Chapter 6

INTERMITTENT CURING OF CONCRETE

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The principal purpose of this investigation is to determine the initial wet curing period necessary for concrete pavements from studies of the effects upon strength of the initial moist curing period, of various periods of alternate dry and wet curing, of increased air temperatures, and of combined water.

Synopsis of Procedure. Initial curing periods of 1, 3, 7, and 21 days followed by 19 different methods of subsequent curing were used The test specimens included 1680—4 by 8 in cylinders which were weighed and tested at nine different ages for each of these various methods of curing All cylinders were handled in groups of three, the average of the three results being used They were weighed immersed, surface dry, and oven dry, these values being used in the calculation of the percentage of combined water All were broken dry after being kept in a 250° F. oven for two days

Conclusions. It is difficult to draw general conclusions without some word of reservation Saturated cylinders lost about 33 per cent of their moisture after 21 days in the laboratory air Under these conditions a seven inch concrete pavement would require all the water from a 0 45 in. rainfall to saturate it again after a 21 day drying. There are not sufficient data available to estimate how much water would be lost from the concrete in a pavement but it would probably be much less than that from the small specimens used in this investigation The mere presence of sufficient water to combine with the cement adds little to the strength This is brought out by the air cured specimens of series No 18 which in their air dry condition still retained 50 per cent of their original water at an age of 320 days (See Figure 26) but which were far below other methods of curing in strength Concrete placed in the late fall must depend upon its initial curing for its strength until well into the next spring. In selecting an initial curing period one must definitely keep in mind the age at which the concrete strength is desired Reasoning thus we may conclude that.

1 An initial curing period of less than three days is not economical

2 For high early strength, for use in northern climates in the late fall, and for extremely dry localities, an initial curing period of 4 to 7 days is advisable

3 Almost any form of intermittent curing up to 10 days dry to 1 day wet produces satisfactory ultimate results A dry period of 21 days following the initial curing reduces the 320 day strengths by only 6 4 per cent when the initial wet curing period is three days and the intermittent curing is reasonably thorough

4 No high temperatures to which concrete pavements may be subjected in humid areas will be harmful to the concrete

5 The percentage of combined or retained water is roughly proportionate to the compressive strength

More detailed conclusions together with the facts pointing to their justification will be found under "Interpretation of Results"

Methods of Procedure

Cement The cement was a well known brand purchased from ordinary stock, and the entire lot was thoroughly intermixed and tested before using

Sand The sand was a mixed sand obtained from two sources, it contained 80 per cent by absolute volume of the coarser sand and 20 per cent of the finer sand, and produced a very uniform grading

Coarse Aggregate The coarse aggregate was a Wisconsin trap-rock of good quality, possessing a low absorption and a low abrasion loss It was graded from ¼ to 1 inch

Concrete Mix Because of the small size of the specimens to be made and the angularity of the coarse aggregate, a comparatively rich mix was used The proportions by absolute volume were 1:2 59 2 71 The free water used amounted to 19 per cent of the volume of the finished concrete, giving a water-cement relation of 5 35 gallons per sack. This mix had an average slump of 1 93 inches and an average flow of $\frac{15\ 83 \text{ inches}}{10 \text{ inches}}$

Preparation of Specimens It was desired to run all specimens in groups of three using the average values so as to remove as many variations as possible As this necessitated a large number of cylinders, a small specimen was considered necessary in order to keep the investigation within reasonable limits Consequently the specimen selected was 4 in in diameter and 8 in in height The bottom of the mold and the side slot were securely filled with melted paraffin so as to virtually eliminate the loss of water during the molding and setting of the specimens The tops were covered with wax paper and damp burlap immediately after being struck off to help prevent the loss of mixing water. The concrete was vibrated into place by means of a propeller-shaped piece of steel actuated by an electric vibrator The propeller was placed in the bottom of the mold and slowly raised and turned and vibrated as the mold was filled with concrete In this way uniformly good specimens without honeycomb were obtained

The specimens were stripped when about 15 hours old and lightly brushed with a fine wire brush to remove any over-rich film or laitance on the surface, in order to make them readily susceptible to absorption or evaporation of water After brushing, the specimens were marked and placed in water for the rest of the initial curing period, the time in the molds being considered a part of that curing period

Various Curing Methods This investigation comprises 19 different subsequent curings, each following a definite initial curing

