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TENSILE AND OTHER PROPERTIES OF CONCRETES MADE WITH VARIOUS TYPES OF CEMENTS

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ABSTRACT

An improved tensile-test method for concrete has been developed. Cylindrical specimens, 4 by 16 inches, are used, and loads are applied at both ends through threaded rods embedded in a rich mortar. Compressive- and tensile-strength and stress-strain determinations have been made for concretes made with various types of cements, including cements with aerating agents, and with various aggregates. At early ages, strengths for moderate-heat cements were but slightly lower than for normal cements, whereas those for high-early-strength cements were considerably higher. Tensile strengths usually attained maximum values between 7 days and 3 months. Tensile strengths depended on compressive strengths, type of cement, type of aggregate, and on sand-gravel ratios.

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I. INTRODUCTION

The tensile strength of concrete is an important factor in its resistance to fracture by bending, shrinkage, freezing and thawing, or differential expansion. Although a number of investigations on both tensile and flexural properties of concretes have been reported, no comparative data on the effect of the newer types of cement are available. The present investigation was undertaken to develop a more satisfactory tensile-test method for concrete than has been used in the past, and particularly to secure data on the compressive, tensile, and stress-strain properties of concretes made with various types of cement, including cements with aerating agents. In addition, the effect of varying the sand-gravel ratio or the type of coarse aggregate on the tensile strength of concrete was studied.

II. TENSILE-TEST METHODS

1. PREVIOUS METHODS

Unlike the compressive test, which has been standardized [1],¹ tensile tests of concrete have been made by a number of different methods [2 to 9]. The dimensions of the specimens have ranged from 12 to 39 in. in length, and from 3 to 6 in. square, or in diameter. The shapes of the specimens have also varied, depending on the method of applying the load. Some investigators [4, 7, 8, 9] used specimens with enlarged ends to which grips were applied. Others [5, 11] cast cylindrical specimens and used grips clamped or wedged to the ends of the test pieces. Besides the use of unduly large specimens, some of these methods are open to objection because of the way the specimens break. Specimens with enlarged ends often break at the junction of the enlarged and reduced portions. Cylindrical specimens, on the other hand, may break near or within the grips [5].

2. IMPROVED METHOD

The type of specimen and method of loading developed in the present investigation are believed to overcome these objections. In principle, the method is similar to that used in the tests of Talbot and of Withey [2, 3].

The new feature of the improved method of determining tensile strength is the application of the load to the concrete under test through threaded rods embedded in a rich mortar molded on the ends of the cylindrical test specimens (fig. 1). The preliminary tests with this method showed that the specimens always broke well within the concrete under test, and that a bond stress of 700 lb/in.² of embedded rod area could be safely used. Thus, for the rods in figure 1, giving about 12 in.² of bond area, no failure in bond or at the ends of the rods will occur for loads up to 8,000 lb., equivalent to a tensile stress in the concrete of 600 lb/in.².

A few tests were made to compare the new method with certain of the older methods. With a 1:4.5 concrete, six specimens were molded and tested by the new method, and six by each of the following methods:

¹ Figures in brackets indicate the literature references at the end of this paper.

A 1:3 mortar made with standard Ottawa sand, as used in cement testing (Federal Specification SS-C-158a), was also tested. Mortar from the same batch was molded into standard briquets and into cylinders of the type used for the new concrete tensile-test method. At 7 days the average strength for three briquets was 295 lb/in.², and for three cylinders, 360 lb/in.². At 28 days the averages were 415 and 565 lb/in.², respectively. The cylinders thus gave 22 and 36 percent higher strengths than the briquets.

III. MATERIALS AND TESTS

1. CEMENTS

The cements used in the tests were five normal portland cements, including a white portland, designated N-1 to N-5, table 1; four moderate-heat portland cements, M-1 to M-4; three high-early-strength portland cements, S1-S3; two portland-pozzolan cements, P-1 and P-2; one high-alumina cement, L; and eight portland cements with rosin, tallow, or vinsol resin as aerating agents ground in at the mill, table 2, C to J. One cement was tested both without and with a soluble aerating agent, sodium lauryl sulfate, added in the laboratory, so that a comparison could be obtained between aerated and unaerated concretes for the same cement, table 2, A and B. Each of the cements within a type was from a different mill.

2. MIXES AND TESTS

For the tests with the various cements, the aggregates were Potomac River sand and gravel. The fineness modulus of the sand varied from 2.6 to 2.8. The maximum size of the gravel was $\frac{3}{4}$ in., with 34 percent passing the $\frac{3}{8}$ -in. sieve and 100 percent retained on the No. 4.

For all but the aerated concretes, two mixes were tested with each of the cements, a 1:2.4:3.6 by weight (mix *B*, 1:6) and a 1:1.75:2.75 by weight (mix *H*, 1:4.5). Only mix *B* was used in the tests on aerated concretes. Compressive and tensile specimens, in triplicate, were made for test at 3, 7, and 28 days, 3 months, and 1 year, except that for the high-early-strength and high-alumina cements tests at 1 day were added and the 3-month compressive tests omitted. In addition to the compressive and tensile tests, stress-strain relations were determined on the concretes made with the cements containing aerating agents.

To study the effect of varying the aggregate proportions, a series of tensile tests was made in which the sand-gravel ratio in a 1:6 mix with the Potomac aggregates was varied. These tests were made with each of three different portland cements. The proportions varied from 1:1.9:4.1 to 1:3.4:2.6, and the water content was varied correspondingly to maintain approximately equal flow values. Tensile strengths at 3 and 28 days were determined.

Another series of tests was made to study the effect of a few different coarse aggregates. For this series, a single cement with Potomac sand was used. The coarse aggregates were Potomac gravel, a New York limestone, an Ohio slag, a Pennsylvania trap-rock, and a New York granite. Two mixes were tested, except for the granite and trap-rock, for which there was only sufficient material

for one mix. For the Potomac gravel, the mixes were the same as for the tests of the various cements. For the other coarse aggregates, the cement-sand ratios were the same as for the Potomac, but the proportions of coarse aggregate were varied with the bulk specific gravities so as to give approximately equal yields of concrete. The water contents were varied to give equal flow values, except in one case where the Potomac gravel was tested in a mix with the same C/W ratio as was used for the other aggregates. Tests were made on the 1:6 mixes at 7 and 28 days, and on the 1:4.5 mixes at 3 and 28 days (table 4).

