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AN INVESTIGATION OF CONCRETE
CURING METHODS

Thesis for the Degree of B. S.
MICHIGAN STATE COLLEGE

Charles R. Ahlstrom
1944

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**SUPPLEMENTARY
MATERIAL
IN BACK OF BOOK**

An Investigation of Concrete
Curing Methods

A Thesis Submitted to

The Faculty of
MICHIGAN STATE COLLEGE

of
AGRICULTURE AND APPLIED SCIENCE

by

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Candidate for the Degree of

Bachelor of Science

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REPLACEMENT
MATERIAL
IN BACK OF BOOK

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Acknowledgement

I wish to express my thanks to the Research Division of the Michigan State Highway Department for the use of equipment and for the keen interest shown by the employees.

INTRODUCTION

In the words of Mr. G.A. Hool, concrete is an artificial stone made by mixing, in the proper proportions, cement, water, and aggregate consisting of large and small particles. Cement is the binding material and the aggregates are the inert materials. To obtain quality concrete, it is necessary to use good materials, to have the concrete mix correctly proportioned, the batch thoroughly mixed and carefully placed in the forms, and then the concrete allowed to harden under suitable curing conditions.

Freshly placed concrete pavement slabs are protected against drying out for a definite period of time after initial hardening has occurred in order to obtain the desired strength and resistance to wear. This treatment is called curing.

Concrete hardens because of chemical reactions which take place between the cement and water. These reactions continue indefinitely so long as the temperatures are favorable and moisture is present to complete the hydration. The strength and quality of concrete, therefore, are dependent upon its age and the conditions under which it cures. If concrete is cured under dry atmospheric conditions, some of the water in the concrete will evaporate before the chemical reactions have continued for a sufficiently long time to obtain a reasonable proportion of the maximum strength attainable. In general, good practice requires that all concrete should be protected against permanent drying out for at

least one week. Evaporation of the water from the concrete can be prevented by several curing methods. The types Of curing I have investigated are four of the most common. (i.e. wetted burlap, ponding, membrane, and calcium chloride admixture) Also, for comparison purposes I carried out investigations on concrete that was cured by the atmosphere only. (i.e. air curing)

Proper curing, in addition to increasing the strength, has a marked effect on other qualities of concrete, particularly resistance to the action of the elements. Continuous curing in the early stages of hardening, helps to produce a hard dense surface and to prevent scaling, especially important in pavements, and other surfaces subject to the action of wetting and drying, and freezing and thawing.

OBJECT

The object of this experiment was to determine through actual laboratory tests which of the common curing methods mentioned above produces the best concrete. It is my belief that all other factors remaining constant, the strength and resistance to scaling of the concrete will vary with the method of curing.

It was the primary purpose of this experiment to prove which curing method is most satisfactory. Also, tests were carried out investigating the daily moisture gain or loss in the concrete with each type of curing. Specimens were also made and subjected to the action of freezing and thawing to determine their relative anti-scaling properties.

To determine the quality of concrete produced by each of the five curing methods, seven day, twenty-eight day, and six week compressive strength tests were run and comparisons between the individual curing methods were made.

TRIAL MIX DESIGN

The proportioning of the concrete in this entire research problem was arrived at by the water-cement ratio and the slump test. This method of proportioning is generally termed "proportioning by trial mix."

In proportioning concrete by the trial mix method, the water-cement ratio is used to determine the compressive strength of the concrete, and the slump test to determine the workability or consistency. There are three general rules to be observed:

1. Use the exact amount of water with each sack of cement to produce the desired compressive strength. If there is water present in the aggregates, this water must be included when determining the amount of water used for the mix.
2. Use enough fine and coarse aggregates with the cement and water to give a concrete mix of the consistency needed for the particular work in question. This consistency should be specified by the slump in inches.
3. Use the fine and coarse aggregates so that as large a proportion of aggregates as is practical may be used with the cement and water, and yet have a mix of the desired consistency. In general, to avoid the possibility of a harsh mix, the weight of the fine aggregate should not be more than the

weight of the coarse aggregate, or less than half the weight of coarse aggregate.

In hand mixing, which I used in this experiment, correct proportioning and thorough mixing is essential. Excess water may mean less strength, more voids, laitance, perhaps separation of the aggregates in the forms, and perhaps washing away of the cement. Too little mixing means less strength, non-uniformity of consistency, and harsh-working concrete.

The concrete for the specimens used in these investigations was designed by the trial mix method, using six gallons per sack of cement for water, and arriving at a three inch slump. Following the three general rules for trial mix design, the quantities arrived at for a one-fifth batch sack were:

Cement-----19#

Fine agg.--50#

Coarse agg.-83#

Therefore, the mix weight is 19:50:83 or 1:2.63:4.37.

Mixing time-----10 min.

Slump-----3 in.

SEVEN DAY COMPRESSIVE STRENGTH
COMPARISONS

INTRODUCTION

The object of this experiment was to determine which of the five curing methods (i.e. air, ponding, wetted burlap, membrane, and calcium chloride admixture) produced the concrete with the highest seven day compressive strength after six days of curing. Twenty-five specimens, five each for the five types of curing, were made and molded in the standard cylinder, six inches in diameter and twelve inches high. The twenty five test specimens were all made on the same day and under exactly similar conditions.

