt. of sample ($=w$)
0.000	321.0	0.0	.0000
0.052	332.3	11.3	.0352
0.094	333.2	12.2	.0380
0.178	335.4	14.4	.0448
0.321	338.7	17.7	.0552
0.405	340.1	19.1	.0595
0.326	339.2	18.2	.0567
0.146	336.5	15.5	.0483
0.049	333.6	12.6	.0392

The lack of reversibility as described above is shown by materials of various kinds.

Although the phenomenon has not been investigated extensively here, there is little reason to doubt that portland cement pastes all show essentially the behavior described above. This matter of hysteresis is significant and should be kept in mind in connection with the theoretical discussion that follows later in this paper. It is a principal reason for believing that ordinary laws of chemical reaction cannot be applied to the reactions involving the gain or loss of evaporable water.

Besides the effects common to many materials, portland cement paste exhibits certain irreversible phenomena not found among some other types of materials. This is shown in Fig. 2-6B, where the second desorption-and-adsorption curves of the sample are given.

A break in the second desorption curve at $p = 0.395\ p_s$ will be noted. After equilibrium at this pressure had been established, the cryostat was set to produce a lower pressure, but during the night the temperature controls failed, the pressure rose to $p = 0.82\ p_s$ and the sample-weight increased, giving the point indicated by the cross. (This point probably does not represent an equilibrium value, but is close to it.) When proper operation of the cryostat was restored, the point at $p = 0.315\ p_s$ was obtained.

The light-line curves in Fig. 2-6B are those of Fig. 2-6A, shown for comparison. The marked difference between the first and second cycles is believed to be due to two factors: One is the irreversible shrinkage (described in Part 1) that reduces the capacity of the sample for evaporable water. The other is the additional hydration of the cement in the sample that occurs while the sample is subjected to vapor pressures above about $0.8\ p_s$. Although these samples had been stored in water for several years they seem to have contained unhydrated clinker that was exposed when the thin wafers were prepared.

No explanation for one feature of the irreversibility has been found. Note that on the first desorption the minimum weight reached was 309.8 mg. On the second desorption the minimum weight was 319.6 mg. Continued hydration has the effect of increasing the minimum weight, but the increase shown here is much too great to be accounted for in this way. It is possible that the observed minimum weight for the first desorption was in error by several milligrams. However, the original data offer no clue as to the nature or cause of the error, if there was one.

Fig. 2-6C shows the third desorption and a partial third adsorption curve. The third *de*sorption curve differs from both the first and second desorption curves, but the third *ad*sorption is practically the same as the second adsorption. In fact, when the results are expressed as percentage of the minimum weight, the second and third adsorption curves are identical. Tests on other samples show that after the first cycle of drying and wetting the adsorption curves are reproducible. But the indications of a limited amount of data are that the desorption curves are greatly influenced by small variations in experimental conditions and are difficult to reproduce exactly.

On the third desorption, Fig. 2-6C, after the weight corresponding to $0.4\ p_s$ had been established, the pressure was intentionally lowered stepwise with the result indicated by the graph. This illustrates what was said above about the irreversibility of this process in the range of pressures where the curves form a loop. Note that the points cut across the loop and join the desorption curve. This behavior is similar in character to that obtained with other materials(3). It should be noted, however, that the vapor pressure at which the loop closes is much lower than that observed with other materials. Moreover, the loop closes at a much lower pressure than would be predicted from Cohan's hypothesis(4).

The size and shape of the hysteresis loop, and the course of the curve when the process is reversed within the limits of the loop, are probably characteristic of the physical structure of the hardened paste(4,5). At any rate the whole phenomenon cannot be understood until these loops can be adequately interpreted. However, practically all the measurements reported in this paper were of adsorption only. Therefore, the interpretation of the adsorption curve is the only part of the problem that can be considered here.

Along with the measurements described above, measurements were made on the sample described in Table 18. This sample was prepared from a neat-cement cylinder that had been molded under high pressure with w/c only 0.12 by weight.

The results are given in Tables 18 to 23 and in Fig. 2-7, all three cycles being shown on the same graph. The features pointed out in Fig. 2-6 can be seen here also, and others besides. Note that the effect of the reversal in pressure that occurred during the second desorption was somewhat different from that on the other specimen. Note also that the lower parts of the second and third desorption cycles are identical. The indication is that with a specimen as dense as this, the paste becomes "stabilized" after the first drying so that desorption as well as adsorption curves are reproducible, provided that the specimen is always saturated at the start. The differences among the desorption curves in the upper range are believed to be due to slight differences in the degree of saturation at the beginning of the desorption part of the cycle.

Comparison of the results obtained with high-vacuum and air-stream apparatus

Fig. 2-8 and Tables 24 and 25 give adsorption data for two granulated pastes, the data being obtained first with the air-stream apparatus and then, about three years later, with the high-vacuum apparatus. The granules had been sealed in glass ampoules during the three-year interval. The later tests were made on samples from the same lot of granules as the earlier ones, but not on the same samples as used in the first test. Thus, the curves obtained by each method were first-adsorption curves.

The granules had originally been dried by the regular procedure used in connection with the air-stream method, that is, over Dehydrite in a

TABLE 18—FIRST DESORPTION CURVE ON SLAB PREPARED FROM CEMENT 14675

High-vacuum apparatus
Age 4 years 29 days
Original w/c = 0.12 by weight
Molded under 24,000 lb/in² pressure

p/p_s (= x) (p_s = 23.756 mm of Hg)	Wt. of sample, mg	Evaporable water in sample		
		mg	Fraction of dry wt. of paste (= w)	
1.000	664.4	47.8	0.0775	Initial wt. sat'd
?	647.9	31.3	0.0508	Wt. after 6 min. pumping
1.000	742.8	126.2	0.2046	Droplets condensed on sample
0.942	656.4	39.8	0.0645	
0.780	653.3	36.7	0.0595	
0.663	652.0	35.4	0.0574	
0.509	649.7	33.1	0.0537	
0.351	647.4	30.8	0.0500	
0.250	643.4	26.8	0.0435	
0.193	641.5	24.9	0.0404	
0.099	638.1	21.5	0.0349	
0.000	616.6	00.0	0.0000	

TABLE 19—FIRST ADSORPTION CURVE ON SLAB PREPARED FROM CEMENT 14675

High-vacuum apparatus

p/p_s (= x) (p_s = 23.756 mm of Hg)	Wt. of sample, mg	Evaporable water in sample	
		mg	Fraction of dry wt. of paste (= w)
0.000	616.6	00.0	0.0000
0.064	627.6	11.0	0.0178
0.155	629.9	13.3	0.0216
0.193	630.2	13.6	0.0221
0.249	631.5	14.9	0.0242
0.350	632.7	16.1	0.0261
0.446	634.0	17.4	0.0282
0.598	638.7	22.1	0.0358
0.745	642.5	25.9	0.0420
0.855	645.8	29.2	0.0474
0.959	653.8	37.2	0.0603
1.000	664.4*	47.8	0.0775

*Original weight.

TABLE 20—SECOND DESORPTION CURVE ON SLAB PREPARED FROM CEMENT 14675

High-vacuum apparatus

p/p_s $(= x)$ $(p_s = 23.756$ mm of $Hg)$	Wt. of sample, mg	Evaporable water in sample	
		mg	Fraction of dry wt. of paste $(= w)$
1.000 (a)	685.1	68.5	0.1111
0.957	656.4	39.8	0.0645
0.848	653.8	37.2	0.0603
0.594	648.7	32.1	0.0521
0.397	646.4	29.8	0.0483
0.82 (b)	650.7	34.1	0.0553
0.314	642.2	25.6	0.0415
0.194	639.4	22.8	0.0370
0.128	637.6	21.0	0.0341
0.078	635.8	19.2	0.0311
0.004	622.0	5.4	0.0088
0.000	616.6	0.0	0.0000

(a) Water visible on sample.
(b) Temperature controls failed and caused pressure to rise.

TABLE 21—SECOND ADSORPTION CURVE FOR SLAB PREPARED FROM CEMENT 14675

High-vacuum apparatus

p/p_s $(= x)$ $(p_s = 23.756$ mm of $Hg)$	Wt. of sample, mg	Evaporable water in sample	
		mg	Fraction of dry wt. of paste $(= w)$
0.000	616.6	0	0
0.042	626.1	9.5	0.0154
0.112	629.4	12.8	0.0208
0.220	631.0	14.4	0.0234
0.364	633.0	16.4	0.0266
0.450	634.5	17.9	0.0290
0.596	638.7	22.1	0.0358
0.806	644.3	27.7	0.0449
1.000	662 (est)	45.4 (est)	0.0736 (est)

TABLE 22—THIRD DESORPTION CURVE FOR SLAB PREPARED FROM CEMENT 14675

High-vacuum apparatus

p/p_s (= x) (p_s = 23.756 mm of *Hg*)	Wt. of sample, mg	Evaporable water in sample	
		mg	Fraction of dry wt. of paste (= w)
0.807	655.3	38.7	0.0628
0.624	647.9	31.3	0.0508
0.467	645.1	28.5	0.0462
0.370	643.3	26.7	0.0433
0.202	639.2	22.6	0.0367
0.052	634.8	18.2	0.0295
0.043	632.5	15.9	0.0258
0.000	616.6	00.0	0.0000

TABLE 23—THIRD PARTIAL ADSORPTION AND PARTIAL DESORPTION CURVES FOR SLAB PREPARED FROM CEMENT 14675

High-vacuum method

p/p_s (= x) (p_s = 23.756 mm of *Hg*)	Wt. of sample, mg	Evaporable water in sample	
		mg	Fraction of dry wt. of paste (= w)
0.00	616.6	0	0
0.052	627.6	11.0	0.0178
0.094	628.9	12.3	0.0199
0.178	631.1	14.5	0.0235
0.321	633.3	16.7	0.0271
0.405	634.2	17.6	0.0285
0.326	633.8	17.2	0.0279
0.146	631.6	15.0	0.0243
0.049	628.7	12.1	0.0196

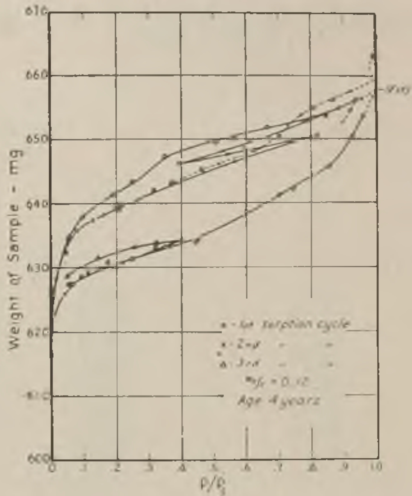


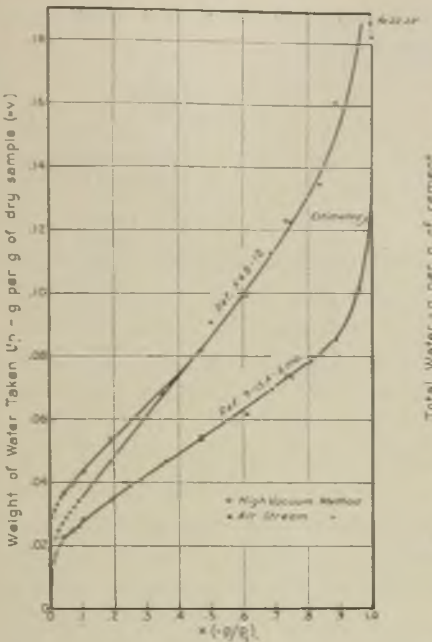
Fig. 2-7—Sorption isotherms for neat cement slab made from cement 14675
Data from Tables 18 to 23

vacuum desiccator. In the high-vacuum procedure these granules were exposed to the vapor pressure generated by ice at the temperature of dry ice, the lowest pressure used. After the final exposure to this low pressure in the high-vacuum apparatus, the samples were ignited. The final weights compared with those obtained after the earlier tests are given below:

	Sample No.	
	9-15A-6M	K4B-1Q
Loss on ignition as dried originally (g/g)................	0.1428	0.1927
Loss on ignition as dried in high-vacuum apparatus (g/g)....	0.1506	0.1922

Note that the water content of K4B-1Q was the same (within the limits of probable error) under both drying conditions and that therefore the sample as received from the sealed ampoule was not changed by the exposure to the lowest vapor pressure used in the high-vacuum apparatus. As mentioned in connection with Table 5, above, this provides data for estimating the vapor pressure of the desiccant used in earlier tests. The vapor pressure over ice at dry ice temperature (-78 C) is given as 0.56 microns of mercury.(5) The pressure relative to the saturation pressure at 25 C is therefore about 24 x 10^{-6}.

The data for the other sample, 9-15A-6M, indicate that the two drying conditions were not exactly alike, the amount of water removed in the original drying being somewhat greater than that removed in the



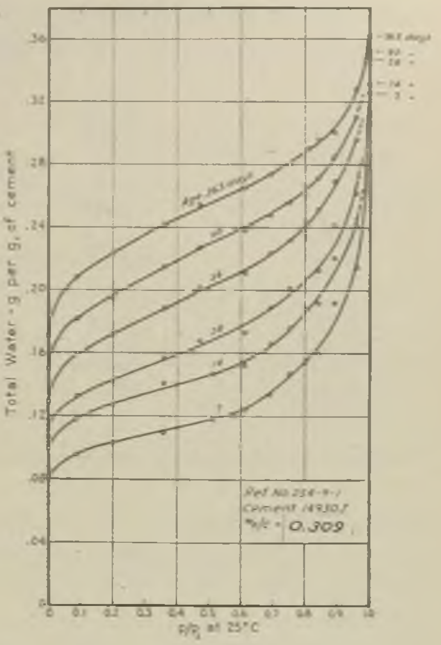


Fig. 2-8 (left)—Adsorption isotherms (25 C) for granular samples

Data from tables 24 and 25, Part 2, and from Tables A-8 and A-27 of Appendix to Part 2

Fig. 2-9 (right)—Adsorption isotherms showing effect of curing (air-stream apparatus)

TABLE 24—FIRST ADSORPTION CURVE FOR GRANULAR SAMPLE 9-15A-6M

High-vacuum method

p/p_s (= x)	Wt. of sample, mg	Evaporable water in the sample	
		mg	Fraction of dry wt. of sample (= w)
0.00	431.3	0.0	.0000
0.055	441.1	9.8	.0227
0.073	442.0	10.7	.0249
0.104	443.6	12.3	.0284
0.193	446.3	15.0	.0347
0.244	448.5	17.2	.0400
0.349	450.9	19.6	.0455
0.472	454.7	23.4	.0542
0.738	463.1	31.8	.0738
1.000			.1250*

*Observed value 0.1569, but known to be too high because of condensation in sample and spring. 0.1250 is based on the estimated water content of the sample in the saturated state.

TABLE 25—ADSORPTION CURVE FOR GRANULAR SAMPLE K4B-1Q

High-vacuum method

p/p_s $(= x)$	Wt. of sample, mg	Evaporable water in the sample	
		mg	Fraction of dry wt. of sample $(= w)$
0.00	542.2	0.0	.0000
0.055	562.2	20.0	.0369
0.073	563.7	21.5	.0395
0.104	566.3	24.1	.0442
0.193	571.4	29.2	.0540
0.244	574.0	31.8	.0587
0.349	579.4	37.2	.0686
0.472	586.6	44.4	.0819
0.738	608.9	66.7	.1230
1.000			.2295*

*Original water content after drying and resaturating.

high-vacuum apparatus. This would indicate that the vapor pressure over the magnesium perchlorate hydrate is somewhat less than that over ice at -78 C. However, there is some reason to believe, as pointed out before, that the drying agent in the original tests was sometimes inadvertently $Mg(ClO_4)_2 + Mg(ClO_4)_2.2H_2O$ instead of $Mg(ClO_4)_2.2H_2O + Mg(ClO_4)_2.4H_2O$. This could be one of those instances.

In regard to the course of the curves over the lower range of vapor pressures, we will show later that theoretically the presence of air should reduce the amount of adsorption in the manner shown by the plotted data for K4B-1Q. That is, the two series of points for this sample differ only as they theoretically should. It will be seen later that in other important respects the two series of points have the same significance and that the two methods give essentially the same result.

The two series of points for sample 9-15A-6M fall practically on the same line. Theoretically, the crosses should drop below the circles in the low-pressure range. The fact that they do not can be accounted for by the data given above showing that the sample used in the original tests (air-stream method) was dried to a lower water content than the sample used in the later tests (high-vacuum method). It will be seen later that the drier the sample the higher the "knee" of the adsorption curve. It therefore seems that by chance alone the effect of the difference in initial water content exactly offset the effect of the presence of air.

These data indicate that adsorption in the presence of air is essentially the same as that in the absence of air when the small effect of the air itself is taken into account. This is important, for it shows that the interpretations worked out by other investigators for adsorption from a pure gas phase can be applied with modifications to the adsorption of water vapor from a mixture of air and water vapor.

It should be noted that practically all the data given in this paper were obtained by the air-stream method. *Unless otherwise stated, it is correct to assume that all adsorption data were obtained by the air-stream method.*

Effect of extent of hydration on the position of the adsorption curve

Fig. 2-9 gives a group of adsorption curves for a given kind of paste at different stages of hydration. The paste was obtained from mortar prisms that had been cured continuously in water for periods ranging from 7 days to one year. The results shown are typical except that they represent a Type IV, rather than a Type I, cement. Since the plots of water contents are expressed in terms of the weight of the original cement in the sample, the ordinates at $p/p_s = 0$ give the amounts of non-evaporable water and those at $p/p_s = 1$* give the total water contents at saturation. The curves illustrate the following general conclusions that are applicable to all samples tested, regardless of original water-cement ratio, age, or type of cement.

(1) The total water held at saturation ($p/p_s = 1$) increases as the length of the curing period increases.

(2) The non-evaporable water content also increases.

(3) The amount of water held at any intermediate vapor pressure increases with the length of the curing period.

(4) The evaporable water content, which is the difference between the total and the non-evaporable water, *de*creases as the length of the curing period increases.

The changes that take place during the period of curing are illustrated in another way in Fig. 2-10. This, like Fig. 2-9, represents a group of samples that were similar except for the extent of hydration at the time of test; they were prepared from mortar cubes all made from the same mix. Here the bottom curve represents the non-evaporable water and the top the total water content. The intermediate curves represent the water content after the originally dry samples had reached equilibrium with the relative vapor pressures indicated on the curves.

Note that all curves originate at (0,0) except the upper one. This one begins at a point representing the original water-cement ratio (corrected for bleeding). That is, zero age represents the time before any hydration takes place. At that time all the water in the sample will

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*The topmost point has been plotted at $p/p_s = 1$ despite the fact that consideration of the effect of dissolved alkalies shows that it should be plotted at a lower p/p_s. This point is discussed further in connection with the effect of dissolved alkalies in Part 3.

have a relative vapor pressure of 1.0* and not any of it would be held if exposed to an atmosphere having any lesser water vapor pressure. At any time after hydration begins, only a part of the water can be lost in an atmosphere having an appreciable vapor pressure.

The rise of the top curve is due to absorption of water by the specimen from the curing tank. The points represent dried-and-resaturated granules and therefore are probably slightly below the level representing the capacity of the paste before drying, as explained before.

The rise of the bottom curve indicates the progress of hydration and, as will be shown later, is proportional to the increase in volume of the solid phase of the paste. The heights of the next three curves above the bottom curve ($p/p_s = 0.09; 0.19;$ and 0.36) are believed to depend on the total surface area of the solid phase and hence to depend primarily on the quantity of gel present. It will be shown later that the positions of these lower curves are independent of the total porosity of the sample. Although this particular plotting does not make it apparent, it is a fact that the position of the points representing pressures greater than about $0.475\ p_s$ depend on the total porosity of the sample as well as on the extent of hydration. The basis for these interpretations and the uses made of the information are subjects treated in later parts of this paper.

Fig. 2-11 gives some of the same data that appear in Fig. 2-9 in terms of a unit weight of dry paste rather than weight of original cement as before. It therefore shows the evaporable water only. Note that as the length of the period of wet curing increases, the total evaporable water decreases and the amount held at low vapor pressures increases. Since the total evaporable water may be taken as a measure of the total porosity of the hardened paste, this graph shows that the amount of water held at vapor pressures near the saturation pressure depends on the porosity of the sample. On the other hand, the amounts of water held at low pressures appear here to vary inversely with the porosity. However, it will be proved that the amount held at low pressure does not depend on porosity.

Influence of original water-cement ratio (w_o/c) on the shape of the adsorption curve

Fig. 2-12 to 2-15 present adsorption curves for samples having different water-cement ratios but the same degree of hydration as measured by the non-evaporable water content. The points for these curves were obtained by interpolations on plots such as that shown in Fig. 2-10. The four figures represent three different cements, two different degrees of hydration, and three (in one case, four) different water-cement ratios. Considered together, they show that differences in age and original water-cement ratio have no influence on the shape of the lower part of the ad-

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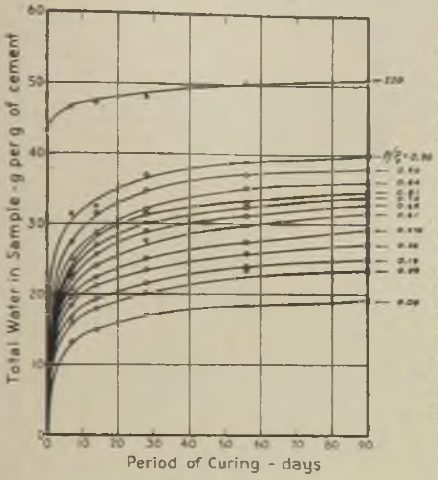
*Again neglecting the effect of dissolved alkalies.



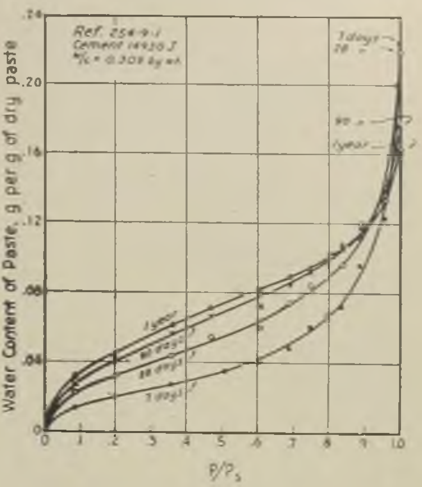
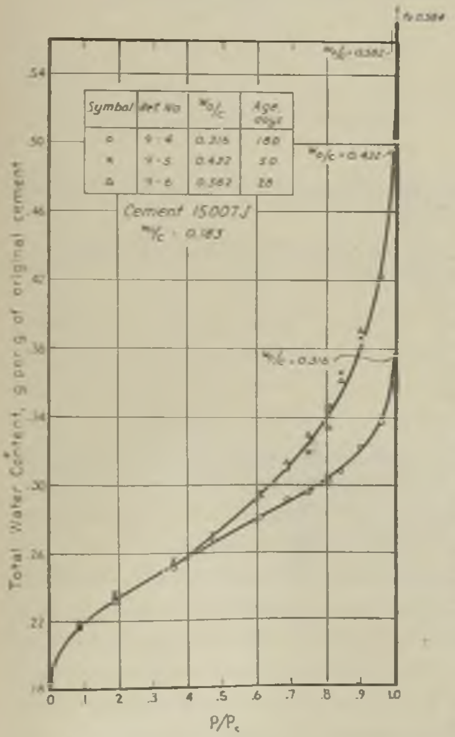


Fig. 2-10 (left)—Changes in amounts of water held at any given vapor pressure as influenced by the length of the curing period

Cement 15007J-Ref. 9-5 w_o/c = 0.433

Fig. 2-11 (right)—Adsorption isotherms showing evaporable water only



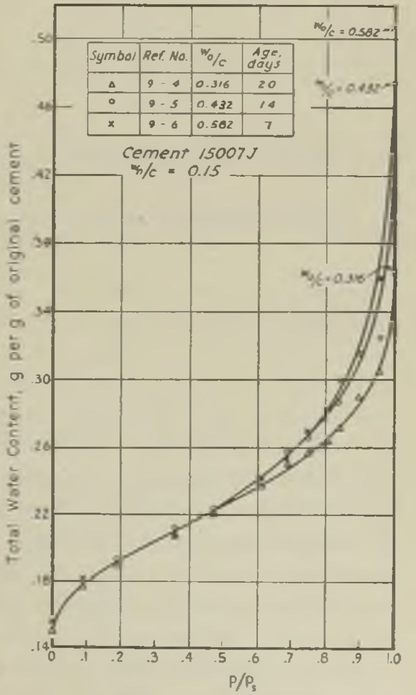
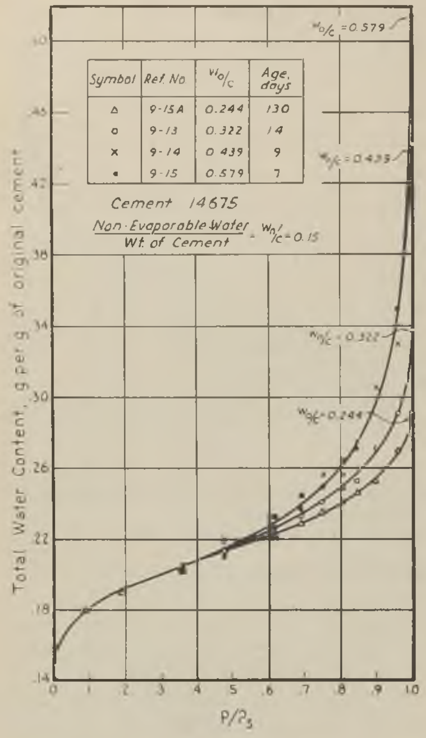


Fig. 2-12 (left)—Adsorption isotherms for samples of different w_o/c but equal non-evaporable water

Fig. 2-13 (right)—Adsorption isotherms for samples of different w_o/c but equal non-evaporable water



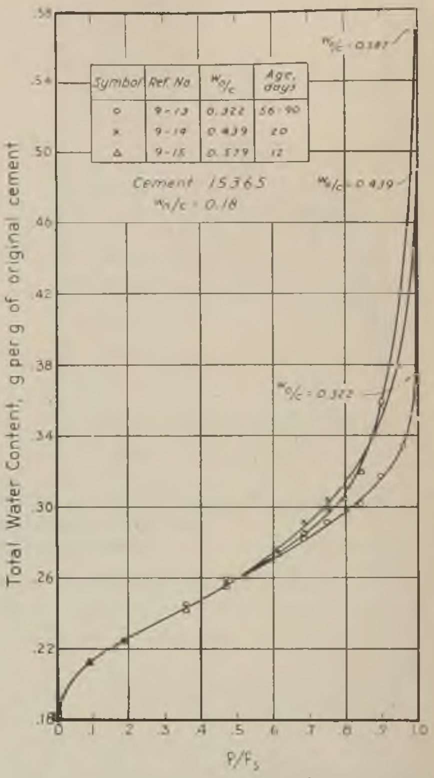
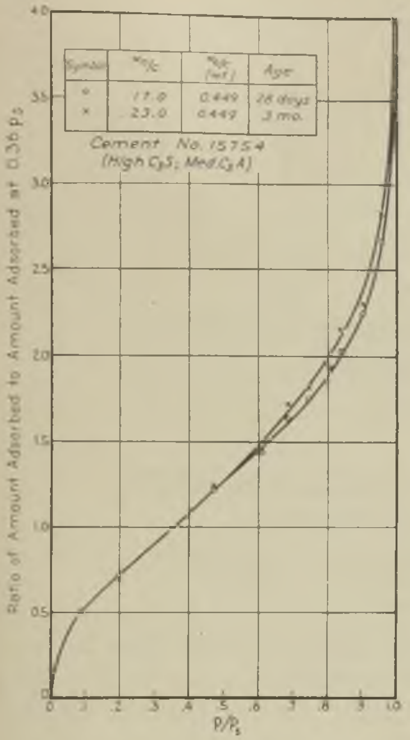


Fig. 2-14 (left)—Adsorption isotherms for samples of different w_o/c but equal non-evaporable water

Fig. 2-15 (right)—Adsorption isotherms for samples of different w_o/c but equal non-evaporable water

sorption curves apart from the effect on the level of the starting point: at a given degree of hydration the same curve holds for all ages and water ratios. In other words, the amount of water taken up in the lower third of the range of vapor pressures depends only on the extent of hydration and hence only on the increase in quantity of hydration-product in the sample. On the other hand, the total amount of evaporable water depends upon the porosity of the solid phase which *at a given degree of hydration* depends upon the original water-cement ratio.