TABLE XXIV

Series No	Intermittent Curing			Ratio of Wet to Dry Days	Initial Curing Period Days Submerged Including Time in Molds
	Days in Air	Days in Water	Temperature of Air Degree F		
1	6	1	70	0 17	1, 3, 7, 21 Then 15 days air at 70°F
2	6	1	70	0 17	1, 3, 7, 21
3	10	1	70	0 10	3, 7
4	2	2	70	1 00	3, 7
5	6	2	70	0 33	1, 3, 7, 21
6	10	2	70	0 20	3, 7
7	2	4	70	2 00	3, 7
8	6	4	70	0 67	1, 3, 7, 21
9	10	4	70	0 40	3, 7
10	6	1	110	0 17	7
11	6	4	110	0 67	7
12	6	1	150	0 17	3, 7, 21
13	6	4	150	0 67	3, 7, 21
14	2	1	70	0 50	3, 7
15	6	4	70	0 67	1, 3, 7, 21 Then 15 days air at 70°F
16	6	1	110	0 17	7 Then 15 days air at 110° F
17	6	4	110	0 67	7 Then 15 days air at 110 F
18	Continuously dry		70	0	1, 3, 7, 21
19	Continuously wet				3 duplicate series

period of 1, 3, 7, or 21 days, however, only 6 of the 19 series have been carried out for each of the four different initial curing periods Each of the 19 treatment methods will be given a number called the series number by which they may be referred to hereafter The essential data for the 19 series are given in outline form in Table XXIV Thus, when we consider the different initial curing periods, we find we have 47 methods of curing in 19 series For each method of curing 27 concrete cylinders were prepared, to be weighed and broken in groups of three, at nine ages throughout the investigation

Cylinders stored in air were placed on racks in a high ceilinged corridor (about 40 feet), thus allowing ample opportunity for the free circulation of air. The average air temperature for the test was 75.6° F. and the average relative humidity was 50 per cent. Cylinders to be immersed were placed in open tanks of water where the average temperature maintained was 71.4° F. Cylinders to be stored at 110° F., and 150° F., and 250° F. were placed in electric ovens with automatic temperature control.

The weights of the cylinders to be used in the calculation of the percentages of combined water were taken only after the last curing period. As has been stated the cylinders were broken in groups of three at nine ages throughout the test. Specimens were broken at the end of each curing cycle for the first three cycles, and thereafter at the end of the cycle nearest to 20, 40, 80, 160, 320 and 640 days of age. The specimens were first weighed immersed in water at the end of their given immersion period. They were then weighed in a surface-dry condition, and placed in a 250° F. oven for two days, after which the final dry weight was obtained. The two days in the 250° F. oven were not included in the recorded age of the specimens.

Calculation of Combined Water. The method employed in calculating the percentage of combined water does not necessarily give the exact numerical value. It should, however, give results which are comparable one with another, and which are at least proportional to the true percentage of combined water. The method is based on the assumption that all voids in the original mix were filled with water and that during the setting process all water hydrated by the cement still retained its original volume. It is believed that during the two days in the 250° F. oven all water not firmly fixed by the cement is driven off. The difference between the surface dry weight and immersed weight supplies the volume of the specimen, while the difference between the surface dry weight and the oven dry weight indicates the amount of water which was not hydrated by the cement. If we subtract the water not hydrated from the original water content we should have the amount of water hydrated or combined with the cement. This is calculated in percentage by volume of the total mixing water. A sample calculation is given below.

(1) Weight Immersed	(2) Saturated Surface Dry Weight	(3) Dry Weight 2 Days at 250°F	(4) Weight (2) Minus Weight (1)	(5) Weight (2) Minus Weight (3)	(6) Moisture by Vol — $\frac{(5)}{(4)}$x100 Per Cent	(7) $\frac{(6)}{Cl}$x100	(8) Retained Water 100—(7) Per Cent
16.25	26.69	25.27	10.44	1.42	13.60	68.51	31.49

Note. Item (7) is obtained by dividing the percentage of water driven off by the percentage by volume of total water in the original concrete (in this case Cl—19.85 per cent). In other words, item (7) is the percentage of original water not retained, and 100 minus item (7) is the percentage of water retained or combined.

Compression Tests All cylinders were broken dry in groups of three, so that plotted results are the average of at least three tests Although every effort was made to make uniform concrete, a correction system was established to compensate for slight fluctuations in the various batches For every complete series of 27, three additional preliminary cylinders were made These were always broken at the age of three days and a running average kept of their strength If the preliminary cylinders varied more than 10 per cent from the running average, the entire series was duplicated and the complete test run on both series In comparing the results of pairs of duplicate