In all of the above tests, a set of three specimens was tested at each test age. The cements used in the series of tests with various aggregates and sand-gravel ratios were of different brands or lots from those mentioned in section III-1.

IV. PREPARATION OF TEST SPECIMENS

1. COMPRESSIVE SPECIMENS

All mixing and molding of the test specimens was done in a laboratory maintained at $70^{\circ} \pm 3^{\circ}$ F. The 6 by 12 in. compression cylinders were prepared by ASTM method C39-39 [1]. The mixing time was generally 2 minutes. It was found, however, that the 2 minutes of hand mixing was not sufficient to incorporate substantial amounts of air where the cements contained aerating agents. Hence these concretes were mixed for 3 minutes.

Flow values were determined by ASTM method C124-39, [1, P. 337] except that the mold was filled without rodding, and the table dropped 15 times through a distance of $\frac{1}{8}$ in. The cement-water ratio was generally 1.66 for the 1:6 mix and 2.05 for the 1:4.5 mix (6.8 and 5.5 gal/bag, respectively) but was varied somewhat to maintain approximately equal flows.

The tops of the compression cylinders were capped with neat-cement paste, not less than 4 hours after molding them. For the slower-setting cements, capping the cylinders in less than 4 hours after molding, results in distortion of the caps.

The cylinders were left in the laboratory for 24 hours, then removed from the molds and stored in the damp room at $70^{\circ} \pm 3^{\circ}$ F until tested.

2. TENSILE SPECIMENS

The method of molding the tensile-test specimens can be seen in figure 1. The $\frac{3}{8}$ -by-4-in. threaded rods were held in position by the holes in the bottom plate, *B*, and the mold was held in place by the pins in the plate. The mortar for the ends of the tensile specimen consisted of the test cement and sand, 1:1.8 by weight, with a C/W (cement-water) ratio of 2.4 to 2.6. Sufficient mortar for a set of three tensile specimens was mixed in a pan, by hand. The lower ends of three specimens were then molded by rodding the mortar, in two layers, each about 2 in. in depth, so as to extend about 1 in. above the ends of the threaded rods, figure 1. Concrete, sufficient for 3 specimens, was then mixed and placed in the mold in two 4-in. layers, each rodded with 20 strokes of the tamping rod. The remaining mortar was then placed and rodded into the top of each mold.

The plates, *T*, were then placed in position over the tops of the molds and the threaded rods inserted through the holes, with some turning and vertical motion to secure good bond to the mortar. The rods extended 1 in. beyond each end of the specimen to provide for the plates used in testing, figure 1, and had a length of 3 in. embedded in the mortar. The space between the ends of the rods and the concrete contained a mixture of mortar and concrete.

The threaded rods were lightly greased before molding into the tensile specimens, and could be readily removed by splitting the cylinders. The same rods were then used in other specimens.

The tensile specimens were stored and cured under the same conditions as the compressive specimens.

V. TEST METHODS

1. COMPRESSIVE AND TENSILE TESTS

The compressive tests were made in a 300,000-lb. hydraulic testing machine at a rate of loading of 1,000 lb./in.² a minute. The tensile tests were made in a 100,000-lb. beam-and-poise, screw-driven testing machine, operating at an idle head speed of 0.05 in. per minute. One-half-inch plates, *P*, figure 1, were attached to the specimen, and eye-bolts, *E*, attached to the plates. The loads were applied through bars passing through the eye of each bolt and resting against the testing-machine heads.

2. STRESS-STRAIN DETERMINATIONS

Strains were measured with two Tuckerman optical strain gages [10], extended to a 6-in. gage length. The gages were seated on thin brass plates attached with plaster of paris to the specimen, and were diametrically opposite each other. An initial stress of 50 or 100 lb/in.² for the compressive specimens, or of 10 lb/in.² for the tensile specimens, was applied for the first readings. Rates of loading were the same as for the strength tests, but the loads were maintained as nearly constant as possible while the gages were being read. Strains were measured to less than one-millionth.

However, because of the difficulty of maintaining constant loads with the hydraulic machine, any load increment may be in error by as much as 400 lb, equivalent to 14 lb/in.² on a 6- by 12-in. cylinder, corresponding to a strain error of 4×10^{-6} for a modulus of 3.5×10^6 lb/in.² This error is less than 2 percent of the strain at a stress of 1,000 lb/in.², and correspondingly lower at higher stresses.

VI. TEST RESULTS AND DISCUSSION

1. CONCRETES MADE WITH VARIOUS CEMENTS

(a) GENERAL

The test results for two concrete mixes with the various cements, and for the aerated concretes, are given in tables 1 and 2. For any one specimen of a set of three, the deviation from the average was usually less than 10 percent, both for the tensile and compressive specimens. Practically none of the tensile fractures occurred at a distance of less than 2 in. from the ends of the threaded rods, and about 80 percent of the fractures were within 2 in. of the middle of the specimen.

TABLE 1.—Compressive and tensile strengths of concretes made with various types of cement

[Each strength value is the average for 3 test specimens]

