RP529

CLAY IN CONCRETE

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ABSTRACT

The effect on the compressive strength, absorption, and permeability of concretes of substituting clay either for 10 per cent of the volume of the cement or for 7½ per cent of the volume of the fine aggregate were studied. A basic mix without clay and containing five bags of cement per cubic yard of concrete served as a reference. All concretes were of the same consistency as determined by a penetration test. Three different cements and three different clays were used in a number of combinations. All specimens were kept in damp storage at 70° F. for 28 days and thereafter some were stored outdoors and the rest were subjected to freezing and thawing. Specimens were tested for compressive strength at the ages of 7 and 28 days and for strength, absorption, and permeability at 3, 6, and 9 months, and 1, 2, and 3 years.

The substitution of clay for 10 per cent of the volume of the cement caused a small (zero to 10 per cent) decrease in the compressive strength of the concrete at ages greater than three months. The permeability was not changed appreciably.

Substituting clay for 7½ per cent of the volume of the fine aggregate increased the compressive strength of the concrete from 1 to 37 per cent. The permeability at the early test ages was decreased but increased at later ages both actually and relative to the concrete without clay. All of the concretes were practically impermeable in these tests.

The replacement of 7½ per cent of the sand in one case and 10 per cent of the cement in the other by equal volumes of clay slightly increased the absorption for those specimens stored outdoors, but did not appreciably change that of specimens frozen and thawed.

The clay admixtures had no apparent effect on the resistances of the concretes to freezing and thawing exposure as no disintegration took place among those which were kept damp. All of the specimens, with and without clay, which were subjected both to an occasional drying and to freezing and thawing exposure were disintegrated.

The differences in absorption, permeability, and resistance to freezing and thawing between concretes containing and not containing clay were small.

CONTENTS

I. INTRODUCTION

1. PURPOSE

The investigation described herein was conducted at the Bureau of Standards, Washington, D. C., with the cooperation of Hugh L. Cooper & Co. (Inc.), New York, N. Y.

An effort was made in this study to determine the value of clay as an admixture in concrete of a type commonly used in construction and was one of several investigations of the same nature sponsored by Col. Hugh L. Cooper.

The qualities of concrete which were measured were compressive strength, absorption, resistance to a freezing and thawing exposure, and permeability to water under pressure.

2. OUTLINE OF INVESTIGATION

Three general types of concrete were made which are designated by the Roman numerals: I, II, and III. No. I contained no added clay. No. II had the same proportions of dry ingredients as No. I except that clay was substituted for 10 per cent (by volume) of the cement. No. III had the same dry ingredients as No. I except that 7½ per cent of the dry rodded volume of the sand was replaced by an equal volume of clay.

It was specified that: (1) The dry rodded volume of the sand should be 1.15 times the volume of the voids in the coarse aggregate for the plain concrete and for that in which 10 per cent of the cement was replaced by clay, (2) the plain concrete and that in which 7½ per cent of the sand was replaced by clay should have a cement content of five bags per cubic yard, and (3) the consistency of all mixes should be such that a man walking in a large mass of the fresh concrete would sink to a depth greater than 3 inches and less than 8 inches.

Condition No. 3 relative to consistency would have required the production of concrete on a field scale in order to make a satisfactory test. As this was not feasible the water content of mix No. I, plain concrete without clay, was varied, using one-tenth cubic yard batches, until a consistency was obtained which was judged to satisfy the requirement. The amounts of water to use with mixes II and III, containing clay, were then determined by trial such that their workabilities as measured by the penetration test described in Section IV were the same as for mix No. I. The proportions are given in Table 1.

TABLE 1.—*Proportions of concrete*

Method	Mix	Cement	Water	Clay	Sand	Crushed rock
Parts by bulk volume	I	1	1.07	0	2.02	4.40
	II	1	1.22	.11	2.25	4.89
	III	1	1.11	.15	1.87	4.40
Parts by weight	I	1	.71	0	2.22	4.77
	II	1	.81	.08	2.46	5.30
	III	1	.74	.11	2.05	4.77
Percentage by weight	I	11.49	8.15	0	25.50	54.86
	II	10.35	8.37	.88	25.51	54.90
	III	11.53	8.49	1.30	23.65	55.03
Percentage by absolute volume	I	8.8	19.7	0	23.2	48.3
	II	7.9	20.1	.8	23.1	48.1
	III	8.8	20.4	1.2	21.4	48.2

Three complete sets of specimens were made using three different brands of cement. In addition, three complete sets of those containing clay were made using three different kinds of clay. In all, there were 21 distinct mixtures.

Specimens of each mixture were made for testing in compression at the ages of 7 and 28 days (after storage in a damp closet) and 3, 6, and 9 months and 1, 2, and 3 years after storage out of doors. Absorption and permeability test specimens were prepared for testing first at age 3 months and then retesting at the ages of 6 and 9 months and 1, 2, and 3 years.

In order to provide for two types of exposure, namely, out of doors and freezing and thawing, additional specimens were made for those tests later than age 28 days, all specimens being kept for the first 28 days in damp storage.

For each different mixture and storage condition (and age in the case of the compressive test specimens) 3 compressive, 3 absorption, and 6 permeability test specimens were made, or a grand total of 1,260 specimens.

II. MATERIALS

1. CEMENTS

Cement No. 1 was a finely ground, high early-strength Portland. Nos. 2 and 3 were ordinary Portlands, No. 2 being a smooth, easy working cement, and No. 3 a harsh cement as indicated by previous tests [1] made at the Bureau of Standards. All complied with the requirements of the Federal Specification SS–C–191 for Cement, Portland. The specific gravities [2] were 3.137, 3.135, and 3.178, respectively, and the percentages of water required for normal consistency were 25.8, 23.0, and 22.2, respectively.