The data just considered show that the lower third of the adsorption curve has the same shape for different ages and different porosities of samples made from the same cement. Fig. 2-16 and 2-17 are presented to show that the lower third of the curves have the same shape not only for these conditions but also for different cement compositions. These plots are like those of Fig. 2-12 to 2-15 except that the scale of ordinates is the ratio of the amount of water taken up at a given pressure to the



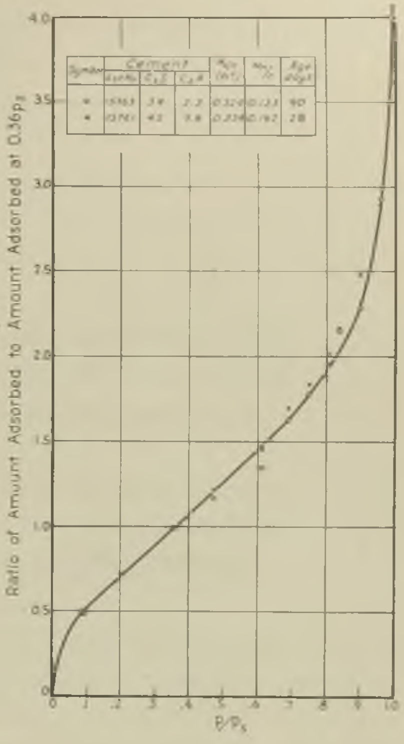


Fig. 2-16 (left)—Adsorption isotherms for which the amount adsorbed is expressed as a ratio to the amount adsorbed at $p/p_s = 0.36$

Different degrees of hydration

Fig. 2-17 (right)—Adsorption isotherms for which the amount adsorbed is expressed as a ratio to the amount adsorbed at $p/p_s = 0.36$

Different cements and different degrees of hydration

amount taken up at a pressure of 0.36 p_s. The coincidence in the lower range of pressures proves that the lower part of the curves can be represented by the same form of mathematical expression.

Empirical relationship between the amount of adsorption at low pressures and the non-evaporable water content

Fig. 2-18 shows typical relationships between the amount of water held at low vapor pressure and the non-evaporable water content for samples prepared from two different cements. Symbols of different shape for the same cement designate different original water-cement ratios, and different points of the same shape represent a mix of given water ratio at different stages of hydration.

Although these data were among the first obtained in this investigation and as a consequence show the influence of imperfect laboratory technique, they illustrate adequately the fact that with any given cement

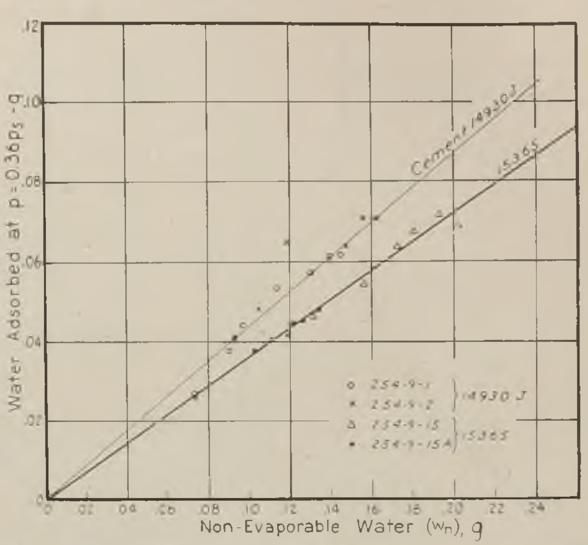


Fig. 2-18—Relationship between amount of water held at low pressure and the non-evaporable water content for two different cements

the adsorption at low vapor pressure (any pressure below about 0.4 p_s) is directly proportional to the extent of hydration as measured by the non-evaporable water content. A study of this relationship will be presented in another part of this paper.

General results from various cements

The results of some of the adsorption tests and measurements of non-evaporable water are shown in graphical form for various cements* in Fig. 2-19 to 2-23. In Fig. 2-19, for example, the total evaporable water is represented by the height of the column above the horizontal reference line and the non-evaporable water by the length of the column extending downward. The proportions of evaporable water held between various relative vapor pressures are shown by the relative lengths of the blocks making up the column. As will be shown later, the length of the first block above the zero line (up to line 0.35) is approximately proportional to the surface area of the cement gel. By assuming that the surface area is proportional to the amount of cement gel, the length of this block may also be taken to indicate the relative amount of cement gel in the sample.

The effect of differences in water-cement ratio for specimens of the same age is shown in Fig. 2-19 and 2-20. The effect of prolonging the period of curing for specimens of the same initial water-cement ratio can best be seen by reference to Fig. 2-21, 2-22, and 2-23. In reading these diagrams it is helpful to remember that at zero age there would be

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*For characteristics of the cements, see Appendix to Part 2.

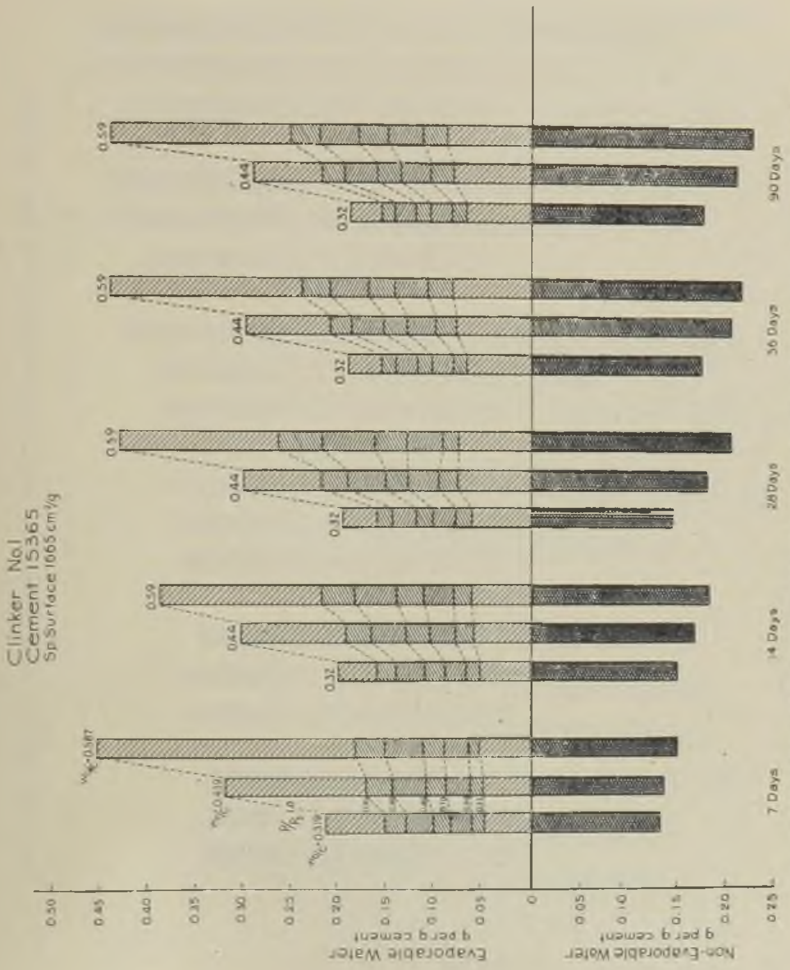

Fig. 2-19—Effect of water-cement ratio on the hardened paste at the ages indicated

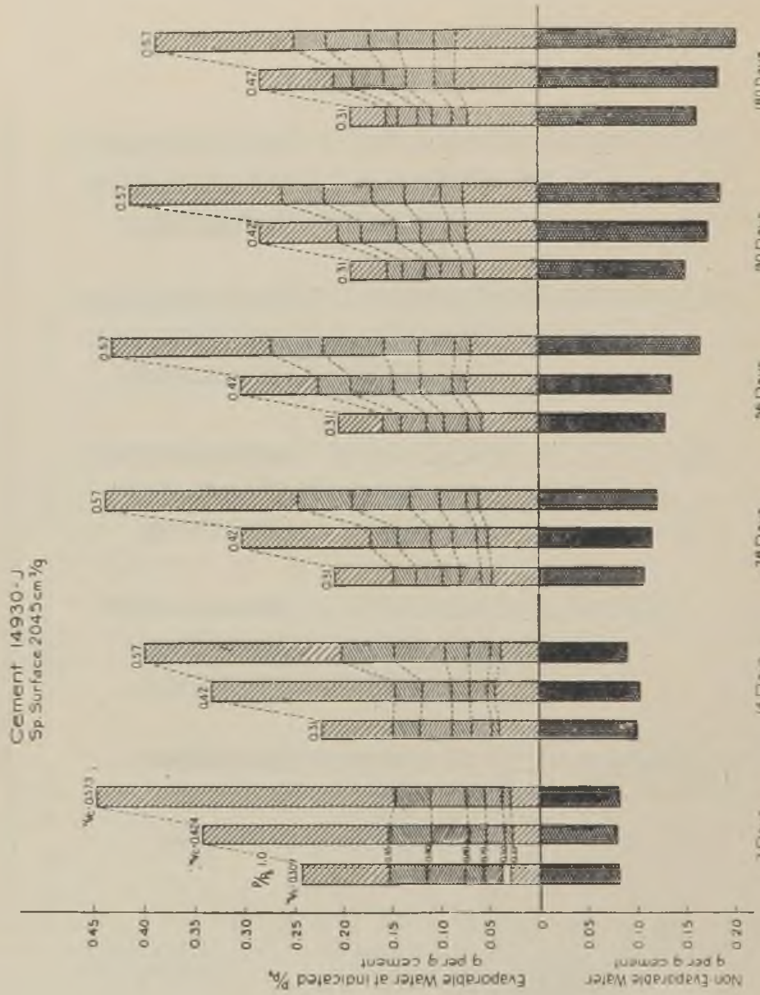

Fig. 2-20—Effect of water-cement ratio on the hardened paste at the ages indicated

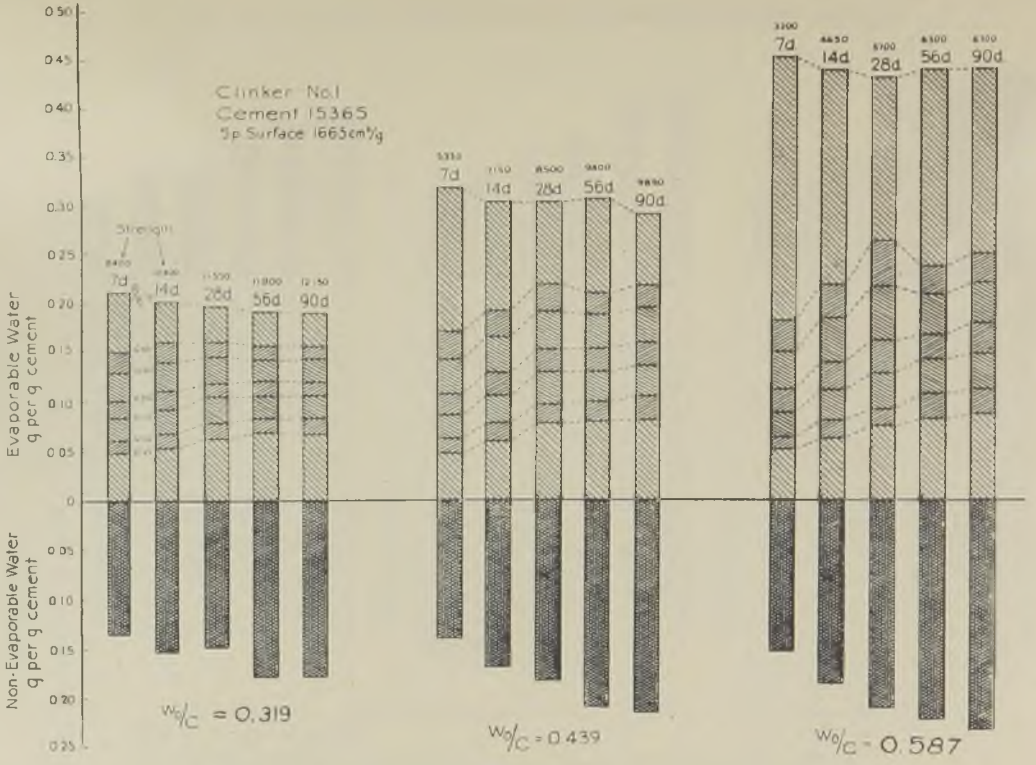

Fig. 2-21—Effect of age on hardened paste at the water-cement ratios indicated

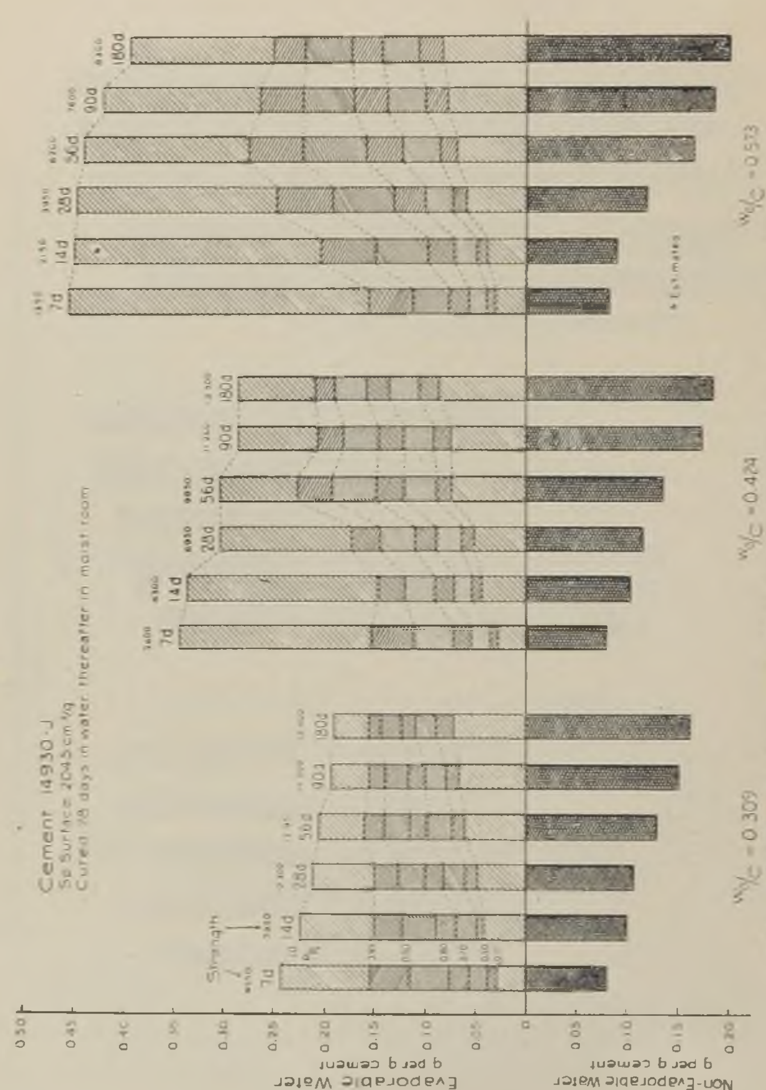

Fig. 2-22—Effect of age on hardened paste at the water-cement ratios indicated

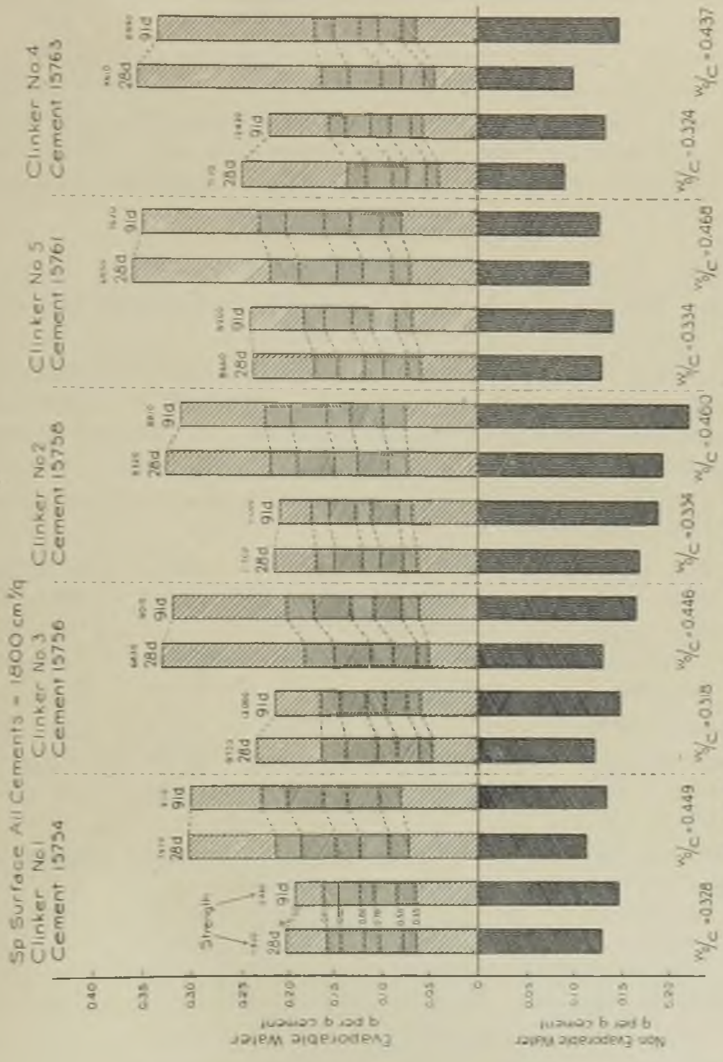

Fig. 2-23—Effect of age on hardened pastes of five different cements

no non-evaporable water and hence no column extending downward and the column for evaporable water would have a height equal to the original water-cement ratio, corrected for bleeding. Therefore, the difference between the height of the evaporable water column and the original water ratio indicates the degree of reduction in porosity brought about by the curing.

Some of the irregularities shown in these diagrams are believed to be due to imperfections in experimental technique. It seems probable that a given group of diagrams representing regular changes in w_o/c or in age should show a regular pattern of change. In most of the interpretations built up in later parts of this paper, these irregularities are ignored.

EFFECT OF STEAM CURING

One test only of steam-cured material was made. The result was so significant, however, that it will be given here. The procedure was as follows: a paste of normal consistency was made, composed of 1 part cement 15756, 0.71 part pulverized silica (Lot 15918), and 0.43 part water, by weight. This was made into two prisms 1x1x11¼ in. The prisms were cured over night in the molds and then were steamed at 420 F in an autoclave for about 6 hours, after which they were immersed in water over night. The bars were then crushed and a 48-80 mesh sample taken for adsorption tests.

Two-inch cubes were made from the same cement-silica mixture, but with slightly higher water-cement ratio—0.50 instead of 0.43. These were cured continuously under water for 28 days. They were then crushed, granular samples were taken, and adsorption characteristics were determined in the usual way.

The results of these tests are given in Table 26 and Fig. 2-24. They show that curing at high temperature radically alters the adsorption characteristics. Note particularly that about 90 percent of all the evaporable water was taken up at pressures above 0.8 p_s. The significance of this will be discussed more fully in the succeeding parts of the paper.

SUMMARY OF PART 2

The water in saturated hardened cement paste is classified as evaporable and non-evaporable. This classification is based on the amount of water retained by a specimen dried in a vacuum desiccator at 23 C over the system $Mg(ClO_4)_2.2H_2O + Mg(ClO_4)_2.4H_2O$. The pores in a hardened paste are defined as those spaces occupied by evaporable water.

This part of the paper deals with measurements of non-evaporable water and the adsorption isotherms of the evaporable water in various samples of hardened cement paste.

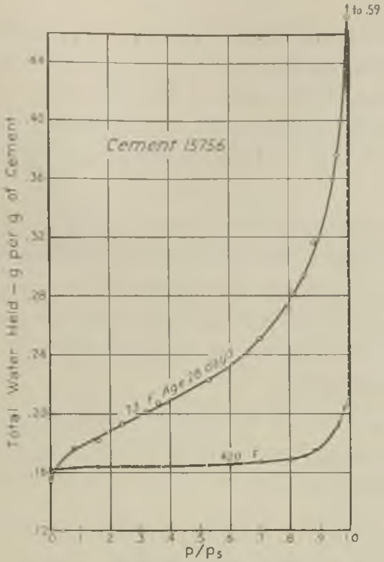

Fig. 2-24—Effect of steam curing on adsorption characteristics

TABLE 26—EFFECT OF STEAM CURING

Cement 15756

Relative vapor pressure	73 F for 28d w_o/c = .478	Autoclaved at 420 F w_o/c = .43
(w_n)*	(.1537)	(.1615)
0.08	.0220	.0015
0.16	.0329	.0017
0.24	.0390	.0028
0.32	.0478	.0025
0.36	.0530	.0026
0.53	.0689	.0038
0.70	.0969	.0052
0.81	.1283	.0081
0.85	.1408	.0090
0.88	.1623	.0131
0.96	.2230	.0300
1.00	.4367	.3009

*w_n = non-evaporable water.

A general description of materials and experimental apparatus and procedures is given, with reference to the Appendix to Part 2 for more complete information. Data are presented on the stability of the hydrates of the constituents of portland cement, in the presence of different desiccating agents. Indications are that of the microcrystalline hydrates that might occur in hardened cement paste, only the calcium sulfoaluminate would be decomposed to an appreciable extent by the desiccant used in these studies.

The experiments were for the most part made on granular samples prepared from the original cylinders or cubes. Data are presented indicating that the granular samples were representative of the original pastes, except for pastes of comparatively high porosity.

The empirical aspects of the experimental results are described and discussed. Adsorption and desorption curves from the same sample present a so-called hysteresis loop similar to those found for other materials. In addition, the curves show some features of irreversibility not commonly found among other materials. Most of the study pertains to adsorption isotherms only.

Adsorption of water vapor from humidified streams of air (air-stream apparatus) was found to be the same as adsorption from water vapor alone (high-vacuum apparatus), except at pressures below about 0.3 p_s, where the adsorption in the absence of air was expected to be greater than that in the presence of air. The curves obtained by the two methods are believed to have the same significance.

Graphs are presented from which the following conclusions are drawn:

(1) The total water held at saturation ($p/p_s = 1.0$) increases as the length of the curing period increases.

(2) The non-evaporable water content also increases.

(3) The amount of water held at any intermediate vapor pressure increases with the length of the curing period.

(4) The evaporable water content, which is the difference between the total and the non-evaporable water, decreases as the length of the curing period increases.

Curves are presented showing that differences in age and original water-cement ratio have no influence on the shape of the lower part of the adsorption curves. On the other hand, the position of the upper part of the curve and the total amount of evaporable water in a saturated specimen depend on both age and original water-cement ratio. These conclusions apply to all cements.

For a given cement the amount of *evaporable* water held at any pressure up to about 0.4 p_s is directly proportional to the *non*-evaporable water content. The proportionality constant is different for cements of different type.

An adsorption curve for cement paste cured for six hours in the autoclave at 420 F is compared with the curve obtained from a similar paste cured at 73 F for 28 days. Results show that curing at high temperature and pressure produces adsorption characteristics radically different from those observed in specimens cured in the ordinary way.

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2. F. M. Lea, *Cement & Cement Mfgr.* v. 5, p. 395 (1932).
3. K. S. Rao, "Hysteresis in Sorption," *J. Phys. Chem.* v. 45 (3) pp. 500-531 (1941).
4. L. H. Cohan, *J. Am. Chem. Soc.* v. 66, p. 98 (1944).
5. N. A. Lange, *Handbook of Chemistry*, 4th Edition, p. 1269.

Appendix to Part 2

CONTENTS

DESCRIPTIONS OF MATERIALS AND TABULATIONS OF ORIGINAL DATA

Information is given in this appendix concerning the materials used in each series and concerning the preparation of test specimens and samples. This information supplements that given in the text.

Also given are tabulations of the original data. The authors regard such a full presentation desirable because of the uniqueness of the data and because of the speculative nature of the interpretation offered in the text. That is, alternative interpretations may occur to other investigators in this field and we consider that they should have access to the original material.

Characteristics of cements

The cements used in any given series can be readily identified in Table A-1. Their chemical and physical properties are tabulated in order of lot numbers in Tables A-2 and A-3.

Description of specimens made in series 254-265

Mortar Specimens: Truncated cones: Base 4 in.; top 1½ in.; altitude 6 in.

Cement: Lot 14502 (see Tables A-2 and A-3 for characteristics).

Aggregate: A mixture of Elgin sand and Ottawa silica graded as follows:

Weight, per cent of size indicated					
Ottawa Silica		Elgin Sand			
200–100	100–48	48–28	28–14	14–8	8–4
2.4	4.9	23.6	29.9	16.3	22.9

TABLE A-1—SERIES INDEX TO CEMENTS

Series	Cement Nos.					
254-265	14502					
254-MRB	14898-39AQ 14904-45AQ 14910-52AQ	14899-40PC 14905-46PC 14911-51PC	14900-41SC 14906-47SC 14912-53SC	14901-42AQ 14907-48AQ 14913-54AQ	14902-43PC 14908-49PC 14914-55PC	14903-44SC 14909-50SC 14915-56SC
254-K4B	13721-1S 13733-5S 13740-7P 13765-15Q 13780-20Q	13722-1P 13734-5P 13741-7Q 13766-16S	13723-1Q 13735-5Q 13752-11P 13767-16P	13730-4S 13736-6S 13753-11Q 13768-16Q	13731-4P 13737-6P 13763-15S 13778-20S	13732-4Q 13738-6Q 13764-15P 13779-20P
254-7	14675					
254-8	14930J 15014J	15007J	15008J	15011J	15012J	15013J
254-9	14930J	15007J	15011J	15013J	15365	
254-11	15495 15761	15497 15763	15669 16198	15754 16213	15756 16214	15758
254-13	15367 15923* 15930*	15498 15924* 15932*	15623 15925* 15933*	15670 15926* 15934*	15699 15927* 15935*	15921* 15929*
254-16	15754 16189	15756	15758	15761	15763	16186
254-18	13495	14675	15365	13723-1Q		

*All cements marked * were ground in the laboratory. The rest were ground in commercial plants.

Mixes: Specimens represented the following mortar mixes, by weight: 1:0 (neat); 1:1½; 1:1, 1:2, 1:3, 1:5, 1:7.

Mixing: Each batch was mixed 30 sec. dry and 2 min. wet in a small power-driven, open-tub mixer.

Molding: Cones were cast in watertight molds of known capacity, the mortar being puddled with a light tamper.

Measurements: The weight of the filled calibrated mold was measured to 1 g immediately after filling, and again after 20-24 hr. in the fog-room. On stripping, the specimens were weighed in air and in water.

Curing: In molds in the fog-room for the first 20-24 hr.; in the fog-room thereafter. Temperature: 70 F.

Drying: The granular samples were dried in air-filled desiccators over concentrated sulfuric acid.

Composition of specimens: See Table A-4.

Analysis of granular samples: See Table A-5.

Adsorption data: See Table A-6.

TABLE A-2—CHEMICAL ANALYSES AND COMPUTED COMPOUND COMPOSITION

All computations are based on the weight of the cement unless otherwise indicated. The computed compositions are based on the oxide analyses corrected for free lime but not for other minor constituents.