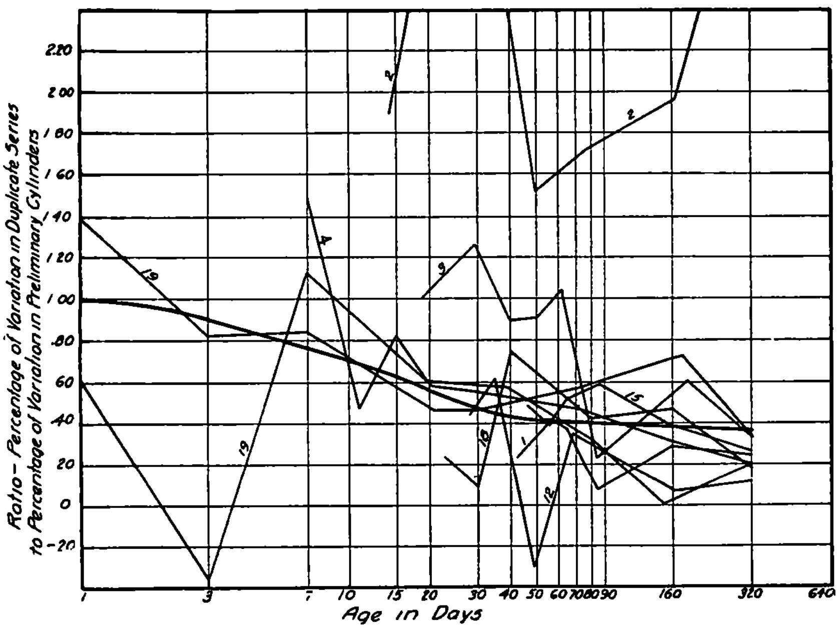

Figure 17 Correction Curve for Compressive Strength Based on a Comparison of Duplicate Series and Preliminary Cylinders

series it was found that the percentage difference between the two duplicates became less as the age increased Hence if a percentage correction was to be applied to a given series because its preliminary cylinders were either lower or higher than average, this correction would become less as the age increased Figure 17 shows what portion of the percentage variation in the preliminary cylinders was used in making corrections at various ages This figure was obtained by plotting the relation between the various pairs of series which were duplicated It shows the ratio of the relative strengths of pairs of duplicate series at various ages as compared to the ratio of the strength of the preliminary cylinders for those two series.

Take for an example the correction of the strength of a given series at age 80 days if the preliminary cylinders were three per cent below the average of the preliminary cylinders. The correction would be 0 4 of 3 or 1.2 per cent, and if the strength were 8,000 pounds, the correction would amount to 96 lb per sq. in

All series whose preliminary cylinders varied more than 2 per cent from the average were thus corrected, and when two duplicate series were run, the average of the two corrected duplicate series was used.

Interpretation of Results

Effect of Initial Curing As might be expected, the effect of initial curing is most marked in the early ages This effect is gradually toned down as the age increases. This is especially true if some adequate form of intermittent curing is carried on during the interval This effect is strikingly shown in Figure 18 These curves were obtained by averaging all of the five complete series containing some form of intermittent curing (Nos 1, 2, 5, 8, and 15) For the ten day age, however, it was necessary to use series No. 18 with air curing after the initial curing period, because ten day results could not be obtained from the other series It will be noted that this procedure is substantially correct, because all intermittent curings begin with the dry period. From Figure 18 we see that at age ten days, a seven day initial curing is a decided advantage, but that at age 160 days the three and seven day initial curings produce about equal strengths Figure 19 indicates that for a 3 day initial curing period, a 21 day dry period immediately after the initial curing reduces the strength only about 6 4 per cent

On examining Figures 20, 21, and 22 we find that the 21 day initially cured specimens excel only in the unusual cases as in series No 1 where the initial curing period is followed by 21 days in air, or in series Nos 12 and 13 where the air temperature is 150° F , or as in series No. 18 which is cured continuously in air. Examination of the various series for the percentage of combined water shows that in almost all cases the three and seven day initial curing periods produce the highest percentage of retained water.

From these facts we may conclude that.

(1) An initial curing longer than seven days is seldom justified

(2) If adequate intermittent curing is assured, a three day initial curing seems adequate.

(3) For high early strength or for localities where adequate intermittent curing is not assured, a seven day initial curing is advisable.

