These values were based on ordinary standard portland cement; no high-early-strength cements were included. The average 3CS content increased about 0.5 per cent per year from 1877 to 1910; from 1910 to 1937 the rate was about 0.7 per cent per year.

It is difficult to determine the precise effect on concrete produced by changes in compound composition of the cement; such changes never occur singly, but are accompanied by changes in other compounds and generally by variations in fineness. Increase in 3CS is generally accompanied by a corresponding decrease in dicalcium silicate.

Cement manufacturers became interested in compound composition and for the first time became more tolerant of finer grinding of cement when it was pointed out that a high 3CS clinker ground much easier than one of low 3CS. It appears probable that the 3CS content of Illinois cements increased 8 to 10 per cent during the years covered by the paper.

### *A Chicago Laboratory Studied the Concrete-Making Qualities of Illinois Cements*

While definite changes in fineness and composition cannot be attributed with certainty to a given cement at a given date, they are almost certain to apply to the average of a group of cements over a period of years. Fortunately it is not necessary to speculate on whether Illinois cements followed the usual trend during the first part of the period covered by the paper, since we have the results of an independent investigation *which was made at the time with the same cements.* In 1916 an investigation was begun in Chicago under the writer's direction for the sole purpose of studying changes in the concrete-making qualities of the same cements from time to time.

For the major part of our work at the Structural Materials Research Laboratory, Lewis Institute, a blend of 4 or 5 brands of the same cements was used. The cements were purchased from local dealers. Each lot of cement as well as the blend was subjected to physical and chemical tests; one group consisted of 6 x 12-in. concrete cylinders made from each blend for test at ages of 7 days to 10 years. Sand and gravel from the same source and of a fixed grading up to 1½ in. was used throughout, the same quantity of cement (1-5 mix by volume), also the same water-ratio (.54 by weight) and the same methods of mixing, molding and curing. During the first 15 years the specimens were made by the same men. Controllable factors were the same from lot to lot and year to year, except the cement.

A summary of the first 15 years of these laboratory tests was published in the *Engineering News-Record,* Apr. 20, 1933. That report shows an age-strength curve for 12 lots of the blend tested during the 5 years 1926-30 (mid-year 1928); these values can be compared with the 1928 tests by Mr. Glover. Values are given also for 3 lots for 1930-31; these can be compared with the average for these two years by Mr. Glover. This comparison gives the following increase in concrete strength for 2½ years 1928 to 1930-31, using here only the values from 7 to 28 days:

| Tests by | Specimen | Increase in Strength—Per Cent | | | | | Average Age days |
|---|---|---|---|---|---|---|---|
| | | 7d. | 14d. | 21d. | 28d. | Av. | |
| Chicago Laboratory.................. | Cyl. | 30 | — | — | 23 | 26½ | 17½ |
| Illinois Highways..................... | Beam | — | 23 | 23 | — | 23 | 17½ |

The above years and ages were selected purposely to cover the *period of transition* from the old to the new method of proportioning by the Illinois Division of Highways and to include the 14-day test age which is emphasized in the paper.

The strength increases at average age of 17½ days are about the same for the two groups of tests; the somewhat higher precentage for the Chicago tests is due to the use of the 7-day value which, as shown below, gave a higher-than-average increase.

Fig. A shows a more complete comparison between these two groups of tests from 3 days to 6 months. A single straight line to a log-scale of ages represents both groups. Except for erratic values at 5 and 7 days, all tests might have been parts of the same series—a remarkable concordance when we consider the wide differences in aggregates, method of loading and the conditions under which the concrete was manufactured and the tests made. Both groups of tests show that the greatest increase in concrete strength came at the earlier ages.

*Increase in Strength of Illinois Highway Concrete*

The score stands about as follows, based on 14-day tests in Table 1:

| Method of Proportioning | Period | Average Annual Increase in 14-day Strength—Per Cent |
|---|---|---|
| Old Method | 1928-1929 (last year) | 7 |
| Transition | 2½ yr. Chicago tests, (Fig. A) | 10 |
| " | 2½ yr. Highway " " | 9½ |
| New Method | 1 year 1929 to 1930 | 8 |
| " " | 2 " " " 1931 | 11 |
| " " | 3 " " " 1932 | 11½ |
| " " | 4 " " " 1933 | 8 |
| " " | 5 " " " 1934 | 6½ |
| " " | 6 " " " 1935 | 6 |
| " " | 7 " " " 1936 | 5 |
| " " | 8 " " " 1937 | 4½ |
| " " | 9 " " " 1938 | 4 |
| " " | 10 " " " 1939 | 4 |