2. SAND

Potomac River sand, all obtained at the same time, was used throughout. A summary of the properties of the sand is given in Table 2.

TABLE 2.—*Properties of the sand* [a]

Passing sieve No.	Percentage, by weight
4	99
8	92
16	78
30	57
50	15
100	3
Fineness modulus	2.56
Percentage, by weight, removed by decantation	2.4
Percentage of water absorption by weight in 30 minutes	.7
Percentage of voids (dry rodded condition)	37.8
Pounds per cubic foot (dry rodded condition)	103
Apparent specific gravity	2.656

[a] The test methods used were those of the American Society for Testing Materials, as follows:
C 41–24, 1930 Book of A. S. T. M. Standards, II, p. 155.
D 136–28, 1930 Book of A. S. T. M. Standards, II, p. 618.
C 30–22, 1930 Book of A. S. T. M. Standards, II, p. 153.
C 29–27, 1930 Book of A. S. T. M. Standards, II, p. 151.
D 55–25, 1930 Book of A. S. T. M. Standards, II, p. 614.
The apparent specific gravity of the sand was determined by the use of Le Chatelier flasks and water, the final readings being taken 18 minutes after immersing the material. The values were adjusted for temperature, those given corresponding to a temperature of 4° C.

[1] P. H. Bates and J. R. Dwyer, Cement as a Factor in the Workability of Concrete, Proc. Am. Conc. Inst., vol. 24, p. 43, 1928.

[2] Determined on samples previously dried at 115° C. using Le Chatelier flasks and alcohol. All values were adjusted for temperature, those given corresponding to a temperature of 4° C.

3. COARSE AGGREGATE

The crushed rock was very dense limestone quarried at Martinsburg, W. Va. The sieve analysis (with square opening sienes) showed 98.5 per cent by weight finer than 1½ inches, 63.2 per cent finer than ¾-inch, 33.1 per cent finer than ⅜-inch, and 1.1 per cent finer than a No. 4 sieve. Additional data on the physical properties of the coarse aggregate are given in Table 3.

TABLE 3.—*Physical properties of coarse aggregate* [a]

Fineness modulus	7.05
Percentage of water absorption by weight in 24 hours	.2
Percentage of voids (dry rodded condition)	40.3
Pounds per cubic foot (dry rodded condition)	102
Apparent specific gravity	2.737

4. CLAYS

The selection of the clays used in the investigation was made with the object of obtaining materials which when mixed with water would give "short," "medium plastic," and "plastic" mixtures. In this order they were: No. 1. A red surface clay from Occoquan, Va.; No. 2, a blue clay from Baltimore, Md.; and No. 3, a yellow clay from Alexandria, Va. The percentage by weight passing a No. 200 sieve (washed), the percentage by weight loss on ignition (after drying at 110° C.), and the specific gravity [3] for No. 1 clay were 76, 7.1, and 2.690; for No. 2 clay 93, 5.0, and 2.658; and for No. 3 clay 95, 5.0, and 2.698, respectively.

As these clays were all used in the manufacture of brick they probably were relatively free from the organic materials that are usually found near the surface of the ground, but it appears that a test in mortar or concrete is the only sure and practical method known of determining the suitability of a clay in this respect. The 7 and 28 day compressive strength results obtained with concretes containing the three clays indicated that they contained little if any injurious organic material.

The weights of all clays when dry and pulverized were found to be about 70 pounds per cubic foot and this value was used in proportioning the concretes.

III. PREPARING THE CONCRETE

1. TREATMENT OF MATERIALS

The cements were stored in air-tight steel barrels (of six or seven bag capacity) until used.

The sand and rock after drying were stored in bins indoors, the crushed rock being separated into three sizes by means of a rotary screen.

The clays were dried in lumps on the laboratory floor, pulverized in a dry pan to pass a No. 14 sieve and stored in a dry place in canvas bags. All proportioning was done by weight.

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[a] The test methods used were those of the American Society for Testing Materials as follows:
C 41-24, 1930 Book of A. S. T. M. Standards II, p. 155.
C 29-27, 1930 Book of A. S. T. M. Standards II, p. 151.
D 30-18, 1930 Book of A. S. T. M. Standards II, p. 612.
The apparent specific gravity was determined also by using Le Chatelier flasks and water, making the final readings 18 minutes after immersion.

[3] Using the same methods as for the cements. See footnote 2, p. 259.

2. PROPORTIONING AND MIXING

The proportions of the materials used in the several mixes are shown in Table 1. Altogether there were 21 concretes differing from each other either in clay content, kind of clay, or brand of cement. In order to minimize the effects of uncontrolled factors having seasonal variations the general plan of mixing adopted consisted in the division of the work into three parts such that when one-third or two-thirds of the total number of specimens had been made all of the 21 concretes were equally represented. The mixing was done in a one-tenth cubic yard capacity Wonder mixer having a speed of 13 r. p. m. The capacity was such that two batches were required to make one-third of the specimens for one concrete. Fabrication was started in April and finished in November. After weighing all materials the crushed rock, sand, and cement were placed in the mixer in the order named. Immediately thereafter the clay and water, thoroughly mixed together, were added. The period of mixing was two minutes after all materials were in the mixer.

IV. PROPERTIES OF THE FRESH CONCRETE

1. WORKABILITY

The time required for making the workability measurements was about 15 minutes per batch. The slump test was made according to standard methods [4] except that the slump cone had a top diameter of 3½ inches instead of 4. The penetration test as given below was considered to give a true index of the workability and for this test the whole batch was used.