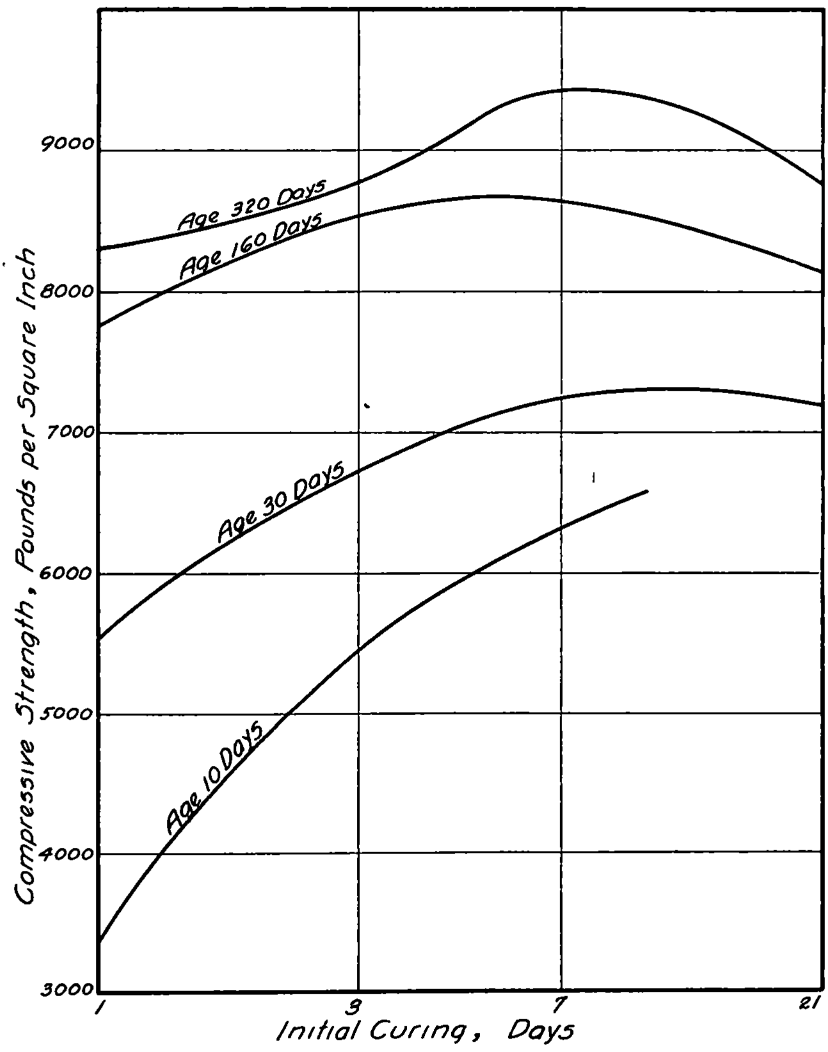

Figure 18 Effect of Initial Curing. The Values Used are the Averages of Series 1, 2, 5, 8 and 15 Except for the 10 Day Age in Which Air Curing Was Used After Initial Curing (Series 18)

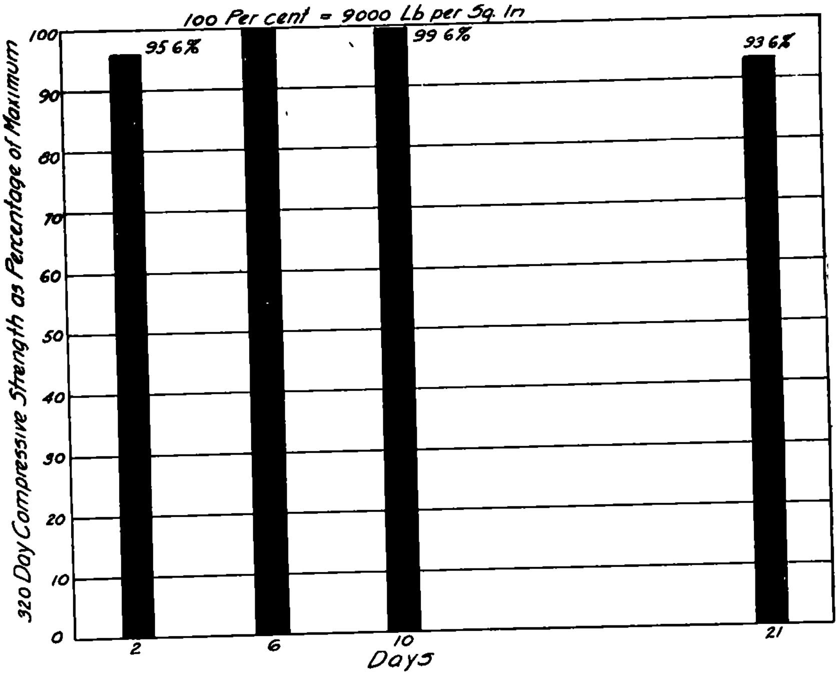

Figure 19 Relation of Time in Days of Initial Drying Period in Air at 70° F After a 3 Day Initial Curing in Water to Relative Compressive Strength Series 1 to 9 Incl, 14, and 15.

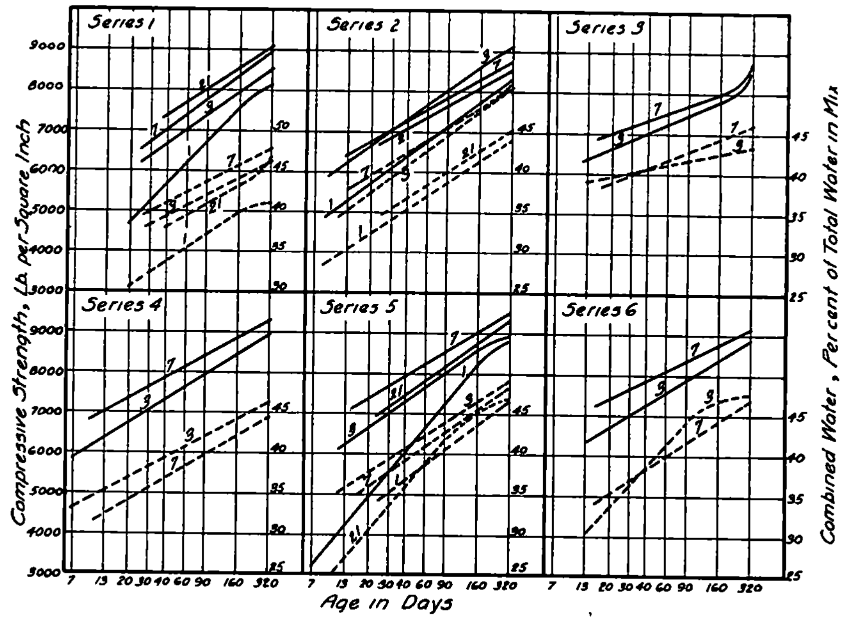

Figure 20 Relation Between Strength, Amount of Combined Water and Age for Various Intermittent Curing Conditions Number of Initial Curing Days as Shown on Diagrams Strength Curves Solid Lines, Combined Water Curves Broken Lines

