permeable than that with 1-inch maximum diameter stone, and this is less permeable than that with ½-inch stone.*

(3) Concrete of cement, sand and gravel, is less permeable than concrete of cement, screenings and broken stone; that is, for equal permeability, a slightly smaller quantity of cement is required with rounded aggregates like gravel than with sharp aggregates like broken stone.*

(4) Concrete of mixed broken stone, sand and cement, is more permeable than concrete of gravel, sand and cement, and less permeable than

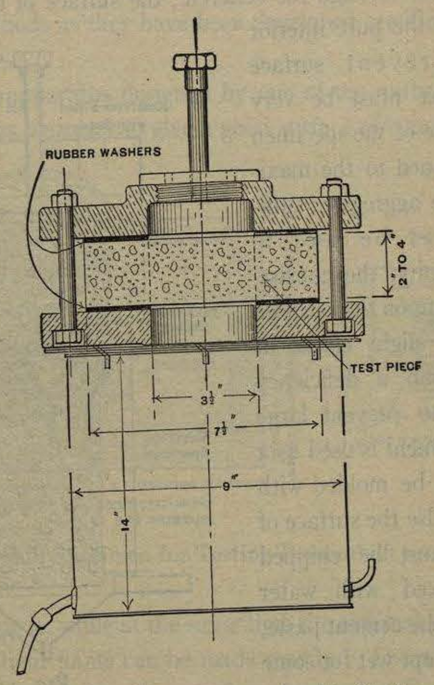


FIG. 115. Permeability Specimen used at St. Louis. (*See p.* 349.)

similar concrete of broken stone, screenings and cement; that is, for water-tightness, less cement is required with rounded sand and gravel than with broken stone and screenings.*

(5) Permeability decreases materially with age.*

(6) Permeability increases nearly uniformly with the increase in pressure.*

(7) Permeability increases as the thickness of the concrete decreases, but in a much larger inverse ratio.*

(8) Of mortars containing the same percentage of cement but of variable granulometric composition, the most impermeable are those containing

* "Laws of Proportioning Concrete," by Fuller and Thompson, Transactions American Society Civil Engineers, Vol. LIX, 1907, p. 72.



equal parts of coarse grains, *G*, and fine grains, *F* (see p. 142), the latter including the cement.*

(9) Decomposition by the passage of sea-water through mortars mixed in equal proportions by weight increases as the sand contains more fine grains.†

(10) Medium and fairly wet consistencies produce concrete much more water-tight than dry consistencies, and slightly more water-tight than very wet consistencies.†

(11) The surface of concrete as molded is much more water-tight than the bottom of a specimen, because of the fine material which rises to the top.†

## RESULTS OF TESTS OF PERMEABILITY

The table which follows gives the comparative permeability of concrete specimens 18 inches in length and 6 inches square, made up as shown in Fig. 114. The various qualities are referred to in paragraphs which follow:

**Effect of Shape of Stone Upon Permeability.** In the table it is noticeable that the most permeable concrete is that composed of broken stone and screenings; the next, that containing broken stone and natural sand; and the most water-tight of all (comparing similar percentages of cement), the concrete of gravel and sand. The rounded gravel stone and sand evidently flow better and make a more homogeneous mix. It is noticeable also in the Jerome Park permeability tests that the results from the sand and gravel specimens were the most uniform.

**Effect of Percentage of Cement Upon Permeability.** The table on the following page illustrates the very great increase in water-tightness with the richness of the mixture. The most extreme differences are noticed in the specimens with broken stone and screenings.

**Increase of Permeability With Pressure.** A comparison of the columns in the table shows that the rate of flow increases nearly uniformly with the increase of pressure.

**Effect of Thickness of Concrete Upon Permeability.** Other experiments, not here recorded, indicate that the rate of flow increases as the thickness of the concrete decreases, but in a much larger inverse ratio. Speci-

* R. Feret in Annales de Ponts et Chaussées, 1892, II, p. 109.

† "The Consistency of Concrete," by Sanford E. Thompson, Proceedings American Society for Testing Materials, Vol. VI, 1906, p. 358.

mens 17 inches in length in proportions 1 : 6.5 by weight were practically water-tight, whereas specimens of half that length passed considerable water.

*Effect on Permeability of Percentage of Cement, Character of Aggregate and Pressure,*

BY FULLER AND THOMPSON* (See p. 351.)