The fresh concrete was placed in a 20-inch diameter container to a depth of 14½ inches. A rectangular area 12 by 3 inches bearing on the surface of the concrete was loaded with a 160-pound weight. The average penetration of three trials was taken as a measure of the workability of the batch.

TABLE 4.—*Average values from workability tests*

Mix	Slump	Flow	Penetration
	Inches	*Per cent*	*Inches*
I. Plain concrete (without clay)	4.0	49	2.3
II. 10 per cent of the cement replaced by clay	3.0	47	2.3
III. 7½ per cent of the sand replaced by clay	2.1	41	2.3

While making the slump and flow tests it was noticed that the change in the shape of the mass was frequently more like a sliding or crumbling action than a true slump or flow. This was particularly true for the concretes not containing clay.

2. WEIGHT PER UNIT VOLUME

After the workability tests were made a dekaliter container was filled and weighed. The concrete was placed in three layers, each layer being rodded until fine material appeared around the edge.

[4] The slump test is described in Proc. Am. Soc. Test. Mat., vol. 26, pt. 1, p. 874, 1926. The flow tests were made by the methods described in the Standard Methods of Making Compression Tests of Concrete (C 39-27), 1930 Book of A. S. T. M. Standards, II, p. 143 except that the drop of the table was one-eighth inch instead of one-half inch.

The weight of the concrete divided by the volume of the container gave the weight per unit volume. The number of bags of cement per cubic yard of concrete was then computed by the use of the following formula:

Bags of cement per cubic yard=(percentage cement, by weight in the mix × (weight per cubic foot of fresh concrete) × 27/94

With the assumption that there were no air voids, the weight per cubic foot was calculated from the weight percentages and the apparent specific gravities of the materials. Thus, the calculated weight per cubic foot of fresh concrete equals:

$$\frac{62.428 \times 100}{\sum \frac{\text{Percentage by weight of material}}{\text{Apparent specific gravity}}}$$

NOTE.—No allowance was made for the absorption of water by the aggregate because the values for apparent specific gravities here used and given elsewhere are weights per unit volume of materials exclusive of the voids or pores accessible to water.

The air voids were determined by means of the equation: Percentage of air voids equals:

$$\frac{\text{Computed weight per cubic foot} - \text{actual weight per cubic foot}}{\text{Computed weight per cubic foot}}$$

While it is theoretically possible to calculate the amounts of air and water voids in concretes by means of these formulas, the results are apt to be in error because of differences between the proportions in the mixer and in the concretes of the specimens. There was loss of water by evaporation and also a loss of water, cement, and the finer portions of the aggregate by adherence to the mixer, dumping pan, and tools. The values shown in Table 5 are averages of the individual observations for the batches immediately preceded by identical batches, in which case the mixer and the pan were not washed out.

It is reasonable to believe that the values for air voids should be slightly higher and those for cement factor slightly lower.

TABLE 5.—*Properties of the fresh concrete*

Mix	Weight of fresh concrete		Air voids	Air and water voids	$\frac{C}{V+C}$ [1]	Bags of cement per cubic yard
	Measured	Computed				
	Lbs./ft.^{3}	*Lbs./ft.*^{3}	*Per cent*	*Per cent*		
I. Plain concrete (without clay)	150.18	150.59	0.3	19.3	0.314	4.958
II. 10 per cent (by volume) of cement replaced by clay	149.27	149.84	.4	19.8	.285	4.438
III. 7½ per cent (by volume) of sand replaced by clay	149.78	149.84	.0	19.8	.307	4.960

[1] Cement-voids ratio where C= absolute volume of cement, and V= volume of air and water voids.

V. TEST SPECIMENS AND STORAGE

1. SPECIMENS

Six by twelve inch cylinders were used for all compressive strength and absorption tests. They were cast in doubly paraffined paper molds. The concrete was placed in three layers and each layer rodded with a ⅝-inch diameter steel rod, having a bullet-shaped end, until the fine material appeared around the edge of the mold.

The permeability specimen was a cylinder of diameter 8 inches and height 9 inches. At the center, surrounded in all directions by about 3¼ inches of concrete, was a 1½-inch diameter paper carton (length, 2½ inches) filled with damp sand. A ¼-inch galvanized-iron pipe threaded on the top end extended into the center of the damp sand and protruded about 1½ inches above the cylinder. It was the means of conveying the water under pressure to the center in making the permeability test. These specimens were cast in steel molds. The procedure consisted in placing two tamped layers of concrete having a combined depth of about 5 inches, inserting the paper carton filled with damp sand, and then adding more concrete to make the total depth 9 inches. A shell of rich mortar was placed directly in contact with the ¼-inch pipe leading to the top of the specimen from the paper carton.

At the time of mixing it was thought that the shell of rich mortar immediately adjacent to the pipe would aid in preventing leakage along the outside of the pipe, but during the tests many of the specimens leaked at this place. This water was not considered as having passed through the concrete and was therefore not included in the measured leakage.

2. CONDITIONS OF STORAGE

Neither the temperature of the materials in the mix nor the temperature of the mixing room was closely controlled; however, all specimens except those for permeability tests were taken to a constant temperature (70° ± 2° F.) room within three hours after molding and remained there for 20 to 24 hours. They were then removed from the molds, the permeability specimens wire brushed on their vertical sides, and all taken to a 90 per cent or greater relative humidity, constant temperature (70° ± 2° F.) room for curing.