Series 1—15 Days in Air at 70° F, then 6 Days Air, 70° F, to 1 in Water.
Series 2—6 Days in Air at 70° F, to 1 Day in Water
Series 3—10 Days in Air at 70° F, to 1 Day in Water
Series 4—2 Days in Air at 70° F., to 2 Days in Water
Series 5—6 Days in Air at 70° F, to 2 Days in Water
Series 6—10 Days in Air at 70° F, to 2 Days in Water

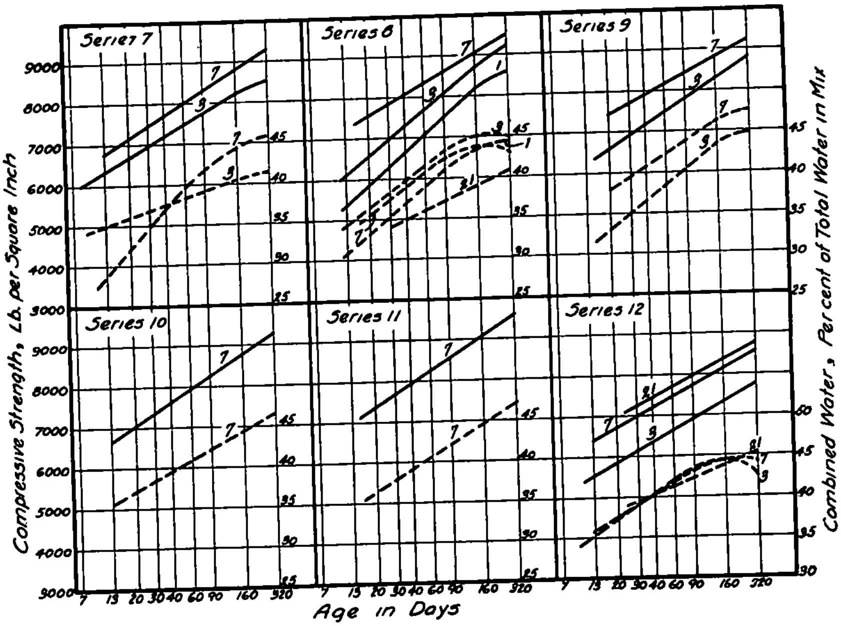

Figure 21 Relation Between Strength, Amount of Combined Water and Age for Various Intermittent Curing Conditions Number of Initial Curing Days as Shown on Diagrams Strength Curves Solid Lines; Combined Water Curves Broken Lines.

Series 7—2 Days in Air at 70° F. to 4 Days in Water
Series 8—6 Days in Air at 70° F. to 4 Days in Water
Series 9—10 Days in Air at 70° F. to 4 Days in Water
Series 10—6 Days in Air at 110° F to 1 Day in Water
Series 11—6 Days in Air at 110° F. to 4 Days in Water
Series 12—6 Days in Air at 150° F to 1 Day in Water

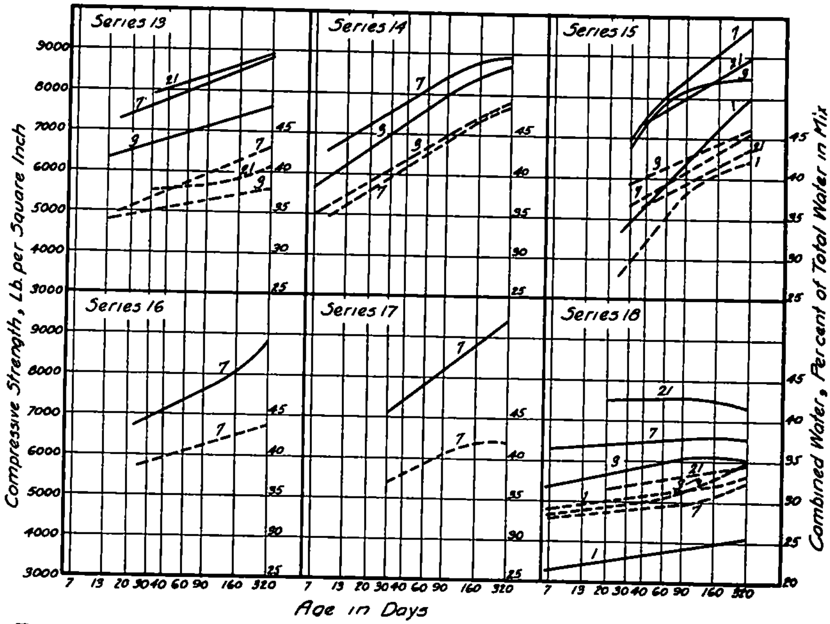

Figure 22 Relation Between Strength, Amount of Combined Water and Age for Various Intermittent Curing Conditions Number of Initial Curing Days as Shown on Diagrams. Strength Curves Solid Lines, Combined Water Curves Broken Lines