Lot No.	Ref. No.	Major Constituents									Minor Constituents								Computed Compound Composition				
		SiO_2	Al_2O_3	Fe_2O_3	Total CaO	MgO	SO_3	Loss on Ign.	In-sol. Res.	Free CaO	FeO	TiO_2	P_2O_5	Mn_2O_3	Na_2O	K_2O	$CHCl_3$ Soluble	CO_2	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$
13495		20.79	6.02	3.11	63.57	3.16	1.65	1.00	0.14	1.11					0.22	0.52			51	21	11	10	2.8
13721†	1S	21.08	6.10	2.15	64.10	2.91	1.80	0.79	0.24	0.36	0.0				0.10	0.97			50.0	22.7	12.5	6.6	3.06
13722†	1P	20.93	6.18	2.17	63.48	2.94	1.80	0.87	0.23	1.18	0.0	0.31			0.10	1.58			44.8	26.3	12.7	6.6	3.06
13723†	1Q	21.13	5.85	2.17	64.18	2.99	1.80	0.79	0.18	1.49	0.30				0.10	1.11			47.0	25.2	11.8	6.6	3.06
13730†	4S	19.02	4.80	6.85	62.12	4.12	1.80	0.90	0.11	0.29	0.0				0.41	0.10			59.9	9.3	1.2	20.8	3.06
13731†	4P	19.13	4.92	6.70	61.63	4.09	1.80	0.97	0.37	3.80	1.46	0.37			0.53	0.20			42.3	23.0	1.7	20.4	3.06
13732†	4Q	18.79	5.08	7.17	61.72	4.21	1.80	0.78	0.20	1.55	1.27				0.37	0.12			52.6	14.2	1.3	21.8	3.06
13733†	5S	23.16	3.33	4.15	64.47	1.52	1.80	1.20	0.14	0.04	0.0				0.27	0.14			52.8	26.7	1.8	12.6	3.06
13734†	5P	22.61	3.31	4.31	63.23	1.52	1.80	2.40	0.13	0.32	0.0	0.16			0.35	0.46			49.5	27.6	1.5	13.1	3.06
13735†	5Q	22.97	3.27	4.40	63.53	1.50	1.80	1.81	0.10	0.41	0.0				0.37	0.42			49.0	29.0	1.2	13.4	3.06
13736†	6S	21.06	5.85	2.97	65.77	1.38	1.80	0.92	0.20	0.00	0.0				0.07	tr.			59.0	15.8	10.5	9.0	3.06
13737†	6P	20.97	5.99	3.03	65.50	1.39	1.80	0.84	0.17	0.35	0.0	0.26			0.10	0.11			56.0	17.8	10.7	9.2	3.06
13738†	6Q	20.99	5.90	3.03	65.57	1.43	1.80	0.83	0.22	0.45	0.03				0.08	0.08			56.4	17.6	10.5	9.2	3.06
13740†	7P	20.46	6.96	2.31	63.23	3.31	1.80	0.80	0.22	0.40	0.03	0.33			0.42	0.58			45.0	24.7	14.5	7.0	3.06
13741†	7Q	20.48	6.89	2.28	63.55	3.36	1.80	0.82	0.20	0.53	0.36				0.32	0.38			46.0	24.0	14.4	7.0	3.06
13752†	11P	21.18	4.70	4.89	65.10	0.78	1.80	0.94	0.19	0.15	0.0	0.34			0.66	0.16			59.6	15.7	4.2	14.9	3.06
13753†	11Q	21.57	4.26	4.48	65.61	0.79	1.80	0.86	0.16	0.33	0.33				0.51	0.08			61.5	15.4	3.7	13.6	3.06
13763†	15S	21.23	5.58	2.90	62.90	4.07	1.80	0.72*	**	0.11	0.0				0.23	0.41			47.4	25.2	9.9	8.8	3.06
13764†	15P	21.21	5.57	2.89	62.59	4.06	1.80	0.85	0.14	1.28	0.0	0.28			0.28	0.86			41.7	29.4	9.9	8.8	3.06
13765†	15Q	21.23	5.58	2.89	62.92	4.06	1.80	0.76*	**	1.39	0.32				0.20	0.40			42.4	28.9	9.9	8.8	3.06
13766†	16S	21.55	6.10	2.49	64.00	3.16	1.80	0.81*	**	0.00	0.0				0.15	0.15			47.0	26.5	12.0	7.6	3.06
13767†	16P	21.51	6.10	2.49	63.83	3.15	1.80	0.93	0.23	0.39	0.35	0.32			0.20	0.38			45.0	27.8	12.0	7.6	3.06
13768†	16Q	21.53	6.10	2.49	63.95	3.16	1.80	0.81*	**	0.30	0.57				0.15	0.25			45.7	27.3	12.0	7.6	3.06
13778†	20S	19.37	7.35	3.77	65.31	0.98	1.80	0.68*	**	0.32	0.0				0.15	0.42			57.5	12.2	13.1	11.5	3.06
13779†	20P	19.35	7.34	3.77	65.08	0.97	1.80	0.91	0.15	1.24	0.0	0.45			0.18	0.76			53.0	15.5	13.1	11.5	3.06
13780†	20Q	19.34	7.34	3.77	65.28	0.98	1.80	0.73*	**	1.38	0.02				0.15	0.45			53.3	15.3	13.1	11.5	3.06

(Continued on next page)

TABLE A-2—(CONTINUED)

Lot No.	Ref. No.	Major Constituents						Loss on Ign.	In-sol. Res.	Free CaO	Minor Constituents								Computed Compound Composition				
		SiO_2	Al_2O_3	Fe_2O_3	Total CaO	MgO	SO_3				FeO	TiO_2	P_2O_5	Mn_2O_3	Na_2O	K_2O	$CHCl_3$ Soluble	CO_2	C_3S	C_2S	C_3A	C_4AF	$CaSO_4$
14502		21.02	6.07	2.75	63.49	2.94	1.76	1.00	0.14	0.96					0.29	0.60			45	26	11	8	3.0
14560		20.78	5.03	3.98	64.99	1.35	2.27	0.99	—	0.39					0.22	0.31			60	17	7	13	4.04
14675		20.76	6.07	2.55	63.83	3.02	1.71	0.95	0.11	1.19					0.26	0.56			48.1	23.2	11.8	7.8	2.90
14898‡	39AQ	20.72	6.45	3.25	63.89	2.6	0.58	0.99	—	0.67									49.4	22.2	11.6	9.9	0.98
14899‡	40PC	20.80	6.52	3.12	63.69	2.5	0.65	0.91	—	1.16									47.5	23.8	12.0	9.5	1.11
14900‡	41SC	20.78	6.64	3.18	64.19	2.5	0.52	0.87	—	0.09									49.2	22.5	12.2	9.7	0.88
14901‡	42AQ	20.68	6.82	3.16	63.78	2.7	0.58	1.04	—	0.67									46.8	24.0	12.7	9.6	0.98
14902‡	43PC	20.72	6.92	3.18	63.63	2.4	0.61	0.92	—	0.97									45.2	25.4	12.9	9.7	1.03
14903‡	44SC	20.78	6.86	3.12	63.78	2.4	0.60	0.99	—	0.13									45.2	25.6	12.9	9.5	1.02
14904‡	45AQ	20.70	6.73	3.35	64.03	2.4	0.52	0.81	—	0.58									48.4	22.9	12.2	10.2	0.88
14905‡	46PC	20.48	6.82	3.12	63.88	2.6	0.57	1.02	—	0.81									48.8	22.0	12.8	9.5	0.96
14906‡	47SC	20.40	6.98	3.14	63.98	2.7	0.36	0.76	—	0.05									49.4	21.3	13.2	9.6	0.60
14907‡	48AQ	20.70	6.95	3.31	63.07	2.7	0.59	0.87	—	0.04									42.7	27.2	12.8	10.0	1.00
14908‡	49PC	20.94	6.79	3.39	63.12	2.7	0.61	1.02	—	0.24									42.0	28.4	12.2	10.3	1.03
14909‡	50SC	21.16	6.72	3.38	63.14	2.7	0.52	0.75	—	0.07									41.3	29.6	12.1	10.3	0.88
14910‡	52AQ	20.92	6.87	3.47	63.30	2.7	0.52	0.18	—	0.10									42.5	28.0	12.3	10.6	0.88
14911‡	51PC	20.88	7.23	3.51	63.09	2.7	0.48	0.23	—	0.04									39.6	30.1	13.2	10.7	0.82
14912‡	53SC	21.04	7.09	3.41	63.40	2.6	0.48	0.30	—	0.06									40.8	29.6	13.0	10.4	0.82
14913‡	54AQ	21.18	7.13	3.39	62.89	2.6	0.75	0.28	—	0.96									36.6	33.2	13.1	10.3	1.28
14914‡	55PC	21.08	7.09	3.49	62.84	—	0.76	0.37	—	0.63									37.3	32.4	12.9	10.6	1.29
14915‡	56SC	21.06	6.59	3.37	62.43	2.5	0.78	0.35	—	0.46									39.3	30.8	11.7	10.2	1.32
14930J		25.42	4.36	3.21	62.46	1.65	1.55	0.81	0.09	tr.					0.22	0.41		0.24	22.7	55.8	6.1	9.8	2.64
15007J		22.78	4.77	3.46	64.92	1.32	1.30	0.84	0.07	0.62					a	a		0.49	48.0	29.1	6.8	10.5	2.22
15008J		22.69	4.87	4.10	64.51	1.27	1.26	0.78	0.09	0.08					0.23	0.51	0.029d		47.7	29.1	6.0	12.5	2.14
15011J		23.09	4.73	3.45	64.62	1.19	1.43	0.67	0.12	0.40					b	b	0.014	0.66	45.1	29.1	6.7	10.5	2.43
15012J		23.65	4.39	3.25	64.53	1.09	1.34	0.77	0.15	0.37					0.22	0.49	0.054		43.0	35.4	6.1	9.9	2.28
15013J		20.98	6.85	2.43	62.75	3.52	1.71	0.74	0.07	0.64					c	c	***		39.0	29.0	14.0	7.0	3.00
15014J		21.18	6.42	2.40	62.96	3.61	1.61	0.70	0.08	0.59					0.32	0.49	0.041		41.7	29.3	13.0	7.3	2.73
15365		20.78	6.42	2.20	63.86	2.48	2.48	0.96	0.19	0.93	0.60	0.28	0.03	0.51	0.17	0.16	0.039	0.32	45.0	28.0	13.3	6.7	4.22
15367K		21.87	6.83	2.23	65.30	2.63	0.41	0.15	0.33	0.98	"	"	"	"	"	"	"	"	45.5	28.4	14.3	6.7	0.70
15495		20.04	5.52	2.50	66.42	1.28	1.82	1.71	0.26	3.14	0.03	0.26	0.08	0.06	0.30	0.40	0.005	0.16	59.4	13.0	10.4	7.6	3.10
15497		19.98	5.55	2.59	66.55	1.33	1.82	1.52	0.15	3.14	"	"	"	"	"	"	"	"	60.1	11.9	10.3	7.9	3.10
15498K		20.92	5.82	2.53	67.71	1.36	0.10	0.85	0.25	2.71	"	"	"	"	"	"	"	"	62.5	13.0	11.2	7.7	0.32

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15623K		23.30	4.58	4.35	65.01	1.44	0.03	1.05	0.25	0.73	nil	0.30	0.14	0.09	0.05	0.17	0.002	0.22	47.6	30.9	4.8	13.2	0.06
15669		27.57	2.09	1.92	63.88	1.72	1.82	0.73	0.06	0.15	nil	0.11	0.03	0.09	0.05	0.22	0.009	0.26	33.0	54.2	2.3	5.8	3.10
15670K		27.95	2.07	1.87	65.61	1.83	0.17	0.26	0.13	0.23	"	"	"	"	"	"	"	"	37.4	51.9	2.4	5.7	0.27
15699K		22.72	5.38	2.48	64.06	3.43	0.20	0.37	0.16	nil	nil	0.25	0.13	0.09	1.13	0.44	0.006	0.16	47.9	29.0	10.1	7.6	0.34
15754		20.85	6.44	2.20	63.96	2.50	2.36	0.92	0.19	0.93	0.60	0.28	0.03	0.51	0.17	0.16	0.039	0.32	45.0	27.7	13.4	6.7	4.0
15756		22.50	4.39	4.14	64.31	1.46	1.73	1.28	0.13	0.49	nil	0.30	0.14	0.09	0.05	0.17	0.002	0.22	48.6	27.9	4.7	12.6	2.9
15758		19.98	5.50	2.55	66.57	1.25	1.84	1.55	0.17	3.14	0.03	0.26	0.08	0.06	0.30	0.40	0.005	0.16	60.6	11.6	10.2	7.7	3.2
15761		22.00	5.25	2.47	62.98	3.42	1.82	0.53	0.07	nil	nil	0.25	0.13	0.09	1.13	0.44	0.006	0.16	44.9	29.2	9.8	7.5	3.1
15763		27.52	2.09	1.96	63.93	1.70	1.88	0.75	0.07	0.15	nil	0.11	0.03	0.09	0.05	0.22	0.009	0.26	33.5	53.6	2.3	6.0	3.2
15921§		21.87	6.83	2.23	65.30	2.63	0.41	0.15	0.33	0.98	0.60	0.28	0.03	0.51	0.17	0.16	0.039	0.32	45.5	28.4	14.3	6.7	0.7
15922§		21.43	6.69	2.19	63.99	2.58	2.36	0.15	0.32	0.96	"	"	"	"	"	"	"	"	44.6	27.8	14.0	6.6	4.0
15923§		20.81	6.50	2.12	62.15	2.50	5.00	0.14	0.31	0.93	"	"	"	"	"	"	"	"	43.3	27.0	13.6	6.4	8.5
15924§		20.92	5.82	2.53	67.71	1.36	0.19	0.85	0.25	2.71	0.03	0.26	0.08	0.06	0.30	0.40	0.005	0.16	62.5	13.0	11.2	7.7	0.3
15925§		20.57	5.72	2.49	66.57	1.34	1.85	0.84	0.25	2.66	"	"	"	"	"	"	"	"	61.4	12.8	11.0	7.6	3.1
15926§		19.86	5.53	2.40	64.28	1.29	5.00	0.81	0.24	2.57	"	"	"	"	"	"	"	"	59.3	12.3	10.6	7.3	8.5
15927§		23.30	4.58	4.35	65.01	1.44	0.03	1.05	0.25	0.73	nil	0.30	0.14	0.09	0.05	0.17	0.002	0.22	49.2	28.5	4.4	12.8	2.7
15929§		22.08	4.34	4.12	61.61	1.36	5.00	1.00	0.24	0.69	"	"	"	"	"	"	"	"	46.6	27.0	4.2	12.1	8.5
15930§		27.95	2.07	1.87	65.61	1.83	0.17	0.26	0.13	0.23	nil	0.11	0.03	0.09	0.05	0.22	0.009	0.26	37.4	51.9	2.4	5.7	0.3
15932§		26.53	1.96	1.78	62.28	1.74	5.00	0.25	0.12	0.22	"	"	"	"	"	"	"	"	35.5	49.3	2.3	5.4	8.5
15933§		22.72	5.38	2.48	64.06	3.43	0.20	0.37	0.16	nil	nil	0.25	0.13	0.09	1.13	0.44	0.006	0.16	47.9	29.0	10.1	7.6	0.3
15934§		22.35	5.29	2.44	63.01	3.37	1.81	0.36	0.16	nil	"	"	"	"	"	"	"	"	47.1	28.5	9.9	7.5	3.1
15935§		21.57	5.11	2.35	60.82	3.26	5.00	0.35	0.15	nil	"	"	"	"	"	"	"	"	45.5	27.5	9.6	7.2	8.5
16186		21.13	6.42	2.20	63.89	2.49	2.45	0.95	0.19	0.93	0.60	0.28	0.03	0.51	0.17	0.16	0.039	0.32	45.0	27.9	13.3	6.7	4.1
16189		22.50	4.38	4.16	64.31	1.46	1.72	1.28	0.13	0.49	nil	0.30	0.14	0.09	0.05	0.17	0.002	0.22	48.7	27.9	4.7	12.6	2.9
16198		27.54	2.09	1.95	63.91	1.71	1.86	0.74	0.07	0.15	nil	0.11	0.03	0.09	0.05	0.22	0.009	0.26	33.4	53.9	2.3	5.9	3.2
16213		20.88	6.48	2.21	63.99	2.52	2.27	0.91	0.25	0.93	0.60	0.28	0.03	0.51	0.17	0.16	0.039	0.32	44.8	27.1	13.4	6.8	3.9
16214		20.81	6.43	2.20	63.90	2.49	2.42	0.94	0.21	0.93	"	"	"	"	"	"	"	"	44.9	27.7	13.3	6.7	4.1

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† Minor constituents on clinker basis.

‡ These analyses were made in the plants furnishing the clinker, except for SO_3 and free CaO which were determined in this laboratory. The values are based on clinker weights instead of cement weights.

§ Ground in laboratory.

K Clinker

* The loss on ignition for the clinker was not determined. The values shown here represent the loss on ignition from the gypsum and that from the clinker.

** Not determined.

*** 0.008% tallow, 0.005% Vinsol resin.

a Alkali analyses made on 15008J.

b " " " " 15012J.

c " " " " 15014J.

d Tallow.

TABLE A-3—DENSITY, SPECIFIC VOLUME,

Lot No.	Density and Specific Volume, as Computed from Displacement in				Specific Surface cm^2/g A.S.T.M.
	Kerosene		Water		
	Density g/cm^3	Sp. Vol. cm^3/g	Density g/cm^3	Sp. Vol. cm^3/g	
13495	3.161	0.316			1868
13721	3.130	0.320			1645
13722	3.110	0.322			1745
13723	3.109	0.322			1535
13730					1735
13731					1800
13732					1705
13733					1790
13734					1715
13735					1665
13736	3.163	0.316			1685
13737	3.152	0.317			1815
13738	3.139	0.319			1715
13740					1655
13741					1655
13752					1740
13753					1610
13763	3.165	0.316			1780
13764	3.143	0.318			1630
13765	3.104	0.322			1800
13766					1845
13767					1735
13768					1745
13778	3.145	0.318			1705
13779	3.135	0.319			1730
13780	3.128	0.320			1695
14502	3.145	0.318			1820*
14560	3.154	0.317	3.184	0.314	1085
14560	3.150	0.318	3.170	0.316	1540
14560	3.155	0.317	3.192	0.314	2045
14560	3.156	0.317	3.206	0.312	2550
14675	3.143	0.318			1865
14898	3.140	0.318			1620
14899					1610
14900					1620
14901	3.150	0.318	3.197	0.313	1640
14902					1590
14903	3.167	0.316	3.225	0.310	1630
14904					1580
14905					1610
14906					1620
14907					1660
14908					1630

a. All those cements marked a were ground in the laboratory. The rest were ground in commercial plants.

b. This includes +325 material.

c. Densities of these cements were not determined. The values given are for cements of similar fineness made from the same clinker, but no allowance was made for differences in gypsum content.

* 1560 cm^2/g by the permeability method.

AND SPECIFIC SURFACE OF CEMENTS

Lot No.	Density and Specific Volume, as Computed from Displacement in Kerosene: Density g/cm³	Kerosene: Sp. Vol. cm³/g	Water: Density g/cm³	Water: Sp. Vol. cm³/g	Specific Surface, cm²/g: A.S.T.M.	Specific Surface, cm²/g: Permeability Method
14909					1630	
14910	3.165	0.316	3.207	0.312	1610	
14911					1620	
14912	3.181	0.314	3.228	0.310	1640	
14913					1640	
14914	3.144	0.318			1610	
14915					1650	
14930J	3.218	0.311	3.290	0.304	2045	
15007J	3.189	0.314	3.260	0.307	2015	
15008J	3.201	0.312	3.239	0.309	1825	
15011J	3.204	0.312	3.263	0.306	1835	
15012J	3.191	0.314			1740	
15013J	3.162	0.316	3.247	0.308	1810	
15014J	3.174	0.315			2010	
15365	3.135	0.319	3.187	0.314	1640	3120
15495	3.101	0.322	3.136	0.319	1440	2780
15497	3.109	0.322	3.178	0.315	2500	5150
15669	3.215	0.311	3.257	0.307	2290	3810
15754	3.135	0.319	3.174	0.315	1800	3420
15756	3.174	0.315	3.209	0.312	1800	3060
15758	3.107	0.322	3.158	0.317	1800	3570
15761	3.155	0.317	3.210	0.312	1800	2950
15763	3.215	0.311	3.252	0.308	1800	2760
15921 a	3.135 c	0.319	3.190 c	0.314	1820	2870
15922 a	“	“	“	“	1890	3350
15923 a	“	“	“	“	2070	4850
15924 a	3.107 c	0.322	3.16 c	0.316	1815	2930
15925 a	“	“	“	“	1870	3360
15926 a	“	“	“	“	2020	4580
15927 a	3.176 c	0.315	3.22 c	0.310	1800	2860
15929 a	“	“	“	“	2080	4770
15930 a	3.215 c	0.311	3.25 c	0.308	1795	2630
15932 a	“	“	“	“	2050	4280
15933 a	3.155 c	0.317	3.21 c	0.312	1820	2960
15934 a	“	“	“	“	1855	3480
15935 a	“	“	“	“	2080	4480
16186	3.135	0.319	3.188	0.314	1702 b	3200
16189	3.174	0.315	3.214	0.312	1849 b	3200
16198	3.215	0.311	3.254	0.308	2014 b	3200
16213	3.135	0.319	3.179	0.315	1263	2430
16214	3.135	0.319	3.184	0.314	1528	2920

TABLE A-4—UNIT ABSOLUTE VOLUME COMPOSITION OF THE MORTARS USED IN SERIES 254-265

Ref. No.	Unit Absolute Volume Composition				Water-Cement Ratio		
	Cement	Sand	Water	Air	Volume Basis	Wt. Basis	Gal/Sk.
323	0.5601	—	0.4169	0.0192	0.744	0.236	2.66
506	0.4046	0.2438	0.3331	0.0189	0.823	0.262	2.95
509	0.3195	0.3850	0.2826	0.0129	0.884	0.268	3.17
512	0.2221	0.5353	0.2264	0.0162	1.019	0.323	3.65
515	0.1666	0.6022	0.2075	0.0237	1.245	0.395	4.46
518	0.1062	0.6399	0.2250	0.0289	2.118	0.670	7.59
521	0.0787	0.6638	0.2216	0.0359	2.816	0.893	10.09

TABLE A-5—ANALYSES OF GRANULAR SAMPLES USED FOR ADSORPTION AND NON-EVAPORABLE WATER MEASUREMENTS IN SERIES 254-265

Ref. No.	Cement Cont. Sol. SiO_2 Meth. % dry weight	Cement Cont. SO_3 Meth. % dry weight	Ignition Loss, % dry weight	CO_2(1) Loss % dry weight	Non-Evap. Water(2) % dry weight	Non-Evap. Water, % cement content		Sand Content (by difference)	
						Sol. SiO_2	SO_3 Meth.	Sol. SiO_2	SO_3 Meth.
323	85.6(3)	—	14.42	0.67	13.7	16	—	0.7	—
506	66	70	17.50	4.99	12.5	19	18	21.0	17.8
509	57	62	19.01	7.58	11.4	20	18	23.1	26.3
512	47	52	20.45	9.91	10.5	22	20	42.4	37.0
515	41	47	22.63	11.86	10.8	26	23	48.0	42.5
518	39	42	21.92	12.40	9.5	24	23	51.8	48.6
521	34	36	21.26	13.22	8.0	23	22	57.7	55.5

(1) CO_2 comes chiefly from calcareous sand (Elgin).
(2) Non-evaporable water obtained by correcting loss on ignition for CO_2-loss.
(3) Ignited weight taken as cement content since this is a neat paste.

TABLE A-6—ADSORPTION DATA FOR SERIES 254-265

Age: 110 days

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g dry weight						
	Ref. 323	Ref. 506	Ref. 509	Ref. 512	Ref. 515	Ref. 518	Ref. 521
w_n	.137	.125	.114	.105	.108	.095	.080
0.11	.1474	.1384	.1237	.1121	.1141	.1008	.0836
0.20	.1552	.1448	.1310	.1183	.1199	.1060	.0884
0.36	.1649	.1544	.1396	.1254	.1274	.1128	.0945
0.50	.1752	.1626	.1472	.1331	.1353	.1206	.1009
0.61	.1811	.1683	.1526	.1382	.1400	.1264	.1052
0.75	.1947	.1800	.1634	.1491	.1532	.1443	.1224
0.80	.1962	.1826	.1649	.1510	.1558	.1453	.1252
0.826	.2013	.1862	.1703	.1569	.1636	.1560	.1327
0.888	.2085	.1941	.1776	.1629	.1731	.1651	.1431
0.93	.2201	.2022	.1868	.1730	.1850	.1865	.1592
0.98	.2225	.2053	.1887	.1767	.1888	.1991	.1718
SSD	.250	.220	.210	.197	.227	.267	.259

w_n = non-evaporable water, p/p_s = about 24x10^{-6}.
SSD = Water content of granular sample, saturated, surface-dry for sample that had been dried and resaturated.

Description of specimens made in series 254-MRB

Neat Specimens: Cylinders, 1x7 in.

Cements: See Tables A-1 to A-3.

Burning Conditions: Lot Nos. 14910, 14911, 14912: hard burned; Lot Nos. 14913, 14914, 14915; soft-burned; others: normal plant burning. Changes in burning condition were brought about by changing length of burning zone.

Cooling Condition: The symbol PC signifies cooling by regular plant method; SC signifies slow cooling by storage in an insulated box where temperatures at or above red-heat were maintained for about 24 hours; AQ signifies cooling to temperatures below dull-red within 10 seconds by use of an air-blast.

Grinding: In the laboratory mill with enough added gypsum for 1.8 percent total SO_3.

Mixing: The cement was placed with water in a kitchen-type mixer and mixed for 2 minutes, allowed to rest for 1 minute, and then mixed for 1 minute. $w/c = 0.5$ by weight at mixing.

Casting: The pastes were poured into 1x7-in. waxed-paper cylinders.

Curing: In the molds under water. Molds stored horizontally.

Drying: The granular samples were dried in a vacuum desiccator over $Mg(ClO_4)_2 \cdot 2H_2O$.

Adsorption Data: See Table A-7.

TABLE A-7—ADSORPTION DATA FOR SERIES 254-MRB

Water-cement ratio corrected for bleeding

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement								
	14898-1AQ $w_o/c =$ .382 Age 120d	14899-1PC $w_o/c =$ .388 Age 120d	14900-1SC $w_o/c =$ .446 Age 126d	14901-2AQ $w_o/c =$ .391 Age 126d	14902-2PC $w_o/c =$ .393 Age 133d	14903-2SC $w_o/c =$ .424 Age 133d	14904-3AQ $w_o/c =$ .425 Age 162d	14905-3PC $w_o/c =$ .411 Age 162d	14906-3SC $w_o/c =$ .476 Age 173d
w_n	.2171	.2225	.2274	.2228	.2273	.2271	.2284	.2299	.2355
.088	.2615	.2614	.2684	.2629	.2665	.2664	.2723	.2757	.2794
.20	.2737	.2781	.2848	.2755	.2825	.2823	.2891	.2924	.2966
.355	.2977	.3034	.3111	.2992	.3092	.3091	.3143	.3184	.3271
.51	.3179	.3209	.3245	.3116	.3285	.3277	.3333	.3393	.2510
.61	.3298	.3355	.3534	.3332	.3422	.3448	.3485	.3529	.3702
.69	.3461	.3511	.3656	.3437	.3578	.3602	.3578	.3631	.3831
.75	.3610	.3666	.3852	.3649	.3743	.3797	.3749	.3811	.4048
.80	.3675	.3724	.3918	.3700	.3807	.3842	.3824	.3879	.4107
.84	.3782	.3813	.4000	.3803	.3883	.3926	.3941	.3982	.4217
.89	.3971	.3983	.4100	.3908	.3981	.3996	.4168	.4176	.4438
.96	.4318	.4225	.4459	.4491	.4475	.4401	.4553	.4469	.4737
SSD	.4604	.4581	.5082	.4911	.5013	.5106	.4897	.4898	.5496
SSDO	—	—	.5267	.5031	.5108	.5261	.4993	.5021	.5673

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement								
	14907-4AQ $w_o/c =$ .406 Age 173d	14908-4PC $w_o/c =$ .394 Age 200d	14909-4SC $w_o/c =$ .483 Age 200d	14910-5AQ $w_o/c =$ .460 Age 204d	14911-5PC $w_o/c =$ .464 Age 204d	14912-5SC $w_o/c =$ .489 Age 212d	14913-6AQ $w_o/c =$ .410 Age 212d	14914-6PC $w_o/c =$ .423 Age 222d	14915-6SC $w_o/c =$ .437 Age 222d
w_n	.2191	.2250	.2255	.2282	.2294	.2252	.2206	.2253	.2240
.088	.2605	.2673	.2669	.2704	.2723	.2703	.2665	.2675	.2667
.20	.2789	.2853	.2846	.2865	.2940	.2883	.2839	.2847	.2830
.355	.3037	.3108	.3119	.3142	.3166	.3167	.3075	.3101	.3097
.51	.3231	.3327	.3346	.3365	.3383	.3416	.3275	.3293	.3299
.61	.3354	.3463	.3496	.3470	.3496	.3558	.3389	.3443	.3441
.69	.3459	.3573	.3639	.3533	.3571	.3698	.3514	.3537	.3562
.75	.3629	.3764	.3871	.3793	.3832	.3907	.3678	.3736	.3759
.80	.3683	.3835	.3948	.3844	.3905	.3956	.3704	.3771	.3787
.84	.3766	.3920	.4061	.3952	.4017	.4048	.3771	.3847	.3869
.89	.4027	.4136	.4333	.4280	.4365	.4300	.4061	.4137	.4149
.96	.4279	.4394	.4659	.4706	.4801	.4547	.4314	.4347	.4327
SSD	.4606	.4771	.5477	.5131	.5259	.5473	.4767	.4870	.5203
SSDO	.4741	.4922	.5725	.5348	.5458	.5675	.4932	—	.5296

Key: *SSD* = Water content of granular sample, saturated, surface-dry for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.
AQ = Air quenched.
PC = Plant cooled.
SC = Slow cooled.
w_n = Non-evaporable water; p/p_s = about 24×10^{-6}.

Description of specimens made in series 254-K4B

Neat Specimens: Cylinders, 1x7½ in.

Cements: See Tables A-1 to A-3.

Cooling: Symbol P signifies regular plant cooling; S signifies slow cooling after reheating clinker; Q signifies quick cooling after reheating clinker.

Grinding: In the laboratory mill with enough added gypsum for 1.8 percent total SO_3.

Mixing: The cement was placed with water in a kitchen-type mixer and mixed for 2 minutes, allowed to rest for 2 minutes, and then mixed for 2 minutes. $w/c = 0.5$ by weight at mixing.

Casting: The pastes were poured into 1x7½-in. cylindrical molds.

Curing: In the molds stored horizontally under water for 20-24 hrs.; under water thereafter. Temperature: 70 F.

Drying: The granular samples (48-100 mesh) were dried in a vacuum desiccator over $Mg(ClO_4)_2.2H_2O$.