Specimens used for 7 and 28 day compressive strength tests were tested as soon as taken from the damp closet. The specimens stored outdoors after the 28-day damp curing period were brought into the laboratory for one week before testing in order to minimize the variations in moisture content. The specimens that had been frozen and thawed were tested within an hour after removal from water. The set of specimens subjected to freezing and thawing were frozen in air and thawed in water. The usual cycle was 20 to 22 hours in the freezing chamber and 2 to 4 hours in water. The specimens were not at any time permitted to dry, with the exception of those cylinders used for absorption determinations. The minimum air temperatures in the freezing room for any cycle varied from −5° to +23° F., but were usually between +10° and +20° F. Figure 1 shows the results of measurements made on two different days of the air and concrete temperatures in the freezing chamber. The temperature of the concrete was determined by thermocouples embedded in the center of the 6 by 12 inch cylinders.

VI. RESULTS OF TESTS

1. COMPRESSIVE STRENGTH

The cylinders used for compressive tests at ages up to and including one year with few exceptions were prepared for test by grinding the ends to plane surfaces. Those tested at the age of 2 years were

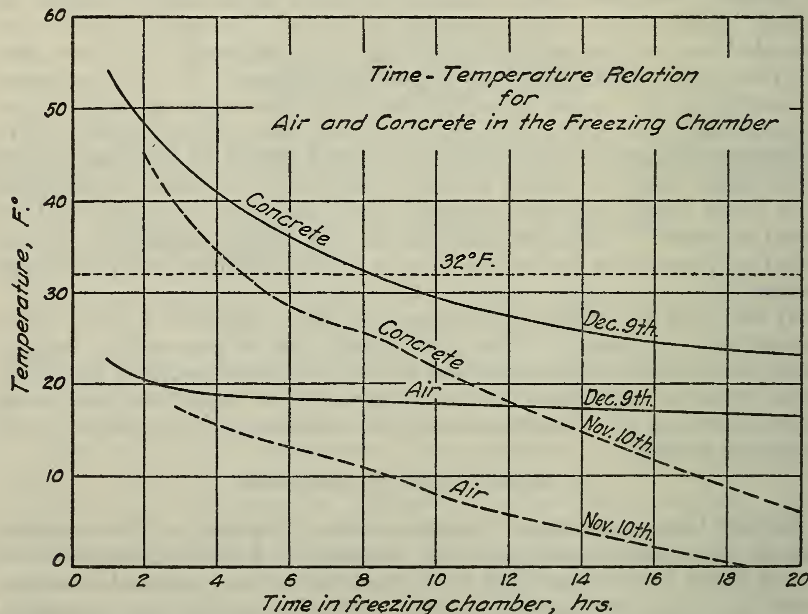

Figure 1.—*Temperatures in the freezing and thawing tests*

capped the day before the test with a rich high early strength Portland cement mortar. The capped outdoor specimens probably gave values a little lower than would have been obtained by the original method.

The data are given in Figures 2, 3, and 4 where the plain concrete without clay represents the average of three tests. Since there were no significant differences found between the compressive strengths of the concretes containing different clays the results obtained for all were averaged for the purpose of comparison with the plain concrete. Hence for each plotted point representing concrete containing clay, three times the number of specimens were used for its determination as were used for the corresponding point for the plain concrete.

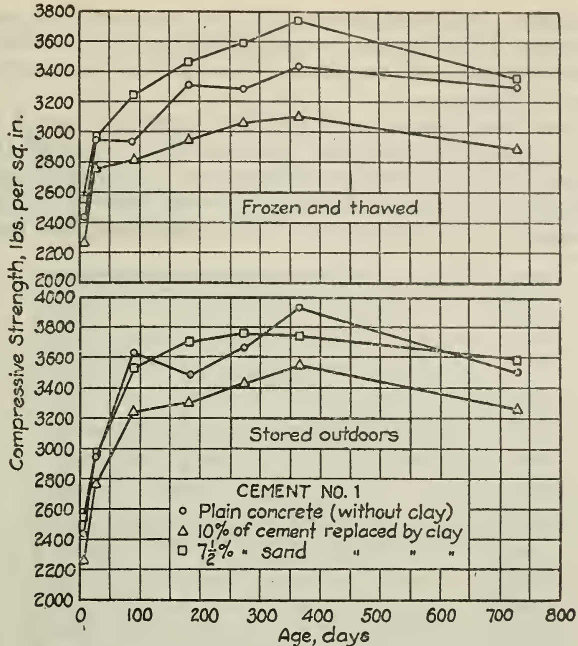

FIGURE 2.—*Age-compressive strength relations of concretes I, II, and III with cement No. 1*

TABLE 6.—*Effect of clay admixtures on compressive strength*

CEMENT NO. 1

Concrete	Cement content	Water/cement [1] by volume	Compressive strengths in per cent of concrete No. I without clay at ages of— 7 days	28 days	3 months	6 months	9 months	1 year	2 years
	Bags/yd.[3]		*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
I. No clay	4.96	1.03	100	100	100	100	100	100	100
II. 10 per cent of cement replaced by clay	4.44	1.18	93	94	92	92	93	90	90
III. 7½ per cent of sand replaced by clay	4.96	1.07	105	101	103	105	106	102	102
CEMENT NO. 2									
I. No clay	4.96	1.03	100	100	100	100	100	100	100
II. 10 per cent of cement replaced by clay	4.44	1.18	109	113	104	94	96	97	100
III. 7½ per cent of sand replaced by clay	4.96	1.07	131	137	125	114	118	116	114
CEMENT NO. 3									
I. No clay	4.96	1.03	100	100	100	100	100	100	100
II. 10 per cent of cement replaced by clay	4.44	1.18	100	101	104	96	97	98	99
III. 7½ per cent of sand replaced by clay	4.96	1.07	119	113	117	106	112	112	109

[1] Corrected for absorption of the aggregate.