Series 13—6 Days in Air at 150° F to 4 Days in Water
Series 14—2 Days in Air at 70° F. to 1 Day in Water.
Series 15—15 Days in Air at 70° F to 4 Days in Water
Series 16—15 Days in Air at 110° F then 6 Days in Air at 110° F to 1 Day in Water
Series 17—15 Days in Air at 110° F. then 6 Days in Air at 110° F to 4 Days in Water
Series 18—Continuously in Air at 70° F

(4) A one day initial curing following by average intermittent curing produces a strength at 320 days of about 88 2 per cent of the maximum

(5) A 21 day period following the 3 day initial curing period reduces the strength only 6 4 per cent at age 320 days

Effect of Intermittent Curing The effect of intermittent curing may be shown by comparing the curves for three day initial curing in each of the various series. (Figures 20, 21, and 22) The three day initial curing values are used because these values are less erratic,

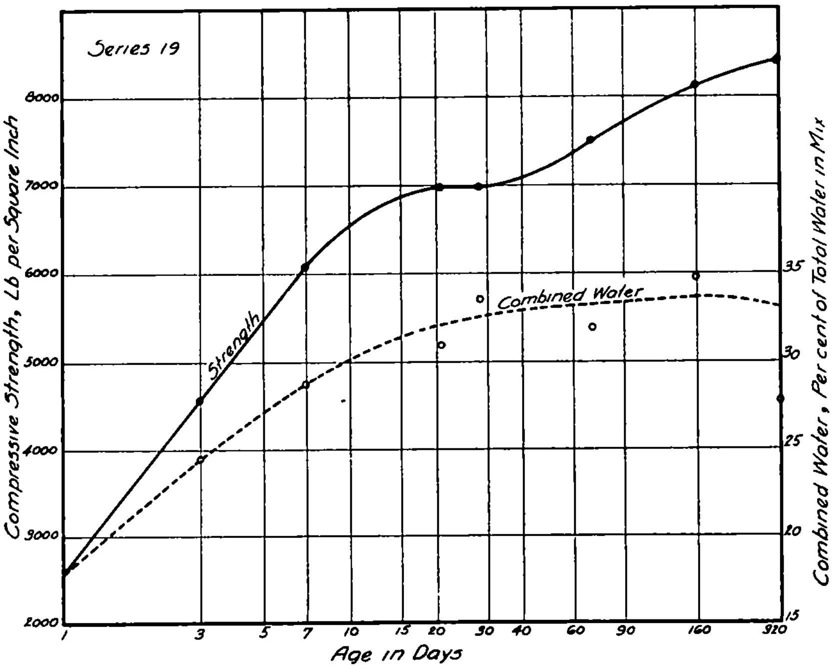

Figure 23. Relation Between Strength, Amount of Combined Water and Age, for Specimens Continuously Under Water Strength Curve Solid Line; Combined Water Curve, Broken Line

and because they produce high ultimate strength, bringing out the full effect of the intermittent curing One of the striking disclosures is that after age 40 days almost all forms of intermittent curing are better than continuous curing under water as represented by series No 19 The explanation of the sudden dip in series No 19 at age 20 days is not readily apparent. That there is such a dip, however, can scarcely be doubted, for the points of this curve as seen in Figure 23 represent an average of nine cylinders each One possible explanation is that free lime formed during the setting of the cement is dissolved and removed by the water. There is further evidence pointing to this action contained in the combined water curves as will be pointed out later.

Referring again to the three day initial curing curves in Figures 20, 21, and 22, we find that a six day drying period gives better results than either a two or a ten day period Series Nos 8, 2, and 5 all yield superior results, and all contain six day drying periods The longer moist periods of two to four days seem to be advantageous when used with a ten day drying period, but when a two day drying period is used a moist period of one to two days yields better results. A 21 day drying period immediately after the initial curing cuts down the early strength considerably, but apparently it has but little effect on the final strength, as illustrated in series Nos 1 and 15 From these data, we may conclude that

1 Intermittent curing is superior to continuous immersion.
2 Drying periods of approximately six days are the most advantageous.
3 A 2 to 4 day moist period is advantageous when used with a 10 day drying period, but for a 2 day drying period a 1 or 2 day moist period yields better results
4 A 21 day dry period following a 3 day initial curing does not permanently harm the concrete when followed by reasonable intermittent curing