Type of cement	Identification ¹ number	C/W ² by weight	Flow	Compressive strength (lb/in. ²) at—						Tensile strength (lb/in. ²) at—					
				1 day	3 day	7 day	28 day	3 mo.	1 yr.	1 day	3 day	7 day	28 day	3 mo.	1 yr.
MIX B. 1:6 BY WEIGHT															
Normal	N-1	1.66	%		1,490	2,260	4,440	5,030	5,540		170	240	355	360	355
Do.	N-2	1.66	48		1,420	2,260	4,300	5,440	5,960		170	230	415	430	450
Do.	N-3	1.66	48		1,520	2,730	4,800	5,420	5,800		170	255	395	365	370
Do.	N-4	1.66	45		1,490	2,820	5,030	5,900	6,160		200	285	440	425	400
Normal (white)	N-5	1.66	55		1,560	2,660	4,560	5,040	5,960		195	290	425	385	430
Average					1,490	2,550	4,630	5,370	5,880		180	260	405	395	400
Moderate heat	M-1	1.66	57		1,030	1,760	3,550	5,560	6,530		135	200	355	435	470
Do.	M-2	1.66	46		1,040	2,170	4,560	5,250	6,480		150	260	395	375	435
Do.	M-3	1.66	50		1,440	2,510	4,420	5,330	6,340		195	285	385	405	445
Do.	M-4	1.66	50		1,380	2,350	4,480	5,460	5,800		190	275	430	405	405
Average					1,220	2,200	4,250	5,400	6,290		170	255	390	405	440
Portland-pozzolan	P-1	1.66	47		800	2,060	4,670	5,530	5,860		135	230	415	370	410
Do.	P-2	1.55	52		1,140	1,910	3,000	3,900	4,270		160	235	315	310	355
Average					970	1,980	3,830	4,710	5,070		150	230	365	340	380
High-early strength	S-1	1.66	49	1,020	2,580	3,690	5,420		5,690	150	300	430	505	410	435
Do.	S-2	1.59	54	1,150	2,730	3,980	5,500		5,280	160	300	435	460	365	365
Do.	S-3	1.66	44	1,020	3,310	4,280	6,150		5,970	155	365	445	480	420	390
Average				1,060	2,870	3,980	5,690		5,650	155	320	435	480	400	395
High alumina	L	1.66	58	4,030	4,270	4,980	5,510		4,130	295	330	290	275		220

See footnotes at end of table.

Tensile Properties of Concretes

TABLE 1.—Compressive and tensile strengths of concretes made with various types of cement—Continued

Type of cement	Identification ¹ number	C/W ² by weight	Flow	Compressive strength (lb/in. ²) at—						Tensile strength (lb/in. ²) at—					
				1 day	3 day	7 day	28 day	3 mo.	1 yr.	1 day	3 day	7 day	28 day	3 mo.	1 yr.
MIX H. 1:4:5 BY WEIGHT															
Normal	N-1	2.05	49	-----	2,210	3,360	5,270	6,010	6,650	-----	265	390	465	425	455
Do.....	N-2	2.05	52	-----	2,080	3,230	5,360	6,790	7,910	-----	250	360	530	530	525
Do.....	N-3	2.05	53	-----	2,380	3,990	5,900	6,610	7,700	-----	285	435	470	505	490
Do.....	N-4	2.05	52	-----	2,280	4,070	6,620	7,050	8,030	-----	300	410	515	500	485
Normal (white).....	N-5	2.05	59	-----	2,390	3,450	5,290	6,130	7,480	-----	250	350	460	465	515
Average.....				-----	2,270	3,630	5,690	6,520	7,550	-----	265	390	490	485	495
Moderate heat.....	M-1	2.05	61	-----	1,670	2,780	5,020	6,880	8,400	-----	230	310	520	535	595
Do.....	M-2	2.05	47	-----	1,760	3,250	5,880	6,750	7,690	-----	235	400	490	485	520
Do.....	M-3	2.05	42	-----	2,100	3,620	5,230	6,580	7,820	-----	285	440	480	465	545
Do.....	M-4	2.05	40	-----	2,110	3,390	5,860	6,320	7,490	-----	300	425	515	475	460
Average.....				-----	1,910	3,260	5,500	6,630	7,850	-----	260	390	500	490	530
Portland-pozzolan.....	P-1	2.05	50	-----	1,390	2,520	5,610	6,460	6,780	-----	210	310	480	470	545
Do.....	P-2	1.88	54	-----	1,760	2,880	4,340	4,960	5,510	-----	225	315	415	385	435
Average.....				-----	1,580	2,700	4,980	5,710	6,140	-----	220	310	445	430	490
High-early strength.....	S-1	2.05	42	-----	1,750	3,580	4,680	5,770	-----	210	390	525	530	495	510
Do.....	S-2	1.96	47	-----	1,790	3,600	5,070	6,120	-----	7,150	240	420	520	495	415
Do.....	S-3	1.94	47	-----	1,540	3,770	4,710	6,300	-----	7,290	205	410	465	500	490
Average.....				-----	1,690	3,650	4,820	6,060	-----	7,270	220	405	505	510	475
High alumina.....	L	2.05	51	-----	4,590	-----	5,250	6,310	-----	4,560	375	435	445	350	-----

¹ Numbers following the type letter signify different brands of that type.

² Ratio of weight of cement to weight of water in the mix.

TABLE 2.—*Properties of aerated concretes (mix B: 1:6 by weight)*

[Each strength or modulus value is the average for 3 test specimens]

Cement ¹	Aerating agent	C/W by weight	Flow	Weight of fresh concrete	Compressive strength at—					Tensile strength at—				Modulus of elasticity/10 ⁶ at 28 days			
					3 day	7 day	28 day	3 mo.	1 yr.	3 day	7 day	28 day	3 mo.	Compression	Tension		
			%	lb/ft. ³	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	lb/in. ²	
A	None	1.66	45	146.2	2,580	4,650	220	305	385	380	4.1	4.0					
B ²	Sodium lauryl sulfate	1.82	46	137.8	2,050	3,720	190	290	345	360	3.6	3.3					
C	Rosin	1.66	45	141.2	1,150	1,970	3,830	3,930	4,540	190	270	360	355	3.6	3.5		
D	Tallow	1.74	45	139.9	1,230	2,190	3,060	4,200	4,640	220	275	330	385	3.6	3.5		
E	do	1.66	43	141.6	1,470	2,340	4,210	4,130	4,520	210	330	325	310	3.7	3.6		
F	do	1.66	46	139.6	1,210	2,180	3,430	3,790	3,940	185	270	355	325	3.4	3.3		
G	do	1.68	46	143.2	1,440	2,500	4,070	4,860	5,310	210	300	390	415	3.7	3.6		
Average				141.1	1,340	2,400	3,690	4,250	4,600	210	290	350	360	3.6	3.5		
H	Vinsol resin	1.74	46	142.3	1,710	2,710	4,310	4,780	5,340	255	320	390	405	3.9	3.6		
I	do	1.70	45	143.6	1,920	2,960	4,380	5,050	5,520	250	320	350	390	3.9	3.8		
J	do	1.77	47	141.2	1,350	2,510	3,960	4,630	5,560	190	250	315	410	3.7	3.7		
Average				142.4	1,660	2,730	4,160	4,820	5,470	230	295	350	400	3.8	3.7		

¹ These cements were of different lots or brands from those listed in table 1.