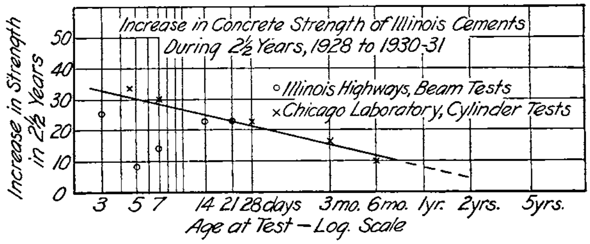


FIG. A—INCREASE IN CONCRETE STRENGTH OF ILLINOIS CEMENTS DURING TWO AND ONE-HALF YEARS—1928 TO 1930-31

At 3 different places in the paper attention is directed to the increase of 35 per cent in the modulus or rupture during the 3 years 1929 to 1932. It will be noted that this gives the highest average annual increase recorded; it probably represents also the years of greatest increase in 3CS in cement and the most pronounced increase in fineness. During 1929-32 the majority of cement manufacturers were giving unusual attention to attempts to improve their product in order to meet the new competition from the high-early-strength cements. The paper does not state whether any high-early-strength cements were included.

Let us assume for the sake of argument that one-half of the increase in concrete strength was due to increased fineness of the cement. We saw above that 14-day mortar strength increased 1.35 per cent for each 10 sq. cm. increase in fineness. The annual increase in specific surface necessary to account for one-half the 35 per cent increase in concrete strength in 3 years will be:

$$\frac{.35 \times 10}{3 \times 2 \times .0135} = 43 \text{ sq. cm. per gm.}$$

It seems to me that this is not an unlikely figure for average annual increase in fineness during this period. The value of the paper would be enhanced if Mr. Glover gave average cement fineness for each year, weighted in accordance with the number of tests reported for a given cement.

*Conclusions*

The above values show that the annual increase in Illinois highway concrete strength was practically uniform:

(1) Under the old method of proportioning.
(2) During the transition from the old to the new method.
(3) During first 4 or 5 years of the new method.

The strength increase in Illinois highway concrete, tested in beams, was parallel with that of compression tests of cylinders carried out at Chicago at the same time on the same cements.

It is apparent that the increased strength is confined principally to the early history of the concrete and becomes insignificant after about 1 year.

The paper gave no information on the composition or fineness of cements used; however it appears that Illinois concrete merely kept pace with the improved quality of the cements and owed nothing to the new method of proportioning; all the evidence indicates that the concrete strength would have shown the same year-to-year increase if the old method had been continued.

Judged by the results given in the paper, and our knowledge of changes which have occurred in the properties of cement, we can find no justification for the added cost of the new method of proportioning.

* * *

My remarks should not be construed as disparaging the high quality of Illinois highway concrete. Concrete giving moduli of rupture of 800 to 900 p.s.i. at 14 days, even when tested in short beams, is undoubtedly of satisfactory quality. We should not be confused as to the factors which have contributed to the marked increase in the early strengths during the past dozen years.

AUTHOR'S CLOSURE

Mr. Abrams' discussion is directed almost entirely toward refuting the statement made in the paper that "the increase in flexural strength is far greater than can be accounted for by any increase in the quality of the cements used during the period," meaning the period 1929 to 1932, inclusive. His conclusions are summarized in the statement that "all the evidence indicates that the concrete strength would have shown the same year-to-year increase if the old method had been continued," which implies indirectly that be believes that the State Illinois is spending money unjustifiably to control the quality of concrete.

The statement to which Mr. Abrams takes exception was based on the results of the tests made on the cements actually shipped and used in construction jobs in Illinois during the period mentioned. The number of tests made on these cements ranged from 13,000 to 15,000 per year during the four-year period from 1929 to 1932, inclusive, and were not less than 7,700 during any one year of the twelve-year period from 1928 to 1939, inclusive. The number of tests, therefore, is sufficient to carry considerable weight in any discussion and the results should indicate with certainty the trend of any change in quality of cement. Table 5 included as a part of this discussion shows the average 7-day and 28-day standard briquet strengths for each year of the twelve-year period, the percentage of increase in the average