Effect of Air Temperature Figure 24 shows the effects of the air temperature on the compressive strength With a seven day initial curing the air temperature in the range from 70° to 150° F has surprisingly little effect on the compressive strength It must be borne in mind also that these higher temperatures were attained in an electric oven, and that the humidity was consequently much lower, with a resulting faster rate of drying This faster drying apparently did little harm during the six day drying periods, as the 70 and 110 degree curves are not far apart, and the 150 degree values are but slightly lower Figure 24c indicates that when the initial curing period is followed by 21 days in air, the 110 degree temperature is at a slight disadvantage Figures 20, 21, and 22 show the 150° F temperature at a decided disadvantage when used with a three day initial curing period No values were obtained for a three day initial curing period with 110° air temperatures

From these data we may conclude that seasonal temperature variations above 70° F. would have little effect on the final concrete strength, if initially cured for seven days and if accompanied by reasonably intermittent curing

Significance of Combined Water The effect of the percentage of combined water (temperature 250° F.) is not so well defined as one might desire The chief trouble is that the values obtained are

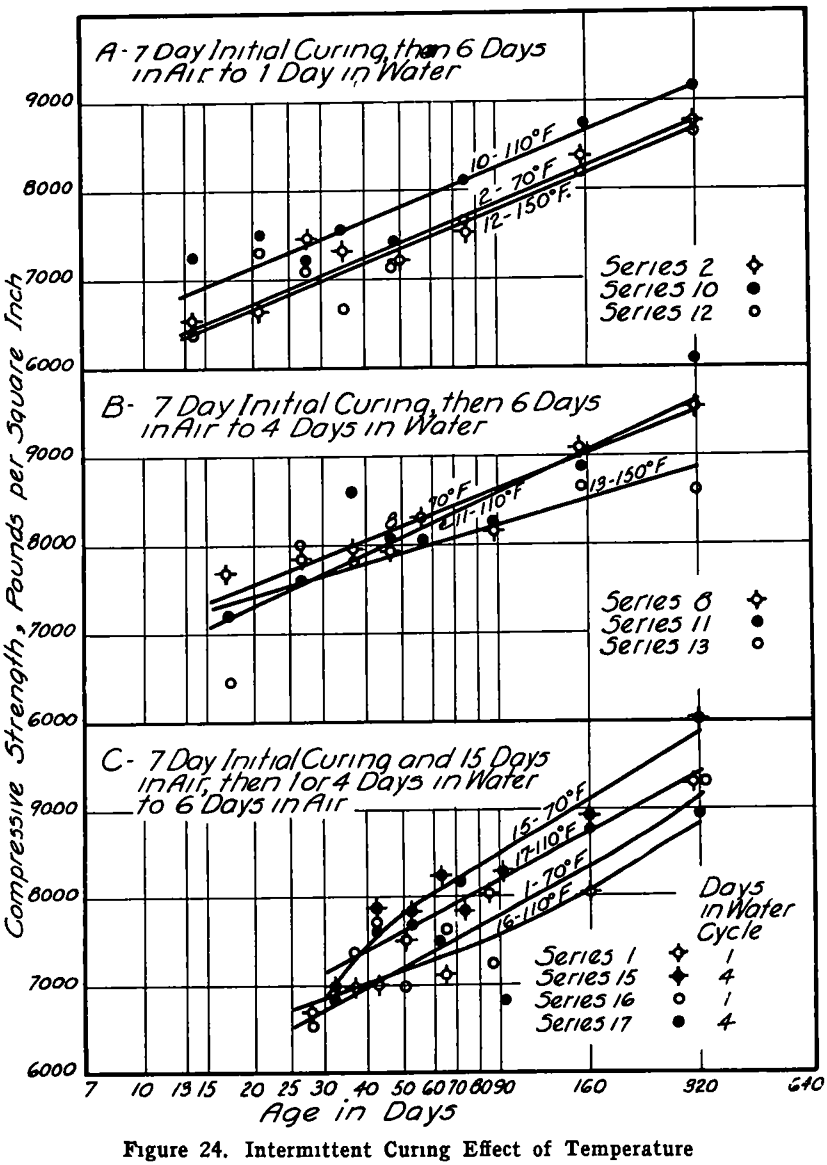

Figure 24. Intermittent Curing Effect of Temperature

somewhat erratic and make it difficult to draw definite conclusions. Figure 25 shows the relation between strength and percentage of