² Normal cement A, with 0.05 percent of a soluble aerating agent added in the laboratory.

(b) VARIATION IN STRENGTH FOR CEMENTS WITHIN A TYPE

There was sometimes considerable variation in strength for different cements within a type, as, for instance, for the two portland-pozzolan cements, table 1. However, for both the normal and the high-early-strength portland cements, the variation of either compressive or tensile strength from the average for the type was, at any age, less than 16 percent. Somewhat greater variation is found among the moderate-heat cements. The aerated concretes, table 2, also show considerable variation, as is to be expected from the effect of the various aerating agents on the weight per cubic foot of concrete. This varied from 138 to 144 lb compared with 146 lb for the unaerated concrete made with cement A.

(c) VARIATION IN STRENGTH WITH TYPE OF CEMENT

In figure 2 the average strengths for each type of cement are plotted against age. For both mixes the strengths for the high-early-strength cements, both in tension and compression, for ages up to and including 28 days are higher than for all others, except for the 1:4.5 mix with the high-alumina cement.

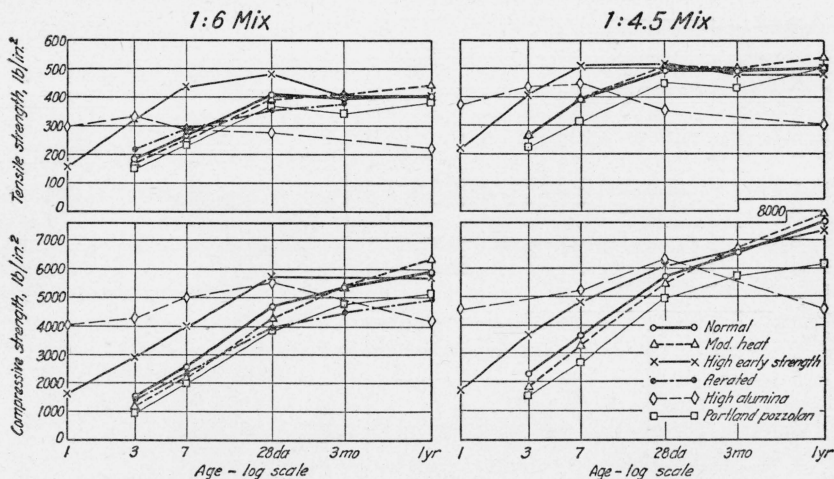


FIGURE 2.—Age-strength relations for concretes made with various types of cement.

Strength values are averages for each type of cement.

In figure 2 it may be seen that to attain an average compressive strength of 4,600 lb/in.² requires about 28 days for the normal cements, 1:6 mix, and about 12 days for the high-early-strength cements in the same mix. Similarly, for an average tensile strength of 400 lb/in.², attained by the normal cements in 28 days, only about 6 days are required by the high-early-strength cements. A similar relation is seen for the 1:4.5 mix. Thus it appears that the use of a high-early-strength cement is of greater advantage in securing high early tensile than high early compressive strength.

For both the 1:6 and 1:4.5 mixes, the moderate-heat cements gave strengths up to about 28 days somewhat lower than those for the normal cements. After 3 months there is a tendency for the moderate-

heat cements to give slightly higher strengths, both in tension and compression, than the normal cements.

The aerated concretes, represented only by the 1:6 mix, show a wider range of strengths than the other types, as is to be expected both from the variety of aerating agents used and the number of cements tested. Although the tensile strengths at the early ages are on the average slightly higher than those for the normal cements, at the later ages there is a tendency for both tensile and compressive strengths to fall below those for the normal cements.

The two portland-pozzolan cements differed widely from each other, table 1. For one of these, the strengths up to 7 days were within the range of those for the moderate-heat portland cements; however, after 7 days the strengths for this cement were appreciably lower than those given by the moderate-heat cements. The other portland-pozzolan cement gave relatively low strengths only up to 3 or 7 days, but thereafter the strengths were within the range of those for the normal cements.

The high-alumina cement is unique in showing very high early strength (at 3 days or less). However, compressive strengths began retrogressing some time after 28 days and tensile strengths some time after 3 days for the 1:6 mix and 7 days for the 1:4.5 mix, so that at 1 year the strengths for this cement, both in tension and compression were no higher than at 1 day, and were less than for any other type of cement.

(d) EFFECT OF AGE OF CONCRETE ON STRENGTH

While the concretes made with two of the three high-early-strength cements (table 1) showed slight retrogression in compressive strength for the 1:6 mix after 28 days, those made with all the other types of cement except the high-alumina showed continued increase in compressive strength, for both mixes, up to a year. Tensile strengths, however, usually reached a maximum value at some time between 7 days and 3 months, followed by retrogression (table 1). The maximum tensile strengths obtained for the 1:6 mix with the high-early-strength cements were higher than those for the same mix with the other cements (fig. 2). However, the high-early-strength cements showed relatively large retrogressions, and, at 3 months and thereafter, gave about the same tensile strengths as the normal cements. For the 1:4.5 mix, two of the three high-early-strength cements gave maximum values at 7 days, but these were no higher than those attained by other cements at later ages. One of the three cements (S-2, table 2) of this type showed large retrogression for this mix.

The average strengths for the moderate-heat cements at 1 year were the highest for all cements tested. For the normal and portland-pozzolan cements, any retrogression between 28 days and 3 months was usually followed by some recovery, so that, at 1 year, the tensile strengths are never more than 10 percent lower than at 28 days, and are often higher.

The retrogressions in tensile strengths of concretes after certain ages may be due to retrogression in mortar tensile strengths, since such retrogression occurs with mortar briquets. The retrogressions may also be due in part to decrease in bond strength between gravel and mortar. Considerable gravel fracture was noted at 28 days,

and there was some tendency for the percentage of gravel fractured to decrease with age thereafter.