Adsorption Data: See Table A-8.

Description of specimens made in series 254-7

Mortar Specimens: Truncated cones: base, 4 in.; top, 2 in.; altitude, 6 in.

Cement: Lot 14675. See Tables A-2 and A-3 for characteristics.

Batches: The batches were made up as follows:

Ref. No.	Mix by Wt.	Weights, gms. per batch						Cement g	Water, ml
		Ottawa Silica			Cow Bay Sand				
		200–100	100–48	48–28	28–14	14–8	8–4		
7–1	1–0	—	—	—	—	—	—	4000	1010
7–2	1–½	36	73	125	579	301	386	3000	830
7–3	1–1	54	110	187	868	453	578	2250	675
7–4	1–2	77	157	266	1234	644	822	1600	570
7–5	1–3	86	177	299	1389	724	925	1200	545
7–6	1–4	90	184	311	1447	654	1064	938	590
7–7	1–5	90	184	311	1447	654	1064	750	570

Mixing: Each batch was mixed 30 sec. dry and 2 min. wet, in a small power-driven, open-tub mixer.

Molding: From each batch 3 watertight molds of known capacity were filled. The mortar was puddled with a light tamper.

Measurements: The weight of the filled calibrated mold was measured to 1 g immediately after filling, and again after 20-24 hr. in the fog-room. On stripping, the weights of the specimen in air and in water were obtained.

Curing: In molds in the fog-room for the first 20-24 hr.; under water thereafter. Temperature: 70 F. Some of the molds were not stripped until the specimens were 48 hr. old, but the specimens were nevertheless immersed after the first 24 hr.

Drying: The granular samples were dried in a vacuum desiccator over $Mg(ClO_4)_2.2H_2O$.

Cement-Silica Specimens: Cylinders cast in test tubes (⅞ x 6 in.)

Cement: Lot 14675. See Tables A-2 and A-3 for characteristics.

Silica: Lot 13239. 95 percent passing No. 200-mesh sieve.

Proportions:

Ref. No.	Proportions by Wt.			c/SiO_2	Nominal w/c	
	Cement c	Silica SiO_2	Water w		wt.	gal/sk
1	0.736	0	0.264	100/0	0.36	4.06
2	0.590	0.148	0.262	80/20	0.444	5.00
3	0.483	0.260	0.257	65/35	0.530	5.97
4	0.411	0.336	0.253	55/45	0.618	6.96
5	0.376	0.376	0.248	50/50	0.660	7.43

Mixing: Cement and silica were premixed by tumbling them together in a large glass bottle. The dry material was placed with water in a kitchen-type mixer, and mixed for 2 minutes, allowed to rest for 3 minutes, and then mixed for 2 minutes.

Casting: The pastes were poured into ⅞ x 6 in. test tubes which had previously been calibrated by filling them with water from a burette.

Curing: The level-full test tubes were stored under water until the third day after casting, at which time the glass molds were broken off and the specimens were reimmersed in water where they remained until tested.

Drying: The granular samples were dried in a vacuum desiccator over $Mg(ClO_4)_2 \cdot 2H_2O$.

Test Results: All test results are given in Part 5.

Description of specimens made in series 254-8

Mortar Specimens: Cubes, 2 in.

Cements: See Tables A-1 to A-3.

Pulverized Silica: About same fineness, volume basis, as cement.

Proportions:

Mix	Relative Proportions			w/c by weight (approx.)
	Cement	Pulverized Silica	Std. Ottawa Sand	
A	1	0	1.64	0.33
B	1	0.330	2.30	0.46
C	1	0.707	3.07	0.61

Mixing: Each batch was mixed 30 sec. dry and 2 min. wet, in a small power-driven, open-tub mixer before making slump test. Slump-sample returned to tub and batch mixed additional 30 sec. before casting.

Slump Test: Made in duplicate on 6-in. cone. Water adjusted to give 1½-2-in. slump.

Molding: From each batch 3 cubes were cast in previously weighed, 3-gang, steel molds.

Measurements: The weight of the filled molds was measured to 1 g immediately after filling, and again 2-2¼ hr. later after carefully removing any accumulated water with a suitable absorbent. The molds were dried and weighed again just prior to stripping. After stripping, the cubes were weighed in air and in water.

Curing: In molds in the fog-room for the first 20-24 hr.; then under water for 27 days; thereafter in the fog-room.

Drying: The granular samples were dried in a vacuum desiccator over $Mg(ClO_4)_2 \cdot 2H_2O$.

Composition of Specimens: The composition of the hardened cubes, derived from the measurements mentioned above, are given in Table A-9.

TABLE A-8—ADSORPTION DATA FOR SERIES 254-K4B

Water-cement ratios corrected for bleeding

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement											
	13721–1S $w_o/c = .470$ Age 174d	13722–1P $w_o/c = .473$ Age 180d	13723–1Q $w_o/c = .425$ Age 180d	13730–4S $w_o/c = .463$ Age 144d	13731–4P $w_o/c = .460$ Age 138d	13732–4Q $w_o/c = .450$ Age 138d	13733–5S $w_o/c = .427$ Age 150d	13734–5P $w_o/c = .453$ Age 146d	13735-5Q $w_o/c = .456$ Age 150d	13736-6S $w_o/c = .471$ Age 196d	13737–6P $w_o/c =$ Age 191d	13738–6Q $w_o/c = .447$ Age 191d
w_n	.2231	.2332	.2290	.1786	.1772	.1773	.1650	.1589	.1650	.2148	.2297	.2220
.09	.2666	.2769	.2709	.2128	.2072	.2087	.1994	.1936	.1983	.2568	.2729	.2612
.20	.2830	.2934	.2863	.2268	.2173	.2211	.2136	.2071	.2140	.2723	.2904	.2764
.355	.3123	.3208	.3143	.2464	.2363	.2396	.2337	.2253	.2311	.2978	.3181	.3011
.50	.3910	.3478	.3405	.2646	.2516	.2554	.2502	.2404	.2491	.3266	.3487	.3277
.61	.3561	.3595	.3508	.2772	.2647	.2689	.2608	.2517	.2610	.3397	.3634	.3368
.69	.3746	.3783	.3673	.2917	.2783	.2777	.2770	.2667	.2756	.3574	.3818	.3535
.75a	.3899	.3894	.3799	.2159	.3056	.2999	.2975	.2889	.2968	.3675	.3940	.3667
.80b	.3962	.3999	.3878	.3180	.3121	.3037	.2999	.2922	.2996	.3761	.4020	.3734
.84	.4029	.4079	.3943	.3259	.3215	.3112	.3091	.3010	.3088	.3824	.4095	.3801
.89	.4294	.4457	.4269	.3718	.3698	.3528	.3482	.3446	.3513	.4099	.4337	.4145
.96	.4477	.4727	.4497	.4116	.4056	.3916	.3839	.3842	.3890	.4318	.4554	.4478
SSD	.5433	.5590	.5022	.5098	.5122	.4949	.4976	.5093	.5139	.5085	.5189	.5125
SSDO	.5572	.5755	.5149	.5249	.5349	.5148	.5102	.5193	.5268	.5295	.5462	.5361

(Concluded on next page)

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement												
	13740-7P $w_o/c = .473$ Age 164d	13741-7Q $w_o/c = .480$ Age 171d	13752-11P $w_o/c = .445$ Age 164d	13753-11Q $w_o/c = .440$ Age 172d	13763-15S $w_o/c = .485$ Age 202d	13764-15P $w_o/c =$ Age 196d	13765-15Q $w_o/c = .445$ Age 202d	13766-16S $w_o/c =$ Age 322d	13767-16P $w_o/c = .464$ Age 223d	13768-16Q $w_o/c = .456$ Age 223d	13778-20S $w_o/c = .472$ Age 170d	13779-20P $w_o/c = .462$ Age 167d	13780-20Q $w_o/c = .436$ Age 176d
w_n	.2395	.2390	.1864	.1896	.2173	.2109	.2201	.2096	.2256	.2250	.2308	.2329	.2262
.09	---	.2810	---	.2267	.2589	.2494	.2591	.2501	.2709	.2689	.2736	.2730	.2664
.20	.3051	.2988	.2386	.2403	.2735	.2653	.2735	.2695	.2869	.2854	.2914	.2894	.2816
.355	.3372	.3256	.2611	.2651	.3017	.2874	.2972	.2933	.3163	.3131	.3183	.3130	.3073
.50 c	.3653	.3536	.2782	.2826	.3224	.3133	.3050	.3094	.3379	.3324	.3443	.3383	.3326
.61	.3812	.3660	.2904	.2944	.3343	.3238	.3234	.3323	.3522	.3427	.3597	.3531	.3447
.69	.4003	.3840	.3074	.3125	.3665	.3387	.3583	.3441	.3749	.3673	.3766	.3636	.3624
.747 d	.4098	.3960	.3188	.3240	.3794	.3514	.3596	.3595	.3869	.3778	.3888	.3821	.3740
.802 e	.4215	.4048	.3316	.3346	.3758	.3588	.3604	.3693	.3987	.3927	.3974	.3908	.3811
.84	.4284	.4110	.3378	.3401	.3906	.3634	.3749	.3844	.4048	.3925	.4035	.3977	.3870
.89	.4518	.4450	.3767	.3770	.4202	.3979	.4174	.4114	.4331	.4255	.4301	.4245	.4157
.96	.4671	.4671	.4098	.4148	.4391	.4244	.4542	.4376	.4500	.4426	.4499	.4440	.4366
SSD	.5564	.5489	.5162	.5087	.5362	.5008	.5290	.5459	.5253	.5021	.5426	.5124	.5080
SSDO	.5751	.5639	.5323	.5158	.5613	.5167	.5445	.5641	.5413	.5196	.5544	.5548	.5194

a–p/p_s = 0.747 for Refs. 6-S, 6-P and 6-Q.
b– " = 0.802 for Refs. " " " "
c– " = 0.476 for Refs. 15-S, 15-P, and 15-Q; p/p_s = 0.47 for Refs. 16-S, 16-P, and 16-Q.
d– " = 0.75 for 16-S, 16-P, and 16-Q.
e– " = 0.805 for " " " ".

Key:
SSD = Water content of granular sample, saturated, surface-dry for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.
S = Slow cooled after reheating clinker.
P = "Plant cooled."
Q = Quick-cooled after reheating clinker.
w_n = Non-evaporable water; p/p_s = about 24×10^{-6}.

TABLE A-9—UNIT ABSOLUTE VOLUME COMPOSITION OF THE MORTARS USED IN SERIES 254-8

Cement No.	Ref. No.	Unit Absolute Volume Composition at End of the 2nd Hour				w/c at 2 hours	Cement Content of Paste
		Cement	Water	Air	Silica		
14930J	8–1	.2375	.2431	.035	.4843	.311	.494
	8–2	.1692	.2466	.032	.5521	.443	.407
	8–3	.1271	.2492	.029	.5953	.595	.338
15007J	8–28	.2363	.2649	.021	.4776	.344	.471
	8–29	.1698	.2567	.025	.5491	.464	.398
	8–30	.1288	.2500	.024	.5978	.595	.340
15008J	8–32	.1647	.2477	.055	.5322	.462	.399
	8–33	.1251	.2405	.055	.5796	.590	.342
15011J	8–40	.2407	.2508	.022	.4870	.319	.490
	8–41	.1730	.2494	.018	.5598	.442	.410
	8–42	.1298	.2522	.015	.6029	.595	.340
15012J	8–44	.1606	.2419	.077	.5207	.461	.399
	8–45	.1202	.2472	.068	.5636	.624	.329
15013J	8–46	.2345	.2532	.040	.4721	.332	.481
	8–47	.1713	.2520	.025	.5516	.453	.405
	8–48	.1260	.2455	.046	.5825	.599	.339
15014J	8–50	.1566	.2595	.079	.5045	.510	.376
	8–51	.1201	.2511	.074	.5548	.644	.324

Adsorption Data: See Table A-10.

TABLE A-10—ADSORPTION DATA FOR SERIES 254-8

Water-cement ratio corrected for bleeding

	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement								
p/p_s	14930J-8-1 $w_0/c =$ .311 Age 447d	14930J-8-2 $w_0/c =$ .443 Age 362d	14930J-8-3 $w_0/c =$ .595 Age 362d	15007J-8-28 $w_0/c =$ .344 Age 479d	15007J-8-29 $w_0/c =$ .464 Age 440d	15007J-8-30 $w_0/c =$ .595 Age 479d	15008J-8-32 $w_0/c =$ .462 Age 463d	15008J-8-33 $w_0/c =$ .590 Age 463d	15011J-8-40 $w_0/c =$ .319 Age 478d
w_n	.1808	.2006	.2101	.1980	.2169	.2323	.2105	.2208	.1843
.09	.2199	—	.2616	.2370	.2578	.2760	.2472	.2604	.2210
.20	.2360	.2641	.2765	.2538	.2759	.2939	.2641	.2798	.2375
.36	.2566	.2889	.3048	.2765	.2997	.3183	.2863	.3022	.2565
.47	.2681	.3042	.3224	.2918	.3191	.3367	.3024	.3237	.2699
.61	.2798	.3205	.3444	.3100	.3411	.3574	.3221	.3480	.2836
.69	.2888	.3346	.3624	.3179	.3591	.3752	.3361	.3690	.2912
.75	.2994	.3495	.3842	.3249	.3739	.3972	.3471	.3828	.2979
.81	.3057	.3626	.3975	.3350	.3832	.4126	.3673	.4084	.3080
.84	.3132	.3732	.4082	.3401	.3919	.4298	.3789	.4278	.3107
.89	.3290	.4024	.4674	.3489	.4221	.4831	.3933	.4461	.3218
.96	.3479	.4234	.4909	.3762	.4477	.5266	.4442	.5206	.3460
SSD	.3934	.5314	.6852	.4248	.5267	.6711	.5383	.6763	.2892
SSDO	.4132	.5431	.7060	.6228	.5600	.7178	—	—	—

	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement								
p/p_s	15011J-8-41 $w_0/c =$ .442 Age 368d	15011J-8-42 $w_0/c =$ .595 Age 368d	15012J-8-44 $w_0/c =$ .461 Age 464d	15012J-8-45 $w_0/c =$ .624 Age 464d	15013J-8-46 $w_0/c =$ .332 Age 339d	15013J-8-47 $w_0/c =$ .453 Age 333d	15013J-8-48 $w_0/c =$ .599 Age 333d	15014J-8-50 $w_0/c =$ .510 Age 487d	15014J-8-51 $w_0/c =$ .644 Age 487d
w_n	.2102	.2218	.2109	.2227	.2185	.2407	.2527	.2472	.2527
.09	.2503	.2640	.2519	.2657	.2567	.2829	.2932	.2885	.2961
.20	.2667	.2817	.2694	.2835	.2737	.2991	.3103	.3079	.3152
.36	.2921	.3073	.2922	.3080	.2934	.3252	.3348	.3373	.3439
.47	.3149	.3329	.3137	.3315	.3076	.3446	.3546	.3587	.3685
.61	.3345	.3548	.3336	.3586	.3163	.3643	.3793	.3834	.3951
.69	.3463	.3745	.3504	.3761	.3333	.3746	.3942	.4050	.4205
.75	.3581	.3931	.3613	.3892	.3424	.3931	.4148	.4199	.4422
.81	.3657	.4003	.3794	.4145	.3468	.4002	.4281	.4359	.4627
.84	.3828	.4232	.3906	.4320	.3514	.4089	.4387	.4436	.4732
.89	.4131	.4659	.4066	.4546	.3673	.4375	.4820	.4656	.5065
.96	.4338	.4975	.4608	.5295	.3826	.4619	.5203	.5116	.5701
SSD	.5246	.6426	.5738	.6978	.4245	.5587	.6886	.6355	.7769
SSDO	.5306	.6756	—	—	.4461	—	—	—	—

Key: *SSD* = Water content of granular sample, saturated, surface-dry for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.
w_n = Non-evaporable water; p/p_s = about 24×10^{-6}.

Description of specimens made in series 254-9

Mortar Specimens: Cubes, 2-in.; Prism, 2x2x9½ in.

Cements: See Tables A-1 to A-3.

Pulverized Silica: Lot 15282. Specific surface, volume basis, about the same as that of cement.

Batches: The batches were made up as follows:

Mix	Weights, gms. per batch			Water (approx.)	Nominal w/c by Weight
	Cement	Pulverized Silica	Std. Ottawa Sand		
A	1900	—	3100	620	0.326
B	1350	450	3100	610	0.452
C	1000	730	3100	600	0.600

Mixing: As in Series 254-8.

Slump Test: As in Series 254-8.

Molding: From each batch 12 cubes and 1 prism were cast in previously weighed steel molds.

Measurements: Cubes: as in Series 254-8. Prism: the prism was weighed in air and in water at 28 days.

Curing: As in Series 254-8.

Drying: As in Series 254-8.

Test results for series 254-9

Composition of Hardened Specimens: The composition of the mortars in the hardened cubes, derived as in Series 254-8, is given in Table A-11.

TABLE A-11—UNIT ABSOLUTE VOLUME COMPOSITION OF THE MORTARS USED IN SERIES 254-9

Cement No.	Ref. No.	Mix	Unit Absolute Volume Composition at the End of the 2nd Hour				*w/c* at 2 hrs. (wt. basis)
			Cement	Water	Air	Silica	
14930J	9–1	A	.2401	.2437	.0308	.4863	.309
	9–2	B	.1718	.2397	.0284	.5610	.424
	9–3	C	.1268	.2380	.0292	.6072	.573
15007J	9–4	A	.2402	.2474	.0312	.4821	.316
	9–5	B	.1721	.2422	.0289	.5568	.433
	9–6	C	.1292	.2434	.0211	.6062	.570
15011J	9–7	A	.2415	.2493	.0245	.4852	.316
	9–8	B	.1727	.2445	.0240	.5593	.432
	9–9	C	.1288	.2394	.0251	.6073	.582
15013J	9–10	A	.2407	.2538	.0248	.4813	.324
	9–11	B	.1709	.2457	.0341	.5504	.443
	9–12	C	.1260	.2500	.0337	.5912	.611
15365	9–13	A	.2366	.2462	.0439	.4752	.349
	9–14	B	.1711	.2453	.0313	.5536	.439
	9–15	C	.1295	.2388	.0224	.6101	.587
	9–15A	Neat	.5316	.4220	.0487	—	.244

Adsorption Data: See Tables A-12 to A-27.

Chemical Analyses of Dried Granular Samples: See Table A-28.

Compressive Strength: Cubes were tested in compression, two at each age. See Tables 6-2 to 6-6, Part 6 for results. Samples for adsorption measurements were prepared from the broken cubes.

Modulus of Elasticity: The modulus of elasticity was determined from sonic measurements on the prism. See Table A-29 for results.

TABLE A-12—ADSORPTION DATA FOR REF. 254-9-1, CEMENT 14930J

w/c (by wt.): Original 0.316; after bleeding 0.309
w_n = non-evaporable water; p/p_s = about 24×10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement						
	7 days	14 days	28 days	56 days	90 days	180 days	365 days
w_n	.0804	.0994	.1071	.1292	.1497	.1620	.1704
.088	.0957	.1183	—	—	—	—	—
.089	—	—	.1327	.1598	.1812	.2000	—
.090	—	—	—	—	—	—	.2080
.20	.1018	.1273	.1421	.1725	.1963	.2160	.2232
.355	.1097	.1407	—	—	—	—	—
.36	—	—	.1557	.1893	.2155	.2335	.2422
.47	—	—	.1680	.2024	.2271	.2482	.2547
.51	.1185	.1473	—	—	—	—	—
.61	.1247	.1533	.1738	.2109	.2338	.2598	.2654
.69	.1341	.1661	.1898	.2240	.2477	.2678	.2743
.75	.1477	.1763	.2007	.2323	.2558	.2754	.2800
.80	.1547	.1879	.1905	.2347	.2608	.2811	—
.81	—	—	—	—	—	—	.2904
.84	.1599	.1925	.2136	.2521	.2715	.2915	.2963
.89	.1863	.2201	.2408	.2697	.2851	.3054	.3012
.96	.2152	.2421	.2623	.2974	.3105	.3184	.3282
SSD	.3258	.3324	.3493	.3473	.3522	.3576	.3627
SSDO	.3457	.3520	.3516	.3605	.3667	.3703	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-13—ADSORPTION DATA FOR REF. 254-9-2, CEMENT 14930J

w/c (by wt.): Original 0.441; after bleeding 0.424
w_n = non-evaporable water; p/p_s = about 24×10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement						
	7 days	14 days	28 days	56 days	90 days	180 days	365 days
w_n	.0798	.1029	.1165	.1352	.1735	.1853	.1953
.088	.0957	.1227	—	—	—	—	—
.089	—	—	.1444	.1697	.2093	.2268	—
.090	—	—	—	—	—	—	.2396
.20	.1020	.1315	.1542	.1889	.2254	.2473	.2569
.355	.1075	.1487	—	—	—	—	—
.36	—	—	.1700	.2089	.2485	.2693	.2791
.47	—	—	.1819	.2194	.2643	.2873	.2987
.51	.1160	.1511	—	—	—	—	—
.61	.1214	.1551	.1892	.2388	.2751	.3075	.3154
.69	.1335	.1722	.2076	.2516	.2939	.3184	.3286
.75	.1446	.1797	.2142	.2666	.3065	.3295	.3358
.80	.1517	.1928	.2051	.2671	.3133	.3347	—
.81	—	—	—	—	—	—	.3507
.84	.1573	.1976	.2359	.2955	.3240	.3520	.3614
.89	.1879	.2426	.2784	.3238	.3496	.3720	.3735
.96	.2189	.2693	.3103	.3684	.3797	.3894	.4114
SSD	.3981	.4426	.4769	.4738	.4879	.4852	.5109
SSDO	.3995	.4626	.4936	.4864	.5017	.5024	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-14—ADSORPTION DATA FOR REF. 254-9-3, CEMENT 14930J

w/c (by wt.): Original 0.600; after bleeding 0.573
w_n = non-evaporable water; p/p_s = about 24x10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement						
	7 days	14 days	28 days	56 days	90 days	180 days	365 days
w_n	.0822	.0896	.1214	.1638	.1850	.2008	.2142
.089	.1022	.1118	.1521	.1979	.2238	.2422	.2625
.20	.1054	.1180	.1635	.2130	.2409	.2601	.2842
.36	.1125	.1289	.1814	.2343	.2637	.2841	.3125
.47	.1192	.1337	.1848	.2484	.2814	.3032	.3327
.61	.1271	.1464	.2086	.2634	.3068	.3251	.3508
.69	.1385	.1626	.2173	.2882	.3207	.3398	.3700
.75	.1411	.1712	.2371	.3043	.3372	.3573	.3838
.80	.1553	.1721	.2354	.3182	.3470	.3700	—
.81	—	—	—	—	—	—	.4012
.84	.1673	.2026	.2713	.3380	.3647	.3835	.4176
.89	.1955	.2318	.3099	.3761	.4114	.4261	.4450
.96	.2297	.2807	.3642	.4385	.4485	.4515	.5062
SSD	.4822	.4599	.5944	.6344	.6393	.5640	.6971
SSDO	.4732	.4851	.6021	.6579	.6562	.6028	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-15—ADSORPTION DATA FOR REF. 254-9-4, CEMENT 15007J

w/c (by wt.): Original 0.338; after bleeding 0.316
w_n = non-evaporable water; p/p_s = about 24x10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1259	.1404	.1538	.1681	.1729	.1835
.089	.1503	.1687	.1824	.2147	.2105	—
.09	—	—	—	—	—	.2170
.20	.1612	.1816	.1950	.2167	.2234	.2311
.36	.1759	.1982	.2126	.2353	.2419	.2513
.47	.1848	.2111	.2270	.2496	.2574	.2672
.61	.1949	.2243	.2449	.2651	.2752	.2814
.69	.2082	.2378	.2587	.2752	.2821	.2907
.75	.2185	.2440	.2657	.2810	.2891	.2962
.80	.2215	—	.2715	.2856	.2941	—
.81	—	—	—	—	—	.3026
.84	.2319	.2584	.2781	.3004	.3030	.3092
.89	.2520	.2810	.2979	.3077	.3146	.3235
.96	.2856	.2921	.3131	.3269	.3276	.3378
SSD	.3541	.3643	.3654	.3794	.3712	.3773
SSDO	.3716	—	.3747	.3853	—	.3921

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-16—ADSORPTION DATA FOR REF. 254-9-5, CEMENT 15007J

w/c (by wt.): Original 0.467; after bleeding 0.433
w_n = non-evaporable water; p/p_s = about 24×10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1334	.1498	.1714	.1847	.1924	.2018
.089	.1585	.1801	.2026	.2336	.2341	—
.09	—	—	—	—	—	.2396
.20	.1698	.1942	.2169	.2399	.2500	.2555
.36	.1843	.2128	.2357	.2593	.2714	.2778
.47	.1972	.2243	.2522	.2751	.2917	.2979
.61	.2085	.2415	.2763	.2975	.3158	.3152
.69	.2232	.2570	.2906	.3128	.3284	.3315
.75	.2312	.2657	.3020	.3249	.3394	.3411
.80	.2364	—	.3132	.3302	.3460	—
.81	—	—	—	—	—	.3520
.84	.2517	.2867	.3191	.3527	.3607	.3614
.89	.2774	.3158	.3432	.3713	.3802	.3994
.96	.3157	.3254	.3695	.3899	.3980	.4111
SSD	.4667	.4764	.4913	.5002	.5092	.5502
SSDO	.5000	.4971	.5106	.5156	—	.5605

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-17—ADSORPTION DATA FOR REF. 254-9-6, CEMENT 15007J

w/c (by wt.): Original 0.610; after bleeding 0.570
w_n = non-evaporable water; p/p_s = about 24×10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1560	.1634	.1839	.2035	.2049	.2132
.089	.1824	.1921	.2191	—	—	—
.09	—	—	—	.2398	.2428	—
.20	.1918	.2066	.2341	.2561	.2603	.2758
.36	.2078	.2210	.2536	.2781	.2811	.3006
.47	.2209	.2342	.2668	.2975	.3038	.3218
.61	.2423	.2523	.2943	.3240	.3266	.3460
.69	.2545	.2694	.3136	.3405	.3407	.3589
.75	.2705	.2864	.3297	.3524	.3578	.3810
.80	.2816	.2870	.3347	.3585	—	—
.81	—	—	—	—	.3656	.3918
.84	.2998	.3140	.3634	.3836	.3818	.4151
.89	.3240	.3409	.3921	.4132	.4155	.4430
.96	.3597	.3774	.4244	.4456	.4413	.4780
SSD	.5084	.5300	.5845	.5900	.6019	.6676
SSDO	.5630	.5846	.6219	.6347	.6186	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-18—ADSORPTION DATA FOR REF. 254-9-7, CEMENT 15011J

w/c (by wt.): Original 0.353; after bleeding 0.316
w_n = non-evaporable water, p/p_s = about 24x10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement						
	7 days	14 days	28 days	56 days	90 days	180 days	365 days
w_n	.1137	.1333	.1430	.1557	.1643	.1705	.1760
.089	.1415	.1584	.1785	.1892	.1961	.2039	—
.09	—	—	—	—	—	—	.2111
.20	.1484	.1686	.1953	.2035	.2098	.2191	.2276
.36	.1617	.1838	.2069	.2211	.2268	.2359	.2468
.47	.1703	.1960	.2193	.2295	.2410	.2509	.2573
.61	.1808	.2038	.2312	.2401	.2531	.2632	.2685
.69	.1935	.2197	.2448	.2535	.2622	.2716	.2764
.75	.1942	.2289	.2534	.2627	.2704	.2817	.2861
.80	.2112	.2319	.2548	.2684	.2746	.2873	—
.81	—	—	—	—	—	—	.2931
.84	.2209	.2535	.2738	.2767	.2812	.2951	.3002
.89	.2480	.2787	.2955	.2905	.3015	.3125	.3109
.96	.2697	.3059	.3186	.3140	.3138	.3216	.3341
SSD	.3487	.3575	.3619	.3591	.3617	.3646	.3721
SSDO	.3587	.3710	.3696	.3713	.3685	.3794	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-19—ADSORPTION DATA FOR REF. 254-9-8, CEMENT 15011J

w/c (by wt.): Original 0.459; after bleeding 0.432
w_n = non-evaporable water; p/p_s = about 24x10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1228	.1527	.1654	.1781	.1913	.1986
.089	.1514	.1824	.2054	.2154	.2278	—
.09	—	—	—	—	—	.2359
.20	.1618	.1940	.2116	.2269	.2444	.2521
.36	.1762	.2064	.2300	.2464	.2647	.2751
.47	.1828	.2205	.2444	.2656	.2798	.2956
.61	.2005	.2357	.2562	.2858	.3023	.3126
.69	.2140	.2470	.2764	.3000	.3165	.3250
.75	.2254	.2634	.2890	.3119	.3289	.3364
.80	—	.2718	.2993	.3226	.3380	—
.81	—	—	—	—	—	.3437
.84	.2517	.2875	.3108	.3313	.3591	.3587
.89	.2829	.3249	.3251	.3618	.3816	.3827
.96	.3310	.3579	.3778	.3864	.4055	.4108
SSD	.4661	.4932	.4843	.4922	.4952	.4975
SSDO	—	.5155	.5045	.5075	.5165	.5119