Approximately twenty-four hours after the specimens were made, the steel cylinder forms were removed and the specimens were begun in their various types of curing. Calcium chloride was added at the rate of two and one-half pounds per sack of cement for the concrete that was used to make the specimens that were cured by the calcium chloride admixture method. The membrane curing compound was applied at the rate of two hundred square feet per gallon of compound. The compound used for this test was one recommended by the Michigan State Highway Department and its rate of application was also prescribed by them.

At the age of seven days, the twenty-five specimens were broken on the hydraulic press in the concrete laboratory. The pages that follow contain the data and charts of the results that were obtained.

In figuring the experimental average, I first had to apply a statistical method to determine whether or not any of the final figures in the "p.s.i." column deviated too far from

the arithmetic mean of the five items in the column. According to statistics, experimental results are allowed to vary three standard deviations on either side of the arithmetic mean. If any of the experimental results fall outside of the limits set by $(\bar{x} \pm 3\sigma)$, they are to be omitted, and a new arithmetic mean should be found using only the figures that fall within the allowable limits.

In the expression $(\bar{x} \pm 3\sigma)$: $\bar{x} = \frac{\sum x}{\sum f}$ where (x) equals the items in the p.s.i. column and (f) equals the frequency with which they occur. $\sigma = 1.25 \left[\frac{\sum f |x - \bar{x}|}{\sum f} \right]$ where $|x - \bar{x}|$ equals the absolute value of the difference between the item in the p.s.i. column and the arithmetic mean. All computations are shown for finding σ in the following pages. As it happened, no items had to be omitted when figuring the experimental average, since all the values fell within the allowable limits.

AIR CURING

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
1-1-----	5.875"	27.109 ^{sq} "	67,000 [#]	2470
1-2-----	5.875	27.109	65,000	2400
1-3-----	5.875	27.109	64,500	2380
1-4-----	5.875	27.109	58,000	2140
1-5-----	5.8125	26.535	64,000	2415

<u>x</u>	<u>f</u>	<u>f x-x̄ </u>
2470----	1-----	109
2400----	1-----	39
2380----	1-----	17
2140----	1-----	221
2415----	1-----	54
11,805	5	440

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{11,805}{5} = 2361$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{440}{5} = 88$$

$$\sigma = 1.25 \quad M.D. = 1.25(88) = 110$$

$$\begin{aligned} \therefore \text{ALLOWABLE LIMITS} &= \bar{x} \pm 3\sigma \\ &= 2361 \pm 3(110) \\ &= 2361 \pm 330 \end{aligned}$$

$$MAX. = 2691 \text{ P.S.I.}$$

$$MIN. = 2031 \text{ P.S.I.}$$

$$\therefore \text{EXPERIMENTAL AVERAGE} = \underline{\underline{2361 \text{ P.S.I.}}}$$

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WETTED BURLAP

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
3-1-----	5.875 ["] -----	27.109 ^{D"} -----	62,500 [#] -----	2305
3-2-----	5.8125-----	26.535-----	67,000-----	2525
3-3-----	5.875-----	27.109-----	60,000-----	2215
3-4-----	5.8125-----	26.535-----	58,000-----	2190
3-5-----	5.875-----	27.109-----	70,000-----	2580

<u>x</u>	<u>f</u>	<u>f x-x̄ </u>
2305-----	1-----	58
2525-----	1-----	162
2215-----	1-----	148
2190-----	1-----	173
2580-----	1-----	217
<u>11,815</u>	<u>5</u>	<u>758</u>

$$\bar{X} = \frac{\sum x}{\sum f} = \frac{11,815}{5} = 2363$$

$$M.D. = \frac{\sum f |x - \bar{x}|}{\sum f} = \frac{758}{5} = 152$$

$$\sigma = 1.25 M.D. = 1.25(152) = 190$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{X} \pm 3\sigma$$

$$= 2363 \pm 3(190)$$

$$= 2363 \pm 570$$

$$\text{MAX.} = 2933 \text{ P.S.I.}$$

$$\text{MIN.} = 1793 \text{ P.S.I.}$$

$\therefore$ EXPERIMENTAL

$$\text{AVERAGE} = \underline{\underline{2363 \text{ P.S.I.}}}$$

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PONDING

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
2-1-----	5.875 ["] -----	27.109 ^{sq"} ----	72,000 [#] -----	2660
2-2-----	5.875-----	27.109-----	67,500-----	2490
2-3-----	5.8125-----	26.535-----	70,000-----	2640
2-4-----	5.875-----	27.109-----	60,000-----	2215
2-5-----	5.875-----	27.109-----	69,500-----	2565

<u>x</u>	<u>f</u>	<u>f/x-$\bar{x}$/</u>
2660----	1-----	146
2490----	1-----	24
2640----	1-----	126
2215----	1-----	299
2565----	1-----	51
<u>12,570</u>	<u>5</u>	<u>646</u>