TABLE 5—AVERAGE STANDARD BRIQUET STRENGTHS AND COMPARISON OF YEAR-TO-YEAR INCREASE IN STRENGTH OF BRIQUETS AND PAVEMENT CONCRETE

| Year | No. of Cars Tested | Amount of Cement (Barrels) | Briquet Strength (Pounds) | | Per Cent Increase in Strength | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | Briquets | | Concrete | |
| | | | 7-Day | 28-Day | 7-Day | 28-Day | 7-Day | 14-Day |
| 1928 | 20,502 | 5,027,687 | 307 | 402 | ..... | .... | .... | .... |
| 1929 | 12,984 | 3,250,348 | 314 | 411 | 2.3 | 2.2 | 3.2 | 7.0 |
| 1930 | 13,504 | 3,434,441 | 325 | 417 | 3.5 | 1.5 | 3.6 | 7.9 |
| 1931 | 14,990 | 3,830,971 | 338 | 427 | 4.0 | 2.4 | 14.6 | 13.4 |
| 1932 | 15,351 | 4,005,478 | 340 | 435 | 0.6 | 1.9 | 8.9 | 9.9 |
| 1933 | 12,540 | 3,254,089 | 338 | 431 | -0.6 | -0.9 | -0.1 | -1.0 |
| 1934 | 9,514 | 2,367,187 | 339 | 425 | 0.3 | -1.4 | 0.9 | -0.1 |
| 1935 | 7,703 | 1,947,927 | 349 | 433 | 2.9 | 1.9 | 0.8 | 0.6 |
| 1936 | 8,554 | 2,086,846 | 349 | 436 | 0.0 | 0.7 | -1.2 | 0.5 |
| 1937 | 8,398 | 2,042,960 | 354 | 443 | 1.4 | 1.6 | 2.2 | 1.4 |
| 1938 | 8,023 | 1,961,414 | 363 | 450 | 2.5 | 1.6 | 1.2 | 0.8 |
| 1939 | 8,718 | 2,064,788 | 367 | 446 | 1.1 | -0.9 | 3.0 | 1.7 |
| Total | 140,781 | 35,274,136 | 4,083 | 5,156 | 18.0 | 10.6 | 37.1 | 42.1 |
| Av. | 11,732 | 2,939,511 | 340 | 430 | 1.64 | 0.96 | 3.37 | 3.83 |
| 1929 to 1932, inclusive | | | | | 8.3 | 5.8 | 29.3 | 34.6 |
| 1932 to 1939, inclusive | | | | | 7.9 | 2.5 | 7.0 | 3.8 |

The number of plants shipping cement for highway construction during any one year was not less than 10 nor more than 19. The number of tests of the cement may be considered equal to the number of cars shipped, as seldom more than one test was made for each car.
The percent increase in strength of concrete is calculated from the data for pavement concrete in Table 1.

briquet strength from year to year, and the percentage of increase in the average pavement concrete beam strength from year to year, calculated from the 7-day and 14-day data given in Table 1 of the paper.

The standard briquet test has been specified by the American Society for Testing Materials as an acceptance test for cements for a long period of years and should provide a true indication of the quality of cements. Assuming that this is the case, Table 5 shows that during the twelve-year period there was an average improvement in the quality of the cements, measured by average year-to-year increases in briquet strength, of 1.64 per cent and 0.96 per cent for the 7-day and 28-day tests, respectively. During this same period there was an average year-to-year increase in the strength of the concrete of 3.37 per cent and 3.83 per cent for the 7-day and 14-day tests, respectively, or more than twice as much for the concrete as for the briquets, based on the 7-day tests. Considering individual years, it is seen that the peak of the improvement in cements did occur between the years 1928 and 1932, coincidental with the period of development of the Illinois method of proportioning as stated by Mr. Abrams. But the increases in concrete strength for the years 1931 and 1932 were 14.6 per cent and 8.9 per cent, respectively, based on the 7-day tests, as compared with corresponding increases in briquet strength of 4.0 per cent and 0.6 per cent. Considering the increases in the briquet strength and concrete strength during the period 1929 to 1932, inclusive, on the basis of the direct comparison provided by the 7-day tests, it is seen that the briquet strength increased 8.3 per cent, while the concrete strength increased 29.3 per cent, an increase of more than 3.5 times as much. It is not illogical to conclude, therefore, that improvement in the quality of cements used was responsible for less than one-third of the increase in the 7-day concrete strength obtained during this period.