(c) EFFECT ON STRENGTH OF CEMENT CONTENT OF CONCRETE

In general, the concrete with the higher cement content (1:4.5 mix) gave higher strength, for all cements, than the 1:6 mix, at correspond-

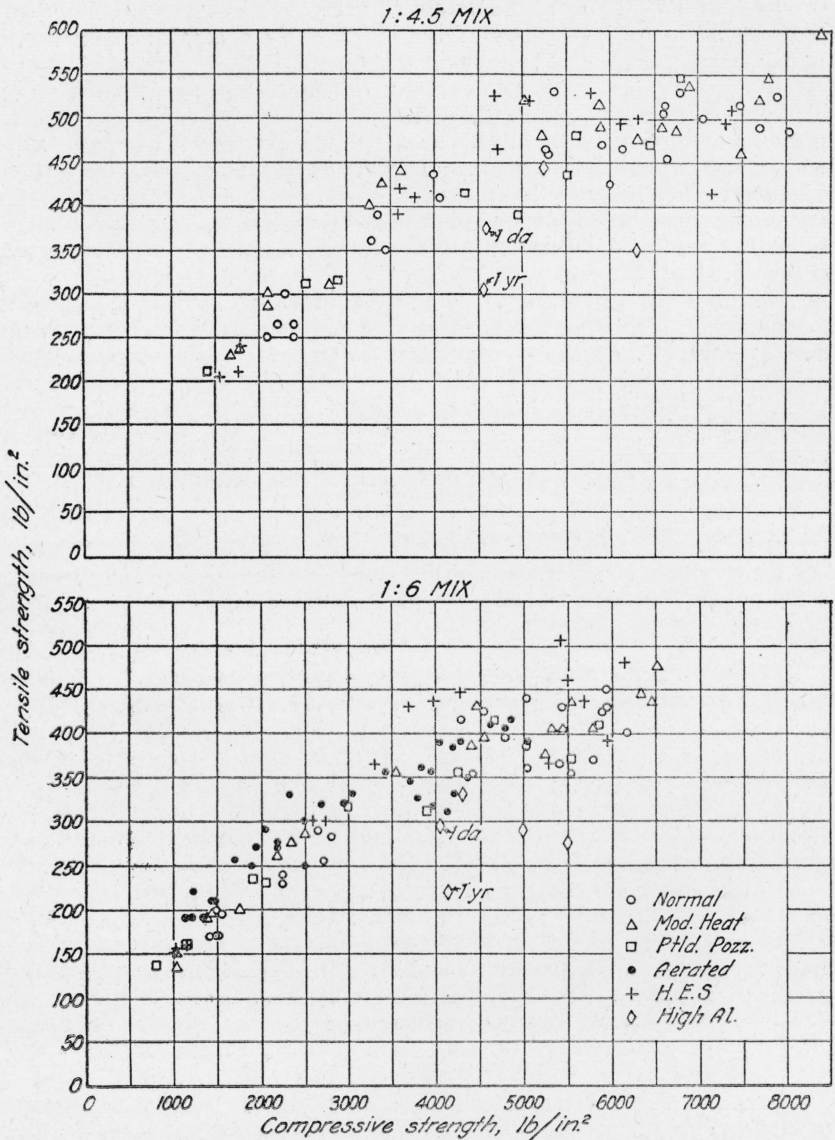


FIGURE 3.—Relations between compressive and tensile strengths.

ing ages. However, there are some noteworthy differences between the rates of increase of tensile and of compressive strength. For instance, comparing the 1:4.5 mix with the 1:6 mix for the normal

cements, we see (fig. 2) that to attain an average compressive strength of 4,600 lb/in.² requires 28 days for the 1:6 mix and about 14 days for the 1:4.5 mix. Similarly, the average tensile strength for the 1:6 mix is about 400 lb/in.² at 28 days, and this is attained by the richer concrete in only 8 days. A similar relation for the two mixes with the high-early-strength cements can also be seen. Thus the use of the richer mix is of greater advantage in securing high early tensile than high early compressive strength.

(f) RELATIONS BETWEEN COMPRESSIVE AND TENSILE STRENGTHS

In figure 3 the tensile strengths have been plotted against the corresponding compressive strengths for each of the two mixes, for all ages. It is seen that there is a fair relation between compressive and tensile strengths.

For equal compressive strengths, tensile strengths tend to be somewhat higher for the 1:4.5 mix than for the 1:6. There is also a tendency for the aerated concretes to have higher tensile strengths for equal compressive strengths up to about 2,500 lb/in.² than the other 1:6 concretes. The high-alumina cement shows appreciably lower tensile strength, for equal compressive strengths, than the other cements.

(g) STRESS-STRAIN RELATIONS

The stress-strain curves for the 1:6 concretes made with cements containing aerating agents and for cement A (the normal cement used for the tests with a soluble aerating agent), are shown in figures 4 and 5. The cements are arranged in the order of compressive strengths.

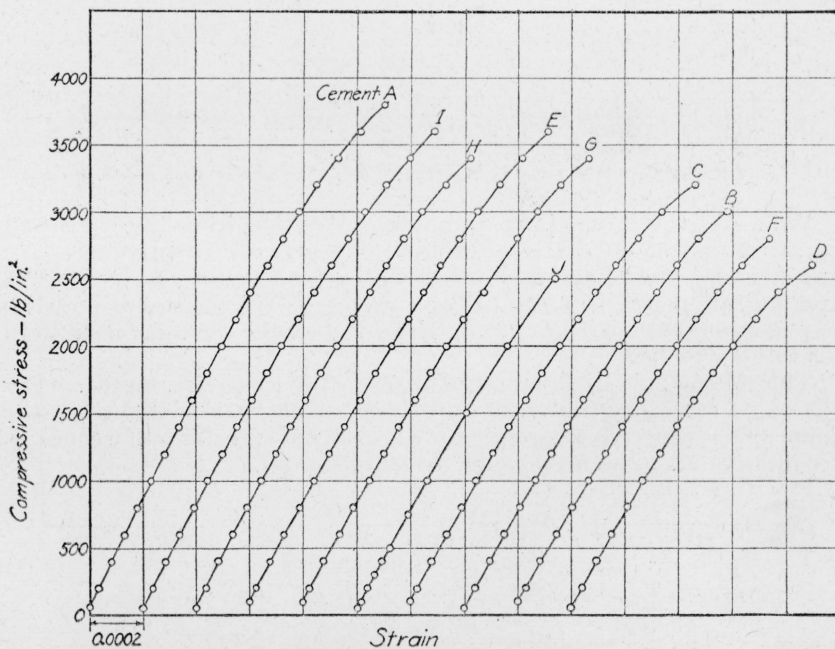


FIGURE 4.—Stress-strain relations for 1:6 concretes in compression.