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{12570}{5} = 2514$$

$$M.D. = \frac{\sum f |x - \bar{x}|}{\sum f} = \frac{646}{5} = 129$$

$$\sigma = 1.25 M.D. = 1.25 (129) = 161$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 2514 \pm 3(161)$$

$$= 2514 \pm 483$$

$$MAX. = 2997 \text{ P.S.I.}$$

$$MIN. = 2031 \text{ P.S.I.}$$

$\therefore$ EXPERIMENTAL

$$AVERAGE = \underline{\underline{2514 \text{ P.S.I.}}}$$

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MEMBRANE

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
4-1-----	5.8125 ["] -----	26.535 ["] -----	70,000 [#] -----	2640
4-2-----	5.8125-----	26.535-----	67,000-----	2525
4-3-----	5.875-----	27.109-----	67,500-----	2490
4-4-----	5.8125-----	26.535-----	73,000-----	2755
4-5-----	5.8125-----	26.535-----	66,000-----	2490

<u>x</u>	<u>f</u>	<u>f x-x̄ </u>
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2640-----	1-----	60
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2525-----	1-----	55
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2490-----	1-----	90
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2755-----	1-----	175
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<u>2490-----</u>	<u>1-----</u>	<u>90</u>
12,900	5	470

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{12900}{5} = 2580$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{470}{5} = 94$$

$$\sigma = 1.25 \text{ M.D.} = 1.25 (94) = 118$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 2580 \pm 3(118)$$

$$= 2580 \pm 354$$

$$\text{MAX.} = 2934 \text{ P.S.I.}$$

$$\text{MIN.} = 2226 \text{ P.S.I.}$$

EXPERIMENTAL

$$\text{AVERAGE} = \underline{\underline{2580}} \text{ P.S.I.}$$

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CaCl₂ ADMIXTURE

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
5-1-----	5.8125" ^{D"}	26.535 [#]	89,000	3360
5-2-----	5.875	27.109	82,500	3045
5-3-----	5.875	27.109	96,000	3540
5-4-----	5.875	27.109	90,000	3320
5-5-----	5.875	27.109	100,000	3690

<u>x</u>	<u>f</u>	<u>f x-x</u>
3360-----	1-----	31
3045-----	1-----	346
3540-----	1-----	149
3320-----	1-----	71
3690-----	1-----	299
<u>16,955</u>	<u>5</u>	<u>896</u>

$$\bar{X} = \frac{\sum x}{\sum f} = \frac{16955}{5} = 3391$$

$$M.D. = \frac{\sum f |x - \bar{x}|}{\sum f} = \frac{896}{5} = 179$$

$$\sigma = 1.25 M.D. = 1.25 (179) = 224$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{X} \pm 3\sigma$$