In Table 6 the compressive strengths are expressed as percentages of the strengths of the concretes containing no clay. For this comparison the results from all specimens of a kind were averaged regardless of type of exposure.

For the concretes made with the finely ground rapid hardening cement No. 1, the substitution of clay for 10 per cent of the cement reduced the strength an average of from 8 to 10 per cent and the substitution of clay for 7½ per cent of the sand caused an increase in strength of from 1 to 6 per cent. With the other two cements the

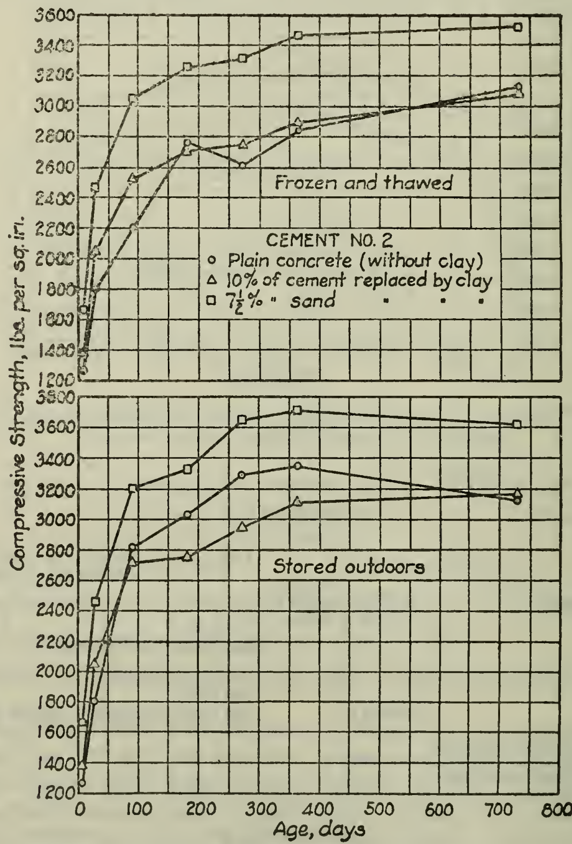

FIGURE 3.—*Age-compressive strength relations of concretes I, II, and III with cement No. 2*

substitution of clay for 10 per cent of the cement had practically no effect, but the substitution for 7½ per cent of the sand caused an appreciable increase in strength varying from 6 to 37 per cent. With all cements, the ratio of the strengths of concretes II and III containing clay to the strength of concrete I without clay tended to become smaller with an increase in age.

Statistical measures of the dispersions of the compressive strength data for the three types of concrete (I, II, and III) were calculated to determine the effect of the clays on the uniformity of the concretes. Two measures of the dispersions for each type of concrete were computed. One was a measure of the dispersion in the strengths of specimens of like composition but from different batches and the other of the variations among specimens of the same batch. Both of these showed that the variations in the strengths of cylinders of concretes containing clays were less than for those of concrete containing no clay. On the average the dispersions were about one-fourth larger for the concretes without clay than for those containing a clay admixture. However, as the differences between the statistical measures of the dispersions in the strengths of the concretes with and

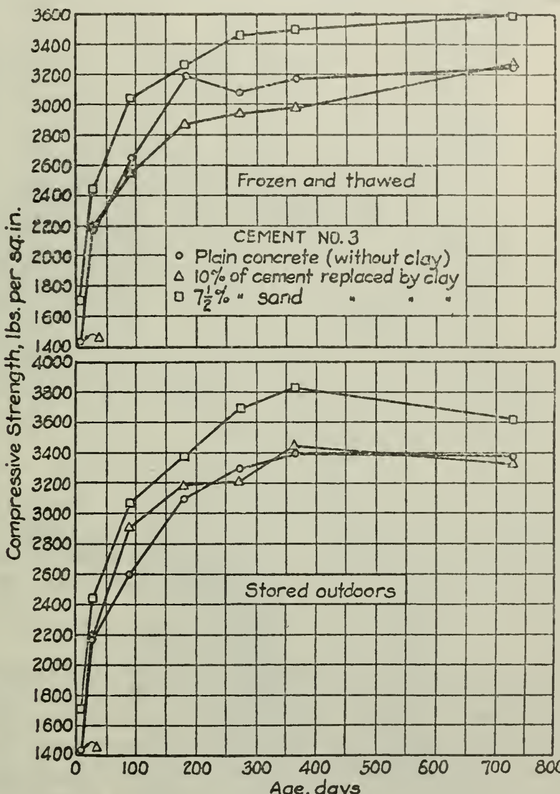

Figure 4.—*Age-compressive strength relations of concretes I, II, and III with cement No. 3*

without clays were only from 1.0 to 2.6 times the probable errors of the differences, the data do not show positively that the additions of clays improved the uniformity of the concretes. That is, the differences in the uniformity were only large enough in comparison to the precision of the statistical measures to give a strong indication that the apparently beneficial results of the clay admixtures were not due to chance.

2. ABSORPTION

In making water-absorption determinations at the ages indicated in Table 7, 6 by 12 inch cylinders were dried in a gas oven at temperatures varying between 100° and 130° C. for three days and subsequently immersed in water for three days. The absorption was computed as the difference between the dry weight and the weight after immersion, expressed as a percentage of the dry weight. Each value in Table 7 is an average of the results obtained from 9 specimens, 3 each from 3 cements. The cylinders used for the three months' test were retested at the ages of 6 and 9 months to give the values shown.