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-20—ADSORPTION DATA FOR REF. 9-9, CEMENT 15011J

w/c (by wt.): Original 0.610; after bleeding 0.582
w_n = non-evaporable water; p/p_s = about 24×10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1314	.1567	.1756	.1953	.2046	.2136
.089	.1573	.1871	.2176	.2332	.2427	—
.09	—	—	—	—	—	.2523
.20	.1693	.1994	.2231	.2484	.2600	.2693
.36	.1804	.2132	.2418	.2688	.2831	.2914
.47	.1901	.2244	.2562	.2897	.2977	.3139
.61	.2037	.2385	.2695	.3121	.3212	.3364
.69	.2160	.2529	.2948	.3294	.3408	.3526
.75	.2290	.2679	.3065	.3413	.3566	.3684
.80	—	.2804	.3179	.3590	.3692	—
.81	—	—	—	—	—	.3756
.84	.2574	.2999	.3344	.3684	.3939	.3990
.89	.2946	.3381	.3527	.4134	.4291	.4344
.96	.3453	.3931	.4233	.4469	.4588	.4670
SSD	.5576	.5258	.5793	.6471	.6212	.5800
SSDO	—	.5657	.6146	.6726	.6306	.6156

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-21—ADSORPTION DATA FOR REF. 9-10, CEMENT 15013J

w/c (by wt.): Original 0.326; after bleeding 0.324
w_n = non-evaporable water; p/p_s = about 24×10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1488	.1639	.1711	.1802	.1913	.1877
.089	.1748	.1909	.2028	.2147	—	—
.09	—	—	—	—	.2260	.2299
.20	.1859	.2042	.2161	.2277	.2409	.2426
.36	.2001	.2186	.2324	.2452	.2586	.2615
.47	.2110	.2304	.2472	.2602	.2760	.2763
.61	.2287	.2465	.2634	.2790	.2912	.2907
.69	.2386	.2604	.2761	.2899	.3015	.2917
.75	.2509	.2705	.2843	.2952	.3100	.3058
.80	.2541	.2680	.2857	.2979	—	—
.81	—	—	—	—	.3135	.3103
.84	.2653	.2863	.3004	.3104	.3212	.3151
.89	.2729	.2997	.3114	.3218	.3342	.3307
.96	.3019	.3110	.3228	.3335	.3417	.3418
SSD	.3745	.3831	.3781	.3852	.3873	.3784
SSDO	.3745	.3831	.3914	.3995	.4018	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-22—ADSORPTION DATA FOR REF. 9-11, CEMENT 15013J

w/c (by wt.): Original 0.459; after bleeding 0.443
w_n = non-evaporable water; p/p_s = about 24×10^{-8}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1556	.1828	.1770	.2085	.2152	.2356
.089	.1830	.2143	.2131	—	—	—
.09	—	—	—	.2460	.2530	.2761
.20	.1932	.2269	.2272	.2604	.2695	.2933
.36	.2079	.2434	.2455	.2843	.2940	.3179
.47	.2190	.2572	.2626	.3017	.3124	.3372
.61	.2369	.2814	.2822	.3212	.3306	.3572
.69	.2447	.2911	.2985	.3363	.3426	.3660
.75	.2578	.3026	.3129	.3518	.3555	.3797
.80	.2614	.3051	—	—	—	—
.81	—	—	—	.3557	.3649	.3908
.84	.2788	.3228	.3316	.3690	.3763	.3958
.89	.2991	.3481	.3690	.3927	.4034	.4127
.96	.3247	.3698	.3933	.4115	.4265	.4547
SSD	.4435	.4831	.5248	.5298	.5643	.5705
SSDO	.4793	.5137	.5419	—	—	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-23—ADSORPTION DATA FOR REF. 9-12, CEMENT 15013J

w/c (by wt.): Original 0.635; after bleeding 0.611
w_n = non-evaporable water; p/p_s = about 24×10^{-8}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1583	.1828	.2028	.2208	.2357	.2447
.089	.1841	.2129	.2368	—	—	—
.09	—	—	—	.2582	.2778	.2856
.20	.1941	.2238	.2502	.2737	.2937	.3029
.36	.2063	.2395	.2663	.2971	.3173	.3272
.47	.2176	.2532	.2850	.3151	.3372	.3460
.61	.2345	.2747	.3075	.3396	.3579	.3690
.69	.2432	.2848	.3232	.3578	.3747	.3841
.75	.2584	.3003	.3395	.3731	.3946	.3983
.80	—	.3034	—	—	—	—
.81	—	—	—	.3796	.4029	.4166
.84	.2792	.3229	.3576	.3974	.4191	.4221
.89	.3018	.3507	.3995	.4296	.4557	.4468
.96	.3244	.3763	.4244	.4563	.4930	.5102
SSD	.5148	.5497	.5798	.6136	.7162	.6707
SSDO	.5743	.6200	.6438	—	—	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-24—ADSORPTION DATA FOR REF. 9-13, CEMENT 15365

w/c (by wt.): Original 0.326; after bleeding 0.319
w_n = non-evaporable water; p/p_s = about 24×10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1326	.1515	.1488	.1786	.1789	.1815
.09	.1596	.1803	.1803	.2133	.2133	.2168
.20	.1681	.1903	.1933	.2275	.2269	.2311
.36	.1809	.2043	.2106	.2461	.2460	.2495
.47	.1925	.2181	.2242	.2574	.2591	.2608
.61	.2052	.2313	.2414	.2725	.2734	.2740
.69	.2134	.2434	.2489	.2796	.2824	.2870
.75	.2244	.2541	.2571	.2898	.2926	.2922
.81	.2319	.2625	.2649	.2962	.2973	.2992
.84	.2391	.2688	.2783	.3017	.3026	.3078
.89	.2662	.2907	.2938	.3190	.3184	.3173
.96	.2906	.3123	.3036	.3367	.3341	.3344
SSD	.3570	.3669	.3639	.3847	.3702	.3791
SSDO	—	.3842	—	—	—	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-25—ADSORPTION DATA FOR REF. 254-9-14, CEMENT 15365

w/c (by wt.): Original 0.459; after bleeding 0.439
w_n = non-evaporable water; p/p_s = about 24×10^{-5}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1394	.1711	.1841	.2105	.2150	.2224
.09	.1665	.2031	.2230	.2502	.2571	.2651
.20	.1758	.2142	.2377	.2655	.2730	.2819
.36	.1893	.2315	.2599	.2889	.2962	.3088
.47	.2009	.2470	.2757	.3062	.3165	.3250
.61	.2138	.2619	.2961	.3257	.3346	.3460
.69	.2237	.2767	.3102	.3366	.3512	.3626
.75	.2343	.2894	.3256	.3518	.3638	.3699
.81	.2419	.3008	.3322	.3621	.3717	.3830
.84	.2512	.3104	.3476	.3681	.3791	.3925
.89	.2828	.3399	.3761	.3968	.4044	.4094
.96	.3098	.3646	.3966	.4188	.4288	.4429
SSD	.4182	.4724	.5034	.5133	.5113	.5344
SSDO	—	.4877	—	—	—	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-26—ADSORPTION DATA FOR REF. 254-9-15, CEMENT 15365

w/c (by wt.): Original 0.610; after bleeding 0.587
w_n = non-evaporable water; p/p_s = about 24x10^{-6}
w_t = total water
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement					
	7 days	14 days	28 days	56 days	90 days	180 days
w_n	.1530	.1855	.2102	.2213	.2296	.2546
.09	.1820	.2194	.2495	.2653	.2741	.2967
.20	.1922	.2321	.2646	.2820	.2918	.3139
.36	.2063	.2496	.2872	.3032	.3176	.3406
.47	.2162	.2636	.3030	.3249	.3357	.3609
.61	.2298	.2819	.3262	.3484	.3611	.3821
.69	.2395	.2937	.3382	.3641	.3783	.4056
.75	.2531	.3108	.3541	.3767	.3910	.4175
.81	.2578	.3139	.3637	.3898	.4074	.4347
.84	.2716	.3306	.3773	—	.4177	.4456
.89	.3060	.3706	.4197	.4228	.4461	.4681
.96	.3489	.4139	.4587	.4809	.5104	.5318
SSD	.5157	.5804	.6272	.6400	.6614	.6637
SSDO	.5707	.6031	—	—	—	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.

TABLE A-27—ADSORPTION DATA FOR REF. 254-9-15A, CEMENT 15365

w/c (by wt.): Original 0.246; after bleeding 0.244
w_n = non-evaporable water; p/p_s = about 24x10^{-6}
w_t = total waer
(w_e = evaporable water can be obtained from the relationship $w_e = w_t - w_n$)

p/p_s	Total Water, w_t, Retained at Relative Vapor Pressure and Age Indicated, g/g cement							
	7 days	14 days	28 days	56 days	90 days	180 days	270 days	
							A	B
w_n	.1152	.1259	.1358	.1396	.1452	.1554	.1691	.1722
.081	—	—	—	—	—	—	.1910	.1918
.09	.1380	.1501	.1611	.1684	.1741	.1856	—	—
.161	—	—	—	—	—	—	.2000	.1999
.20	.1465	.1591	.1709	.1785	.1837	.1956	—	—
.238	—	—	—	—	—	—	.2053	.2063
.322	—	—	—	—	—	—	.2111	.2116
.36	.1572	.1713	.1830	.1901	.1967	.2090	.2159	.2152
.47	.1658	.1811	.1933	.2002	.2061	.2177	—	—
.53	—	—	—	—	—	—	.2275	.2277
.61	.1763	.1918	.2034	.2123	.2182	.2266	—	—
.69	.1846	.1993	.2116	.2211	.2240	.2355	—	—
.70	—	—	—	—	—	—	.2397	.2402
.75	.1988	.2133	.2217	.2256	.2306	.2399	—	—
.81	.2021	.2146	.2259	.2324	.2389	.2459	.2509	.2504
.84	.2116	.2254	.2305	—	.2412	.2489	—	—
.85	—	—	—	—	—	—	.2582	.2588
.88	—	—	—	—	—	—	.2634	.2619
.89	.2317	.2414	.2487	.2426	.2509	.2536	—	—
.96	.2508	.2599	.2613	.2594	.2698	.2724	.2775	.2771
SSD	.3064	.2948	.3028	.2960	.2969	.2836	.2906	.3024
SSDO	.3128	.3076	—	—	—	—	—	—

Key: *SSD* = Water content of granular sample in saturated, surface-dry condition for sample that had been dried and resaturated.
SSDO = Water content of granular sample that was brought to saturated condition without preliminary drying.
A and B refer to separate rounds.

TABLE A-28—ANALYSES OF GRANULAR SAMPLES USED FOR ADSORPTION AND NON-EVAPORABLE WATER MEASUREMENTS IN SERIES 254-9

w/c at 2 hr. (wt. basis)	Composition of Dry Samples at Age Indicated, percent dry weight																				
	7 days			14 days			28 days			56 days			90 days			180 days			365 days		
	Cmt.	SiO_2	H_2O	Cmt.	SiO_2	H_2O	Cmt.	SiO_2	H_2O	Cmt.	SiO_2	H_2O	Cmt.	SiO_2	H_2O	Cmt.	SiO_2	H_2O	Cmt.	SiO_2	H_2O
										Cement 14930J											
0.309	84.7	7.9	7.5	80.4	11.7	8.0	70.6	22.0	7.6	73.9	16.6	9.6	69.9	19.6	10.5	76.9	10.6	12.5	70.1	18.0	11.9
0.424	66.1	27.9	5.3	62.5	30.2	6.4	52.0	42.0	6.1	48.5	45.0	6.6	55.1	35.4	9.6	60.4	28.4	11.2	54.4	35.0	10.6
0.573	46.5	49.8	3.8	33.8	63.6	3.0	40.4	54.7	4.9	46.0	46.5	7.5	46.8	44.5	8.7	49.7	40.3	10.0	46.4	43.6	9.9
										Cement 15007J											
0.316	76.3	14.1	9.6	74.3	15.3	10.4	74.2	14.4	11.4	77.5	9.5	13.0	77.6	9.0	13.4	75.8	10.3	13.9			
0.433	60.5	31.5	8.1	58.2	33.1	8.7	57.4	32.8	9.8	60.8	27.9	11.2	60.6	27.7	11.7	47.9	42.5	9.7			
0.570	48.1	44.4	7.5	48.1	44.0	7.9	48.4	42.8	8.9	47.9	42.4	9.7	47.5	42.3	10.2	32.6	60.5	7.0			
										Cement 15011J											
0.316	79.0	12.1	9.0	71.7	18.9	9.6	75.5	13.7	10.8	72.8	15.7	11.3	73.7	14.2	12.1	78.6	8.0	13.4	78.8	7.3	13.9
0.432	51.0	42.8	6.3	58.9	32.1	9.0	58.5	31.8	9.7	58.1	31.5	10.4	61.0	27.3	11.7	57.9	30.6	11.5			
0.582	47.5	46.2	6.2	47.3	45.3	7.4	45.9	46.0	8.1	44.6	46.7	8.7	48.0	42.3	9.8	45.7	44.5	9.8			
										Cement 15013J											
0.324	80.3	7.7	12.0	80.2	6.7	13.1	79.1	7.3	13.5	79.1	6.7	14.2	78.0	7.1	14.9	62.5	25.8	11.7			
0.443	62.7	27.5	9.8	59.4	29.8	10.8	25.1	70.5	4.4	58.1	29.7	12.1	51.0	37.0	11.0	53.4	34.1	12.6			
0.611	46.1	46.6	7.3	47.7	43.6	8.7	45.4	45.4	9.2	45.0	45.1	9.9	35.2	56.5	8.3	40.4	49.8	9.9			
										Cement 15365											
0.319	82.2	7.0	10.9	78.3	9.8	11.9	50.1	42.4	7.5	76.8	9.4	13.7	76.6	9.7	13.7	72.5	14.3	13.2			
0.439	62.2	29.2	8.7	60.6	29.0	10.4	51.9	38.6	9.6	60.0	27.4	12.6	58.6	28.6	12.8	56.1	31.3	12.5			
0.587	45.4	47.6	7.0	48.5	42.5	9.0	44.8	45.8	9.4	46.6	43.0	10.3	46.5	42.9	10.7	47.7	40.2	12.1			

Cement content estimated from *CaO* determination. Water content estimated from ignition loss corrected for ignition loss of cement. Silica content found by difference.

TABLE A-29—YOUNG'S MODULUS OF MORTARS USED IN SERIES 254-9

Cement No.	*w/c* at 2 hrs. (wt. basis)	Young's Modulus at Age Indicated* millions of lb/in²					
		7 days	14 days	28 days	56 days	90 days	180 days
14930J	.309	4.47	4.98	5.45	5.50	5.75	6.00
	.424	3.67	4.30	4.85	5.14	5.36	5.66
	.573	2.57	3.34	4.13	4.71	4.87	5.20
15007J	.316	5.18	5.35	5.58	5.54	5.48	5.73
	.433	4.65	4.85	5.08	5.14	5.35	5.32
	.570	4.23	4.50	4.92	5.03	5.08	(a)
15011J	.316	5.10	5.45	5.62	5.76	5.88	6.00
	.432	4.55	4.85	5.20	5.30	5.42	5.48
	.582	4.13	4.48	4.83	4.89	5.00	5.00
15013J	.324	5.05	5.17	5.30	5.40	5.47	5.65
	.443	4.37	4.68	4.85	(a)	(a)	(a)
	.611	3.78	3.97	4.36	4.45	4.50	4.65
15365	.319	5.30	5.42	5.58	5.78	5.78	—
	.439	4.64	5.27	5.03	5.18	5.40	—
	.587	4.40	4.81	4.96	5.03	5.03	—

*Values are for a single prism.
(a) Prism broken.

TABLE A-30—UNIT ABSOLUTE VOLUME COMPOSITION OF THE MORTARS USED IN SERIES 254-11

Cement No.	Ref. No.	(See page 317)	Unit Absolute Volume Composition at 2 hours				*w/c* at 2 hours, (wt. basis)
			Cement	Silica	Air	Water	
15758	11–1	A	.2395	.4660	.0437	.2526	.334
	11–2	B	.1721	.5398	.0382	.2506	.460
15756	11–3	A	.2443	.4828	.0233	.2551	.318
	11–4	B	.1781	.5604	.0087	.2525	.446
15763	11–5	A	.2434	.4827	.0237	.2508	.324
	11–6	B	.1741	.5562	.0245	.2458	.437
15761	11–7	A	Note 1	—	—	—	.334
	11–8	B	—	—	—	—	.468
15754	11–9	A	.2409	.4746	.0315	.2540	.328
	11–10	B	.1727	.5484	.0271	.2526	.449
16213	11–11	B	.1775	.5592	.0135	.2497	.443
16214	11–12	B	.1766	.5580	.0131	.2522	.448
16198	11–13	B	.1745	.5621	.0121	.2512	.443
15669	11–14	B	.1725	.5579	.0157	.2538	.451
15495	11–15	B	.1764	.5488	.0302	.2445	.442
15497	11–16	B	.1731	.5453	.0266	.2549	.464

Note 1: The specimens with Cement 15761, expanded in the molds and hence it was impossible to obtain satisfactory data for calculating the composition.
See p. 333 for description of specimens.

TABLE A-31—ANALYSES OF GRANULAR SAMPLES USED FOR ADSORPTION AND NON-EVAPORABLE WATER MEASUREMENTS IN SERIES 254-11

Cement No.	*w/c* at 2 hrs. (wt. basis)	Cement-, Silica-, and Non-Evaporable Water-Content of 35-100-Mesh Samples at Age Indicated, g/g dry weight					
		28 days			90 days		
		Cement	Silica	Non-Evap. Water	Cement	Silica	Non-Evap. Water
15758	.334	.783	.084	.134	.773	.079	.148
	.460	.598	.284	.117	.607	.258	.135
15756	.318	.788	.115	.097	.776	.108	.116
	.446	.616	.302	.082	.617	.279	.104
15763	.324	.834	.089	.077	.788	.107	.105
	.437	.647	.288	.065	.169	.289	.092
15761	.334	.802	.068	.130	.798	.059	.144
	.468	.630	.253	.117	.611	.260	.130
15754	.328	.767	.102	.131	.760	.091	.148
	.449	.591	.293	.116	.588	.277	.135
16213	.443	.5834	.3082	.1084			
16214	.448	.5864	.3130	.1006			
16198	.443	.6160	.3165	.0675			
15669	.451	.6287	.2976	.0736			
15495 (1)	.442	.5422	.3873	.0705			
15497 (1)	.464	.5560	.3424	.1016			

(1) Age 6 days.
See p. 333 for description of specimens.

TABLE A-32—FLEXURAL STRENGTH AND YOUNG'S MODULUS OF ELASTICITY OF MORTARS MADE WITH SPECIAL CEMENTS FOR THE BASIC-RESEARCH PROGRAM—SERIES 254-11

Cement No.	*w/c* at 2 hrs. (wt. basis)	Flexural Strength at Age Indicated lb/in²		Young's Modulus at Age Indicated millions of lb/in²	
		28 days	90 days	28 days	90 days
15758	.334	1395	1275	6.0	6.1
	.460	1090	970	5.5	5.4
15756	.318	1170	1295	5.8	6.4
	.446	915	1010	5.1	5.6
15763	.324	1035	1345	5.4	6.0
	.437	765	1115	4.7	5.5
15761	.334	1145	980	5.6	5.7
	.468	1015	790	5.2	5.3
15754	.328	1275	1210	6.0	6.5
	.449	1035	945	5.4	5.7

Flexural strength is the average of results for two prisms.
Young's modulus was calculated from the resonance frequency of vibration found by the electrodynamic method. The values for 28 days are the average of results for 12 prisms; those at 90 days, the average for 2 prisms.
See p. 333 for description of specimens.

TABLE A-33—ADSORPTION DATA FOR SERIES 254-11

Water-cement ratios corrected for bleeding

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement													
	Cement 15758 Ref. No. 11-1 $w_0/c = 0.334$		Cement 15758 Ref. No. 11-2 $w_0/c = 0.460$		Cement 15756 Ref. No. 11-3 $w_0/c = 0.318$		Cement 15756 Ref. No. 11-4 $w_0/c = 0.446$		Cement 15763 Ref. No. 11-5 $w_0/c = 0.324$		Cement 15763 Ref. No. 11-6 $w_0/c = 0.437$		Cement 15761 Ref. No. 11-7 $w_0/c = 0.334$	
	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days
w_n	.1707	.1912	.1962	.2227	.1229	.1492	.1325	.1684	.0922	.1335	.1013	.1487	.1621	.1798
.09	.2019	.2255	.2326	.2601	.1472	.1802	.1578	.1997	.1128	.1624	.1231	.1802	.1908	.2141
.20	.2153	.2401	.2472	.2767	.1581	.1931	.1690	.2141	.1216	.1750	.1330	.1952	.2037	.2287
.36	.2331	.2596	.2680	.2993	.1725	.2105	.1839	.2313	.1328	.1909	.1447	.2118	.2211	.2476
.47	.2448	.2730	.2844	.3179	.1813	.2217	.1940	.2457	.1414	.2005	.1535	.2246	.2339	.2615
.61	.2606	.2879	.3045	.3375	.1931	.2445	.2055	.2598	.1530	.2112	.1651	.2343	.2483	.2755
.69	.2741	.3008	.3212	.3571	.2071	.2507	.2204	.2791	.1653	.2273	.1803	.2548	.2621	.2911
.75	.2817	.3060	.3300	.3637	.2170	.2566	.2323	.2867	.1737	.2355	.1903	.2630	.2706	.3003
.81	.2931	.3176	.3452	.3798	.2295	.2706	.2469	.3065	.1833	.2458	.2012	.2782	.2808	.3137
.84	.3004	.3266	.3548	.3918	.2373	.2754	.2556	.3128	.1910	.2544	.2097	.2910	.2899	.3206
.89	.3186	.3420	.3772	.4144	.2520	.2908	.2746	.3298	.2042	.2653	.2267	.3055	.3079	.3355
.96	.3504	.3752	.4273	.4605	.2973	.3215	.3310	.3924	.2416	.3015	.2777	.3651	.3490	.3733
SSD	.3975	.4162	.5247	.5682	.3751	.3764	.4721	.5127	.3554	.3674	.4287	.5030	.3978	.4144

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement										
	Cement 15761 Ref. No. 11-8 $w_0/c = 0.468$		Cement 15754 Ref. No. 11-9 $w_0/c = 0.328$		Cement 15754 Ref. No. 11-10 $w_0/c = 0.449$		p/p_s	Cement 16213 Ref. No. 11-11 $w_0/c = 0.443$	Cement 16214 Ref. No. 11-12 $w_0/c = 0.448$	Cement 16198 Ref. No. 11-13 $w_0/c = 0.443$	Cement 15669 Ref. No. 11-14 $w_0/c = 0.451$
	28 days	90 days	28 days	90 days	28 days	90 days		28 days	28 days	28 days	28 days
w_n	.1852	.2120	.1703	.1951	.1967	.2301	w_n	.1720	.1854	.1098	.1084
.09	.2192	.2501	.2020	.2284	.2336	.2704	.081	.2043	.2188	.1322	.1283
.20	.2346	.2673	.2150	.2418	.2480	.2866	.161	.2152	.2302	.1400	.1385
.36	.2555	.2899	.2337	.2615	.2695	.3114	.238	.2229	.2380	.1454	.1472
.47	.2722	.3071	.2475	.2766	.2869	.3308	.322	.2338	.2491	.1537	.1545
.61	.2882	.3256	.2617	.2904	.2959	.3488	.36	.2394	.2552	.1569	.1582
.69	.3056	.3454	.2737	.3059	.3223	.3699	.53	.2579	.2778	.1692	.1726
.75	.3166	.3545	.2806	.3125	.3338	.3788	.70	.2826	.3080	.1944	.1951
.81	.3304	.3734	.2926	.3227	.3482	.3942	.81	.2864	.3288	.2174	.2226
.84	.3415	.3827	.2986	.3297	.3562	.4063	.85	.3144	.3401	.2262	.2334
.89	.3666	.4001	.3118	.3387	.3758	.4187	.88	.3356	.3550	.2484	.2528
.96	.4221	.4562	.3381	.3578	.4161	.4616	.96	.3691	.3906	.2903	.3090
SSD	.5350	.5626	.3887	.3991	.5289	.5560	*SSD*	.4880	.5084	.4748	.4784

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement	
	Cement 15495 Ref. No. 11-15 $w_0/c = 0.442$ Age 6 days	Cement 15497 Ref. No. 11-16 $w_0/c = 0.464$ Age 6 days
w_n	.1300	.1825
.081	.1525	.2125
.161	.1604	.2237
.238	.1659	.2309
.322	.1728	.2402
.36	.1810	.2456
.53	.1873	.2765
.70	.2100	.2990
.81	.2306	.3228
.85	.2435	.3386
.88	.2625	.3539
.96	.3151	.4028
SSD	.4515	.5100

SSD = Water content of granular sample, saturated, surface-dry for sample that had been dried and resaturated.
w_n = Non-evaporable water;
p/p_s = about 24×10^{-6}

TABLE A-34—UNIT ABSOLUTE VOLUME COMPOSITION OF THE MORTARS USED IN SERIES 254-13

Clinker No.	Ref. No.	Unit Absolute Volume Composition at 2 hours				w/c at 2 hours (wt. basis)
		Cement	Silica	Air	Water	
15367*	13–1	.2853	.2444	.0201	.4506	.494
	13–2	.2870	.2458	.0147	.4528	.493
	13–3	.2909	.2492	.0045	.4553	.489
	13–4	.2879	.2466	.0133	.4523	.491
15367**	13–1B	.2828	.2422	.0362	.4400	.486
	13–2B	.2828	.2422	.0297	.4458	.488
	13–3B	.2822	.2417	.0358	.4414	.488
	13–4B	.2849	.2441	.0240	.4476	.492
15623	13–5	.2931	.2529	.0053	.4489	.470
	13–6	.2919	.2519	.0058	.4504	.474
	13–7	.2920	.2520	.0063	.4497	.473
	13–8	.2898	.2501	.0073	.4528	.480
15699	13–9	.2827	.2436	.0204	.4537	.498
	13–10	.2824	.2433	.0219	.4530	.499
	13–11	.2816	.2427	.0232	.4529	.499
	13–12	.2796	.2410	.0297	.4503	.498
15498	13–13	.2888	.2444	.0200	.4472	.488
	13–14	.2909	.2462	.0154	.4480	.487
	13–15	.2905	.2458	.0114	.4524	.493
	13–16	.2909	.2462	.0124	.4509	.491

*First round of measurements.
**Second round of measurements.

TABLE A-35—ANALYSES OF THE GRANULAR SAMPLES USED FOR ADSORPTION AND NON-EVAPORABLE WATER MEASUREMENTS IN SERIES 254-13

Clinker No.	Ref. No.	Wt. % SO_3	w/c at 2 hrs. (wt. basis)	Composition of 35-100-Mesh Samples, g/g dry weight		
				Cement	Silica	Water
15367*	13–1	1.5	0.493	.518	.370	.111
	13–2	1.9	0.493	.519	.371	.110
	13–3	2.4	0.489	.520	.372	.108
	13–4	3.5	0.491	.524	.374	.102
15367**	13–1B	1.5	0.486	.519	.371	.110
	13–2B	1.9	0.488	.518	.370	.112
	13–3B	2.4	0.488	.518	.370	.112
	13–4B	3.5	0.492	.521	.372	.106
15623	13–5	1.5	0.470	.536	.383	.081
	13–6	2.0	0.474	.536	.383	.081
	13–7	2.5	0.473	.536	.383	.081
	13–8	3.5	0.480	.538	.384	.078
15699	13–9	1.5	0.498	.523	.373	.104
	13–10	2.0	0.499	.524	.374	.102
	13–11	2.5	0.499	.525	.374	.101
	13–12	3.5	0.498	.527	.376	.097
15498	13–13	1.5	0.488	.521	.371	.108
	13–14	2.0	0.487	.523	.373	.104
	13–15	2.5	0.493	.523	.372	.105
	13–16	3.5	0.491	.525	.375	.100

*First round of measurements.
**Second round of measurements.

Description of specimens made in series 254-11

Mortar Specimens: Cubes, 2 in.

Cements: See Tables A-1 to A-3.

Pulverized Silica: Lot 15918. Specific surface (Wagner), 6000 cm^2/cm^3.

Batches: Same as Mixes A and B of Series 254-9.

Mixing: Each batch was mixed 30 sec. dry, 1½ min. wet, allowed to rest 3 min., and then mixed 2 min. more in a small, power-driven, open-tub mixer. Batches remixed 30 sec. after slump test.

Slump Test: As in Series 254-8.