$$= 3391 \pm 3(224)$$

$$= 3391 \pm 672$$

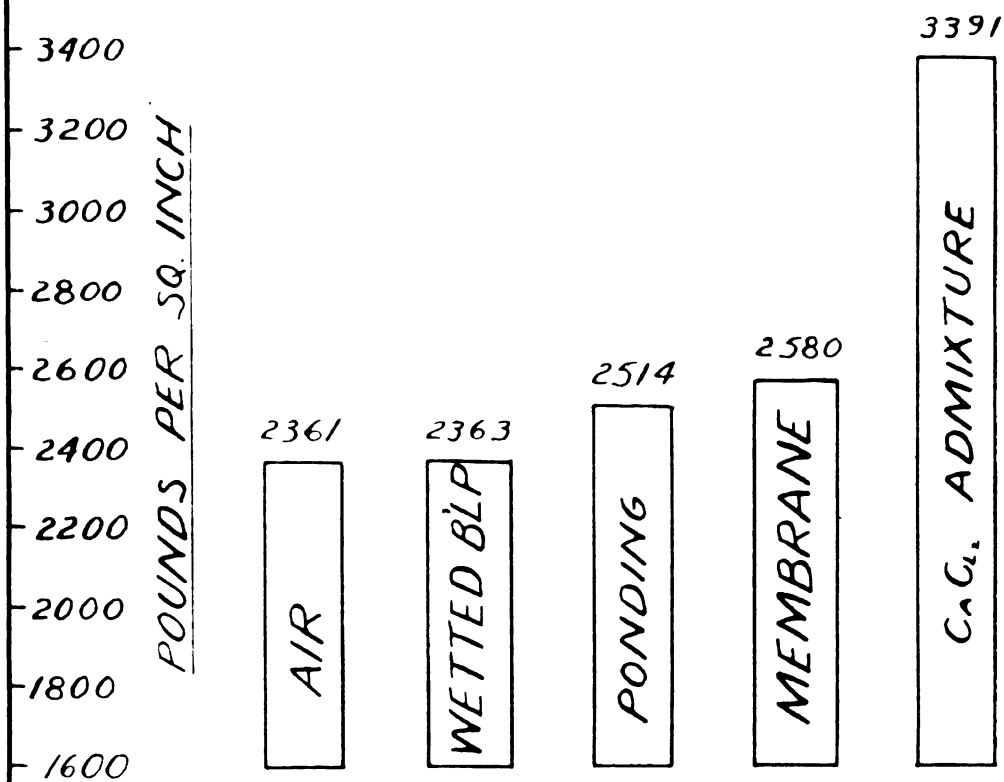
$$\text{MAX.} = 4069 \text{ P.S.I.}$$

$$\text{MIN.} = 2719 \text{ P.S.I.}$$

EXPERIMENTAL

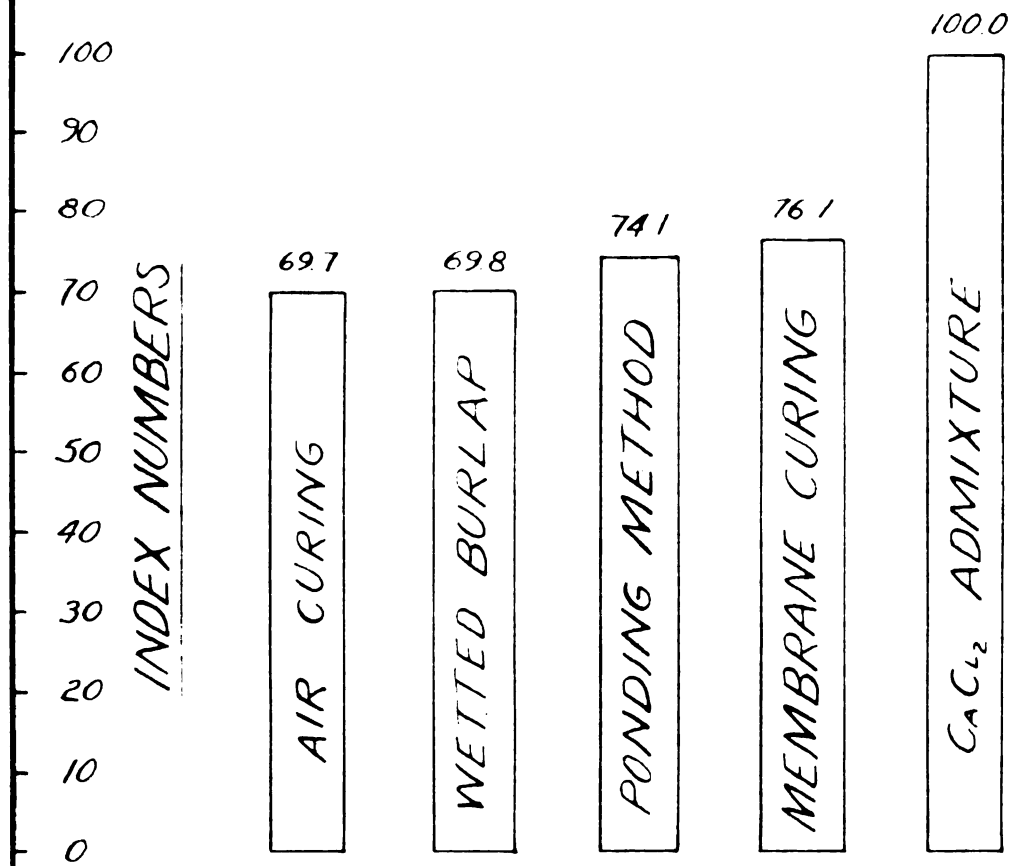
$$\text{AVERAGE} = \underline{\underline{3391 \text{ P.S.I.}}}$$

7 DAY COMPRESSIVE
STRENGTH RESULTS
AFTER 6 DAYS
OF
CURING



METHODS OF CURING

7 DAY COMPRESSIVE
STRENGTH RESULTS
COMPARED BY
INDEX NOS.



METHODS OF CURING

CONCLUSION: The most striking observation as seen from the foregoing charts, is the profound action that a small amount of calcium chloride will have upon the early strength of concrete. It bears out the claims made by the Calcium Chloride Association that calcium chloride, used integrally in concrete mixes, permits removal of forms and further construction to be placed of concrete opened for use in much less than the usual time.

Another observation made as a result of adding calcium chloride to the mix was that a much more workable concrete was obtained. Also, after the steel cylinder forms were removed, a marked benefit was obtained in production of a smoother, whiter surface than was evident on specimens subjected to other curing methods.

It is also interesting to note that membrane curing produced a concrete that was slightly better than curing by ponding and considerably better than curing by wetted burlap. This brings out a point that perhaps it isn't as beneficial as is thought to allow concrete to absorb what moisture it desires when curing it. The membrane compound merely keeps, or attempts to keep, what water is in the mix from escaping and, in a similar manner, keeps the concrete from absorbing moisture.

28 DAY AND 6 WEEK
COMPRESSIVE STRENGTH
RESULTS

INTRODUCTION

In this test the same procedure was carried out as was followed on the seven-day compressive strength tests, except that the twenty-five specimens were allowed to cure for twenty-seven days and were broken on the twenty-eighth day.

For the six week test the same procedure was also followed except that the specimens were cured for forty-one days and were broken on the forty-second.

The first group of data that follows is the results of the twenty-eight day tests. The second group of data is from the six-weeks specimens.

