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Concrete Strength in Structures

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The significance of concrete compressive strength measurement by various methods was investigated. Pairs of slabs from three concretes were subjected to good and poor curing. Cores and push-out cylinders were removed at six ages up to 1 year and tested for strength. Corresponding tests of molded cylinders brought the total specimens to 216 cores, 216 push-out cylinders, and 270 molded cylinders.

The data indicate that two concepts of strength should be distinguished: (1) strength as a measure of load-carrying capacity in structures, and (2) strength as a measure of concrete quality and uniformity. The relation of the latter (determined by standard cylinder tests) to the former (determined on cores from the structure) is extremely variable.

Keywords: age; compressive strength; concrete cores; concretes; curing; strength; quality control; testing.

■ WHAT IS THE STRENGTH of concrete? That question is as unfathomable as Pilate's quest for "truth," and those who seek the answer are often as unaware as he was of the elusiveness of their quarry.

Like truth, *concrete* strength is not an absolute. To assign a value to it, we must circumscribe the concept with conditions. We conceive of strength vaguely as a measure of load-carrying capacity and know that we can get an indication of that property of concrete by squeezing a chunk of it until it gives up and collapses. That is simple enough but, unfortunately, the ability to withstand that kind of treatment cannot be expressed as a single value. The number will change from day to day as the cement hydrates. The rate and amount of change will depend upon temperature and moisture, and the effects of these will interact with cement composition. The number can be varied over a wide range by changing the test conditions: size of specimen, relation between coordinate dimensions, rate of loading, moisture content, method of preparing the specimen, and the degree of restraint at bearing surfaces.

All this may seem beside the point. Concrete structures must carry loads and the engineer must have a measure of that ability. An arbitrary system has evolved which, superficially at least, has worked well. A strength value, usually called f_c', is selected for or assigned to the concrete, on the basis of which stereotyped calculations permit selection of exact dimensions and amounts of reinforcement needed to assure that imposed loads will be safely carried. Steps are taken to see that the concrete used in the structure will provide the required f_c'.

Although the procedure has certain Alice-in-Wonderland attributes, that fact can perhaps be disregarded on the ground that the system works. What does it matter that the loading conditions in the structure bear no resemblance to those by which we test concrete for strength? Why worry that field curing conditions cannot approach the ideal provided for standard test specimens? Why bicker over the fact that strength development of the same concrete will differ tremendously in slabs, beams, walls, and columns simply because of shape and massiveness of sections?

The easy answer is that we need not be concerned because, as already mentioned, the system works. Doesn't this mean that our fictitious assumptions average out to the truth—that they comprise a series of compensating errors that yield a correct answer? Possibly, but maybe not! It may mean that evolution has yielded a method so conservative that the range of variation in actual strength potential in the structure, broad as it is, is almost always upward from complete safety. If that is the case, we may be doing one or both of two things: first, we may be overbuilding in the sense of using more and better concrete than is needed; and second, we are probably expending a great deal of unnecessary worry on minor strength deficiencies indicated by our conventional tests. In short, our system is workable but may be far from correct.

The matter is worth looking into. Recent researches have shown that measurements of concrete strength in structures do not correlate consistently with the standard tests which provide the basis for design and acceptance.[1–5] We should at least consider the feasibility of separating our concepts of strength into two distinct categories:

1. *Design* strength for development of structural sections and calculation of load-carrying capacity.
2. *Control* strength as a measure of proper quality and uniformity of the concrete used in the work.

The design strength should correspond, at least in a relative sense, to the level which will be attained in the particular structure under the actual conditions of construction. The control strength should be selected for the specific situation and materials to assure attainment of the design strength in the structure. Inspection should aim at enforcing the control strength proportions and seeing that construction practices are such as to assure development of the design strength.

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Researches are being conducted at the Joint Laboratory of the National Sand and Gravel Association and National Ready Mixed Concrete Association at the University of Maryland to investigate the need for reevaluating strength concepts. This paper discusses a phase of that work which pertains to the strength factor in concrete design. A previous paper[4] considered problems of testing. A third paper, in the process of being offered for publication, will deal with a limited study of specimen size in relation to measured strength of cores.

SCOPE OF TESTS

To compare the development of concrete strength in full-sized structural elements with standard tests of molded specimens, pairs of concrete slabs were made at three different times. The first and third pairs were of high strength and moderate strength concretes made with different high-early-strength (Type III) cements; the second was moderate strength with regular

TABLE 1—CHARACTERISTICS OF FRESH CONCRETE (SERIES 189)*

Date mixed	Description of cement	Cement content	Water content	Slump	Unit weight	Air content	Temperature
			U. S. customary units				
		lb per cu yd	lb per cu yd	in.	lb per cu ft	percent	F
2-21-66	Type III, Sample 1	427	292	1.8	148.5	2.4	71
3-15-66	Type I	478	333	6.8	140.8	7.2	63
4-18-66	Type III, Sample 2	413	317	4.8	142.8	5.3	70
			Metric units				
		kg per m^3	kg per m^3	cm	kg per m^3	percent	C
2-21-66	Type III, Sample 1	253	173	4.6	2380	2.4	22
3-15-66	Type I	283	197	17.3	2256	7.2	17
4-18-66	Type III, Sample 2	245	188	12.2	2288	5.3	21

*Concrete mixed in 2.8 cu yd (2.1 m^3) batches in truck mixers. Aggregate batched at plant; cement and water incorporated at laboratory placement site.

(Type I) cement. The slabs were 5 ft wide, 9 ft long, and 6 in. deep (150 x 270 x 15 cm), cast from concrete made with crushed limestone, coarse and fine aggregate, and mixed in a truck mixer.

Each slab was provided with 36 special plastic inserts for cast-in-place cylinders 4 in. in diameter by 6 in. long (10 x 15 cm) which could be removed for compressive strength test at selected ages. The slabs were also equipped with pipe wells and sensing devices to permit periodic measurement of relative humidity at various locations and depths. Each slab was of sufficient area to permit drilling 36 cores 4 in. (10 cm) in diameter for strength tests paralleling the push-out cylinders. In connection with each pair of slabs, a total of ninety 6 x 12-in. (15 x 30 cm) cylinders was molded from the same concrete.

One slab of each pair was given excellent curing. *It was* sprayed with membrane curing compound as soon as the water sheen had disappeared and later covered with wet burlap and sheet plastic. The burlap was kept wet and in place covered by the sheet plastic for 14 days, after which it was removed to expose the surface to the air of the laboratory. At 28 days the forms were removed and the slab raised 6 in. (15 cm) from the floor to permit drying from all surfaces.

The second slab was given poor curing more nearly typical of usual field practice. It was left uncovered after placement, and was stripped and raised 6 in. (15 cm) from the floor at 3 days.