*Thickness of Specimens 18 inches. Area of contract 36 square inches.*
Maximum diameter of stone $2\frac{1}{4}$ inches.

| PROPORTIONS BY WEIGHT | PERCENTAGE OF CEMENT TO TOTAL DRY MATERIALS | KIND OF MATERIAL | | TIME IN WHICH WATER APPEARS AFTER STARTING PRESSURE | RATE OF FLOW OF WATER IN GRAMS PER MINUTE, AT THE FOLLOWING PRESSURES, PER SQUARE INCH | | | |
|---|---|---|---|---|---|---|---|---|
| | | Stone | Sand | | | | | |
| | % | | | min. | 20 lb. | 40 lb. | 60 lb. | 80 lb. |
| 1 : 11.5 | 8.0 | Crushed stone | Screenings | 7 | 25 | 161 | 237 | 273 |
| 1 : 9 | 10.0 | " | " | 3 | 11 | 24 | 37 | 49 |
| 1 : 7 | 12.5 | " | " | 3 | 15 | 22 | 30 | 38 |
| 1 : 5.8 | 15.0 | " | " | 5.5 | 5 | 8 | 10 | 12 |
| 1 : 8.8 | 10.2 | Crushed stone | Sand | 9 | 4 | 11 | 17 | 22 |
| 1 : 6.9 | 12.7 | " | " | 10 | 2 | 2 | 3 | 3 |
| 1 : 5.5 | 15.6 | " | " | | 0 | 0 | 0.7 | 1.4 |
| 1 : 10.8 | 8.5 | Gravel | Sand | 3 | 15 | 25 | 38 | 43 |
| 1 : 8.4 | 10.6 | " | " | 17 | 1 | 3 | 5 | 6 |
| 1 : 6.5 | 13.0 | " | " | 100 | 0 | 0 | 0 | 0.5 |
| 1 : 5.3 | 15.9 | " | " | 98 | 0 | 0 | 0 | 1.4 |

**Rate of Flow.** The Jerome Park tests indicate that if the surface of the concrete is clean and the water pure, the flow is very nearly constant for a considerable period. During a four hours' test there was no appreciable differences in the rate of flow. This result is somewhat contrary to other tests, but it is probable that in many cases the apparent plugging up of the pores is due to impurities in the water or to the early age of the concrete.

**Effect of Size of Stone Upon Permeability.** The following table gives the comparative permeability of concrete in the same proportions mixed with stone of different maximum size. The difference in this case is evidently due to the greater density of the concrete composed of the large stone.

* Transactions American Society Civil Engineers, Vol. LIX, 1907, p. 132.



*Effect of Size of Stone on Permeability*

BY FULLER AND THOMPSON* (*See p.* 352.)

*Thickness of Specimens 18 inches. Area of contact 36 square inches.*
Aggregates, crushed stone and natural sand.

| PROPORTIONS BY WEIGHT | PERCENTAGE OF CEMENT TO TOTAL DRY MATERIAL | MAXIMUM SIZE OF STONE | TIME IN WHICH WATER APPEARS | RATE OF FLOW OF WATER IN GRAMS PER MINUTE AT THE FOLLOWING PRESSURES PER SQ. IN. | | | |
|---|---|---|---|---|---|---|---|
| | % | in. | min. | 20 lb. | 40 lb. | 60 lb. | 80 lb. |
| 1 : 2.9 : 5.7 | 10.2 | $2\frac{1}{4}$ | 7 | 1 | 4 | 8 | 12 |
| 1 : 2.9 : 5.7 | 10.2 | 1 | 26 | 0 | 5 | 10 | 15 |
| 1 : 2.9 : 5.7 | 10.2 | $\frac{1}{2}$ | 29 | 0 | 10 | 17 | 20 |

**Effect of Coarseness of Sand Upon Permeability.** As stated, tests by Mr. Feret have indicated that for maximum watertightness more fine sand is required than for maximum strength. This is borne out by tests by one of the authors, the results of which are given in the following table. The tests were made in connection with the preparation of specifications for the Waltham Reservoir.†

*Tests to determine Relative Permeability of Concrete with Coarse and Fine Bank Sand*

BY SANFORD E. THOMPSON. (*See p.* 353.)

*Proportions 1 : 3 : 6 by Volume or 1 : 2.8 : 5.7 by Weight. Age 32 days*

| CHARACTER OF SAND | DENSITY $c + s + g$ | WATER PASSING IN GRAMS PER MINUTE |
|---|---|---|
| (1) All coarse | 0.853 | 145.1 |
| (2) $\frac{5}{6}$ coarse, $\frac{1}{6}$ fine | 0.846 | 10.4 |
| (3) $\frac{2}{3}$ coarse, $\frac{1}{3}$ fine | 0.843 | 43.0 |
| (4) All fine | 0.813 | 30.2 |

*Analyses of Natural Bank Sand and Screened Gravel used in Tests*

| SIEVE | TOTAL PER CENT PASSING SIEVES | | |
|---|---|---|---|
| | Coarse Sand | Fine Sand | Screened Gravel |
| | % | % | % |
| 1 inch | | | 100 |
| $\frac{1}{2}$ inch | | | 50 |
| $\frac{1}{4}$ inch | 100 | | 0 |
| No. 5 | 88 | | |
| No. 12 | 77 | 100 | |
| No. 40 | 32 | 96 | |
| No. 200 | 3 | 27 | |

*Transactions American Society of Civil Engineers, Vol. LIX, 1907, p. 136.
†See Chapter XXVIII.