AIR CURING

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
A-1 (1-1)-----	5.750" ² -----	25.967 ² -----	85,000 [#] -----	3280
A-2 (1-2)-----	5.8125-----	26.535-----	87,500-----	3300
A-3 (1-3)-----	5.875-----	27.109-----	95,000-----	3500
A-4 (1-4)-----	5.8125-----	26.535-----	93,000-----	3500
A-5 (1-5)-----	5.8125-----	26.535-----	87,000-----	3280

<u>x</u>	<u>f</u>	<u>f x-x̄ </u>
3280-----	1-----	92
3300-----	1-----	72
3500-----	1-----	128
3500-----	1-----	128
<u>3280-----</u>	<u>1-----</u>	<u>92</u>
16,860	5	512

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{16,860}{5} = 3372$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{512}{5} = 102$$

$$\sigma = 1.25 M.D. = 1.25(102) = 127.5$$

$$\begin{aligned} \therefore \text{ALLOWABLE LIMITS} &= \bar{x} \pm 3\sigma \\ &= 3372 \pm 3(127.5) \\ &= 3372 \pm 382.5 \end{aligned}$$

$$MAX. = 3754.5 \text{ P.S.I.}$$

$$MIN. = 2989.5 \text{ P.S.I.}$$

$$\therefore \text{EXPERIMENTAL AVERAGE} = \underline{\underline{3372 \text{ P.S.I.}}}$$

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MEMBRANE

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>P.s.i.</u>
D-1 (4-1)-----	5.8438 ["] -----	26.820 ["] -----	90,000 [#] -----	3355
D-2 (4-2)-----	5.8125-----	26.535-----	92,500-----	3485
D-3 (4-3)-----	5.8438-----	26.820-----	95,000-----	3540
D-4 (4-4)-----	5.8125-----	26.535-----	97,000-----	3660
D-5 (4-5)-----	5.8438-----	26.820-----	97,000-----	3610

<u>x</u>	<u>f</u>	<u>f x-x̄ </u>
3355	1	175
3485	1	45
3540	1	10
3660	1	130
3610	1	80
<u>17,650</u>	<u>5</u>	<u>440</u>

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{17650}{5} = 3530$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{440}{5} = 88$$

$$\sigma = 1.25 M.D. = 1.25 (88) = 110$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 3530 \pm 3(110)$$

$$= 3530 + 330$$

$$MAX. = 3860 \text{ P.S.I.}$$

$$MIN. = 3200 \text{ P.S.I.}$$

EXPERIMENTAL

$$AVERAGE = \underline{\underline{3530}}$$

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CaCl₂ ADMIXTURE

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
E-1 (5-1)-----	5.8438-----	26.820----	100,000-----	3725
E-2 (5-2)-----	5.8125-----	26.535----	102,500-----	3860
E-3 (5-3)-----	5.8438-----	27.109----	105,000-----	3870
E-4 (5-4)-----	5.8125-----	26.535----	117,500-----	4425
E-5 (5-5)-----	5.8438-----	26.535----	121,500-----	4580

<u>x</u>	<u>f</u>	<u>f/x-$\bar{x}$</u>
3725-----	1-----	367
3860-----	1-----	232
3870-----	1-----	222
4425-----	1-----	333
<u>4580-----</u>	<u>1-----</u>	<u>488</u>
20,460	5	1642

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{20,460}{5} = 4092$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{1642}{5} = 328$$

$$\sigma = 1.25 (M.D.) = 1.25 (328) = 410$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 4092 \pm 3(410)$$

$$= 4092 \pm 1230$$

$$MAX = 5322 \text{ P.S.I.}$$

$$MIN. = 2862 \text{ P.S.I.}$$

$\therefore$ EXPERIMENTAL

$$AVERAGE = \underline{\underline{4092 \text{ P.S.I.}}}$$

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PONDING

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
B-1 (2-1)-----	5.875 ["] -----	27.109 ["] -----	114,000 [#] -----	4200
B-2 (2-2)-----	5.8125-----	26.535-----	127,500-----	4810
B-3 (2-3)-----	5.875-----	27.109-----	132,500-----	4890
B-4 (2-4)-----	5.875-----	27.109-----	122,000-----	4500
B-5 (2-5)-----	5.8125-----	26.535-----	97,500-----	3680

<u>x</u>	<u>f</u>	<u>f/x-$\bar{x}$</u>
4200	1	216
4810	1	394
4890	1	474
4500	1	84
3680	1	736
22,080	5	1904

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{22080}{5} = 4416$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{1904}{5} = 381$$

$$\sigma = 1.25 M.D. = 1.25(381) = 476$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 4416 \pm 3(476)$$

$$= 4416 \pm 1428$$

$$\text{MAX.} = 5844 \text{ P.S.I.}$$

$$\text{MIN.} = 2988 \text{ P.S.I.}$$

$\therefore$ EXPERIMENTAL

$$\text{AVERAGE} = \underline{\underline{4416 \text{ P.S.I.}}}$$

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WETTED BURLAP

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
C-1 (3-1)-----	5.7813 ["] -----	26.220 ["] -----	130,000 [#] -----	4950
C-2 (3-2)-----	5.875-----	27.109-----	120,000-----	4430
C-3 (3-3)-----	5.7813-----	26.220-----	132,500-----	5050
C-4 (3-4)-----	5.875-----	27.109-----	131,000-----	4830
C-5 (3-5)-----	5.8125-----	26.535-----	122,500-----	4620

<u>x</u>	<u>f</u>	<u>f/x-x̄</u>
4950----	1-----	174
4430----	1-----	346
5050----	1-----	274
4830----	1-----	54
<u>4620----</u>	<u>1-----</u>	<u>156</u>
23,880	5	1004