To the extent that strength of the concrete and other conditions would permit, six cores and six push-out cylinders were removed from each slab at 1, 3, 7, 28, 91, and 364 days. Sets of three of each type specimen were immediately capped and tested in the existing moisture condition. Since the cores were drilled dry (with air as the drill coolant), the representation of moisture condition in the slabs was not disturbed. The other three specimens of each type were immersed in water for 2 days before test. (These were, therefore, two days older than their companions when actually broken.)

For each pair of slabs, molded 6 x 12 in. (15 x 30 cm) cylinders were tested in sets of three at the same ages as the companion specimens removed from the slabs, representing each of the following test conditions: (1) continuous standard moist curing, (2) field curing simulating that of the well-cured slab, (3) soaked for 2 days after good field curing, (4) poor field curing simulating that of the poorly-cured slab, and (5) soaked for 2 days after poor field curing.

Altogether, the program provided 270 molded cylinders, 216 drilled cores and 216 push-out cylinders. Comparisons covered three concretes, two curing conditions, six test ages, and three

TABLE 2—SUMMARY OF STRENGTH TESTS (SERIES 189)*

Age, days§	Compressive strength, psi†												
	6 x 12 in. (15 x 30 cm) molded cylinders					4 x 6 in. (10 x 15 cm) drilled cores‡				4 x 6 in. (10 x 15 cm) Push-out cylinders‡			
	Standard Moist cure	Field cure (good)		Field cure (poor)		Slab well cured		Slab poorly cured		Slab well cured		Slab poorly cured	
		Dry**	Wet**	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
Concrete with Type III cement, Sample I (Mixed 2/21/66)													
1	2390	2380	††	2060	††	††	††	††	††	††	††	††	††
3	3810	3510	††	3170	3790	3160	3250	2510	2850	3360	3710	2720	3280
7	4670	3990	4170	3880	3810	3710	3510	3010	2750	3820	3770	3400	3410
28	5490	4900	4510	4620	4230	4320	3640	3630	3050	4690	4160	3880	3760
91	6170	5490	4840	5050	4290	4470	4130	3620	2840	4800	4440	3860	3590
364	6165	5650	4185	5055	††	4725	3500	3730	2540	5090	4270	4500	3590
Concrete with Type I cement (Mixed 3/15/66)													
1	890	930	1550	850	1600	††	††	††	††	970	1390	790	1340
3	1610	1610	1970	1470	1890	1470	1700	1300	1600	1570	1750	1300	1610
7	2310	2290	2380	2140	2260	2100	2290	1720	1830	2210	2310	1800	1930
28	3730	3460	3360	3010	2820	3190	3040	2450	2110	3170	3210	2520	2230
91	4560	3930	3450	3230	2750	3780	3370	2420	2160	3900	3420	2430	2270
364	5030	3980	3035	3225	2450	3640	3025	2200	1890	4220	3450	2690	2075
Concrete with type III cement, Sample 2 (Mixed 4/18/66)													
1	1980	1950	3110	1730	3090	1880	2770	1500	2530	2290	2980	1710	2800
3	3065	3040	3290	2840	3210	2750	2910	2490	2470	3070	3110	2620	2890
7	3630	3550	3380	3330	3260	2940	3020	2540	2390	3420	3280	2990	2950
28	4150	3900	3680	3910	3410	3420	3060	2880	2580	3720	3340	3290	2990
91	4355	4185	3625	3915	3110	3550	3180	3100	2630	4000	3540	3460	3000
364	4370	4410	3260	3880	2915	4115	2850	3145	2325	4490	3390	3735	2900

*Each entry represents average of tests on three specimens.

†To convert to kg/cm², multiply by 0.0703.

‡4 x 6 in. cylinders corrected for *L/d* using 0.97 factor of ASTM C 42.

§Age at test for dry specimens; wet specimens soaked 44 hr thereafter before being tested.

**Specimens dry or wet at time of test.

††Specimens not obtained.

types of strength test specimens treated two different ways.

TEST RESULTS

Characteristics of the three batches of concrete are shown in Table 1. Although slumps varied considerably, consolidation of the concrete was performed in such a way as to assure proper compaction without segregation. Slabs and molded cylinders were vibrated just sufficiently to avoid honeycomb and permit finishing. Concrete in push-out specimens was consolidated by inserting the vibrator adjacent to, but not within, the plastic insert.

Results of the strength tests are assembled in Table 2. Each value is the average for three specimens. The upper, middle and lower portions of the table represent, respectively, the pairs of slabs made at different times with Type III Cement Sample 1, Type I Cement, and Type III Cement Sample 2. Strengths for the cores and push-out cylinders, which were 4 in. in diameter and 6 in. long (10 x 15 cm) have been corrected to an *l*/*d* of 2 by multiplying the measured strength by 0.97 in accordance with ASTM Method C 42.[6]

Detailed tabulations of individual strengths and descriptions of testing procedures are available on request to the author.

Strength development with age

Fig. 1, 2, and 3 show age-strength relationships for cores and standard cylinders representing the three pairs of slabs. These comparisons indicate the extent to which the standard tests reflected the strength of the concrete in place.

For the high strength concrete containing Type III cement, represented in Fig. 1, there was rapid strength development of standard cylinders at early ages, tapering off after 7 days, and ceasing for all practical purpose after 3 months. Cores from the well-cured slab, tested in their natural moisture condition, lagged well behind the cylinders, attaining at 1 year a strength equal only to that of the 7-day standard cylinders. Cores from the poorly-cured slab never reached the 3-day cylinder strength.