For the compressive specimens the difference in strain values for opposite sides of the same specimen was usually less than 60×10^{-6} for stresses up to three-fourths of the breaking stress; this corresponds to a stress difference of 250 lb/in.² or less. For the tensile specimens the corresponding difference in strain values was usually less than 10×10^{-6} , equivalent to a stress difference of 40 lb/in.² or less. The deviation of the strain for one specimen from the average for a set of three was only about 20×10^{-6} for the compressive tests, and about 3×10^{-6} for the tensile tests.

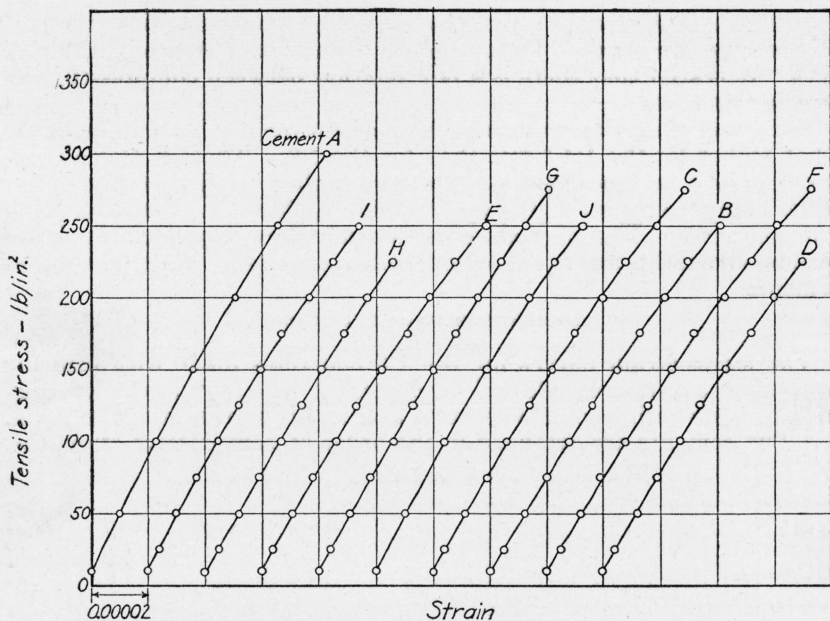


FIGURE 5.—Stress-strain relations for 1:6 concretes in tension.

Values of the initial tangent moduli, obtained from the curves of figures 4 and 5, are given in table 2. In general, both compressive and tensile moduli increase with increasing compressive strengths and weights per cubic foot of the concretes. The compressive moduli varied from 3.4 to 4.1×10^6 lb/in.², and the tensile moduli varied from 3.3 to 4.0×10^6 lb/in.².

The tensile moduli show no relation to the tensile strengths. For the same concrete, the tensile modulus appears to be slightly lower than the compressive modulus. Similar but greater differences in secant moduli have been noted by Johnson [7].

2. EFFECT OF SAND-GRAVEL RATIO AND OF VARIOUS COARSE AGGREGATES ON TENSILE STRENGTH

(a) SAND-GRAVEL RATIO

The results of the tests with Potomac River aggregate in which the sand-gravel ratio was varied are given in table 3. It is seen that for all three cements, K, L, and M, the 1:2.9:3.1 mix gave the highest tensile strengths, both at 3 and 28 days (except in one instance where the strength is within 5 lb of the maximum) despite the fact that the water requirement was higher than for the 1:2.4:3.6 mix. The 1:1.9:4.1 mix, which was deficient in sand, gave low tensile strengths despite the high C/W ratios. The 1:3.4:2.6 mix, which was definitely oversanded, had both a high water requirement and low tensile strengths.

TABLE 3.—Tensile strength of concretes with various sand-gravel ratios

[Each strength value is the average for 3 test specimens]

Mix (proportion by weight) ¹	C/W by wt	Water gal/bag	Flow %	Tensile strength at—	
				3 days lb/in. ²	28 days lb/in. ²
CEMENT K ²					
1:1.9:4.1.....	1.73	6.5	48	145	325
1:2.4:3.6.....	1.66	6.8	49	180	380
1:2.9:3.1.....	1.53	7.4	52	190	430
1:3.4:2.6.....	1.42	7.9	49	160	380
CEMENT L ²					
1:1.9:4.1.....	1.73	6.5	49	180	420
1:2.4:3.6.....	1.66	6.8	44	220	465
1:2.9:3.1.....	1.53	7.4	43	240	460
1:3.4:2.6.....	1.42	7.9	55	175	415
CEMENT M ²					
1:1.9:4.1.....	1.66	6.8	47	145	320
1:2.4:3.6.....	1.61	7.0	45	160	350
1:2.9:3.1.....	1.48	7.6	45	170	365
1:3.4:2.6.....	1.33	8.5	53	140	325

¹ Made of cement, sand, and $\frac{3}{4}$ -in. gravel.² Normal portland cements of different brands or lots from those listed in tables 1 and 2.

(b) COARSE AGGREGATES

In table 4 are given the results of the tests with various coarse aggregates.

For both mixes, Potomac gravel gave the highest strengths of any aggregate at 3 and 7 days, even when the lower C/W ratio was used. At 28 days the Potomac gravel gave higher strength than the other aggregates in the 1:6 mix, but the New York limestone gave the highest value for the 1:4.5 mix. Both the trap-rock and granite gave fairly low values for the 1:4.5 mix at 28 days, whereas the slag, which had about the same bulk specific gravity as Potomac gravel, gave a rather high value.

TABLE 4.—*Tensile strengths of concretes with various coarse aggregates*

[Each strength value is the average for 3 test specimens.]