TABLE 7.—*Absorption of the concretes*

FROZEN AND THAWED

Age	I Plain concrete	II 10 per cent of cement replaced by clays Nos.—			III 7½ per cent of sand replaced by clays Nos.—		
		1	2	3	1	2	3
MONTHS	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Per cent*
3	5.1	4.9	5.0	5.3	5.1	5.3	5.3
6	5.4	5.5	5.2	5.5	5.3	5.5	5.6
9	5.2	5.6	5.6	5.7	5.5	5.4	5.3
Average	5.2	5.3	5.3	5.5	5.3	5.4	5.4
OUTDOOR STORAGE							
3	5.1	5.3	5.3	5.4	5.4	5.6	5.6
6	5.3	5.7	5.7	5.5	5.5	5.6	5.7
9	5.2	5.7	5.8	5.8	5.7	5.6	5.7
Average	5.2	5.6	5.6	5.6	5.5	5.6	5.7

The addition of the clay plus the extra water to maintain the workability approximately the same very slightly increased the absorption. Although not presented in the table, the absorption of the concrete containing No. 2 cement was slightly greater than for the others.

3. RESISTANCE TO FREEZING AND THAWING

The absorption specimens which received the freezing and thawing exposure disintegrated [5] within two years. These cylinders received the same treatment as those subjected to freezing and thawing and later tested in compression, except that they were dried in a gas oven at a temperature of 100° to 130° C. at the ages of 3, 6, and 9 months and 1 year or, roughly, in terms of freezing and thawing, at 40, 100, 150, and 200 cycles. The prime factor was apparently the cement. Those test pieces made with cement No. 1 disintegrated, in general, sooner than the others. No. 3 cement produced the concrete of highest resistance. When the cement was replaced by clay, the table shows that clay No. 2 gave better resistance than the other two clays. In fact, its use distinctly improved the resistance of the concrete made from cements Nos. 1 and 2. The average number of cycles to produce disintegration shown in Table 8 indicate that the concretes containing clay were usually slightly less resistant than the plain concrete, but here again the dispersion of the data was such that too close a comparison is not warranted. Each value in the body of the

[5] A specimen was considered to be disintegrated when 4 or 5 per cent could be broken off with the hands. The disintegration was initially evidenced by crazing.

Figure 5.—*View of permeability test apparatus*

table is the average for three specimens of the number of freezing and thawing cycles sustained before disintegration.

Cylinders that were kept continually damp showed no ill effects (except in a very few cases) from 400 cycles of freezing and thawing. The compressive strength results obtained with these cylinders also indicated that the freezing and thawing exposure unaccompanied by drying was no more severe than the outdoor exposure.

TABLE 8.—*Freezing and thawing cycles sustained before disintegration*

Cement	I Plain concrete	II 10 per cent of cement replaced by clays Nos.—			III 7½ per cent of sand replaced by clays Nos.—		
		1	2	3	1	2	3
1	170	155	285	150	175	185	175
2	265	200	335	180	220	210	150
3	335	295	335	290	260	295	215
Average	256	217	319	206	218	230	179
General average	256	247			209		

4. PERMEABILITY

It was initially planned to test the permeability specimens over a period of 24 hours at a pressure of 40 pounds per square inch at 3 months age and at 100 pounds per square inch at the later ages. After most of the tests had been completed for the age of 6 months it was quite evident that the results being obtained were of little value because of their extreme variability. At the suggestion of Colonel Cooper a few auxiliary tests were made in which the specimens were kept under water pressure for 12 days. The results indicated that a period of at least two weeks under pressure was necessary to obtain a good picture of the behavior of any specimen. For the retests at age 9 months and later ages this procedure was adopted.

The adoption of the 2-week period of test necessitated an enlargement of the testing apparatus such that 50 specimens could be tested at one time. A view of the apparatus is shown in Figure 5. The freezing and thawing specimens were tested with water surrounding them except for the top 1½ inches. The specimens stored outdoors being initially dry were placed in containers having bottom outlets; the only water present, therefore, was that coming through the specimens. Evaporation losses were minimized, and the entrance of water into the containers from the top of the specimen was prevented by the use of rubber bands encircling the top rim of the container and sealed with paraffin to the top edge of the test piece.

A water pressure of 100 pounds per square inch was maintained by means of compressed air on a tank containing tap water. The variation in pressure during a test rarely exceeded 5 per cent and was usually about 2 per cent.

The rate of leakage of a single specimen or the average for a group of specimens rarely remained the same from day to day. Therefore, the relative permeability of one group of specimens as compared with that for another group is different for one time after the beginning of the test than for another, and consequently a statement of permeability or relative permeability in terms of leakage at a given time means little unless it is qualified by a description of the trend. This can best be shown by a graphical representation of the average rates of leakage during the periods of test.