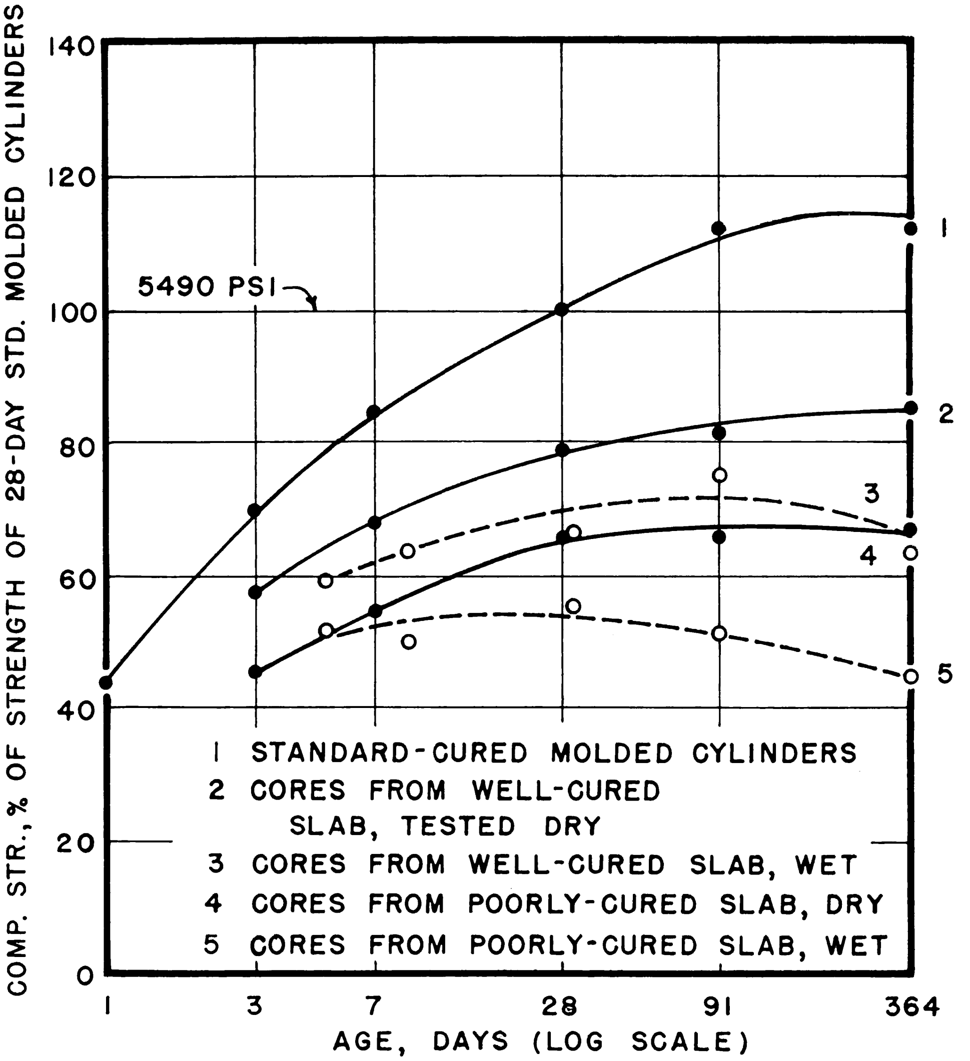

Fig. 1—Strength measures for concrete with Type III cement, Sample 1 (Series 189)

Cores that were soaked before test, from either well- or poorly-cured slabs, tested considerably below their air-dry companions. The fact that they showed little or no strength gain beyond about a week suggests that cement hydration had essentially ceased by that time. The continuous slight increases for the unsoaked cores may merely have reflected the effects of the drying itself.

Fig. 2 shows strength gain relationships for moderate-strength concrete made with Type I cement. It reveals markedly different patterns from those displayed in Fig. 1. Strength gain of standard cylinders was at a slower rate initially but maintained a good pace up to one year. Cores from the well-cured slab, tested air-dry, again lagged in comparison with standard cylinders, but to a lesser degree than for Type III cement. In fact, the core strength at three months equalled the 28-day cylinder strength. Poor curing penalized core strengths more in comparison with good curing for the Type I cement than for Type III, but yielded the same ultimate level of about 70 percent in relation to standard 28-day cylinders.

Unlike the tests with Type III cement, soaked cores from the slabs with Type I cement showed appreciable strength gain to 3 months with good curing and to about 28 days with poor curing. Reductions in core strength caused by soaking were perhaps slightly less over-all for Type I than for Type III cement.

The strength development patterns for concrete with a second sample of Type III cement, shown in Fig. 3, resembled those for the first sample, shown in Fig. 1. Design strength level for the second sample was intentionally reduced about 25 percent below that for the first sample. The most notable difference with the lower-strength concrete was the greater relative strength gain for cores tested dry from the well-cured slab. At 1 year, these core strengths reached essentially the 28-day standard cylinder strength. Again, however, the soaked cores for either condition of

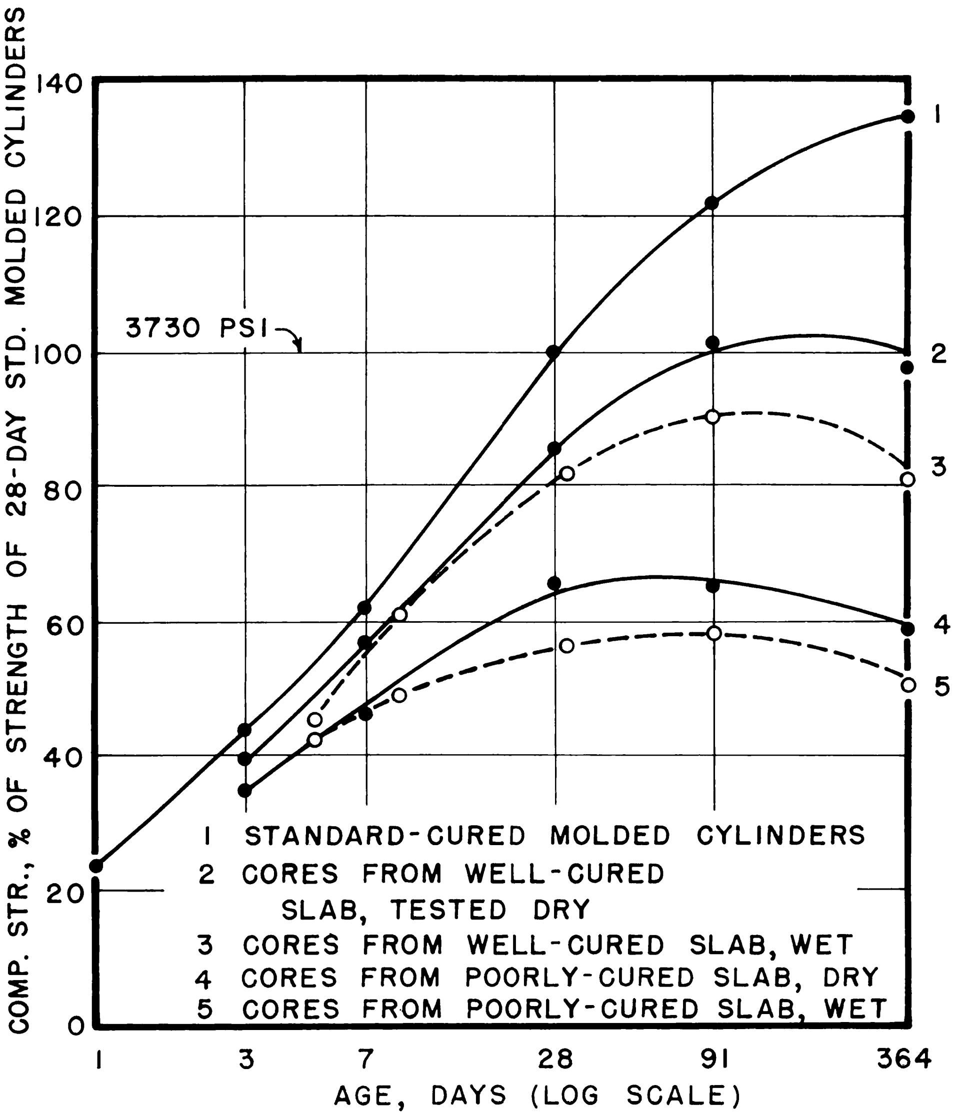

Fig. 2—Strength measures for concrete with Type I cement (Series 189)

curing failed to gain significantly in strength beyond three days.