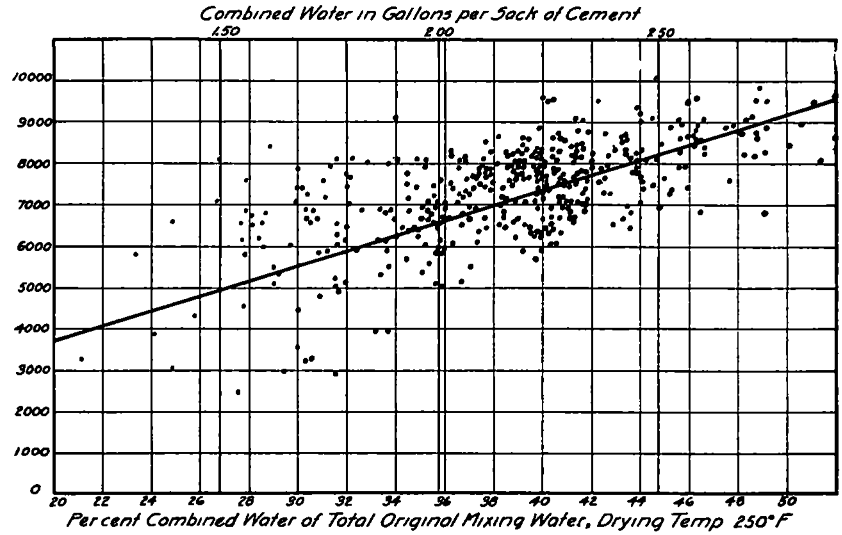

Figure 25. Relation Between Strength and Percentage of Retained Water

retained water. A study of Figures 21, 22, 23, and 24 discloses the following facts:

1 Most methods of intermittent curing result in combining about 45 per cent of the total original water at an age of 320 days
2 Curing continuously in air, as in series No 18, results in a lower percentage of combined water
3 Curing continuously under water as in series No 19, also results in a lower percentage of combined water
4 The percentage of combined water increases with the age as does the strength
5 Specimens having 21 days of initial curing have lower percentages of combined water than specimens cured initially for three or seven days, except in the case of series No. 18 which was cured continuously in air after the initial curing

Item 1 indicates that about 2½ gallons of water per sack of cement is enough combined water to produce these comparatively high strengths Items 2 and 4 are in accordance with reasonable expectations Items 3 and 5, however, are not so readily explainable, since it does not seem reasonable that specimens submerged for a longer time should show a lower percentage of combined water Two possible explanations of this apparent discrepancy present themselves It is possible that after the periods of immersion in the intermittent series, some air remained in the specimen If so, this would affect the computed results on the amount of combined water, indicating too high a value for the intermittent series It is also possible that the water slowly dissolves and removes some of the free lime present in the cement or formed during the hydration process This effect would be to decrease the calculated amount of retained water especially for specimens continuously immersed

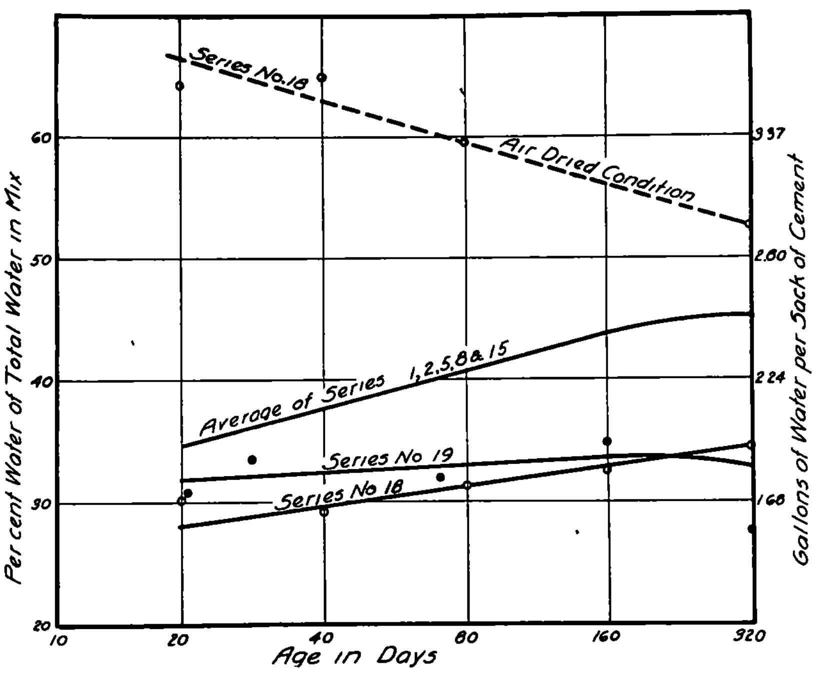

Figure 26 Relation of Water Present in Air Dried Condition to Combined Water as Determined at 250° F.

Messrs Work and Lasseter [1] in some original research work determined that the hydration of tricalcium-aluminate was complete at 28 days The hydration of tricalcium and diacalcium silicates began much more slowly but went on at an increasingly rapid rate up to at least six months In the case of the tricalcium-silicate, only half of the combined water was found present as water of hydration,

[1] Paper by Lincoln T Work and Franklyn P Lasseter in "CONCRETE" March, April and May, 1931 Pp 81-86, 89-92 and 79-84

the remainder being hydrolized and present in the (OH) form as Ca $(OH)_2$ according to the equation

$$3\ CaOSiO_2 + \text{Water} \rightarrow CaOSiO_2\ 2\tfrac{1}{2}\ H_2O + 2\ Ca(OH)_2$$

Going back to original Items 3 and 5 which we were endeavoring to explain, we see that too long an immersion might remove some of the calcium-hydroxide present and thus indicate a lower value for the percentage of combined water. It must be borne in mind in interpreting these results that continuous immersion as in this test would be much more likely to dissolve out free lime from the concrete than would any method of curing ordinarily used