Molding: As for cubes in Series 254-9, except 15 per batch.

Measurements: As in Series 254-8.

Drying: As in Series 254-8.

Composition of Hardened Specimens: Computed as in Series 254-8. See Table A-30.

Chemical Analyses of Dried Granular Samples: See Table A-31. Determinations by same procedure as in Series 254-9.

Compressive Strength: See Table 6-1, Part 6.

Flexural Strength and Modulus of Elasticity: From prisms made from same materials in same proportions as in Series 290. See Table A-32.

Adsorption Data: See Table A-33.

Description of specimens made in series 254-13

Specimens: 2-in. cubes made of cement-silica pastes.

Cements: See Tables A-1 to A-3. Cements were prepared in the laboratory mill from plant-made clinkers. Three grinds of each clinker were made, one with no added gypsum, one with enough added gypsum to give a total SO_3 content of about 2.4 percent, and one with enough to give about 5 percent SO_3. Blends were made to give cements having 1.5, 2.0, 2.5, and 3.5 percent SO_3 and specific surface area (Wagner) of 1800 cm^2/g.

Pulverized Silica: Lot 15918. Specific surface area (Wagner), 6000 cm^2/cm^3.

Weight Proportions: Cement: pulverized silica: water = 1.0 : 0.714 : 0.5.

Mixing: Each batch was mixed with a kitchen-type mixer 2 min., allowed to rest 3 min., and then mixed 2 min. more. Mixing water was cooled before use to give batch temperature of 73 ± 2 F after mixing.

Molding: Three cubes were molded from each batch.

Measurements: As in Series 254-8.

Curing: In water at 73 F. Curing water replaced with fresh water after first 24 hr., twice weekly thereafter.

Drying: As in Series 254-8.

Composition of Hardened Specimens: See Table A-34.

Analyses of Granular Samples: See Table A-35.

Compressive Strengths: See Table 6-7, Part 6.

Adsorption Data: See Table A-36.

Series 254-16

The specimens of this series were prepared for the heat of adsorption studies described in Part 4.

Cements: The cements used were 16186 and 16189, which were prepared from two of the groups of cements described in Series 254-11. No. 16186 was a blend of two cements prepared from clinker 15367, the blend having a specific surface area of 3200 cm^2/g by the permeability method. No. 16189 had the same specific surface area, being a blend of cements prepared from clinker 15623. The clinkers were of Type I and Type II compositions, respectively.

TABLE A-36—ADSORPTION DATA FOR SERIES 254-13

Water-cement ratios corrected for bleeding
Age 28 days

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement				p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement		
	Clinker 15367 Ref. No. 13-1 $w_o/c = 0.493$	Clinker 15367 Ref. No. 13-2 $w_o/c = 0.493$	Clinker 15367 Ref. No. 13-3 $w_o/c = 0.489$	Clinker 15367 Ref. No. 13-4 $w_o/c = 0.491$		Clinker 15367 Ref. No. 13-1B $w_o/c = 0.486$	Clinker 15367 Ref. No. 13-2B $w_o/c = 0.488$	Clinker 15367 Ref. No. 13-3B $w_o/c = 0.488$
w_n	.2147	.2108	.2083	.1938	w_n	.2115	.2158	.2151
.09	.2542	.2504	.2462	.2295	.081	.2500	.2550	.2527
.20	.2732	.2660	.2619	.2438	.161	.2631	.2681	.2653
.36	.2989	.2903	.2864	.2631	.238	.2737	.2779	.2749
.47	.3181	.3101	.3027	.2774	.322	.2893	.2920	.2861
.61	.3403	.3317	.3258	.2961	.36	.2957	.2990	.2957
.69	.3605	.3540	.3439	.3159	.53	.3251	.3274	.3245
.75	.3683	.3610	.3510	.3224	.70	.3563	.3611	.3563
.81	.3854	.3765	.3681	.3396	.81	.3821	.3862	.3847
.84	.3931	.3833	.3779	.3495	.85	.3987	.4034	.3995
.89	.4091	.4046	.3987	.3730	.88	.4131	.4157	.4174
.96	.4502	.4466	.4435	.4313	.96	.4515	.4543	.4591
SSD	.6229	.5781*	.6223	.6176	*SSD*	.6279	.6199	.6206

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement						
	Clinker 15367 Ref. No. 13-4B $w_o/c = 0.492$	Clinker 15623 Ref. No. 13-5 $w_o/c = 0.470$	Clinker 15623 Ref. No. 13-6 $w_o/c = 0.474$	Clinker 15623 Ref. No. 13-7 $w_o/c = 0.473$	Clinker 15623 Ref. No. 13-8 $w_o/c = 0.480$	Clinker 15699 Ref. No. 13-9 $w_o/c = 0.498$	Clinker 15699 Ref. No. 13-10 $w_o/c = 0.499$
w_n	.2035	.1518	.1509	.1515	.1444	.1992	.1937
.081	.2407	.1779	.1744	.1737	.1671	.2346	.2290
.161	.2518	.1833	.1843	.1838	.1773	.2478	.2423
.238	.2607	.1923	.1910	.1919	.1846	.2568	.2504
.322	.2706	.2018	.2009	.2004	.1931	.2704	.2618
.36	.2783	.2072	.2054	.2056	.1989	.2771	.2693
.53	.3002	.2261	.2238	.2230	.2162	.3000	.2891
.70	.3310	.2520	.2596	.2580	.2565	.3322	.3215
.81	.3569	.2783	.2816	.2931	.2920	.3680	.3519
.85	.3752	.2988	.3003	.3112	.3115	.3739	.3603
.88	.3941	.3224	.3169	.3312	.3292	.4113	.3900
.96	.4498	.3858	.3699	.3861	.3834	.4614	.4490
SSD	.6308	.5772	.5959	.5965	.6054	.6210	.6110

(Concluded on next page)

p/p_s	Total Water Retained at Relative Vapor Pressure Indicated, g/g cement					
	Clinker 15699 Ref. No. 13-11 $w_o/c = 0.499$	Clinker 15699 Ref. No. 13-12 $w_o/c = 0.498$	Clinker 15498 Ref. No. 13-13 $w_o/c = 0.488$	Clinker 15498 Ref. No. 13-14 $w_o/c = 0.487$	Clinker 15498 Ref. No. 13-15 $w_o/c = 0.493$	Clinker 15498 Ref. No. 13-16 $w_o/c = 0.491$
w_n	.1917	.1839	.2082	.1992	.2004	.1895
.081	.2247	.2156	.2468	.2355	.2352	.2232
.161	.2373	.2183	.2600	.2474	.2472	.2352
.238	.2462	.2346	.2688	.2554	.2558	.2430
.322	.2561	.2439	.2796	.2659	.2677	.2548
.36	.2643	.2507	.2902	.2747	.2717	.2581
.53	.2828	.2667	.3151	.2957	.2945	.2781
.70	.3144	.3082	.3487	.3273	.3243	.3162
.81	.3501	.3411	.3758	.3523	.3507	.3478
.85	.3587	.3511	.3901	.3661	.3675	.3662
.88	.3920	.3762	.4130	.3848	.3927	.3857
.96	.4526	.4390	.4485	.4374	.4444	.4407
SSD	.6308	.6087	.5485	.5478	.5600	.5742

SSD = Water content of granular sample, saturated, surface-dry for sample that had been dried and resaturated.
* This figure is probably incorrect. By comparison with others, it should be about 0.617.
w_n = Non-evaporable water; p/p_s = about 24×10^{-6}.

Specimens: The specimens were $1\frac{1}{2}$x3-in. neat cement cylinders, nominal w/c = 0.50 by weight. The pastes were mixed with a kitchen-type mixer, following the 2-3-2 schedule described for earlier series. The specimens were cured continuously in water until they were used.

Results of Experiments: Experimental procedures and the results are given in Part 4 of the text.

Series 254-18

This series comprises several experiments using the high-vacuum adsorption apparatus.

Cements: The cements used were 13495, 13723-1Q, 14675, and 15365. These are cements of about average Type I composition.

Specimens: The original specimens were neat-cement pastes. As explained in the text, the samples made with cements 15365 and 13723-1Q were granules prepared previously for Series 254-9 (Ref. 15A, age 180 days) and 254-K4B (Ref. 1Q), respectively. The original specimens from which granular samples were taken were 2-in. cubes.

The specimen made with cement 13495 was a slab, cast on edge, about 0.25 cm thick and 10 cm square. The paste was mixed with a kitchen-type mixer, 2 min. mixing, 3 min. rest, followed by 2 more min. of mixing, w/c = 0.5 by weight. The mold was stored under water immediately after casting. When the paste was 1 day old, the square was cut into 1x10x0.25 cm slabs and these were stored in sealed bottles containing water-saturated cotton. After 7 years and 116 days of such storage, one of the 1x10x0.25 slabs was ground on a plate-glass surface with water and powdered emery until the thickness was reduced to an average of about 0.3 mm. This thin slab was used for adsorption measurements.

The specimen made with cement 14675 was a cylinder about 3 cm in diameter by 4 cm high. The original water-cement ratio was 0.12 by weight. The cement was mixed with the water by kneading with a stiff spatula on a steel plate. The moist mix was then loosely packed into a steel mold. By means of a close-fitting plunger and hydraulic press, the sample was compacted. The applied pressure was 24,000 lb/in^2, which was just enough to bring water to the surface of the specimen. A cross-section of the specimen at time of test was free of visible voids.

The cylinder was removed from the mold immediately after casting and then cured continuously under water in a covered can. It was 4 years 29 days old when used for these experiments.

The sample for adsorption measurements was obtained by sawing out a thin slab parallel to the vertical axis of the cylinder and grinding it to a thickness of about 0.3 mm as described above. The sample used actually comprised two such slabs, each about 1.2 x 3.8 x 0.03 cm.

Test Results. All the experimental data are given in the text.

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Job Problems and Practice

In JPP many Members may participate in few pages. So, if you have a question, ask it. If an answer is of likely general interest, it will be briefed here (with authorship credit unless the contributor prefers not). But don't wait for a question. If you know of a concrete problem solved —in field, laboratory, factory, or office—or if you are moved to constructive comment or criticism, obey the impulse; jot it down for JPP. Remember these pages are for informal and sometimes tentative fragments—not the "copper-riveted" conclusiveness of formal treatises. "Answers" to questions do not carry ACI authority; they represent the efforts of Members to add their bits to the sum of ACI Member knowledge of concrete "know-how."

The Design of Rectangular Tied Columns Subject to Bending (43-176)*

By F. E. RICHART†

The solution shown by Professor Dell* can be obtained, directly, without use of the "unit strip" method. Using the same conditions of load and working stresses, and further following his initial assumption of a depth of 36 in., steel percentage of .01 and his distribution of the steel with ⅝ of it in outer layers and ⅜ at sides of column, the procedure is simple.

Following Building Regulations for Reinforced Concrete (ACI 318-41) (see Equation 28), design the member as an axially loaded column carrying a load P, where

$$P = 400\left(1 + \frac{CDe}{t}\right)$$

From Sec. 1110, (ACI 318-41), $C = \dfrac{.18f'_c + 12800\ p}{.45f'_c\,[1 + (n-1)\ p]} = .476$

Since $\dfrac{De}{t} = \dfrac{ec}{R^2}$, $D = \dfrac{t^2}{2R^2}$

(See ACI Reinforced Concrete Design Handbook, Table 33. R = radius of gyration, transformed section.)

$$D = \frac{1 + (n-1)\ p}{\frac{1}{6} + \frac{11}{32}\,(n-1)g^2\ p} = 5.7,$$ for the steel distribution assumed.

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*See p. 89, ACI JOURNAL, Sept. 1946, *Proc.* v. 43.

†Research Professor of Engineering Materials, Univ. of Illinois, Urbana, Ill.

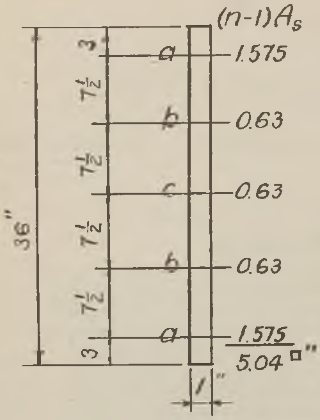

Fig. 1

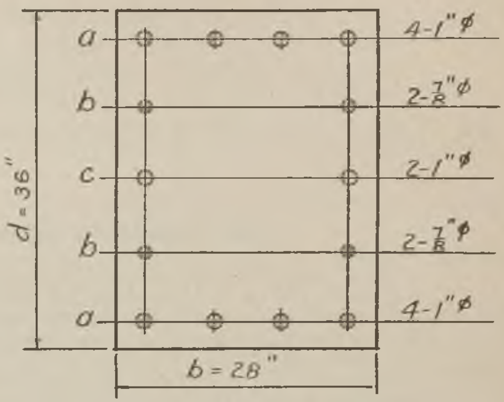

Fig. 2

(Note that if all the steel were placed in the outer layers, the fraction $\frac{11}{12}$ would be changed to ½.

$$\frac{e}{t} = \frac{1}{12}$$

$$P = 400\left(1 + \frac{.476 \times 5.7}{12}\right) = 490.4 \text{ kips} = A_g\,(.18f'_c + 12800\,p)$$

$$A_g = 1003 \text{ sq. in.} \quad b = \frac{1003}{36} = 27.9 \text{ in.} \quad \text{Use 28 in.}$$

$$A_s = 10.03 \text{ sq. in. required.}$$

Cleanouts for Forms (43-178)

By CHARLES MACKLIN*

Final cleaning of concrete cannot be done until the forms are completed. Depressed keys and low spots would be difficult to clean even if they were accessible, but in much of the form work they are inaccessible. The contractor and the inspector usually have different views on what is clean concrete. Holes are sometimes cut in the forms and a limited area may be reached or the debris flushed to another place.

A detail has been used with success and is shown in the accompanying isometric sketch (Fig. 1). The essential part of this detail is to construct a trough which will drain the depressed key and not be obstructed by the formwork. Nearly all of the debris, such as clay, sawdust, tobacco and lunch remains, can be flushed through this trough.

Troughs may be spaced at intervals of 10 to 20 ft. and can be plugged before pouring concrete. They should be large enough to serve as a hand

---

*Rural Route 6, Springfield, Illinois.

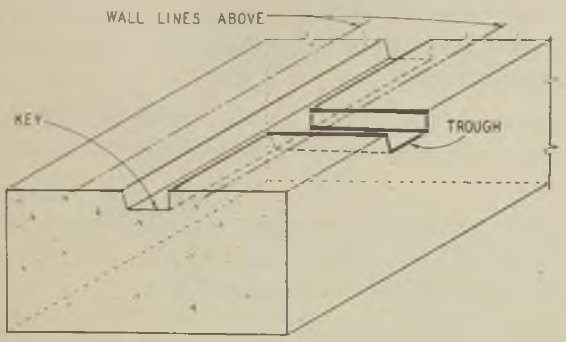

Fig. 1—Isometric sketch of trough detail.

hole and may be made from the same stock as the key. In plugging the trough opening under the forms a pressure of 10 psi is ample for holding the plug in position.

The use of this trough is helpful in column forms and under slabs and its use not only facilitates cleaning but controls the discharge of flushing water.

By R. F. BLANKS*

This is a good suggestion for the improvement of construction joint clean up. We would like to add the precaution, however, that one of these outlets is needed at each end of the joint, close up to the bulkhead. In washing with hose or air-water jets, it is difficult to get much debris to flush out a hole along the run of the joint, but it is easy to flush it out through such a hole if it is at the end of the joint.

Differences in Characteristics of Concrete in the Wet and the Dry State

(43-179)

By F. L. FITZPATRICK†

Reinforced concrete design is based upon a number of assumptions that do not hold, in many cases, during the working life of concrete.

There seems to be need for an exhaustive experimental investigation, over a range of concrete mixes, as to the physical characteristics when tested in various conditions from perfectly dry to fully saturated.

It is broadly known that: 1) concrete expands substantially (and reversibly) by moisture absorption; 2) the strength (in tension and compression, and shear) falls off as the amount of absorbed moisture increases; 3) the modulus of elasticity becomes lower as the amount of absorbed moisture increases; 4) at the same time, bond resistance tends

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*Chief, Division of Engineering and Geological Control and Research, U. S. Bureau of Reclamation, Denver, Colo.

†Rocla Limited, Concrete Engineers, Melbourne, Australia.

to increase, in saturated as compared with dry concrete; 5) the elastic behavior, and the creep (or plastic flow) are different in the case of saturated or partly saturated concrete.

Since no untreated concrete is impervious in the strict sense of the word, these fluctuations are common to all concrete, but in varying degrees.

The basis of design for bond stresses is usually the shearing force. But whereas the actual shearing and diagonal tension values fall away as concrete becomes saturated, bond resistance increases.

The respective safety factors are thereby affected.

In our business, as manufacturers of reinforced concrete pipes for, among other purposes, carrying water under pressure, we have always observed a very marked difference in hydrostatic test performance between pipes tested in air dry state and similar pipes tested in saturated condition. These pipes are of very dense concrete (centrifugally spun using a dry mix and vibration) and typical particulars are shown in Table 1.

TABLE 1

Internal Diameter Inches	Wall Thickness Inches	Circumferential reinforcement area sq. in. per in. of length	Test Pressure psi on which design is based
6	1	.021	110
12	1½	.034	90
18	1¾	.045	80

Our experience has been: 1) pipes which "sweat" under pressure when tested in the dry state will usually become quite tight under the same hydrostatic pressure, if immersed for 4 or 5 hours or more in water; 2) pre-immersion of the pipe in water thus will increase by a substantial amount the pressure required to rupture a reinforced pipe. It will reduce this pressure in the case of an unreinforced pipe.

We used to take the view that the swelling, during immersion, of the concrete, caused a sort of pre-stressing to occur, accounting for the whole improvement, but are now inclined to believe that the superior performance of a reinforced concrete pipe immediately after immersion (when tested hydrostatically) is due in part to a substantial lowering of the modulus of elasticity. This enables the concrete to stretch substantially, and so throws a greater stress upon the reinforcing steel (which in our case is usually arbitrarily figured on a stress of 16,000 psi at the test pressure—disregarding any load taken by the concrete, for the purpose of this calculation).

Failure of a reinforced concrete pipe under hydrostatic pressure occurs only when the tensile stress in the concrete of the pipe wall reaches the limiting value in tension of the concrete, and we base our designs always principally on this.

Considering a typical actual case:

Pipe internal diameter.......15 in.
" wall thickness..........1½ in.
" reinforcement area......05 sq. in. per in. of length of pipe
Modulus of elasticity of concrete in dry condition—Approx. 5,000,000 psi.

Such a pipe normally performs under test approximately as follows, when hydrostatically tested to rupture, at age of 28 days: a) in air dry state—bursting pressure 90 to 100 psi; b) in pre-saturated state—bursting pressure 110 to 125 psi.

Taking the amount of improved pressure resistance as say 22 psi hydrostatic pressure, this is equivalent to increase in tension resistance in the pipe wall of 7.5 x 22 = 165 lb. per 1 in.

We know however that the tensile strength of concrete falls off by at least 20 percent when saturated, hence other phenomena of importance come into the matter.

Figures in Table 2 can be deduced (expressed in terms per 1 in. length of pipe—where length is relevant), re the above-mentioned 15 in. pipe.

TABLE 2

	In Dry State when Tested	In Wet State when Tested
(a) Tension in wall at rupture say.....	95 × 7.5 = 712 lb.	117 × 7.5 = 877 lb.
(b) Modulus of elasticity (Approx.)....................	5,000,000 psi.	Assumed as 4,000,000 psi.
(c) Combined Area (expressed) as concrete...................... (Area concrete + (n—1) × Area of reinforcement)	1.75 sq. in.	1.825 sq. in.
(d) Tension in wall at Rupture........ Combined Area	410 psi (Approx.)	480 psi (Approx.)
(e) Loss in value (20 percent) of the section in tension due to lower tensile value of concrete when saturated	—	$\frac{1.5 \times 410}{5} = 123$ lb.
(f) Improvement in tension value of the section (due to saturation)—gross, taking (e) into consideration		(877 — 712) + 123 = 288 lb. per per 1 in. length

What has produced this 288 lb. (per 1 in. length) improvement in the resistance of the wall section to tension?

To produce such an improvement by the tensioning of reinforcement due to swelling of concrete would require a prestress in the reinforcement of $\frac{288}{.05} = 5760$ psi; also to be considered is the fact that due to drying shrinkage, there may have been a pre-compression in the reinforcement, in the dry state.

Undoubtedly the change in the modulus of elasticity, due to saturation also permits a greater elongation before fracture, so making the reinforcement take a higher share of the load—apart from any prestressing effect.

However, we feel that we do not thoroughly understand precisely what takes place.

Are we to design a concrete with a high absorption and hence a maximum swelling? Otherwise, the denser the concrete, the less the swelling, and the higher the modulus of elasticity—factors tending to low test performance, and partly at least offsetting the higher tensile strength of the concrete.

We do believe that a sound explanation of this is desirable in order to approach properly the design of any reinforced concrete structures likely to work in conditions where concrete becomes saturated at any time.

Most published tests on permeability do not cover cases where the material under test is *under tension during application of the pressure*—in our view they have therefore a very formidable difference from practice.

We should appreciate any comment by those who may have investigated or studied the intricacies of concrete behaviour under stresses, while in varying states as to moisture content.

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Current Reviews

of Significant Contributions in Foreign and Domestic Publications, prepared by the Institute's Reviewers

Beams in prestressed reinforced concrete—II

P. W. Abeles, *Concrete and Constructional Engineering*, V. 41, No. 7, (July 1946) pp. 191-199
Reviewed by Glenn Murphy

In this second installment of the series the author discusses the behavior of cracked prestressed concrete and the safety against cracking. Some of the more recent techniques for producing precast units are described and formulas given for design of fully and partially prestressed rectangular beams.

Some developments in design theories

Concrete and Constructional Engineering, V. 41, No. 7 (July 1946) pp. 181-183
Reviewed by Glenn Murphy

This article presents a condensation of the development of plastic theories for the design of reinforced concrete. The article lists the assumptions and principal results involved in the theories developed by Professor van Langendonck in Brazil, Professor Steuermann in Moscow, Professor V. M. Kelduish in Moscow, Dr. R. H. Evans in England, and by the Swiss Federal Laboratory.

Setting and disintegration of cements

G. Batta. *Bull. Soc. Chim. Belg.*, 1944, V. 53, pp. 1-25; Am. Ceram. Soc. Abs., 1945, V. 24 (8) p. 139. Building Science Abstracts, V. XVIII (New Series) No. 8, August 1945 Highway Research Abstracts

The behaviour of portland cement and sulfate-rich cement (essentially blast furnace slag and gypsum) was investigated before and after setting under the action of aggressive waters containing chlorides and/or sulfates. Sulfate-rich cements behaved well in gypsum-containing water but this is considered to arise from the formation of a protective film consisting mainly of calcium carbonate rather than to any inherent resistivity. Portland cements disintegrated principally on account of the action of the free lime content. Sulfate-aluminate formation under the action of sulfate could not be established in the sulfate-rich cement. A classification of cements is suggested on the basis of a determination of the index H which is defined as lime in solution, or lime having reacted, divided by total lime.

Greater strength, hardness and durability for concrete

T. C. Creaghan, *Building Science Abstracts*, V. XVIII (New Series) No. 8 August 1945, Engineering and Contract Rec., 1945, V. 58 (4), p. 66
Highway Resaerch Abstracts

Evidence is given to show that the use of the vacuum-concrete process for removing the excess water from concrete leads to the attainment of the following desirable aims of the concrete designer: (1) high compressive and tensile strengths, (2) low shrinkage,

(3) minimum disturbance of initial set, (4) high density (increased density of 5 to 10 percent), (5) resistance to freezing and thawing (average vacuum treated concrete will withstand 300-400 cycles), (6) good bond to old concrete in case of repairs (the new concrete being hardened under pressure is squeezed into the interstices of the old), (7) quick set (using high early strength cement and calcium chloride addition a 2000 lb. per sq. concrete can be made in 5 hours), (8) good steel bond (due to the pressure of 12.5 lb. per sq. in. exerted during compaction). It is stated that with the vacuum process, a 4-in. thick wall several feet high may have the forms stripped and bear a 200 lb. weight 15 minutes after pouring.

The proposed code for reinforced concrete of the ministry of works

Concrete and Constructional Engineering, V. 41, No. 7, (July 1946), p. 187

Reviewed by Glenn Murphy

Notice is given that the proposed Code of Practice, "The Structural Use of Normal Reinforced Concrete in Buildings," has been circulated by the Ministry of Works for comment. A number of the recommendations are the same as those in the London County Council By-laws, while others are somewhat different. For example, the ratio of coarse aggregate to fine aggregate is restricted to the limits of 1¼ to 2. Only one grade of cement is recognized and three mixtures (1:1:2, 1:1½:3, and 1:2:4 with water cement ratios of 0.43, 0.51, and 0.58) with 28 days' strengths of 4500, 3750, and 3000 psi are specified. Permissible stresses in flexure are 1500, 1250, and 1000 psi. Allowable stresses in shear are 130, 115, and 100 psi. Allowable tensile stresses in steel vary from 18,000 psi to 27,000 psi. An increase in the allowable stresses of 10 percent is permissible when the concrete is placed by vibration. The water cement ratios for the vibrated concrete are reduced 20 percent.

On the construction of concrete roads and runways

K. Norbel: Schweiz-Bauztg, 1946, V. 127 (3), p. 31. *Road Abstracts*, v. XIII, No. 7, July 2, 1946.

Highway Research Abstracts

Experience in the construction of concrete roads, and examination of Swiss roads which have already been in use for some years, lead to the following conclusions. An overall increase of slab thickness, augmented by doweling, is the most practical method of providing for the higher loads at slab edges. The sill joint recommended by P. Soutter and E. Buhlmann on mainly theoretical grounds has practical drawbacks; the sills tend to be forced into the sub-base, which leads to cracking in the adjacent slabs, and the construction of sills presents difficulties. Most longitudinal cracking seems to be due to the lack of a longitudinal joint or, in the case of a road with a longitudinal joint, to staggering of the transverse joints on either side of it. Expansion joints should be used as sparingly as possible, except before and after pronounced curves. It is not considered that concrete laid in more than one layer each having a different cement content has any practical drawbacks. As concrete slabs about 4 to 7 in. thick, laid on all types of subgrade, have proved satisfactory under heavy traffic, thicknesses of 7 to 9 in. should serve for modern airports.

Durability and void characteristics of concretes containing admixtures

National Bureau of Standards Technical News Bulletin, July, 1946 Highway Research Abstracts

In 1938 an investigation was started at the Bureau to determine the effects produced in both plastic and hardened concrete by the presence of small amounts of organic materials of the air-entraining type. These were added to the cement clinker prior to grinding. At that time the beneficial effects of air entrainment on the workability of plastic concrete and durability of mature concrete were becoming recognized, but concepts concerning the optimum amount of air entrainment and the best methods o-control of air-entrained concrete were not well formulated. Neither was there agreefment on whether the increase in durability was the result of the particular admixture used or of the entrained air regardless of its source.

In order to clarify some of these points, each of six different admixtures was interground in turn with two different clinkers, and two admixtures were added to ground plain cement at the time of mixing the concrete. Special properties of concrete made from these cements were studied by F. B. Hornibrook, Howard Freiberger, and Albert Litvin. In a report of this work, prepared for publication in the *Proceedings* of the American Society for Testing Materials, they show that the air contents of concretes made with the different cements varied over a wide range. The cement contents, flexural strength, and durability factors as determined in freezing and thawing tests, also varied over a wide range. In general, the durability factors increased with air content of the concrete, regardless of the air-entraining agent. Amounts of air in excess of 6 to 8 percent tended to reduce the durability factor.

The pore space in dried specimens was measured by an air-expansion volumenometer and was also calculated from the amount of water absorption. In many cases a larger pore space was indicated by the volumenometer method than by the absorption method. The permeability of dried specimens to air was likewise measured, but no significant difference in air permeability was found between plain concretes and air-entrained concretes.