If strengths of cores tested dry can be taken as the best indication of load-carrying capacity of concrete in a structure, the ability of standard cylinder tests to predict that property can be evaluated. The 28-day cylinder strengths expressed as percentages of 1-year core strengths (considered to approximate a reasonable ultimate) covered the following ranges in relation to:

1. Dry cores from well-cured slabs, 100 to 116 percent
2. Wet cores from well-cured slabs, 123 to 157 percent
3. Dry cores from poorly-cured slabs, 132 to 170 percent, and
4. Wet cores from poorly-cured slabs, 197 to 222 percent

If it is considered more logical to use 7-day cylinder strength as the predictor for Type III cement and 28-day cylinder strength for Type I, the ratios of cylinder to core strengths are compressed slightly to:

1. Dry cores from well-cured slabs, 88 to 103 percent
2. Wet cores from well-cured slabs, 123 to 133 percent
3. Dry cores from poorly-cured slabs, 115 to 170 percent, and
4. Wet cores from poorly-cured slabs, 156 to 197 percent

Thus, only when carefully limited with regard to applicable test ages in relation to type of cement, and only for the condition of cores from well cured concrete tested dry, did the standard cylinder test provide a reasonable and conservative estimate of strength in the structure.

Fig. 4, 5, and 6 provide a history of changes in relative humidity in the top, middle and bottom, respectively, of the four slabs with Type I cement and the second sample of Type III. (Difficulties with instrumentation vitiated humidity data from the slabs with the first sample of Type III cement.) Ambient humidity of the laboratory

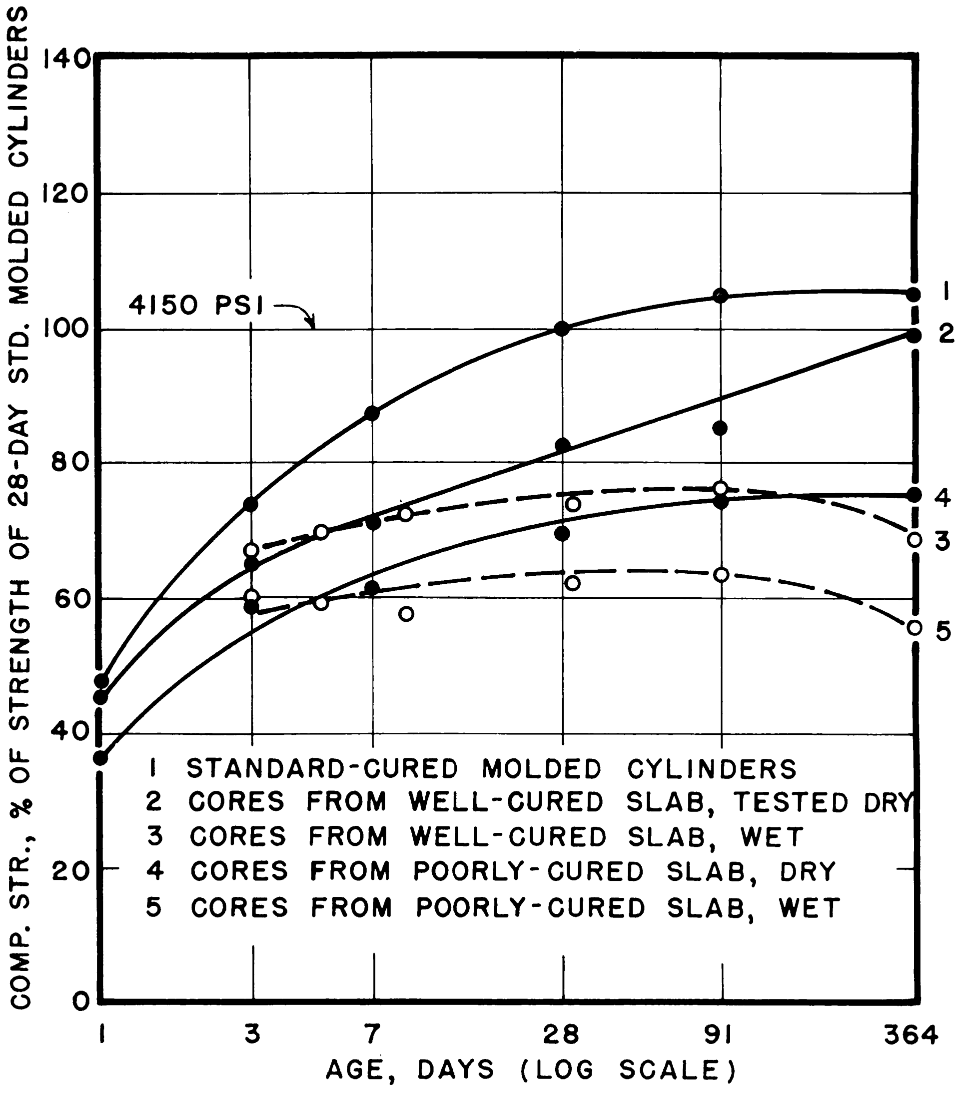

Fig. 3—Strength measures for concrete with Type III cement, Sample 2 (Series 189)

storage area is shown on each curve for comparison. The wells for humidity sensors provided air contact with the concrete at middepth and ¾ in. (2 cm) from top and bottom surfaces by means of closely spaced ¼ in. (0.6 cm) circumferential holes in 1¼ in. (3 cm) diameter copper tubing. The holes were sealed from the inside during concrete placement by tight-fitting rubber plugs which were later forced downward from the holes. The upper ends of the tubes were kept sealed with rubber stoppers except for brief intervals for insertion of sensors, after which the column of air in the tube was allowed to equilibrate with the humidity in the concrete at the level of the holes. Humidity wells were located well away from slab edges. Checks indicated that readings were unaffecetd by transverse location within the area from which strength test specimens were taken. The curves in Fig. 4 to 6 have been smoothed by using running averages of readings over 5 week periods.

The humidity data show expected trends although there are some anomalies. Humidity decreased more slowly within the well-cured slabs than within their poorly-cured companions. Unexpectedly, the bottom surfaces tended to dry more slowly than the tops, even for well-cured slabs where the top was protected by curing compound. This may suggest that the humidity in the confined air space between the laboratory floor and the bottom surfaces of slabs after they had been raised was higher than in the surrounding air where "ambient" humidity was measured. Perhaps also the concrete near the upper surface had increased water content due to bleeding, and hence lost water more freely by evaporation because of greater permeability.