Coarse aggregate	Proportions ¹ by dry wt	C/W by wt	Water	Flow	Tensile strength ² at—		
					3 days	7 days	28 days
			<i>gal/bag</i>	<i>percent</i>	<i>lb/in.²</i>	<i>lb/in.²</i>	<i>lb/in.²</i>
Potomac gravel.....	1:2.4:3.6	1.66	6.8	41	-----	280	445
Do.....	1:2.4:3.6	1.48	7.6	78	-----	240	385
N. Y. limestone.....	1:2.4:4.0	1.48	7.6	43	-----	175	315
Ohio slag.....	1:2.4:3.6	1.48	7.6	40	-----	195	380
Potomac gravel.....	1:1.75:2.75	2.05	5.5	40	315	-----	445
N. Y. granite.....	1:1.75:2.80	1.88	6.0	35	205	-----	405
N. Y. limestone.....	1:1.75:3.00	1.88	6.0	40	205	-----	525
Pa. "trap-rock".....	1:1.75:3.00	1.88	6.0	39	230	-----	380
Ohio slag.....	1:1.75:2.75	1.88	6.0	35	230	-----	460

¹ The amounts of coarse aggregates were varied in proportion to their bulk specific gravities.² The normal cement used for these tests was different from those of the previous tables.

For the 1:4.5 mix, the 28-day tensile strengths vary over a range of almost 1.4 to 1, depending on the coarse aggregate. Kellerman [11] has noted a similar variation, as well as the fact that relative tensile strengths for different aggregates depend on the richness of the mix. The New York limestone, for instance, gave the highest 28-day tensile strength in the rich mix, but the lowest in the leaner mix. A possible explanation is, that with some aggregates, such as Potomac gravel, the bond strength between mortar and coarse aggregate may be relatively high; this would tend to give relatively high strength at the early ages, when little of the coarse aggregate is broken. With the New York limestone, on the other hand, bond strength may be relatively low with the leaner mix, resulting in low strength at the early ages; but this aggregate may itself have higher strength and, when used in a richer mix tending to cause failure of the aggregate, the concrete strength may be rather high.

Some of the fractured sections are shown in figures 6 and 7. Figure 6, *A*, is a section of 1:6 aerated concrete made with Potomac gravel, tested at 3 days. This concrete had an average tensile strength of 220 lb/in², and the failure is mainly in bond of mortar to gravel. *B* is a section of 1:4.5 concrete, also made with Potomac gravel, tested at 28 days. The average tensile strength was 480 lb/in², and considerable gravel fracture may be seen.

In figure 7, *A* is a section of 1:6.4 concrete made with New York limestone and tested at 28 days. The average tensile strength was 315 lb/in², and very little of the stone was fractured. *B* is a section of 1:4.75 concrete made with the same aggregate and tested at 28 days. Here the tensile strength was 525 lb/in², and some aggregate fracture occurred.

VII. SUMMARY

1. An improved tensile-test method for concrete has been developed. Cylindrical specimens, 4 by 16 in. are used, and loads are applied through threaded rods embedded in a rich mortar at the ends of the specimens. The method gave fairly uniform results because of the greater uniformity of stress distribution over the section of failure than is obtained with grips, or in tapered specimens, etc.

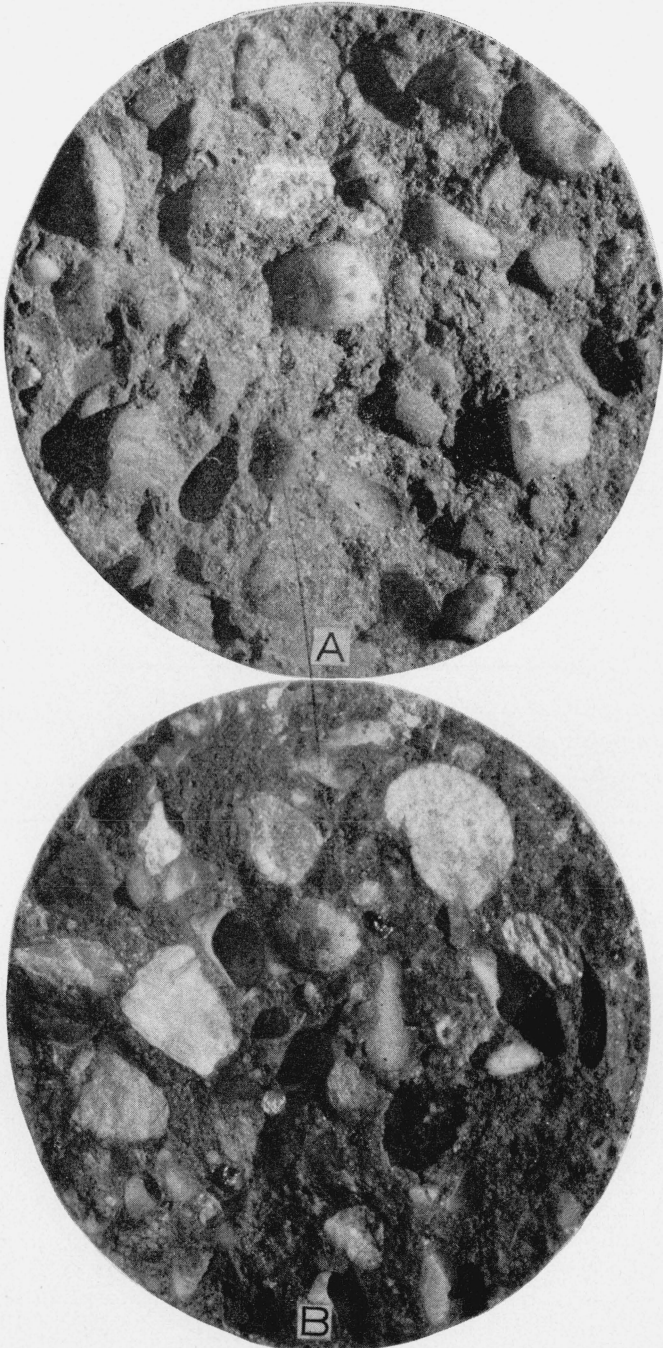


FIGURE 6.—Fractured sections of Potomac River gravel concrete.