Chemical processes in the hardening of portland cement

R. Hedin: Svenska Forskningsinstitutet for Cement och Betong vid Kungl. Tekniska Hogskolan i Stockholm, Handlingar Nr. 3, Stockholm, 1945. Building Science Abstracts, V. XVII (New Series) No. 10, October, 1945
Highway Research Abstracts

The investigations into the chemical effects of accelerators and retarders on the setting of portland cement described by Forsen in the Symposium on the Chemistry of Cements (Stockholm) 1938, have now been extended to include a very detailed study of the hardening of portland cement. The experiments and the data obtained are here recorded in full and the results discussed. The author's conclusions are as follows: The cement minerals first dissolve in water unchanged in composition, those from a frozen "melt" being rather more soluble than the crystalline ones. Ionization takes place, and some hydrolysis so that free silicic acid and aluminum hydroxide exist in solution. The addition of gypsum changes the ionic concentrations and activities; at a sufficiently high aluminate-ion concentration the free silicic acid is coagulated and the aluminum hydroxide precipitated by the silicate ions. The calcium silicate concentration is thus kept very low so that solution is extremely rapid, the reaction being exothermic. The gels formed quickly enclose the cement grains, bringing the reaction to a stop after a relatively short time. An increased calcium-ion concentration (due to additions of specially proportioned clinker) will reduce the activity of the aluminate-ions so that the coagulation of the free silicic acid is inhibited. The silicates and aluminates then form less soluble hydrated compounds so that the solution becomes supersaturated with respect to the hydrates but unsaturated relative to the anhydrous compounds. The reaction proceeds till the water is used up or the anhydrous compounds are completely hydrated, the silicate hydrate to a compound with a lime: silica ratio of 3:2 in saturated limewater or 2:1 in supersaturated limewater. The latter condition rapidly exists as the tri-calcium silicate gradually hydrates so that calcium hydroxide crystallizes out. It has been shown in this investigation that alite is very much more soluble in water than pure tricalcium silicate. The ferrites have a small solubility in water which is nearly zero if high lime and gypsum concentrations exist, so that their influence on the preceding reactions is negligible. They are, however, gradually converted to ferric hydroxide which may also envelop the cement grains and retard solution, or if present in very small amount, be converted to crystalline hydrated compounds of calcium and iron. The alkalis in portland cement being very soluble depress the concentration of the calcium ions so that silicic acid is coagulated even in the presence of excess free lime. With excess of gypsum, however, the calcium ion concentration is raised and coagulation does not occur. When a large excess of a very soluble calcium salt ($CaCl_2$) is added to portland cement, the pH value of the lime solution formed is reduced to about 11. The aluminate hydrates are then more easily soluble than the aluminum hydroxide, which crystallize out to bind the cement grains together, thus producing the so-called "flash" or false set. In the presence of borax, humus, sugar and other substances which form calcium salts with a low degree of association or insoluble calcium compounds, the calcium ion concentration in the solution is never high and hence coagulation of silicic acid is very marked, i.e. a quick set results.

Measuring stresses and deformations in solid materials

Nils Hast, *Proceedings*, No. 178, Royal Swedish Institute of Engineering Research, 1945 (in English)

Reviewed by Glenn Murphy

In this 164-page publication the author discusses the general problem of evaluating the stresses developed in the interior of solid bodies under external load. He describes the principal strain-measuring devices and various types of pressure cells and similar load-measuring apparatus. The distribution of stress in a compression specimen is discussed, and data are presented to show the weakening effect of a soft capping material such as paraffin or rubber. The author also discusses the distribution of stress around the aggregate in concrete, shrinkage stresses in concrete, and stress distribution in brick work.

In discussing the recent developments in design technique the author states, "Nevertheless, the theories of computation alone are not sufficient to advance the development in building technique. Our knowledge of the materials is not yet thorough enough for that. Reliable initial bases must therefore be established by suitable tests of the materials employed and these must be constantly maintained. From these bases theoretical speculations as to computation can then be developed. This is of special importance as regards methods of construction which have not been previously tested in practice

. . . . . .

"If, for example, it is a matter of deciding what is a permissible load on a material in a structure, we proceed as a rule in such a way that minor testbodies of the same material are manufactured and loaded to rupture. But this is not sufficient. We must penetrate into the material and become acquainted with the internal distribution of stress and its variation in building materials which as a rule are very heterogeneous, how this distribution of stress changes with the load on the material, in other words, how the material behaves right up to rupture. It will be first by this means that we shall gain such knowledge of the material that safe premises can be laid down as the basis for computing the actual bearing capacity of a structure."

The author points out the fact that the experimental evaluation of the strains on the inside of a member requires the use of a device which is small, so that it will not interfere with the normal distribution of stress, and which will have no resistance to movement. If stresses are to be measured, the device, in addition to being small, must offer the same resistance to deformation as the material in which it is inserted. He discusses the uses and limitations of mechanical devices, electrical devices, photoelectric apparatus, carbon piles, magento-elastic equipment, piezo electric gages, the photoelastic method, and X-rays, and describes devices which he has developed. These include a deformation gage which has a gage length of 1 cm. and a least count of 2 x 10.

The distribution of stress across the end of a concrete cylinder was measured with his pressure cells. Various caps were used on the cylinder including a 4-mm. layer of paraffin, a 1-mm. layer of paraffin, a 3-mm. sheet of soft rubber, a 3-mm. sheet of hard rubber, and a thin layer of oil. The load was applied in increments, and for each increment readings were taken immediately and after a lapse of time varying from 1½ to 3 hr. For each material the stress was found to vary from a maximum at the center to zero at the outside, the non-uniform distribution of stress being due to the outward flow of the plastic material. Tests were also made using porous wood fiber plates (such as masonite) as a capping material. These indicated practically a uniform stress distribution across the end of the specimen.

Studies of the distribution of stress between the aggregate and the mortar in concrete were made by inserting the author's pressure cells in the vicinity of large pieces of aggregate in test specimens. The results indicate in general that the stress at the ends of the aggregate is higher than the average (the *E* of the aggregate being greater than the *E* of the mortar), and that little stress is transferred from mortar to aggregate by adhesion of the mortar to the aggregate.

Shrinkage deformations and stresses were measured by imbedding instruments in mortar specimens. The results indicate graphically the relatively high initial shrinkage at the surface and the gradual averaging out of the shrinkage strain across the cross section as the interior of the specimen dries.

The pressure distribution in brick masonry was studied by inserting pressure cells in brick which were incorporated into test specimens. Results show an unequal distribution of load across the brick, the highest stress being at the center. The factors contributing to strong brick work are thin mortar joints, thick brick, brick with high tensile strength, mortar with high ultimate compressive strength, and reinforcement of the mortar joints. Tests were made to evaluate the modulus of elasticity and Poisson's ratio of various grades of building brick.

The publication is well written, and evidences careful work on the part of the author. Rather than giving the final word on several somewhat controversial points, the author is indicating the results of an interesting set of studies.

Beams on elastic foundation

M. Hetenyi, 1st Ed., 225 pp., Illustrated, $4.50, The University of Michigan Press, Ann Arbor, Mich.

Reviewed by Gerald Pickett

From theoretical considerations there are two basic types of elastic foundations: One type can be visualized as being composed of rows of closely spaced independent elastic springs; the other type is that of a very deep elastic solid. Except for the last chapter, the present book is concerned with the first type.

The first type is simpler mathematically, and for that reason has been used by investigators in many instances that would be more nearly represented by the second type. However, as the author states, the first type really has a far wider field of application than the second type and, therefore, in such applications should not be regarded as an approximation for the second type.

Derivations of formulas for deflections, slopes, moments and shears are given in detail in the book for almost every conceivable type of loading and end condition of beams on elastic foundations of the first type. Numerous applications are given to engineering problems. Frequent application is made to problems of circular tubes or tanks under axially symmetrical loading but not supported by an elastic foundation. For such problems the tangential forces acting on longitudinal elements correspond to elastic foundation forces and, therefore, these problems become mathematically the same as those of beams on elastic foundations of the first type. One chapter is on cercular arches.

The discussion given in Chapter X of partial continuity in the subgrade should be of particular interest to those concerned with the design of pavement slabs for highways and airports.

The courage and optimism of the author in approaching supposedly difficult problems is refreshing. It takes courage, vision, ingenuity and judgment to obtain workable and practical solutions to difficult problems. The author's solution to the problem of the wedge-shaped beam is an example of his methods. The differential equation for a wedge-shaped beam differs from that for a beam of constant width in that it contains an additional term, a third derivative. To eliminate the third derivative the author (p. 107) makes a change in the dependent variable. This change eliminates the third derivative but introduces three other terms, making a total of five terms in the new differential equation. The author discards three of the five terms and is thus able to write a comparatively simple solution of the reduced equation. Although the simple solution only approximates the correct solution, the author indicates that the difference is negligible for most practical applications. As in this case the author is usually careful to point out the principal limitations of his simplified solution.

In a number of cases the writer would prefer a somewhat different interpretation or emphasis, but on the whole, he considers that the book strikes a good compromise between rigorous and simple treatment, and between detailed development of, and brief statement of formulas.

The writer questions the derivation of the solution given for the problem of a beam of linearly varying depth. (Art. 32). For the fourth order differential equation applying in this case

$$x^3 \frac{d^4y}{dx^4} + 6x^2 \frac{d^3y}{dx^3} + 6x \frac{d^2y}{dx^2} + \frac{k}{EI_0} y = 0$$

the author suggests solutions of the form

$$y = \sum_{0}^{\infty} a_n \left(\frac{x}{l} \right)^{m+n}$$

In order that the above infinite series satisfy the differential equation, the coefficients must be related as follows

$$a_n = \frac{-kl}{EI_o \, (m+n-1) \quad (m+n)^2 \quad (m+n+1)} \quad a_{n-1} \, ,$$

and m must be a root of

$$(m-1) \, m^2 \, (m+1) = 0.$$

The author evidently thought that the sum of four such series with m taking in turn each of the four roots indicated by the equation for m would constitute a general solution. The author states that only that series with $m=1$ will satisfy the condition that $y = 0$ at $x = 0$ and therefore the single series with $m = 1$ is the solution of the problem. The conclusion is no doubt correct, but the reasoning is faulty for two reasons. In the first place, two of the four roots for m are equal, leaving only three distinct roots; $m = -1$, $m = 0$, and $m = 1$. In the second place, when the three series corresponding to the three distinct roots for m are written, and account is taken of the necessary relations between the coefficients, it is found that except for a multiplying factor all three series are actually identical, and therefore are not independent solutions.

Since there are four independent solutions of a fourth order differential equation, and since the form suggested by the author yields only one of these solutions, there exists three other independent solutions. The additional independent solutions can be obtained by repeated application of the method explained by Biot and Von Karman.*

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*"Mathematical Methods in Engineering", Chapter 2, McGraw-Hill, New York, 1940

When this method is applied once, the following is obtained for a second solution

$$y = \log\frac{x}{l}\sum_{0}^{\infty} a_n \left(\frac{x}{l}\right)^{n+1} + \sum_{0}^{\infty} b_n \left(\frac{x}{l}\right)^{n}$$

where

$$a_n = -\frac{\propto}{n(n+1)^2\,(n+2)}\,a_{n-1}$$

$$b_o = -\frac{2a_o}{\propto}$$

$$b_{n+1} = -\frac{(4\,n^3 + 12n^2 + 10n + 2) - \propto a_n}{n(n+1)^2\,(n+2)}$$

$$\propto\ = \frac{kl}{EI_o}$$

The third solution is of the form

$$y = \left(\log\frac{x}{l}\right)^2 \sum_{0}^{\infty} a_n \left(\frac{x}{l}\right)^{n+1} + \log\frac{x}{l}\sum_{0}^{\infty} c_n \left(\frac{x}{l}\right)^{n} + \sum_{0}^{\infty} d_n \left(\frac{x}{l}\right)^{n}$$

and the fourth solution is of the form

$$y = \left(\log\frac{x}{l}\right)^3 \sum_{0}^{\infty} a_n \left(\frac{x}{l}\right)^{n+1} + \left(\log\frac{x}{l}\right)^2 \sum_{0}^{\infty} e_n \left(\frac{x}{l}\right)^{n} + \log\frac{x}{l}\sum_{0}^{\infty} f_n \left(\frac{x}{l}\right)^{n} + \sum_{0}^{\infty} g_n \left(\frac{x}{l}\right)^{n}$$

Since the author had available only one series containing only one arbitrary constant, and he still had two conditions to satisfy at $x = l$, it followed that the single series gave a solution only for a special relation between the properties of the beam and foundation. For the argument to be accepted, it seems that it should be proven that none of the other three independent solutions apply in this case, and to do this, the other three solutions must be known.

Perhaps the rigorous treatment here suggested is out of place in a book of this kind; the author has probably picked the best balance between rigor and simplicity.

Although the writer has not read every sentence, and has checked only a small portion of the mathematical work, he is of the opinion that the book is relatively free of errors. One should expect a number of errors in the first edition of a book in a new field.

Consulting engineers, and those in the design field should welcome this book.

ACI News Letter

Vol. 18 No. 3 JOURNAL of the AMERICAN CONCRETE INSTITUTE November 1946

In the foregoing Proceedings pages of this Journal you will find, this month:

News Letter Contents this Month

ACI BOARD APPROVES PLANS FOR MORE SERVICE

New committee will consolidate ACI technical activities

A new Technical Activities Committee is soon to succeed to the combined functions of the present Advisory and Publications Committees. It will consolidate in one group under the authority of the Board of Direction, responsibility for the subject matter of ACI technical publications and convention programs, inaugurating and supervising the work toward the Institute's chartered objectives—"gathering, correlating and disseminating information for the improvement of the design, construction, manufacture, use and maintenance of concrete products and structures."

Action to this end was taken by the Board at its October meeting, based on recommendations of its Executive Committee in presenting a plan for streamlining administrative procedure to deal more effectively with the expansion and diversification of the Institute's technical program, by two principal devices:

1) a relatively small steering committee (nine members) to deal with all technical activities, for administrative action;

2) a large body of consultants, recruited from ACI membership in as many areas of specialization as technical projects demand—to advise as individual specialists or as groups representing communities of interest, for:

a) critical consideration of contributions offered for ACI publication;

b) competent preliminary survey of the best means for developing information on any proposed project—whether by individual papers or committee reports—and choice of personnel for the preferred means.

The Institute's technical work was for some years shared by a Program Committee with the annual convention as its special responsibility; an Advisory Committee setting up and supervising the work of all technical committees; and a Publications Committee responsible for the technical content of the Journal and some special publications.

The first step a few years ago toward consolidation of responsibility was in abolishing the Program Committee and adding its duties to those of the Publications Committee, since the development of convention programs carried some implied obligations to publish.

The present further consolidation stems from the fact that both Advisory and Publications Committees work to the same end—"gathering information"—but in general by different means. The final choice of these, where intelligent choice was to be made, rested usually with the Board.

There are stages in the emergence of knowledge in special areas when individual papers may serve best; further stages in which committee action carries with it the advantages of correlation toward a consensus.

Recognizing the oneness of Institute objectives and the inter-relatedness of many specialized areas of knowledge, the new administrative set-up tends to provide a means for an important, many-sided advisory body to give counsel, and a very small group to turn advice into action.

This reorganization does not disturb the special, critical and judicial functions of the Standards Committee which will continue with its established responsibilities.

The new committee will be constituted as follows: the chairman appointed annually by the Board of Direction from among its own members to serve for the ensuing convention year, the President and the Secretary-Treasurer (these three to serve as the committee's executive group for necessary prompt action between meetings) and six other Institute members chosen by the Board for such terms that three new appointments or re-appointments shall be made for each convention year.

The new committee takes over (with some modification) the broad framework of divisions of interest within which the Advisory Committee has functioned. This is not without realization that knowledge won't stay in sealed containers; that "divisions" of interest are neither stationary nor self-sufficient; that proper functioning of the Technical Activities Committee requires of its personnel a blending of broad over-all knowledge with a range of specialized knowledge which can be achieved only by the active counsel of many consultants outside its membership.

Thus, the new set-up as envisaged holds two important possibilities for ACI:

1) administrative facility in undertaking an increasingly active program for greater service to a rapidly growing membership;

2) participation by a much greater number of Institute members. It is probably trite to say that the general health of any such organization as ACI will be charted in a rising curve of membership participation.

Following is the set-up of divisions of interest as taken over with some revisions from the departmental set-up of the Advisory Committee.

Concrete research: The promotion of basic and applied research in concrete and concrete materials and the exchange of information on procedure and technique among research men.

Properties of mortars and concretes: Includes such properties of concrete as durability and disintegration phenomena, strength, elastic and plastic properties, volume change, bond, extensibility, watertightness, etc. and the influence of various factors on such properties.

Engineering design: Structural analysis, loads and stresses, engineering and architectural treatments, etc. for buildings, marine structures, hydraulic structures, bridges, railroads, highways, airfields, etc.

Concrete materials and mix design: The physical, chemical, petrographic and concrete-mix making properties of concrete materials; the production or manufacture of such materials; and the design of concrete and mortar mixes. Includes all materials used in compounding concrete, such as cements, aggregates and admixtures; materials embedded in concrete, such as reinforcing, water stops, anchors and materials applied to concrete surfaces, such as paints, curing compounds, waterproofing materials. Includes concrete mix design and those properties of fresh concrete which are essential factors in mix design, such as workability, consistency, plasticity, air content, yield, unit weight.

Concrete construction: Job methods and equipment for all concreting operations, such as batching, mixing, forms, handling, placing, finishing, curing, protection, grouting, cleanup, chipping, bushing, patching, and special concrete construction, such as stucco, gunite, prepacked.

Prefabricated concrete: The design, production and use of prefabricated concrete units such as masonry, architectural and structural units and pipe.

Concrete repair and maintenance: The maintenance, repair and rehabilitation of all types of concrete structures.

Joint activities: All activities carried out jointly or in cooperation with representatives from other organizations.

Proposed for ACI are a newly constituted Board of Direction and higher dues

It is a prerogative of the membership to amend the By-Laws. All the Board of Direction could do after discussion both at Denver in June and at Lake Placid in October was to recommend By-Laws amendment after most careful study of two problems. Each problem had had the consideration and special study of a Board committee. As to Board reconstitution:

More than a year ago, the Board appointed a special committee to "divide the territory occupied by the membership in the six geographical districts, to be designated by numbers, each to be represented by a regional director" (see By-Laws—Article II, Sec. 2).

The membership had increased and as a whole it had shifted geographically. Attempts to equalize the membership among the six regions did not present satisfactory results—districts tended to sprawl with some lack of geographical homogeneity or order.

The Board then considered *why* geographical districts? science has no geographical boundaries; the *man is* more important than his place of legal residence? geographical spread is no more important than spread of professional background, job allegiance and specialization, plus demonstrated potentialities for serving the ACI cause. Thus the Board has recommended and its members (as individual ACI members) and others will shortly be petitioning for By-Laws amendment for reconstitution of the Board as now presented in Article II to effect a future Board made up as follows (provided the convention approves and the membership at large ratifies by letter ballot): a President for a one-year term; two Vice-Presidents for two-year terms (one elected each year); twelve Directors (chosen by the nominating committee with due regard to geographical spread and professional diversification) elected for such terms that four new directors are chosen each year. (An interim provision would continue present directors-at-large whose terms would expire subsequent to the effectiveness of the amendment); three former Presidents last past who remain members of ACI; a Secretary-Treasurer as appointed annually by the Board.

Not only has the Institute increased its publications program (ten Journal's a year instead of six) and increased its staff for greater service, but the cost of materials, services and headquarters space have all increased. The Board faced the need for some recognition of increased burden—especially so in view of still further staff increases needed. The upshot is Board recommendation of By-Laws amendments increasing annual dues rates as follows:

Contributing membership, unchanged at $50.00; Corporation membership increased from $20.00 to $25.00; Individual membership $10.00 to $12.50 (*except* that individual membership dues outside United States will remain at $10.00.); Junior $6.00 to $7.50 and Student $3.00 to $5.00.

Board action taken and recommendations made at the meeting October 7 and 8 seemed to hold large possibilities for the Institute's future. Encouraged by the rapid post-war growth of membership and increased demands for ACI publications, the Board was emphatically "bullish" for ACI. Auspicious, too, was the presence of sixteen of the eighteen Board members for the Lake Placid Club meeting.

—Harvey Whipple

New Members

The Board of Direction approved 87 applications for Membership (64 Individual, 3 Corporation, 15 Junior, 5 Student) received in September.

The Membership total on October 1, 1946, after taking into consideration a few losses by death, resignation and for nonpayment of dues, is 2853.

Abadia, Marcelo, 8 Jose Severo Quinones St., Santurce 34, Puerto Rico

Abraham, J. G., No. 10, Cinna Reddy St., Egmore, Madras, South India

Allied Supply Corp., 1000 Harris St., Charlottesville, Va. (C. Wilson McNeely)

Apthorpe, Robert H., 131 Trafalgar St., Stanmore N. S. W., Australia

Armstrong, H. E., 584 MacLaren St., Ottawa, Ont., Canada

Austin, Harold B., 115 S. Jefferson Ave., Peoria, Ill.

Barker, William D., c/o City Engineers, Ross Dam, Rockport, Wash.

Beckman, Wallace J., 1930-64th St., Brooklyn, N. Y.

Boynton, Robert S., National Lime Association, 927-15th St., N. W., Washington 5, D. C.

Brown, H. C., Canada Cement Co., Belleville, Ont., Canada

Callejas H., Rafael, 8a Calle Poniente No. 62, Guatemala City, C. A.

Case, John, 811 W. Third St., Los Angeles 13, Calif.

Chibaro, Anhony, 58 Paulson Rd.,Waban, 68, Mass.

Childs, Leonard C., 231 S. LaSalle St., Chicago 4, Ill.

Clepper, Frank L., 1024 Dixie Terminal, Cincinnati, Ohio

Concrete Products Corp., R. R. No. 6, Box 4, South Bend, Ind. (P. E. Bohm)

Curtis, George W., 1000 S. Fremont Ave., Alhambra, Calif.

De Blas, Isidoro, c/o Spanish Embassy, 2700-15th St., N. W., Washington, D. C.

Deedes, Walter E., P. O. Box 1168, Reno, Nev.

DeLong, John A., 523 N. 40th St., Omaha, 3, Nebr.

Deuel, C., 4052 Braeburn Way, Los Angeles 27, Calif.

Driscoll, James A., 865 E. 45th St., Brooklyn 3, N. Y.

Durrani, N., Public Works Department, Madras, India

Dusting, Ronald A. S., No. 2 Tennyson Cresent, Forrest Canberra A. C. T., Australia

Gamalero, M. W., The Institute of Inter-American Affairs, 6th Ave., Sur 54, Guatemala, C. A.

Glace, Ivan M., 1001 N. Front St., Harrisburg, Pa.

Gordon, Ronald A., 122 Library Avenue, Wilmington, Ohio

Guest & Sons, C. M., Anderson, S. Carolina (Walter C. Guest)

Hagstrom, R. E., North Central Supply Co., 742 Arundel, St. Paul 3, Minn.

Hall, Roger T., c/o Spidel & Hall, Inc., 1427 Eye St., N. W., Washington 5, D. C.

Hansen, Alfred E., Michigan Theatre Bldg., Muskegon, Mich.

Harwood, Warner, 33 W. Grand Ave., Chicago 10, Ill.

Helland, H. R. F., 904 Frost National Bank Bldg., San Antonio 5, Texas

Hinkson, N. L., 916 Ford St., Golden, Colo.

Hogg, Dwight A., P. O. Box 21, West Hartford 7, Conn.

Homann, Gerald W., 9 De Wolfe St., Cambridge 38, Mass.

Hotes, Frederick L., 1147 S. Adams St., Denver 10, Colo.

Hyslop, Robert B., N. 2913 W. Oval, Spokane 12, Wash.

Jacobus, R. W., c/o Virginia Steel Co. Inc., Richmond, Va.

Kantawala, K. K., c/o Public Works Department, Secretariat Fort, Bombay, India

Kendrick, Edwin A., 45 Minnesota Ave., Five Dock, Sydney, N. S. W., Australia

Kochhar, R. K., c/o Chief Engineer, Public Works Department, Buildings & Roads (West) Lucknow, India

Kopetz, George E., P. O. Box 5087, East Liberty Station, Pittsburgh 6, Pa.

Larson, Carl W., 124 S. Jackson St., Aberdeen, S. Dakota

Lewin, David V., 2300 Chester Ave., Cleveland, Ohio

McCarty, Irving J., 1846 Washington Blvd., Chicago 12, Ill.

McClintock, E. C., Department of Engineering, University of Virginia, Charlottesville, Va.

McKenrick, R. P., c/o Blaw Knox Co., Box 1198, Pittsburgh, Pa.

Malone, Robert E., 4516 N. Kenton, Chicago 30, Ill.

Marbury, Willard H., Mountain Home, Ark.

Matheson, Victor R., 4 Towns Rd., Rose Bay, Sydney, N. S. W., Australia

Mayper, Victor, 110 W. 40th St., New York, N. Y.

Misra, K. N., Executive Engineer, Public Works Department, 40 Grainmarket, Ganeshgunj, Lucknow, United Province, India

Mitchell, M. S., c/o Meech, Mitchell & Meech, 114 McFarland Bldg., Lethbridge, Alberta, Canada

Moran, Robert L., Aerocrete Construction Co. Ltd., 447 Victoria Park Ave., Toronto 13, Ont., Canada

Morgan, Jr., Newlin D., Dept. of Civil Engineering, University of Wyoming, Laramie, Wyo.

Mueller, E. J., Portland Cement Association, 1627 Dierks Bldg., Kansas City 6, Mo.

Mukerjee, A. C., 5 Trilok Nath Road, Luknow, India

Muldowney, Walter E., 1120 Connecticut Ave., Washington, D. C.

Nambiar, K. K., City Engineer, Corporation of Madras, Madras, India

Owens, William H., 248 Boylston St., Boston 16, Mass.

Pardey, Paul L., 6 Wattle Ave., Manly, Sydney, Australia

Pierce, George O., 532 Orange Grove Ave., South Pasadena, Calif.

Potts, George S., 48 Lancelot St., Five Dock, Sydney, N. S. W., Australia

Pugsley, W. E., Concrete Transport Mixer Co., 650 Rosedale, St. Louis 12, Mo.

Reddy, K. R., Greamspet, Chittoor, Madras, S. India

Richardson, James R., Cliff St., Plymouth, Mass.

Sandstedt, Carl Edward, A & M College of Texas, College Station, Texas

Sasso S., Samuel A., Apartado 186, San Jose, Costa Rica

Schaeffler, Joseph C., 78 Irving Place, New Rochelle, N. Y.

Schmidt, Jr., L. A., Chattanooga Bank Bldg., Chattanooga 2, Tenn.

Selby, Lennon, 211-A High Tower Bldg., Oklahoma City 2, Okla.

Shoemaker, William L., 1216 Lenox, Detroit 15, Mich.

Speckels, M. L., Box 672, Kingman, Ariz.

Swanberg, John H., Minn. Dept. of Highways, Exp. Eng. Bldg., University of Minn., Minneapolis, Minn.

Taylor, Joel H., 623 E. Emerson Place, Wilmar, Calif.

Teshima, Harry T., Skating Rink Dorm., 406 E. Armory St., Champaign, Ill.

Thelin, C. Milo, City Hall, Fort Worth, Texas

Velutini, Becla, Altagracia a Salas No. 22, Caracas, Venezuela, S. A.

Viole, Laurence D., 3220 Laurel Canyon Blvd., No. Hollywood, Calif.

Walker, John W., 2024 Blanding St., Columbia, S. C.

Wall, James D., Y. M. C. A., Vicksburg, Miss.

Wallace, W.W.,Portland Cement Association, 33 W. Grand Ave., Chicago 10, Ill.

Wang, Shou Chang, UNRRA Fellowship Section, 1344 Connecticut Ave., Washington 25, D. C.

Weaver, Wayne L., 1319 Second Ave., Boulder, Colo.

Westby, S. H., 830 Wing St., Elgin, Ill.

Williams, H. Roger, The Plaza, Palm Springs, Calif.

WHO'S WHO in this JOURNAL

Richard J. Willson

an ACI Member since 1936, is author of the paper "Lining of the Alva B. Adams Tunnel" which appears on p. 209 of this JOURNAL. A native of Colorado, Mr. Willson studied mining engineering at the Colorado School of Mines. In 1930 he entered the employ of the Bureau of Reclamation as a laborer digging test pits during the investigation of earth embankment materials for Cle Elum Dam in Washington.

He has been with the Bureau since that time with the exception of two years spent with the Callahan Construction Company and Peterson, Shirley, and Gunther during the construction of Madden Dam in Panama.

As a Bureau employee he has come up "through the ranks" to his present position as field area engineer on the Colorado-Big Thompson Project with headquarters at Grand Lake, Colorado. During this period he has had many assignments inincluding hydraulic laboratory model studies, concrete and aggregate investigations for Boulder Dam, foundation drilling and grouting, fabrication of reinforcing steel and concrete mixing plant supervision. In his present assignment he is responsible for the field construction in the western area of the Colorado-Big Thompson Project, including the inlet structures for the tunnel, Granby Dam and dikes and the Granby pump plant and pump canal.

A. Burton Cohen

whose paper "Repair of the Spruce Street Bridge, Scranton, Pa." appears on p. 241, has been a member of the Institute since 1910, and in 1926 became a Wason Medalist with his paper "Correlated Considerations in the Design and Construction of Concrete Bridges." Mr. Cohen received his B.S. in C.E. degree from Purdue University in 1905 and his C.E. degree from there in 1910. Immediately following graduation he accepted a position in the engineering department of the Lackawanna Railroad at Hoboken, N. J., an association which continued until 1920. During this period, Mr. Cohen specialized in reinforced concrete design and grade crossing elimination work in an extensive program of railroad and civic improvement applying concrete design to gain aesthetic and economic value.