The strength curves (Fig. 2 and 3) indicate (on the basis of soaked cores) that strength gain for Type I cement was appreciable up to 91 days for the well-cured slab and to about 28 days for the poorly-cured slab. For the second sample of Type III cement (Fig. 3), strength gain (except for the effects of drying) appeared to cease at about 7 days for good curing and 3 days for poor curing. Comparing these indications with the humidity curves suggests that hydration stopped for Type III cement when humidity was still well above 90 percent at all depths in the slabs. With Type I cement, hydration apparently continued after

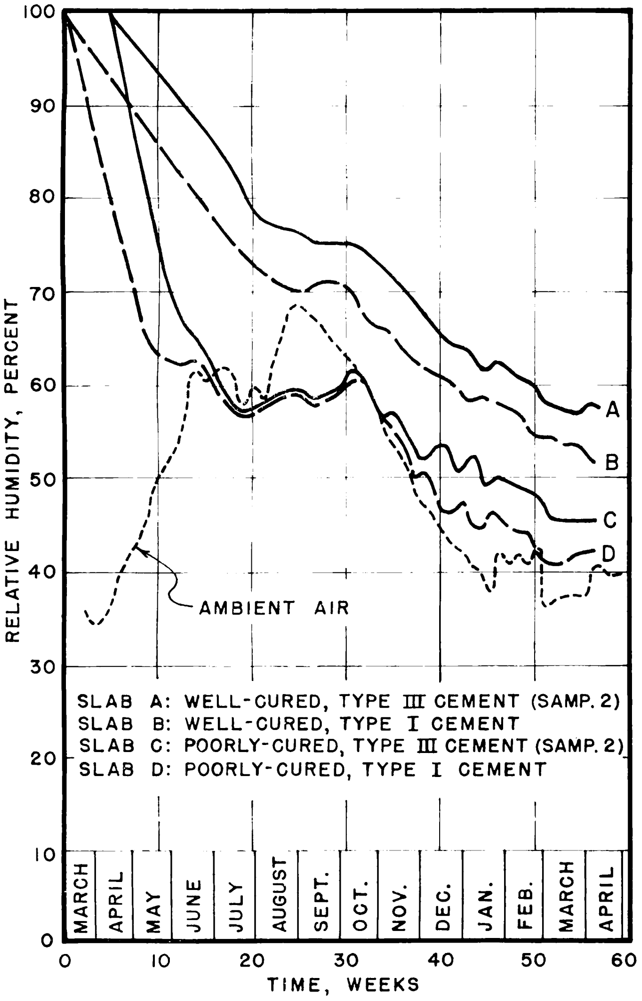

Fig. 4—Relative humidity ¾ in. below top of slab (Series 189)

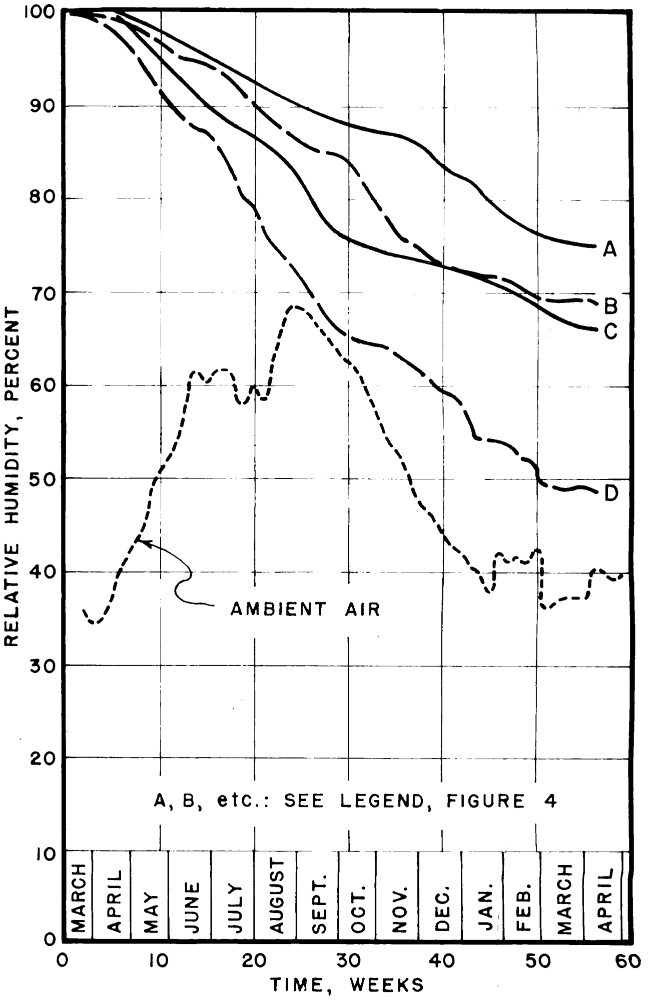

Fig. 5—Relative humidity at middepth of slab (Series 189)

humidity had been reduced to a lower level. Powers[7] states that hydration essentially ceases if relative humidity drops below about 85 percent, but its continuation and extent will be influenced by other factors such as chemical composition and fineness of the cement, and the initial water-cement ratio. The research reported here did not provide the data for thorough analysis of possible hydration attributes of the different concretes, but its indications do not appear to contradict theory.

Simulation of field conditions

Field-cured cylinders are sometimes used in an effort to approximate conditions of strength development in the structure. In this research, cylinders were cured under conditions simulating both the well-cured and poorly-cured slabs and tested at the same ages as the cores drilled from the slabs. Companion tests were also made of cylindrical specimens cast integrally with the slabs in special plastic inserts that permitted them to be forced out (hence "push-out" cylinders) and tested for strength.

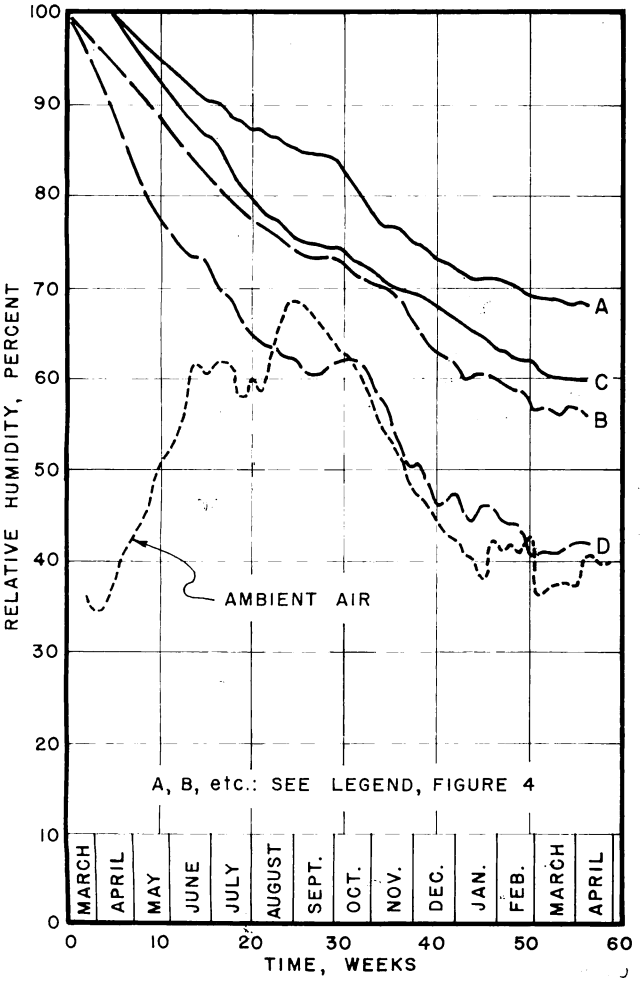

Fig. 6—Relative humidity ¾ in. above bottom of slab (Series 189)

Relationships of core strengths to field-cured molded cylinders and to push-out cylinders are shown in Fig. 7, 8, and 9. Only data for specimens tested in their natural moisture condition are presented. Relationships for specimens soaked 44 hr before test are essentially the same.