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{23880}{5} = 4776$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{1004}{5} = 201$$

$$\sigma = 1.25 M.D. = 1.25 (201) = 251$$

$$\begin{aligned} \therefore \text{ALLOWABLE LIMITS} &= \bar{x} \pm 3\sigma \\ &= 4776 \pm 3(251) \\ &= 4776 \pm 753 \\ \text{MAX.} &= 5529 \text{ P.S.I.} \\ \text{MIN.} &= 4023 \text{ P.S.I.} \end{aligned}$$

∴ EXPERIMENTAL

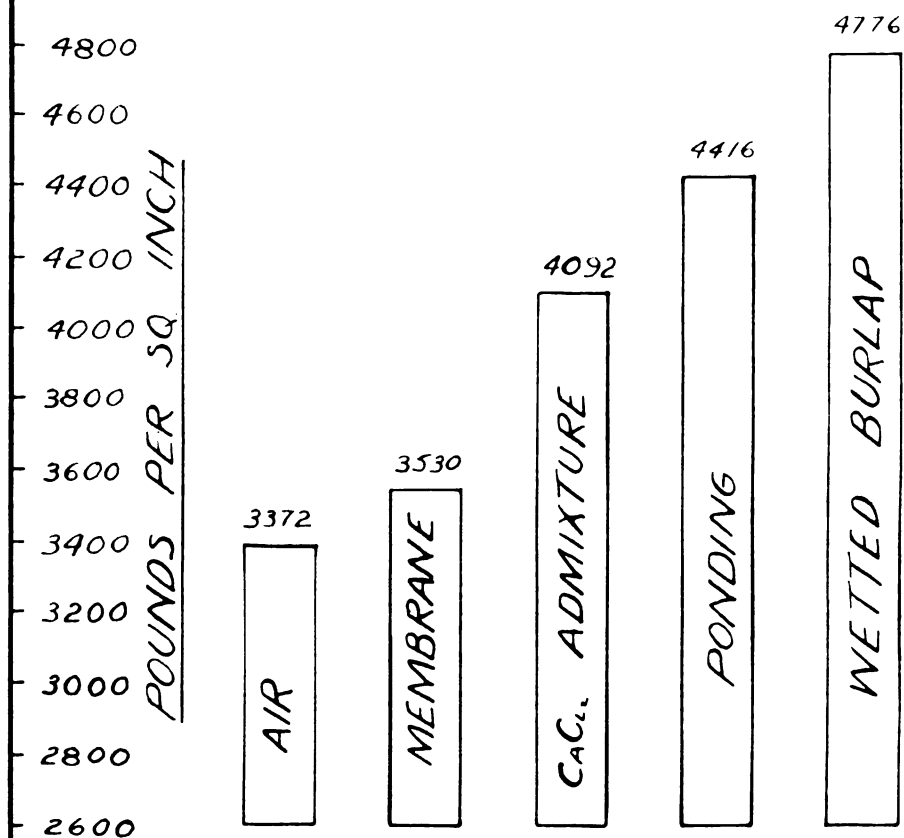
$$\text{AVERAGE} = \underline{\underline{4776 \text{ P.S.I.}}}$$

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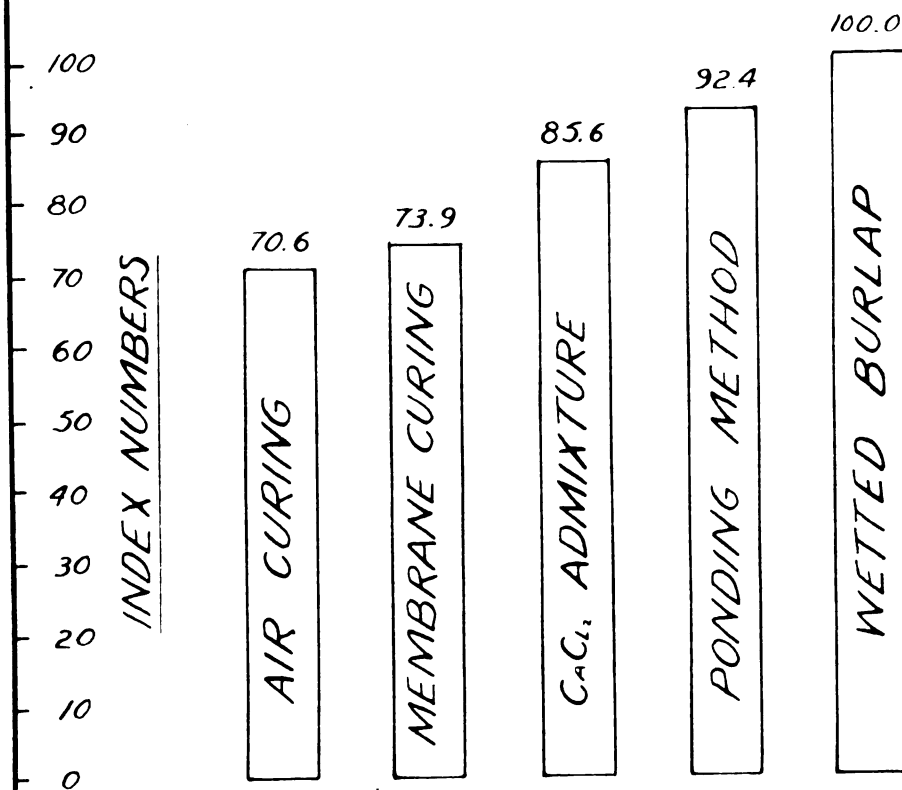
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28 DAY COMPRESSIVE
STRENGTH RESULTS
AFTER 27 DAYS
OF
CURING