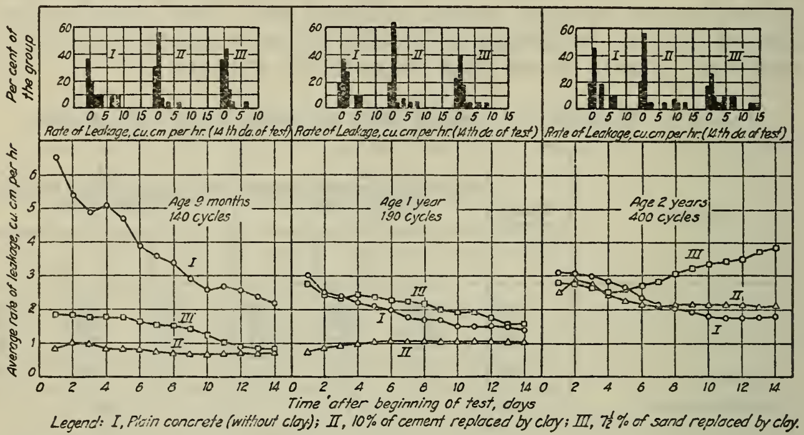

FIGURE 6.—*Comparison of permeabilities of concretes I, II, and III after exposure to freezing and thawing*

The average rates of leakage for several groups of specimens are shown by the curves of Figures 6, 7, 8, and 9. In the same figures the frequency distributions of the rates of leakage on the fourteenth day of test are shown by the histograms. The first column on the left of

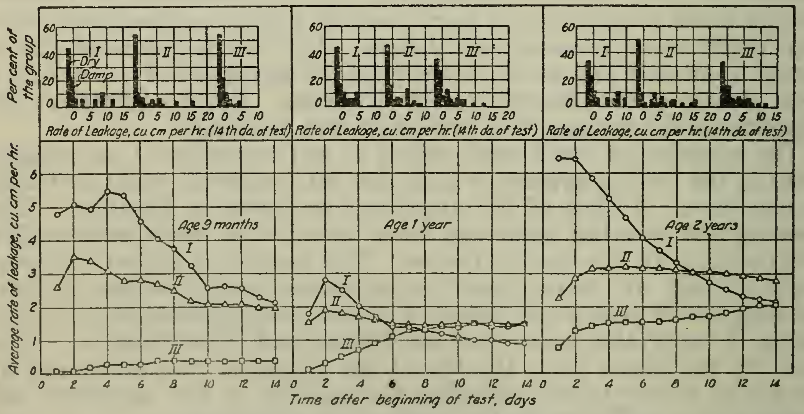

FIGURE 7.—*Comparison of permeabilities of concretes I, II, and III subjected to outdoor exposure*

NOTE.—Of the columns of the histograms to the left, of the abscissa representing zero leakage the one farthest to the left shows the percentage of the group of specimens that were still dry on the outside after 14 days under test and the one nearest the zero abscissa shows the percentage that were damp but not leaking sufficiently to measure.

each of the histograms in Figures 7 and 9, representing specimens of outdoor exposure, indicates the percentage of those of the group that were dry on the outside at the fourteenth day of test. The second column shows the percentage of the total number in a group that were damp, but did not give a measurable amount of leakage.

An inspection of histograms in Figures 6, 7, 8, and 9 will reveal a decidedly skew distribution of rates of leakage. Although the curves in the same figures represent the customary arithmetic mean, it seems that a weighted mean or the median would give a more signi-

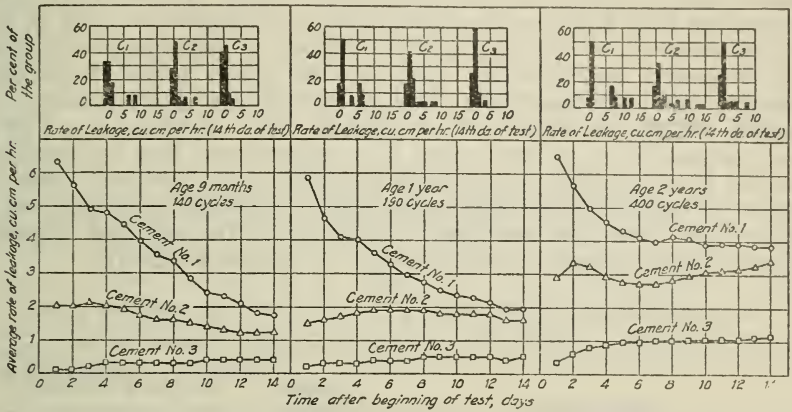

FIGURE 8.—*Effect of kind of cement on the permeabilities of the concretes frozen and thawed*

ficant value. The arithmetic mean is greatly affected by the extreme values, and these are the ones in which there is the least confidence, not merely because of the large numerical value but because it is known that there are certain conditions such as undetected injury to

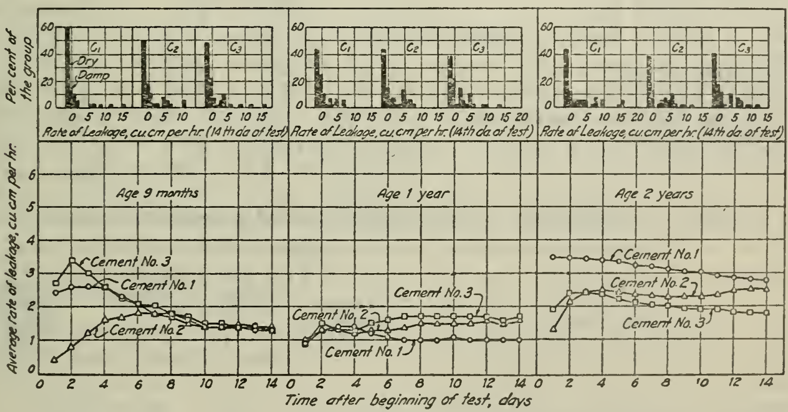

FIGURE 9.—*Effect of the kind of cement on the permeabilities of the concretes stored outdoors*

NOTE.—Of the columns of the histograms to the left of the abscissa representing zero leakage, the one farthest to the left shows the percentage of the group of specimens that were still dry on the outside after 14 days under test and the one nearest the zero abscissa shows the percentage that were damp but not leaking sufficiently to measure.

the specimen, fluctuation of pressure, etc., which have a tendency to increase leakage.