Fig. 7 and 8 indicate that, for either good or poor curing, there was a fairly consistent relationship of core strength to field-cured cylinder strength for all three concretes and all test ages. However, strengths in the slabs as measured on cores were less than corresponding molded cylinders by an average of about 10 percent for good curing and over 20 percent for poor curing. The fact that this difference was not constant suggests that field curing of molded specimens cannot be relied upon to give a dependable indication of the strength to be expected from cores. Concrete in the slabs apparently suffered more from deficiencies in curing than did that in the molded specimens.

Fig. 9 shows good correlation between push-out cylinders and cores for all test conditions and ages, although the core strengths averaged about 7 percent lower. It looks as though, if there is a real desire to have a numerical measure of concrete strength in place, the push-out cylinder may be a satisfactory way to get it. If data from this program can be considered generally applicable, the strength of concrete in place might be taken as 90 percent of the push-out cylinder strength. In no case would the core strength have been overestimated by more than 10 percent.

Reproducibility

Each strength reported in Table 2 is the average of tests on three specimens representing a particular condition. Table 3 analyzes the reproducibility of the replicates based on their ranges, with the 179 sets of three grouped in various ways.

Reproducibility is best for molded cylinders, considerably poorer for push-out cylinders and poorest for cores, with average coefficients of variation for those methods of 2.3, 3.8, and 6.0 percent, respectively. Over-all reproducibility of all testing showed some evidence of improvement with time over the successive three groups of tests, but differences were not provable statistically. The most notable differences occurred for the push-out cylinders where high variability in the early stages could have been caused by inexperience in removing specimens from the slabs.

Field-cured molded cylinders tested dry produced significantly (at $\alpha = 0.01$) less reproducible strengths than standard-cured cylinders, but coefficients of variation were so small in both cases as to make the difference somewhat academic. There was no significant difference in reproducibility between well-cured and poorly-cured field cylinders. The coefficient of variation for field-cured cylinders was reduced slightly by soaking but not in a statistically significant amount. For cores and push-out cylinders, there was no discernible difference in reproducibility between specimens tested dry and after soaking.

There seems to be no clearly defined effect of test age on reproducibility, although statistically significant differences can be identified in scattered cases. For example, the coefficients of variation at three days for both molded cylinders and push-out cylinders are significantly lower than at any other age. However, when all three test methods are considered together, only 1-day results show significantly lower variation than the others. Thus, there is the rather faint suggestion that, when reproducibility is considered in terms of coefficients of variation (percentage basis), the early ages suffer because of their low level.

It is of some interest to compare the reliability of the three methods of strength testing in terms of confidence in average results. If the over-all coefficients of variation in Table 2 are accepted as reliable estimates for each universe:

$$E = \frac{1.645v}{\sqrt{n}}$$

where

E = maximum percentage by which the true average will be below measured average one time in twenty

v = coefficient of variation, percent

n = number of specimens averaged

For sets of three specimens, we find the following:

With molded cylinders where $v = 2.3$ percent, $E = 2$ percent

With push-out cylinders where $v = 3.8$ percent, $E = 4$ percent

With cores where $v = 6.0$ percent, $E = 6$ percent

Thus, under the conditions of this investigation, it appears that any of the three strength test methods was capable of giving a reasonably

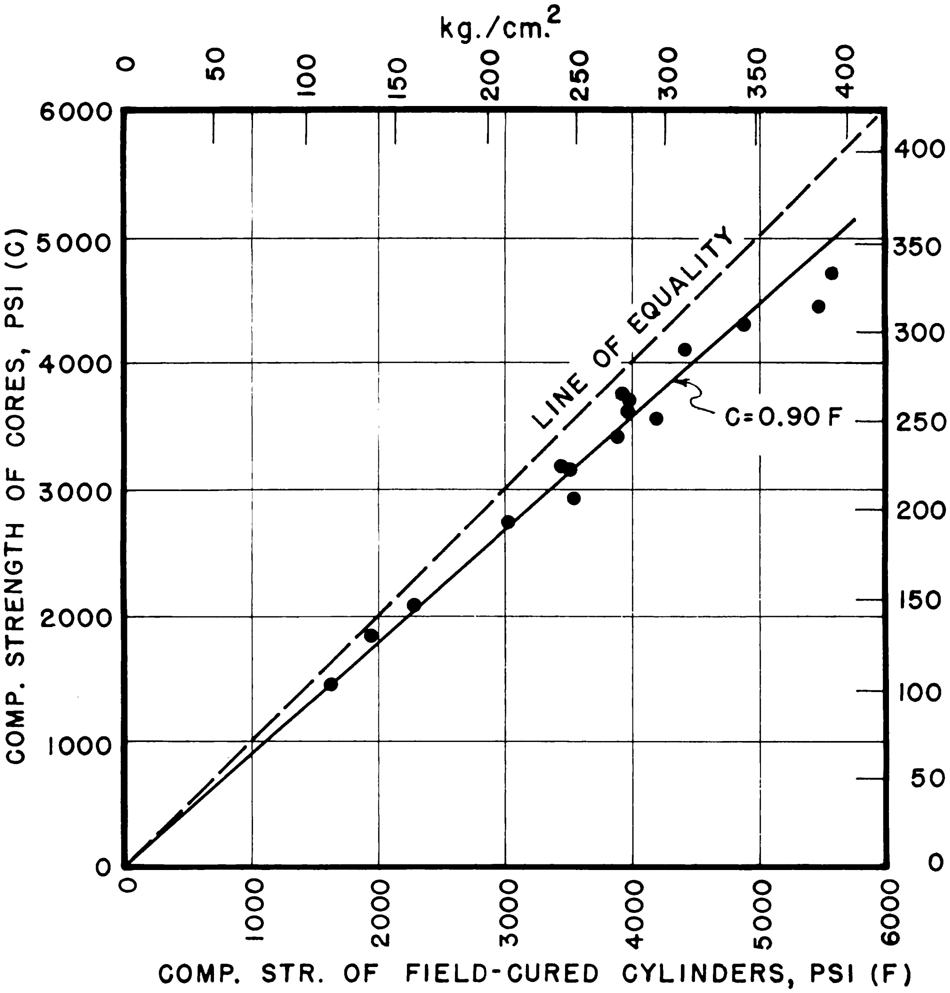

Fig. 7—Relation between cores from well-cured slabs and well-cured field cylinders (Series 189; all concretes and test ages)