METHODS OF CURING

28 DAY COMPRESSIVE
STRENGTH RESULTS
COMPARED BY
INDEX NOS.



METHODS OF CURING

AIR CURING

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
M 1-1-----	5.875"	27.109 ^{sq"}	77,500 [#]	2860
M-1-2-----	5.875	27.109	80,000	2955
M 1-3-----	5.875	27.109	82,000	3025
M 1-4-----	5.875	27.109	80,000	2955
M 1-5-----	5.8125	26.535	82,500	3115

<u>x</u>	<u>f</u>	<u>f/x-$\bar{x}$</u>
2860----	1-----	122
2955----	1-----	27
3025----	1-----	43
2955----	1-----	27
<u>3115----</u>	<u>1-----</u>	<u>133</u>
14,910	5	352

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{14910}{5} = 2982$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{352}{5} = 70$$

$$\sigma = 1.25(M.D.) = 1.25(70) = 88$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 2982 \pm 3(88)$$

$$= 2982 \pm 264$$

$$\text{MAX} = 3246 \text{ P.S.I.}$$

$$\text{MIN.} = 2718 \text{ P.S.I.}$$

$\therefore$ EXPERIMENTAL

$$\text{AVERAGE} = \underline{\underline{2982}} \text{ P.S.I.}$$

MEMBRANE

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
M 4-1-----	5.750 ["] -----	25.967 ["] -----	91,000 [#] -----	3505
M 4-2-----	5.8125-----	26.535-----	100,000-----	3775
M 4-3-----	5.8125-----	26.535-----	101,000-----	3810
M 4-4-----	5.750-----	25.967-----	87,000-----	3360
M 4-5-----	5.8125-----	26.535-----	105,000-----	3960

<u>x</u>	<u>f</u>	<u>f/x-$\bar{x}$</u>
3505-----	1-----	177
3775-----	1-----	93
3810-----	1-----	128
3360-----	1-----	322
<u>3960-----</u>	<u>1-----</u>	<u>278</u>
18,410	5	998

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{18410}{5} = 3682$$

$$M.D. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{998}{5} = 200$$

$$\sigma = 1.25 M.D. = 1.25(200) = 250$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 3682 \pm 3(250)$$

$$= 3682 \pm 750$$

$$MAX = 4432 \text{ P.S.I.}$$

$$MIN. = 2932 \text{ P.S.I.}$$

$$\therefore \text{EXPERIMENTAL}$$

$$\text{AVERAGE} = \underline{\underline{3682}} \text{ P.S.I.}$$

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CaCl₂ ADMIXTURE

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
M 5-1-----	5.8125 ["] -----	26.535 ^{sq} ----	105,000 [#] -----	3960
M 5-2-----	5.875-----	27.109----	102,500-----	3785
M 5-3-----	5.875-----	27.109----	100,000-----	3690
M 5-4-----	5.8125-----	26.535----	101,000-----	3810
M 5-5-----	5.8125-----	26.535----	105,000-----	3960

<u>x</u>	<u>f</u>	<u>f(x-$\bar{x}$)</u>
3960----	1-----	119
3785----	1-----	56
3690----	1-----	151
3810----	1-----	31
<u>3960----</u>	<u>1-----</u>	<u>119</u>
19,205	5	476

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{19205}{5} = 3841$$

$$M.D. = \frac{\sum f |x - \bar{x}|}{\sum f} = \frac{476}{5} = 95$$

$$\sigma = 1.25 (M.D.) = 1.25 (95) = 119$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 3841 \pm 3(119)$$

$$= 3841 \pm 357$$

$$\text{MAX.} = 4198 \text{ P.S.I.}$$

$$\text{MIN.} = 3484 \text{ P.S.I.}$$

$\therefore$ EXPERIMENTAL

$$\text{AVERAGE} = \underline{\underline{3841 \text{ P.S.I.}}}$$

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PONDING

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
M 2-1-----	5.875 ["] -----	27.109 ["] -----	102,500 [#] -----	3780
M 2-2-----	5.8125-----	26.535-----	112,500-----	4250
M 2-3-----	5.8125-----	26.535-----	109,500-----	4130
M 2-4-----	5.750-----	25.967-----	101,000-----	3900
M 2-5-----	5.8125-----	26.535-----	102,500-----	3865

<u>x</u>	<u>f</u>	<u>f/x-$\bar{x}$</u>
3780----	1-----	205
4250----	1-----	265
4130----	1-----	145
3900----	1-----	85
3865----	1-----	120
19,925	5	820