There are no undue differences between the values representing the improvement in cements and those representing the improvement in concrete for years subsequent to 1932. Based on the 7-day tests, the briquet strength increased 7.9 per cent and the concrete strength 7.0 per cent during the entire period 1932 to 1939, inclusive. Although the 28-day briquet strength and the 14-day concrete strength data cannot be compared directly, they do show small but approximately similar percentages of increase during that period. These data show that subsequent to the period of development of the Illinois method of concrete design and proportioning, improvement in quality of cements and increase in the strength of field concrete kept pace with each other almost exactly. The fact that the 7-day briquet and concrete strength data show higher percentages of increase than do the 14-day and 28-day data undoubtedly indicates that most of the improvement after 1932 may be attributed to improvement in the high early strength properties of the cements.

It seems certain, therefore, that the improvement in the quality of the cements during the period of development of the Illinois method of proportioning was far less than the improvement in the quality of the concrete during the same period, and that improvement in quality of the cements and the concrete thereafter kept pace with each other within reasonable and explainable variations. This is still more apparent from the graphical illustrations in Fig. B and C.

Fig. B shows the percentages of year-to-year increase in strength from Table 5 for the 7-day test age. It is seen that these increases are very nearly the same for the briquets and the concrete for all years except 1931 and 1932. For these two years the percentage of increase for the concrete far exceeds the percentage of increase for the briquets, showing that the improvement in cements was far from sufficient to account for the improvement in the concrete, whereas for all other years the improvement in quality of cements and concrete kept fairly well in pace with each other.

Fig. C shows the briquet strengths from Table 5 and the pavement concrete beam strengths from Table 1 for the 7-day test age. It is seen that a considerable increase in concrete strength occurred during

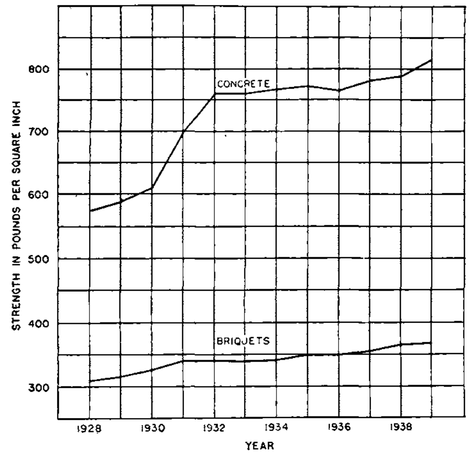


FIG. B—COMPARISON OF IMPROVEMENT IN QUALITY OF CEMENTS AND CONCRETE AS MEASURED BY THE PERCENTAGE YEAR-TO-YEAR INCREASE IN BRIQUET AND BEAM STRENGTHS FOR THE 7-DAY TEST AGE

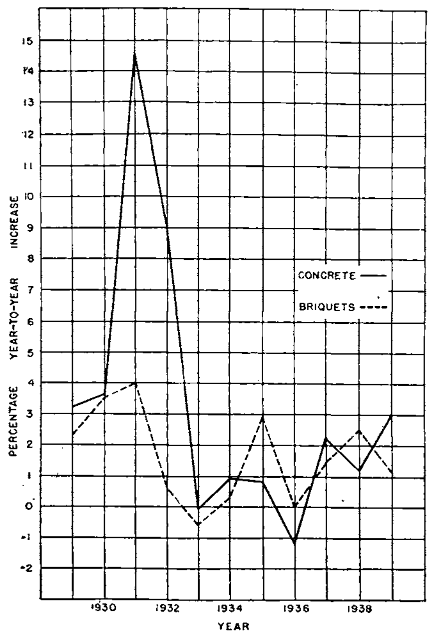


FIG. C—COMPARISON OF THE AVERAGE YEARLY BRIQUET AND BEAM STRENGTHS the years 1931 and 1932 not paralleled by the briquet strength. Except for this, the two curves parallel each other fairly well. This shows that the strength of the concrete increased at a far greater rate in 1931 and 1932 than did the quality of the cements. Comparison for other test ages would show similar results, the 7-day test age having been selected only because it provides a direct comparison.

It should be apparent therefore that the statement to which Mr. Abrams takes exception was not mere expression of opinion or belief. It is not intended to imply that similar results could not have been obtained by some other method of design and proportioning receiving the same degree of attention and strict enforcement of the specifications, but they would not have been obtained had the methods in use before 1930 been continued.