TABLE 3—REPRODUCIBILITY OF STRENGTH MEASUREMENTS (SERIES 189)

	Estimated coefficient of variation, v, based on average of indicated number, n, of ranges for sets of three specimens*							
	Molded Cylinders		Cores		Push-out cylinders		Weighted average of specimen types	
Condition	v, percent	n	v, percent	n	v, percent	n	v, percent	n
Type III cement, Sample 1	2.7	22	6.3	16	5.0	15	4.4	53
Type I cement	2.3	25	5.7	16	3.8	20	3.7	61
Type III cement, Sample 2	2.0	25	5.8	20	2.8	20	3.4	65
All conditions	2.3	72	6.0	52	3.8	55	3.8	179
Standard cure	1.5	15	—	—	—	—	—	—
Good field cure, tested dry	2.5	15	5.7	13	3.4	14	3.8	42
Good field cure, soaked	2.2	13	7.1	13	3.5	14	4.2	40
Poor field cure, tested dry	3.0	15	5.4	13	4.6	14	4.3	42
Poor field cure, soaked	2.2	14	5.3	13	3.3	13	3.6	40
All good field cure	2.4	28	6.4	26	3.5	28	4.0	82
All poor field cure	2.6	29	5.4	26	4.0	27	3.9	82
All dry test	2.8	30	5.6	26	4.0	28	4.1	84
All soaked	2.2	27	6.2	26	3.4	27	3.9	80
All 1-day tests	2.3	13	5.1	4	2.7	8	2.9	25
All 3-day tests	1.6	14	6.4	12	2.5	12	3.7	38
All 7-day tests	2.4	15	5.4	12	5.2	12	4.2	39
All 28-day tests	2.3	15	5.8	12	3.5	11	3.8	38
All 91-day tests	2.9	15	6.1	12	4.4	12	4.3	39

*$v = 0.5907\ \bar{R}$ where $\bar{R}$ = average range for three specimens expressed as percent of their average strength.

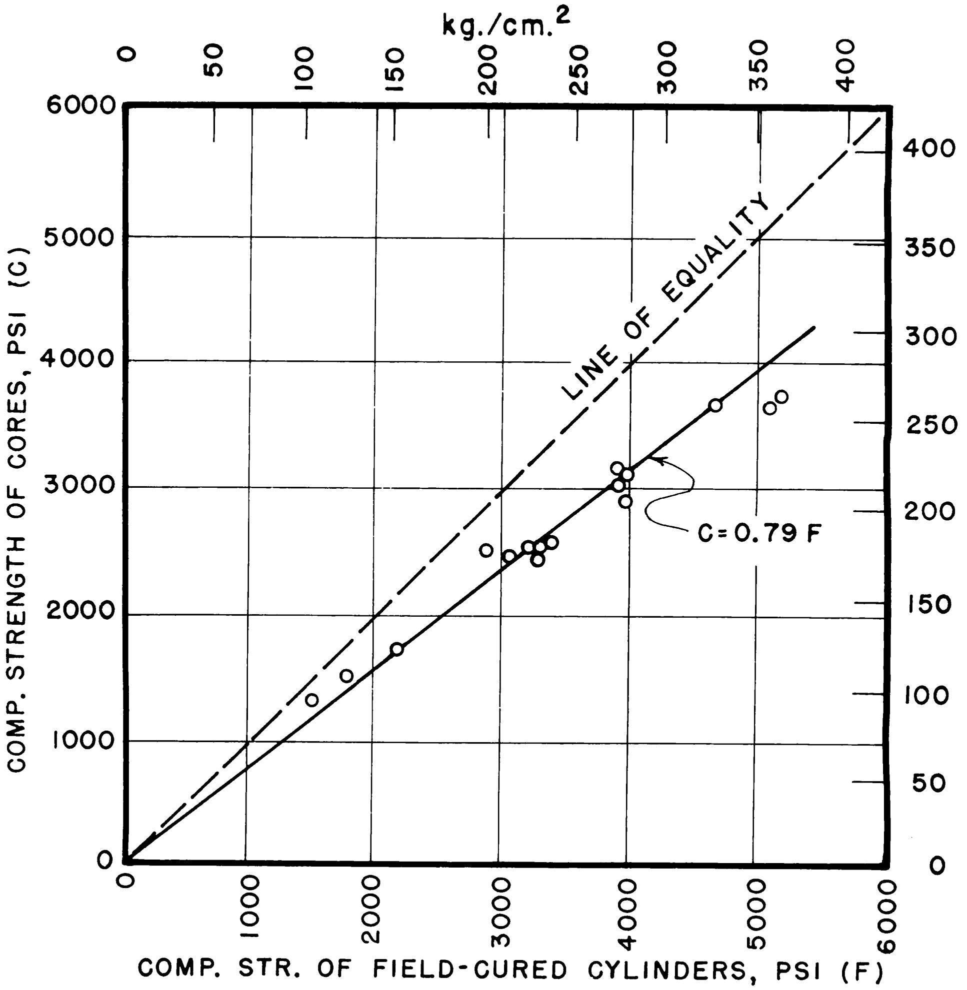

Fig. 8—Relation between cores from poorly-cured slabs and poorly-cured field cylinders (Series 189; all concretes and test ages)