From 1910 to 1920 Mr. Cohen was in charge of the design of all concrete structures built on extensive grade revision work for the Lackawanna including the Tunkhannock and the Martin's Creek Viaducts, two of the largest of such railroad structures in the world. In this period he was also responsible for the design of the extraordinary flat-slab viaduct of the Buffalo Terminal improvement and the South Orange track elevation work, and upwards of 200 grade crossing eliminations through the highly developed suburban section of New Jersey and elsewhere along the Lackawanna Railroad.

Since 1920 Mr. Cohen has been in private practice and has been responsible for the design and construction of many major bridge and grade crossing elimination projects in the eastern states. He was recently commissioned by the city of Niagara Falls to prepare general plans for the elimination of all grade crossings throughout the city.

In addition to his Wason Medal paper and the present paper, Mr. Cohen is author of the following ACI papers: "Progress and Development of Concrete work on the Lackawanna Railroad' (1914), "Reinforced Concrete Flat Slab Railroad Bridges" (1918), and "Supervision and Inspection of Concrete" (1936).

In addition to his membership in the ACI, Mr. Cohen is a Member of A. S. C. E. and Member A. S. T. M. Mr. Cohen was also chairman of ACI Committee S2 "Reinforced Concrete Highway Bridges and Culverts," a member of the ACI Advisory Committee from 1924 to 1930, a member of the Board of Direction as Director, Second District from 1942 to 1944.

Honor Roll

February 1 to Sept. 30, 1946

The Honor Roll for the period February 1, to Sept. 30, 1946 finds T. E. Stanton leading with 22 members and J. L. Savage a close second with 21.

T. E. Stanton	22
J. L. Savage	21
E. W. Thorson	10
R. D. Bradbury	9
Walter H. Price	9
C. C. Oleson	8
Henry L. Kennedy	7
Anton Rydland	6½
J. A. Crofts	6
Newlin D. Morgan	6
Charles E. Wuerpel	5½
Jacob Fruchtbaum	5
Ray C. Giddings	5
Karl W. Lemcke	4½
Hernan Gutierrez	4
Martin Kantorer	4
James A. McCarthy	4
K. E. Whitman	4
H. B. Emerson	3½
E. F. Harder	3½
F. E. Richart	3½
A. Amirikian	3
Birger Arneberg	3
D. R. Cervin	3
Raymond E. Davis	3
Miguel Herrero	3
C. A. Hughes	3
James J. Pollard	3
Lewis H. Tuthill	3
C. S. Whitney	3
A. J. Boase	2½
W. A. Carlson	2½
T. F. Collier	2½
Grayson Gill	2½
H. M. Hadley	2½
Alberto Dovali Jaime	2½
O. G. Julian	2½
F. N. Menefee	2½
E. M. Rawls	2½
H. F. Thomson	2½
Stanton Walker	2½
Wm. R. Waugh	2½
Rene L. Bertin	2
J. F. Barton	2
Emil W. Colli	2
Aloysius E. Cooke	2
R. W. Crum	2
Issac Hausman	2
Denis O. Hebold	2
John T. Howell	2
F. R. McMillan	2
Robert L. Mauchel	2
J. J. Mullen	2
Dean Peabody	2
Henry Pfisterer	2
Raymond C. Reese	2
R. D. Rogers	2
Simeon Ross	2
Moe A. Rubinsky	2
John A. Ruhling	2
H. C. Shields	2
LeRoy A. Staples	2
H. D. Sullivan	2
Flory J. Tamanini	2
J. W. Tinkler	2
John Tucker, Jr.	2
I. L. Tyler	2
Paul L. Battey	1½
R. H. Bogue	1½
H. F. Faulkner	1½
H. J. Gilkey	1½
E. J. Glennan	1½
Axel H. Johnson	1½
Thomas M. Kelly	1½
T. R. S. Kynnersley	1½

Raul Lucchetti	**1½**
John J. Murray	**1½**
Y. G. Patel	**1½**
J. C. Pearson	**1½**
R. D. Rader	**1½**
N. L. Shamroy	**1½**
Thomas C. Shedd	**1½**
A. L. Strong	**1½**
LeRoy A. Thorssen	**1½**
Paul W. Abeles	1
Julius Adler	1
Kasim Atlas	1
Joseph Avant	1
A. F. Barabas	1
J. F. Barbee	1
Hugh Barnes	1
H. J. Bateman	1
F. J. Beardmore	1
R. F. Blanks	1
Joseph W. Body	1
E. K. Borchard	1
H. C. Boyd	1
H. A. Bradt	1
Raymond L. Brandes	1
J. M. Breen	1
S. D. Burks	1
M. E. Capouch	1
Antonio J. Carbonell	1
R. W. Carlson	1
T. J. Cavanagh	1
Frank W. Chappell	1
Anthony D. Ciresi	1
Chas. A. Clark	1
A. R. Collins	1
John Conzelman	1
Holly A. Cornell	1
W. S. Cottingham	1
G. H. C. Crampton	1
Charles A. Daymude	1
F. K. Deinboll	1
C. T. Douglass	1
Clifford Dunnells	1
D. W. Faison	1
Jess Fellabaum	1
A. G. Fleming	1
Alexander E. Forrest	1
Alexander Foster	1
Herman Frauenfelder	1
Meyer Fridstein	1
J. K. Gannett	1
James F. Gill	1
D. E. Gondolfi	1
E. Gonzales Rubio	1
Fred A. Gorham	1
L. E. Grinter	1
Ernst Gruenwald	1
Elliott A. Haller	1
M. J. Hawkins	1
Elmo Higginson	1
Frank R. Hinds	1
G. H. Hodgson	1
W. M. Honour	1
Lyman G. Horton	1
O. W. Irwin	1
M. E. James	1
R. O. Jameson	1
Wm. R. Kahl	1
R. R. Kaufman	1
Edgar R. Kendall	1
Edward F. Keniston	1
Orville Kofoid	1
Guy H. Larson	1
H. Walter Leavitt	1
B. Leon	1
L. S. LeTellier	1
Arthur A. Levison	1
Elbert F. Lewis	1
Bartlett G. Long	1
F. A. Luber	1
James E. McClelland	1
M. J. McMillan	1
Edward P. McMullin	1
F. R. MacLeay	1
D. G. Marler	1
Charles Miller	1
Hugh Montgomery	1
Robert B. B. Moorman	1
Rene Pulido y Morales	1
Ben Moreell	1
I. Narrow	1
Wm. T. Neelands	1
Paul W. Norton	1
Ben E. Nutter	1
Philip Paolella	1
D. E. Parsons	1
A. F. Penny	1
Richard L. Pinnell	1
Harry W. Piper	1
C. J. Posey	1
Herman G. Protze Jr.	1
C. C. Pugh	1
Erik Rettig	1
George P. Rice	1
E. O. Rosberg	1

Maurice G. Roux	1
Arthur Ruettgers	1
G. R. Schneider	1
Herman Schorer	1
John C. Seelig	1
George G. Smith	1
J. H. Spilkin	1
J. Antonio Thomen	1
Hugh F. Tolley	1
Bailey Tremper	1
Harold C. Trester	1
Oscar J. Vago	1
Joseph J. Waddell	1
W. W. Warzyn	1
David Watstein	1
Piers M. Williams	1
George C. Wilsnack	1
Ralph E. Winslow	1
Douglas Wood	1
Ray A. Young	1

The following credits are, in each instance, "50-50" with another Member.

B. G. Anderson
A. Arnstein
J. B. Baird
Michel Bakhoum
Sabahattin Basman
E. Ben-Zvi
E. O. Bergman
Hugh Bigler
Carlos Blaschitz
G. C. Britton
Ernest L. Brodbeck
Fred Burggraf
Fred Caiola
Miles N. Clair
A. B. Cohen
Sam Comess
W. A. Coolidge
R. A. Crysler
Atahualpa Dominguez
G. J. Durant
E. E. Edwards
A. C. Eichenlaub
Axel Erikeson
Harry R. Erps
Cevdet Erzen
E. E. Evans
K. P. Ferrell
G. V. Gezelius
Howard A. Gray
Per O. Hallstrom
Hunter Hanly
Shortridge Hardesty
George N. Harding
H. L. Henson
A. W. Hicks
R. B. Hindman
Meyer Hirschthal
Wm. A. Hohlweg
Ralph B. Horner
Fred Hubbard
Manuel Castro Huerta
H. D. Humphries
W. C. Huntington
Frank H. Jackson
V. P. Jensen
Bruce M. Johnson
Paul A. Jones
George L. Kalousek
W. D. Kimmel
Lane Knight
Henry M. Lees
Wm. Lerch
J. A. McCrory
Douglas McHenry
Ian Macallan
J. B. Macphail
Sidney M. Major Jr.
Charles Mannel
George W. Meyer
Eugene Mirabelli
C. C. More
A. B. L. Moser
Fernando Munilla
T. D. Mylrea
D. Lee Narver
H. T. Nelson
N. M. Newmark
Syberen Frank Nydam
George L. Otterson
Wm. D. Painter
George P. Palo
R. S. Phillips
James D. Piper
David Pirtz
R. F. Powell
Robert B. Provine
Frank A. Randall
F. V. Reagel
Melvin S. Rich
T. E. Shelburne
C. E. Shevling
Harold Oliver Sjoberg
Marvin Spindler
Charles M. Spofford
D. J. Steele
Henson K. Stephenson
Hale Sutherland
M. O. Sylliaasen
R. W. Ullman
Zaldua Uriarte
Jose Vila
D. S. Walter
Ray V. Warren
J. C. Watt
E. C. Wenger
Herbert J. Whitten
Eugene P. H. Willett
E. T. Wiskocil
Ernest B. Wood
R. B. Young

Fritz Emperger

By P. W. Abeles

Dr. Fritz Emperger, Honorary member of the ACI died in Vienna on February 7, 1942. The son of an Austrian technician, he was born on January 11, 1862 and studied civil engineering at the Technical Universities of Prague and Vienna and took his degree in 1885. After having visited the World exhibition in Paris in 1889, he came to the United States and worked as a consulting engineer in New York until 1897. Dr. Emperger built the first bridges combining the use of steel and concrete (Edenpark Bridge in Cincinnati, Ohio and the Housatonic Bridge in Stockbridge. He established the Concrete Steel Construction Co. which subsequently built many such bridges including those under the railway station at Detroit, Mich. From 1897 till 1902 Emperger lectured at the Technical University, Vienna. Afterwards he worked as a consulting engineer, writing and editing publications on reinforced concrete. He founded the well known periodical *Beton und Eisen, Beton Calendar* and a text book on reinforced concrete, whose many volumes have already appeared in their 4th edition.

Much of Dr. Emperger's time was spent in research of reinforced concrete, and he became a driving force in its development. He was the leading personality in the Austrian Reinforced Concrete Committee, established in 1906. He was appointed Chairman of this committee in 1926, after having been Vice-chairman since 1912, and carried out very extensive investigations. As a scientist, Emperger worked mainly by intuition and could draw correct conclusions without lengthy theoretical deliberations. Among his important investigations are those on the co-operation of concrete and steel in columns, on bond resistance and on cracking. He was never afraid of the unorthodox in his methods and, indeed, in his whole attitude. Any new idea of some value received his support. Even in his old age he carried on with his work and devoted his energy to the development of reinforced concrete. At the age of 77 years he made a suggestion regarding partial prestressing as his answer to M. Freyssinet's "Une Revolution dans les Techniques du Beton" (Paris 1936).

Emperger worked for international collaboration not only in reinforced concrete but in structural and bridge engineering. He was Honorary member of many national Associations in addition to the ACI: among them the Institution of Structural Engineers, London, the Royal Institute of Dutch Engineering; the Academy of Works, Prague; and the Academy of Science, Warsaw. He was one of the first to take the degree of Doctor of Technical Science in 1903 and was given the Honorary degree of D.Sc. by several Universities. Dr. Emperger represented Austrian engineers at various international congresses and lectured in many countries on the results of his investigations. His stay in the States as well as his visits to foreign countries apparently made him immune to Nazism although he was appointed their Honorary member when Hitler occupied Austria. Thus Emperger may be considered to be an exception to the great number of scientists who not only supported Hitler when he represented the German Government but also did everything to help him to power.

Note: Dr. Abeles writes as a personal acquaintance of Dr. Emperger's during pre-war years. Like many others, Dr. Abeles was forced to leave Vienna during the German occupation. He now resides in London.

Building industry's first materials handling exposition

The building industry's problems of materials handling will receive special attention at the first national Materials Handling Exposition to be held at the Public Auditorium, Cleveland, Jan. 14-17.

Builders' executives will have the first opportunity to see and compare under one roof competing systems and machinery for materials handling. All phases of materials handling will be discussed during the four-day meeting, with special consideration to problems of builders. Handling on the job, as well as handling for receiving, shipping, loading and warehousing will be discussed and appropriate machinery exhibited on the Exposition floor.

On exhibition will be hoists, hoist mountings, many types of conveyors, hand and power trucks, skids and pallets, tractors and trailers, as well as other devices to reduce costs and increase safety factors.

Admission to the sessions may be obtained from the Exposition management, Clapp & Poliak, Inc., 37 Wall Street, New York, N. Y.

Kanwar Sain

Rai Bahadur Kanwar Sain, Punjab, India, an ACI member since 1939, has been awarded the Order of the British Empire. The O.B.E. is given by the King for services to the empire at home and in the dominions and colonies other than those rendered by the navy and army. It might also be added that the title "Rai Bahadur" represents an award by the Indian government for distinguished service, but it ranks below the O.B.E.

Henry C. Turner

The Turner Construction Company announces the retirement of its founder, Henry C. Turner (Pres. ACI 1920-21) as chairman of the board. J. Archer Turner, president of the company, has been named as successor to his brother, and as chairman, will continue as the senior executive of the company. Admiral Ben Moreell, retiring from active service in the navy where he served from 1937 through 1945 as chief of the Bureau of Yards and Docks (see ACI Jl. October), has been elected president and director. These changes became effective October 1, 1946.

ACI publications in large current demand

Proposed Manual of Standard Practice for Detailing Reinforced Concrete Structures (1946)

Reported by ACI Committee 315, Detailing Reinforced Concrete Structures, Arthur J. Boase, Chairman, this book reached the top of the ACI "best seller" list within one month of its distribution to all ACI members in good standing in July 1946. It is a large format, bound to lie flat and presents typical engineering and placing drawings with discussion calling attention to important considerations in designing practice. It was prepared to simplify, speed, and effect standardization in detailing. It is believed to be the only publication of its kind in English. It is meeting wide acclaim among designers, draftsmen and in engineering schools. Price—$2.50; to ACI Members—$1.50.

ACI Standards—1946

180 pages, 6x9 reprinting ACI current standards: Building Regulations for Reinforced Concrete (ACI 318-41); Minimum Standard Requirements for Precast Concrete Floor Units (ACI 711-46); four recommended practices: Use of Metal Supports for Reinforcement (ACI-319-42); Measuring, Mixing and Placing Concrete (ACI 614-42); Design of Concrete Mixes (ACI 613-44); Construction of Concrete Farm Silos (ACI 714-46); and two specifications: Concrete Pavements and Bases (ACI 617-44) and Cast Stone (ACI 704-44)—all between two covers, $1.50 per copy—to ACI Members, $1.00.

Air Entrainment in Concrete (1944)

92 pages of reports of laboratory data and field experience including a 31-page paper by H. F. Gonnerman, "Tests of Concretes Containing Air-entraining Portland Cements or Air-entraining Materials Added to Batch at Mixer," and 61 pages of the contributions of 15 participants in a 1944 ACI Convention Symposium, "Concretes Containing Air-entraining Agents," reprinted (in special covers) from the ACI JOURNAL for June, 1944. $1.25 per copy; 75 cents to Members.

ACI Manual of Concrete Inspection (July 1941)

This 140-page book (pocket size) is the work of ACI Committee 611, Inspection of Concrete. It sets up what good practice requires of concrete inspectors and a background of information on the "why" of such good practice. Price $1.00—to ACI members 75 cents.

"The Joint Committee Report" (June 1940)

The Report of the Joint Committee on Standard Specifications for Concrete and Reinforced Concrete submitting "Recommended Practice and Standard Specifications for Concrete and Reinforced Concrete," represents the ten-year work of the third Joint Committee, consisting of affiliated committees of the American Concrete Institute, American Institute of Architects, American Railway Engineering Association, American Society of Civil Engineers, American Society for Testing Materials, Portland Cement Association. Published June 15, 1940; 140 pages. Price $1.50—to ACI members $1.00.

Reinforced Concrete Design Handbook (Dec. 1939)

This report of ACI Committee 317 is in increasing demand. From the Committee's Foreword: "One of the important objectives of the committee has been to prepare tables covering as large a range of unit stresses as may be met in general practice. A second and equally important aim has been to reduce the design of members under combined bending and axial load to the same simple form as is used in the solution of common flexural problems."—132 pages, price $2.00—$1.00 to ACI members.

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A reference list of advertisers who participated in the Fifth Annual Technical Progress Issue of the ACI JOURNAL—the pages indicated will be found in the February 1946 issue and (when it is completed) in V. 42, ACI Proceedings. **Watch for the 6th Annual Technical Progress Section in the February 1947 JOURNAL.**

Concrete Products Plant Equipment

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—Testing equipment

SYNOPSES of recent ACI Papers and Reports

Institute papers of this JOURNAL Vol. 18 which are currently available. Unless otherwise noted separate prints are 25 cents each. Starred ★ items are 50 cents. Please order by title and title number.

REINFORCED CONCRETE COLUMNS UNDER COMBINED COMPRESSION AND BENDING.................... 43-1

HAROLD E. WESSMAN—Sept. 1946, pp. 1-8 (V. 43)

Algebraic methods available heretofore for the analysis of the reinforced concrete column subject to combined compression and bending have usually involved the solution of a complex cubic equation and have taken considerable time when applied to particular problems. A new method of successive approximations converging rapidly to an exact answer and avoiding the use of the cubic equation is presented in this paper. The key to the method is the reciprocal relationship existing between the load axis and the neutral axis of the transformed section. The method may be applied to any shape of cross section and any arrangement of reinforcing steel, providing there is one axis of symmetry and the plane of bending coincides with this axis. The theory behind the method is presented and illustrated with three typical problems.

EFFECT OF MOISTURE ON THERMAL CONDUCTIVITY OF LIMEROCK CONCRETE......................... 43-2

MACK TYNER—Sept. 1946, pp. 9-20 (V. 43)

The coefficient of thermal conductivity, k, of limerock concrete is a function of temperature, composition and density or moisture content. No attempt has been made to measure the effect of temperature on k. Holding the temperature reasonably constant, the effect of composition on k has been measured for two limerock concrete mixes (1:5 and 1:7 by volume). The 1:5 mix has a k that is 10 per cent larger than the k for the 1:7 mix.

With the temperature and composition held constant, the effect of moisture on k for the 1:5 and 1:7 mixes has been measured. The moisture content has a very profound effect on k, e.g. increases of moisture from zero to 5 per cent increases the k of 1:5 mix by 23 per cent and from zero to 10 per cent increases the k by 46 per cent. Concretes should be kept dry if their maximum heat insulation effect is desired.

★CEMENT INVESTIGATIONS FOR BOULDER DAM—RESULTS OF TESTS ON MORTARS UP TO AGE OF 10 YEARS...................... 43-3

RAYMOND E. DAVIS, WILSON C. HANNA and ELWOOD H. BROWN—Sept. 1946, pp. 21-48 (V. 43)

The effects of composition and fineness of the laboratory cements employed in cement investigations for Boulder Dam upon strength, volume changes, and sulfate resistance of mortars, are reported for ages up to 10 years. For both wet and dry storage conditions, factors for each of several ages are given which indicate the contribution of each of the four major compounds present in portland cement to tensile and compressive strengths and volume changes.

★ANALYSIS AND DESIGN OF ELEMENTARY PRESTRESSED CONCRETE MEMBERS.......................... 43-4

HERMAN SCHORER—Sept. 1946, pp. 49-88 (Vol. 43)

The purpose of this paper is to outline the analysis and design of elementary prestressed concrete members, such as beams, columns, ties, etc., subjected to internal and external axial forces and bending moments. The internal stresses, caused by the action of the prestress forces, are combined with the stresses due to external loads in three typical loading stages. The first stage considers the stress condition resulting from the simultaneous application of all sustained loads. The second stage determines the stress changes due to normal live loads, based on a truly monolithic participation of the entire concrete area. The third stage assumes a cracked tension zone, which condition introduces the derivation of ultimate stresses and clarifies the influence of the prestress action on the type of failure. The analytical expressions are simplified by means of convenient ratios, which essentially define the sectional shape, the effective steel prestress, and the concrete fiber stresses. Numerical examples serve to illustrate the various steps.

★STUDIES OF THE PHYSICAL PROPERTIES OF HARDENED PORTLAND CEMENT PASTE

(Part 1) **Price 50 cents................43-5a**

(Part 2 and appendix) **Price 75 cents...43-5b**

T. C. POWERS and T. L. BROWNYARD—Oct. 1946, pp. 101-132, Nov. 1946, pp. 249-336 (V. 43)

IN NINE PARTS

Part 1. A Review of Methods That Have Been Used for Studying the Physical Properties of Hardened Portland Cement Paste

Part 2. Studies of Water Fixation
Appendix to Part 2

Part 3. Theoretical Interpretation of Adsorption Data

Part 4. The Thermodynamics of Adsorption
Appendix to Parts 3 and 4

Part 5. Studies of the Hardened Paste by Means of Specific-Volume Measurements

Part 6. Relation of Physical Characteristics of the Paste to Compressive Strength

Part 7. Permeability and Absorptivity

Part 8. The Freezing of Water in Hardened Portland Cement Paste

Part 9. General Summary of Findings on the Properties of Hardened Portland Cement Paste

This paper deals mainly with data on water fixation in hardened portland cement paste, the properties of evaporable water, the density of the solid substance, and the porosity of the paste as a whole. The studies of the evaporable water include water-vapor-adsorption characteristics and the thermodynamics of adsorption. The discussions include the following topics:

1. Theoretical interpretation of adsorption data
2. The specific surface of hardened portland cement paste
3. Minimum porosity of hardened paste
4. Relative amounts of gel-water and capillary water
5. The thermodynamics of adsorption
6. The energy of binding of water in hardened paste
7. Swelling pressure
8. Mechanism of shrinking and swelling
9. Capillary-flow and moisture diffusion
10. Estimation of absolute volume of solid phase in hardened paste
11. Specific volumes of evaporable and non-evaporable water
12. Computation of volume of solid phase in hardened paste
13. Limit of hydration of portland cement
14. Relation of physical characteristics of paste to compressive strength
15. Permeability and absorptivity
16. Freezing of water in hardened portland cement paste

★MINIMUM STANDARD REQUIREMENTS FOR PRECAST CONCRETE FLOOR UNITS 43-6

REPORTED BY ACI COMMITTEE 711—Oct. 1946, pp. 133-148 (V. 43) In special covers

Supersedes 40-17, 42-11.

These minimum standard requirements are to be used as supplements to the ACI "Building Regulations for Reinforced Concrete" (ACI 318-41). With respect to design for strength, i. e., for bending moment, bond and shear stresses, all types shall be designed in accord with standard reinforced design theory and ACI 318-41. With respect to cover, there is in some cases departure therefrom justified by the greater refinement in the finished product when made by factory methods with factory control. Precast floor systems with I-beam type and hollow core type joists are covered. Appendix contains applicable sections of the ACI code (ACI 318-41). This report, originally published in Feb. 1944 Journal, has been revised by the committee and adopted by the Institute as an ACI Standard, Aug. 1946. The committee consists of F. N. Menefee, Chairman, Warren A. Coolidge, R. E. Copeland, Clifford G. Dunnells, H. B. Hemb, Harve Kilmer, Glenn Murphy, Gayle B. Price, John Strandberg, J. W. Warren, Roy R. Zipprodt.

★RECOMMENDED PRACTICE FOR THE CONSTRUCTION OF CONCRETE FARM SILOS 43-7

REPORTED BY ACI COMMITTEE 714—Oct. 1946, pp. 149-164 (V. 43) In special covers

Supersedes 40-10, 42-12.

These recommendations describe practice for use in the design and construction of concrete silos—stave, block and monolithic, for the storage of grass or corn silage. The report is the work of the committee consisting of William W. Gurney, Chairman, J. W. Bartlett, Walter Brassert, Claude Douthett, Harry B. Emerson, William G. Kaiser, R. A. Lawrence, G. L. Lindsay, J. W. McCalmont, Dalton G. Miller, C. C. Mitchell, K. W. Paxton, B. M. Radcliffe, Charles F. Rogers, Stanley Witzel. It was adopted by the Institute as an ACI Standard Aug. 1946.

THE DURABILITY OF CONCRETE IN SERVICE 43-8

F. H. JACKSON—Oct. 1946, pp. 165-180 (V. 43)

This paper discusses the problem of concrete durability with reference primarily to highway bridge structures located in regions subject to severe frost action. Four major types of deterioration are defined and illustrated and several specific matters which have bearing on the problem, including the effect of construction variables, modern vs. old fashioned cements, air entrainment and the so-called "cement-alkali" aggregate reaction, are discussed. The report concludes with a series of recommendations indicating certain corrective measures which should be taken.

WEAR RESISTANCE TESTS ON CONCRETE FLOORS AND METHODS OF DUST PREVENTION 43-9

GEORG WASTLUND and ANDERS ERIKSSON—Oct. 1946, pp. 181-200 (V. 43)

This paper presents a description of tests made on concrete floor specimens of various types in order to determine their resistance to wear and to investigate the character of deterioration of concrete floor surfaces due to traffic. The results of these tests show that concrete floors provided with finish courses containing coarse aggregate up to about ⅜ inch in size and an excess of pea gravel are definitely superior to concrete floors with a finish course containing fine sand only which are common in Sweden at the present time. Moreover, this investigation has helped to elucidate the causes of the often very severe and detrimental dusting of concrete floors. The surface skin of concrete floors is of poor quality and is easily abraded. Dusting can be considerably reduced if the poor surface skin is removed by machine grinding provided that the concrete below the surface skin is of first-rate quality. The paper concludes by proposing a detailed tentative specification for concrete floor finish which differs in essentials from current Swedish practice.

★LINING OF THE ALVA B. ADAMS TUNNEL.................43-10

RICHARD J. WILLSON—Nov. 1946, pp. 209-240 (V. 43)

The 13.03 mile Alva B. Adams Tunnel, excavated under the Continental Divide, as a part of the transmountain water diversion plan of the Colorado-Big Thompson Project. United States Department of the Interior, Bureau of Reclamation, is now lined with concrete. Lining equipment and methods and aggregate processing are described.

REPAIRS TO SPRUCE STREET BRIDGE, SCRANTON, PENNA......43-11

A BURTON COHEN—Nov. 1946, pp. 241-248 (V. 43)

Repairs and reinforcements of the Spruce Street Bridge built in 1893 over the Lackawanna Railroad and Roaring Brook in Scranton, Pa. are described. The effective application of the "Alpha System-Composite Floor Design" reinforced the floor system at the same time a new concrete floor slab was laid. Concrete prices are included and eleven illustrations supplement the text of the paper.

Mark your Calendar—ACI's 43rd Annual Convention, at Cincinnati, February 24-26, 1947

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COUNTY OF WAYNE....}

Before me, a Notary Public in and for the State and county aforesaid, personally appeared Harvey Whipple, who, having been duly sworn according to law, deposes and says that he is the Editor of the JOURNAL OF THE AMERICAN CONCRETE INSTITUTE and that the following is, to the best of his knowledge and belief, a true statement of the ownership, management (and if a daily paper, the circulation), etc., of the aforesaid publication for the date shown in the above caption, required by the Act of August 24, 1912, as amended by the Act of March 3, 1933, embodied in Section 537, Postal Laws and Regulations, printed on the reverse of this form, to wit:

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HARVEY WHIPPLE,
(Signature of editor)

Sworn to and subscribed before me this 24th day of October, 1946.

ETHEL B. WILSON, Notary Public
(My commission expires Aug. 9, 1950)

[SEAL]

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Minimum Standard Requirements for Precast Concrete Floor Units (ACI 711-46)

16 pages in covers: 50 cents per copy (40 cents to ACI Members)

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Proposed Standards

Proposed Manual of Standard Practice for Detailing Reinforced Concrete Structures

Reported by ACI Committee 315. It is a separate publication of large format, bound to lie flat and presents typical engineering and placing drawings with discussion calling attention to important considerations in designing practice. 55 pages; $2.50 per copy. $1.50 to ACI Members. (Distributed to ACI Members in July 1946)

The Nature of Portland Cement Paints and Proposed Recommended Practice for Their Application to Concrete Surfaces

Reported by Committee 616 as information and for discussion only. 20 pages, 25 cents per copy (Reprint from ACI JOURNAL, June 1942)

Proposed Recommended Stresses for Unreinforced Concrete

Reported by Committee 322 as information and for discussion only. 4 pages, 25 cents per copy. (Reprint from ACI JOURNAL, Nov. 1942)

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