An illustration of the large effect of extreme values on the arithmetic mean may be had by referring to Figure 7. The average rate of leakage of the 18 specimens of plain concrete, I, age two years on the second day of test, is 6.4 cm^3 per hour. If the values for two specimens having the greatest leakage were not included, the arithmetic mean for the remaining 16 would be 2.7 cm^3 per hour.

The median values for the several types of concrete when considered without regard to exposure are given in Table 9. Table 10 gives the percentage that had a measurable amount of leakage for each of the several methods of grouping and the change in percentages between ages 9 months and 2 years. The data in Tables 9 and 10 indicate primarily that the concretes were all practically impermeable. A median leakage of from zero to one-half cubic centimeter per hour per specimen was not large when it is remembered that the pressure was 100 pounds per square inch and the thickness of concrete only 3¼ inches. The data show that permeability increased upon successive retests and that the specimens receiving a freezing and thawing exposure had a greater leakage than those stored outdoors.

TABLE 9.—*Median values of rate of leakage on the fourteenth day of test*

Type of concrete	Number of specimens	Median rate of leakage on the fourteenth day of test at ages—		
		9 months	1 year	2 years
Average of all specimens classified according to per cent of clay:		*cm³/hr.*	*cm³/hr.*	*cm³/hr.*
I. No clay	29	0	0.1	0.2
II. 10 per cent of cement replaced by clay	81	0	.1	.2
III. 7½ per cent of sand replaced by clay	77	0	.1	.4
Average of all specimens classified according to the cement used:				
Containing cement No. 1	54	0	0	.4
Containing cement No. 2	71	0	.2	.5
Containing cement No. 3	62	0	.1	.2
Average of specimens classified according to the clay used:				
Containing clay No. 1	52	0	.1	.3
Containing clay No. 2	54	0	.1	.2
Containing clay No. 3	52	0	.2	.5
All specimens classified according to storage:				
Frozen and thawed	61	.3	.4	.5
Stored outdoors	126	0	0	0

TABLE 10.—*Percentage of each group that leaked a measurable amount*

Type of concrete	Number of specimens	Per cent of the group that leaked a measurable amount at ages of—			Change in percentage from 9 months to 2 years
		9 months	1 year	2 years	
I. No clay	29	45	55	59	14
II. 10 per cent of cement replaced by clay	81	47	53	54	7
III. 7½ per cent of sand replaced by clay	77	36	51	61	25
Containing cement No. 1	54	35	47	56	21
Containing cement No. 2	71	49	59	63	14
Containing cement No. 3	62	40	52	53	13
Containing clay No. 1	52	42	52	58	16
Containing clay No. 2	54	37	50	57	20
Containing clay No. 3	52	48	54	58	10
Frozen and thawed	61	67	80	82	15
Stored outdoors	126	30	39	46	16

While the median values show that the plain concrete, I, and that with 10 per cent by volume of the cement replaced by clay, II, have the same permeability at all ages tested, the data of Table 10 indicate that initially I was slightly less permeable than II, but having a greater rate of increase in permeability upon retest, it was at age 2 years slightly more permeable. Concrete No. III, 7½ per cent of the sand replaced by clay, as shown by the data of Table 10, was less permeable at age 9 months than I and II, but had a much greater rate of increase upon retest so that at age 2 years the rate of leakage was about the same. The median value for III at age 2 years is greater than for I and II.

Referring again to the data of Table 10, it may be noted that the concrete made with cement No. 1, the high-early strength cement, was less permeable at the early age than with the concretes made with the ordinary Portlands. Due to the greater rate of increase the permeability of concrete made with cement No. 1 was at the age of 2 years midway between that of the two other concretes. The data show that cement No. 3 produced a less permeable concrete than did cement No. 2. The median values given in Table 9 substantiate the conclusions.

In the case of the clays the indices show a slight advantage of Nos. 1 and 2 over No. 3.

VII. CONCLUSIONS

The replacement of 7½ per cent of the volume of the sand by an equal volume of clay increased the compressive strength 1 to 37 per cent. At 9 months the permeability was decreased; later it was increased both actually and relative to that of the plain concrete without clay. It should be noted, however, that all of the concretes were practically impermeable in these tests.

The substitution of clay for 10 per cent of the volume of the cement, except for the first two or three months in the case of the ordinary Portland cement concrete, caused a decrease in strength of 0 to 10 per cent. The very slight permeability was not appreciably changed.

The replacement of 7½ per cent of the sand in one case and 10 per cent of the cement in the other by equal volumes of clay slightly increased the absorption for specimens stored outdoors, but did not appreciably change that of specimens frozen and thawed.

Four hundred cycles of freezing in air and thawing in water did no apparent injury to the concrete kept continually damp.

The concrete that was dried out after 40, 100, 150, and 200 cycles of freezing in air and thawing in water disintegrated within the range of 85 to 400 cycles.

The difference in absorption, permeability, and resistance to freezing and thawing between concretes containing and not containing clay was small.

VIII. ACKNOWLEDGMENTS

It is a pleasure to acknowledge the assistance of several members of the bureau's staff, especially that of C. W. Ross, who made some of the tests of concrete specimens, and of A. U. Theuer, who made the plasticity tests of the clays. The program for the tests was prepared with the assistance of Col. Hugh L. Cooper, and the work was carried on jointly by the Hugh L. Cooper Co. and the Bureau of Standards.

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