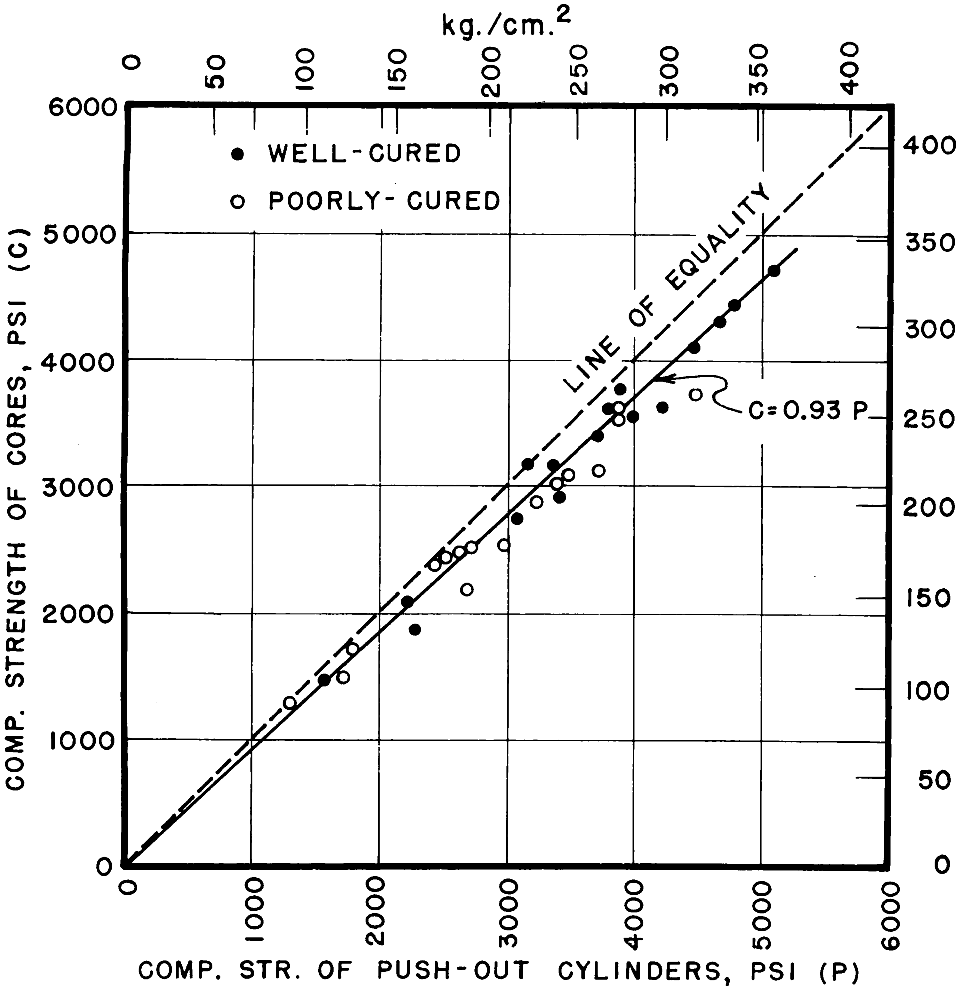

Fig. 9—Relation between cores and push-out cylinders (Series 189; all concretes and test ages)

reliable measurement of whatever property it was measuring.

CONCLUSION

The use of strength tests of standard-cured molded cylinders for control purposes and for checking the acceptability of concrete as pro-ced is well established. These are the legitimate lications for such tests. The researches re-rted here and by other investigators demon-ate that the standard tests do not provide a uantitative measure of concrete's load-carrying capacity in place.

Strength in place as measured on drilled cores will be less than that of moist-cured molded cylinders tested at the same age and will probably never reach the standard 28-day strength even at greater ages. The amount of the deficiency will depend on the efficiency of field curing and will be affected by the type of cement. Other influences not covered in this research, such as the effect of precipitation on concrete outdoors, may alter or even reverse the relationship between cores and cylinders.

Core tests used to check apparent deficiencies in strength indicated by standard cylinders must be interpreted with caution. In many cases cores will not attain the specified strength level, f_c', on which design calculations were based. This should probably not be cause for alarm unless the deficiency is excessive. Design formulas provide a large safety margin sufficient to allow for the fact that field concrete will not be as favorably protected and cured as standard test specimens. When cores are lower than f_c', it simply means that some of that margin of uncertainty has been used. Core tests equalling 75 percent of f_c' provide an excess over calculated working stress of 67 percent, which should be much more than adequate in most cases. Usually, however, cores should not test that low if field practices are proper and overdesign of average strength is adequate.

Field-cured cylinders may provide useful information but do not quantitatively reflect core strength. In the reported program, the latter averaged about 10 percent less than field-cured cylinders for good curing but 21 percent less for poor curing. Thus the field-cured cylinders may be misleading in that they are less adversely affected by improper curing than the structure itself.

Push-out cylinders cast in the slabs provided a fairly reliable measure, relatively, of core strengths. The cores, however, averaged about 7 percent lower. Unlike field-cured cylinders, the push-outs related consistently to cores irrespective of adequacy of curing.

Under the conditions of meticulous care in testing used in this research, all three methods of measuring strength—molded cylinders, push-out cylinders, and cores—were sufficiently reproducible to provide confidence in results consisting of averages for three specimens.

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Sinopsis—Résumé—Zusammenfassung

Resistencia del Concreto en Estructuras

Se investigó el significado de la resistencia a compresión del concreto medida mediante varios métodos. Se fabricaron pares de losas de tres calidades diferentes de concreto y se sometieron a curados adecuados y deficientes. Se obtuvieron corazones y cilindros sacados a presión y a 6 edades diferentes durante un año y se ensayaron para determinar su resistencia. Con los ensayes correspondientes a los cilindros moldeados el total de especímenes fue de: 216 corazones, 216 cilindros sacados a preción, y 270 cilindros moldeados.

Los datos indican que se deben distinguir dos conceptos de resistencia: (1) resistencia como medida de la capacidad de carga de las estructuras, y (2) resistencia como medida de la calidad y uniformidad del concreto. La relación de este último (determinado por ensayes de cilindros estándar) al primero (determinado en corazones de la estructura) es extremadamente variable.

Résistance du Béton dans les Structures

L'auteur a étudié la signification des différentes méthodes de mesure de la résistance en compression du béton. Des coupes de dalles constituées de trois bétons différents ont été soumis à une cure correcte et à une cure incorrecte. Des noyaux de béton et des cylindres obtenus par extrusion ont été prélevés à des âges allant jusqu'à un an et essayés. En tout, il a été essayé 216 noyaux, 216 cylindres obtenus par extrusion et 270 cylindres de comparaison moulés.

Les résultats montrent que l'on doit distinguer deux conceptions de la résistance : (1) résistance en vue de l'évaluation de la capacité de résistance des structures; (2) résistance en vue de l'appréciation de la qualité et de l'uniformité du béton. La relation entre la première (déterminée par des essais de cylindres normalisés) et la seconde (déterminée sur noyaux prélevés sur la structure) est très variable.

Die Festigkeit von Beton in Bauwerken

Die Bedeutung der Methoden zur Bestimmung der Druckfestigkeit von Beton wird studiert. Betonplattenpaare dreierlei Betonqualität werden einer genügenden oder unzureichenden Feuchtlagerung unterworfen. Zu sechs verschiedenen Zeitpunkten bis zu einem Jahr wird die Druckfestigkeit von Bohrkernen und herausgedrückten Zylindern bestimmt. Zusammen mit den in Schalungen hergestellten Zylindern wurden insgesamt 216 Bohrkerne, 216 herausgedrückte Zylinder und 270 in Schalung hergestellte Zylinder geprüft.

Die Ergebnisse zeigen, dass in Hinblick auf die Betonfestigkeit zwischen zwei Grundkonzeptionen unterschieden werden muss: (1) die Festigkeit als ein Mass für die Tragfähigkeit eines Bauwerkes, und (2) die Festigkeit als ein Mass für Betonqualität und Gleichförmigkeit. Die Beziehung zwischen (2) (an Normenzylindern bestimmt) und (1) (an Bohrkernen bestimmt) ist äusserst variabel.