The strength data upon which Mr. Abrams' discussion is based are not given in sufficient detail to arrive satisfactorily at the reason why he should obtain results so far different from those shown in Table 5. The miniature charts in the Engineering-News Record, April 20, 1932, referred to by Mr. Abrams are unsatisfactory for checking the percentages shown by him. It is to be regretted that he did not present also the entire data for the years subsequent to 1931. Inasmuch as the four or five brands of cement represented by Mr. Abrams' data were purchased in the Chicago area, these same brands were undoubtedly used in highway construction in Illinois, but during the twelve-year period covered by the data presented in the paper, not less than ten brands of cement were used during any one year. It is entirely possible that the four or five brands mentioned by Mr. Abrams were not truly representative of all of the cement actually used in Illinois, whereas the data in Table 5 represent all of the cement actually shipped by the various plants, weighted exactly in accordance with the number of cars of each brand shipped. Mr. Abrams does not give information as to the number of test specimens represented by the data which he presents, but it is safe to assume that the number was exceedingly small compared with the total of more than 140,000 tests represented by the data in Table 5, an average of nearly 12,000 tests per year, made under actual working conditions.

The decided increase in concrete strengths between the years 1928 and 1929 was mentioned in the paper and it was observed that this increase was about the same as between the years 1929 and 1930. In 1928 the testing of concrete beams was not done generally on all jobs, as may be seen from the small number of specimens represented for that year in Table 1. It is not known how nearly the 1928 tests presented all of the pavement concrete placed during that year. Some of the increase shown, but apparently not all of it, may be accounted for by improvement in cements, and the control of production of concrete in 1929 may also have been better than in 1928.

Nothing was said in the paper as to whether the water-cement ratio was lowered when the new method of proportioning was introduced, because nothing was definitely known in regard to this, It may be assumed with some certainty, however, that prior to 1930 the mixtures were seldom if ever on the dry side, because the checking of water measuring devices was not required and there was no control over the amount of mixing water used other than adjustments made by visual inspection of the concrete mixtures, supplemented by an occasional slump test. It is quite certain that the degree of control exercised during 1931 and later resulted in a reduction in the water-cement ratio and that this reduction was responsible for some of the gain in concrete strengths. Except in unusual cases, the water-cement ratio now ranges from 5.1 to 5.6 gal. per bag of cement, depending upon the characteristics of the aggregates used.

Mixtures in which high-early-strength cement was used and those in which high-early-strength was obtained by using increased amounts of standard portland cement were not included in the data presented. The use of the 14-day test data for computation of increase in strength had no connection whatever with the fact that this test age showed the highest increase in strength. The specifications under which all of the concrete was produced required that the mixtures be designed for a specified 14-day strength and the various tables show that the greatest number of tests were made at this age. It became customary, therefore, to use the 14-day test age for comparison wherever possible, not only because it was of the most interest from the standpoint of the design of the concrete mixtures, but also because the 14-day strengths should provide the most accurate comparison.

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# Weathering Resistance of Concretes Containing Fly-Ash Cements*

BY
RAYMOND E. DAVIS, HARMER E. DAVIS AND J. W. KELLY†
MEMBERS AMERICAN CONCRETE INSTITUTE

## SYNOPSIS

This investigation, extending the scope of an investigation previously reported, was undertaken to determine whether fly ashes of moderately high carbon content could be used advantageously as puzzolanic replacements for small percentages of portland cement, particularly with regard to weathering resistance of concrete. Eleven fly ashes varying in carbon content (1 to 17 per cent) and fineness (specific surface 2500 to 5500 square centimeters per gram) were each admixed with a modified portland cement, with 10 and 20 per cent of cement replaced by an equal weight of fly ash. The fly-ash cements thus produced were tested to determine the water requirement, time of setting, autoclave expansion, tensile strength of standard mortar, compressive strength of concrete, drying shrinkage of concrete, and resistance of saturated concrete to the action of repeated freezing and thawing. Herein the performance of the fly-ash cements is compared with that of the portland cement, and the influence of carbon content, fineness, and amount of fly ash is shown. On the whole, the use of fly ash resulted in concretes of quality equal or superior to that obtained with the portland cement alone.

## INTRODUCTION

In an investigation previously reported to the Institute,[1] it was found that fly ashes of low carbon content and high fineness are excellent puzzolanic materials when used as replacements, by weight, for as much as 30 per cent of portland cement and—under mass-concrete conditions—for as much as 50 per cent of the portland

*Received by the Institute Nov. 4, 1940.
†Respectively Professor, Associate Professor and Lecturer in Civil Engineering, University of California, Berkeley.
[1]"Properties of Cements and Concretes Containing Fly Ash," by Raymond E. Davis, Roy W. Carlson, J. W. Kelly, and Harmer E. Davis, JOURNAL, Amer. Concrete Inst., May-June 1937 (*Proceedings*, Vol. 33), pp. 577-612.