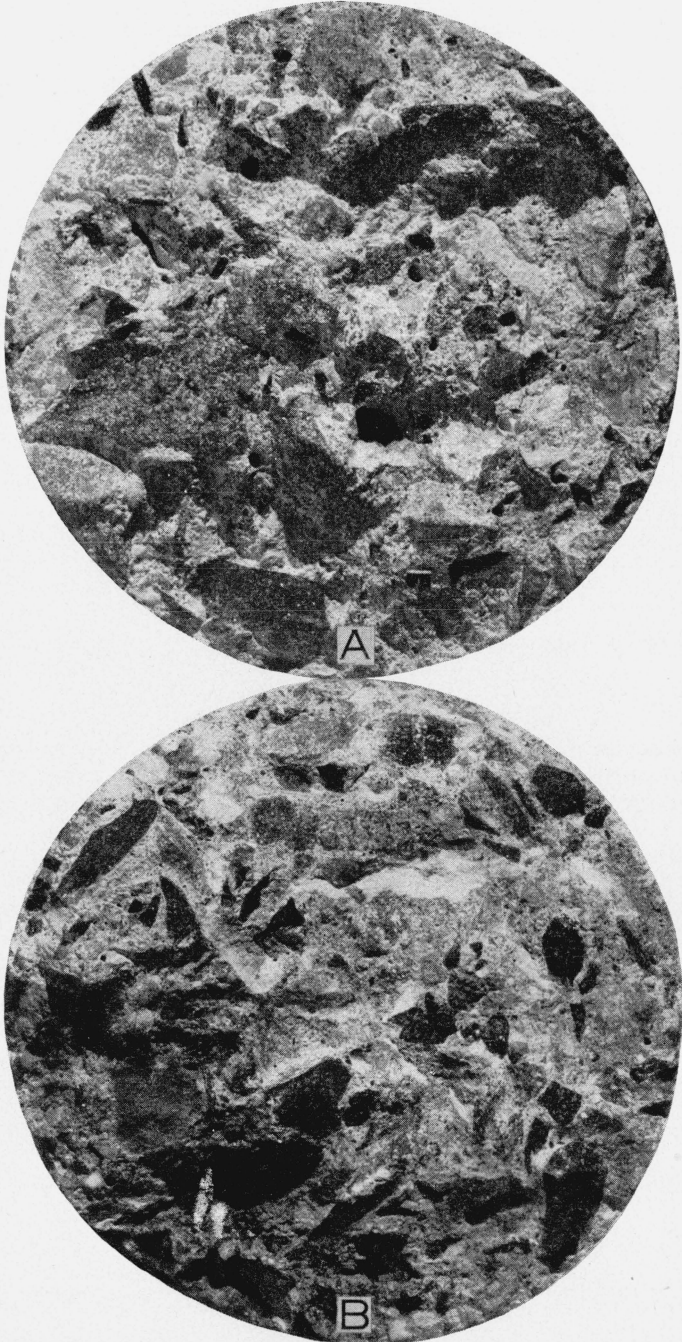


FIGURE 7.—*Fractured sections of New York limestone concrete.*

2. Compressive and tensile strengths and some stress-strain relations were determined for concretes made with a number of cements of various types, including five normal, four moderate-heat, and three high-early-strength portland cements, two portland-pozzolans, one high-alumina cement, and nine portland cements with aerating agents. The effects of various sand-gravel ratios and of various coarse aggregates on tensile strength were also studied.

3. The high-early-strength cements gave higher strengths than the normal cements, both in tension and compression, up to 28 days. The moderate-heat cements gave but slightly lower strengths than the normal cements up to 28 days; thereafter there was some tendency for the moderate-heat cements to give higher compressive and tensile strengths than the normal cements. The cements with aerating agents gave somewhat higher tensile strengths than the normal cements up to 7 days, but thereafter both compressive and tensile strengths were lower than those for the normal cements. Of the two portland-pozzolans tested, one gave rather low early strength but came within the range for the normal cements at later ages; the other gave early strengths comparable to a moderate-heat portland but gave relatively low strengths at later ages. The high-alumina cement gave very high strengths at 1 day but showed comparatively little gain at later ages.

4. Tensile strengths usually attained maximum values between 7 days and 3 months, with retrogression in many cases. However, at 1 year, tensile strengths were generally within ± 10 percent of the 28-day strengths, except for the high-alumina cement, which gave appreciably lower values. The fracture sections of the tensile specimens often showed considerable aggregate breakage at 28 days, and somewhat less at later ages.

5. The 1:4.5 mix generally gave higher strengths for all cements than the 1:6 mix at the same age. The use of either a richer mix with the normal cements, or of a high-early-strength cement, was of greater advantage in securing high early tensile strength than high early compressive strength.

6. Tensile and compressive strengths show a fair relation, but the 1:4.5 mix gave somewhat higher tensile strengths for equal compressive strengths than the 1:6 mix. For compressive strengths up to about 2,500 lb/in.², the 1:6 aerated concretes gave somewhat higher tensile strengths for equal compressive strengths than the 1:6 mix with normal cements. The high-alumina cement gave appreciably lower tensile strengths for equal compressive strengths than the other cements.

7. For the nine aerated 1:6 concretes tested with Potomac River sand and gravel, the weights per cubic foot ranged from 138 to 144 lb. compared with 146 for a corresponding normal cement concrete. Initial tangent moduli of elasticity for the aerated concretes ranged from 3.4 to 3.9×10^6 lb/in.² in compression, and from 3.3 to 3.8×10^6 lb/in.² in tension, compared with 4.1 and 4.0, respectively, for a normal cement concrete. Both the tensile and compressive moduli increased with compressive strengths, which ranged from 3,100 to 4,600 lb/in.² at 28 days.

8. Tensile strengths of concrete varied considerably with the sand-gravel ratio or with the type of coarse aggregate used. A range of 1.4 to 1 in tensile strength at 28 days was noted for different coarse

aggregates, such as slag, crushed stones, and gravel. A crushed limestone gave relatively low tensile strength in a 1:6.4 mix, and rather high strength in a 1:4.8 mix.

Acknowledgments are due the various cement manufacturers, the National Crushed Stone Association, and the National Slag Association for the materials contributed for use in this investigation.

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