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{19925}{5} = 3985$$

$$M.D. = \frac{\sum f |x - \bar{x}|}{\sum f} = \frac{820}{5} = 164$$

$$\sigma = 1.25 (M.D.) = 1.25 (164) = 205$$

$$\therefore \text{ALLOWABLE LIMITS} = \bar{x} \pm 3\sigma$$

$$= 3985 \pm 3(205)$$

$$= 3985 \pm 615$$

$$\text{MAX.} = 4600 \text{ P.S.I.}$$

$$\text{MIN.} = 3370 \text{ P.S.I.}$$

$\therefore$ EXPERIMENTAL

$$\text{AVERAGE} = \underline{\underline{3985 \text{ P.S.I.}}}$$

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WETTED BURLAP

<u>Identification</u>	<u>Diameter</u>	<u>Area</u>	<u>Breaking Force</u>	<u>p.s.i.</u>
M 3-1-----	5.875" [□]	27.109 [□]	105,000 [#]	3880
M 3-2-----	5.8125	26.535	111,500	4200
M 3-3-----	5.8125	26.535	107,000	4030
M 3-4-----	5.8125	26.535	92,500	3490
M 3-5-----	5.8125	26.535	124,000	4675

<u>x</u>	<u>f</u>	<u>f/x-$\bar{x}$</u>
3880-----	1-----	175
4200-----	1-----	145
4030-----	1-----	25
3490-----	1-----	565
4675-----	1-----	620
20,275	5	1530

$$\bar{x} = \frac{\sum x}{\sum f} = \frac{20275}{5} = 4055$$

$$M.O. = \frac{\sum f|x-\bar{x}|}{\sum f} = \frac{1530}{5} = 306$$

$$\sigma = 1.25 (M.O.) = 1.25(306) = 383$$

$$\begin{aligned} \therefore \text{ALLOWABLE LIMITS} &= \bar{x} \pm 3\sigma \\ &= 4055 \pm 3(383) \\ &= 4055 \pm 1149 \end{aligned}$$

$$MAX. = 5204 \text{ P.S.I.}$$

$$MIN. = 2906 \text{ P.S.I.}$$

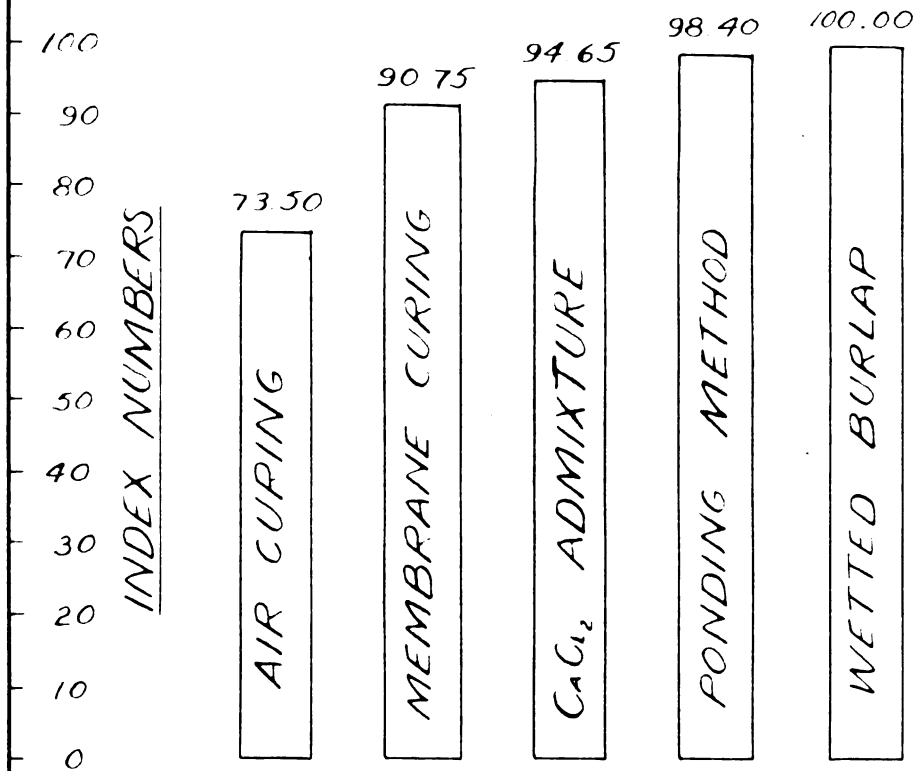
$$\therefore \text{EXPERIMENTAL AVERAGE} = \underline{\underline{4055 \text{ P.S.I.}}}$$

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6 WEEK COMPRESSIVE
STRENGTH RESULTS
AFTER 41 DAYS OF
CURING
REPRESENTED BY
INDEX NOS.



METHODS OF CURING

CONCLUSION: In the twenty-eight day and six week compressive strength results, I obtained a wide range of values resulting from curing by the various methods. It is interesting to observe the shifts in positions on the twenty-eight day and six weeks charts from the positions held by the same curing methods in the charts picturing the seven day results. I find it difficult to explain the shifts of membrane, ponding, and wetted burlap. Evidently, for longer curing periods, it is beneficial to allow the concrete to absorb moisture as is permitted by the wetted burlap and ponding methods. It is logical to notice that the concrete with the calcium chloride admixture losses the position it possessed on the seven day chart since its primary purpose is for high strength at early ages only. However, in longer periods the calcium chloride admixture produces a concrete that is at least somewhat better than if none were added as is shown by its position with respect to air curing.

One may notice from the data sheets that the compressive strengths for the six-week specimens are lower than the compressive strengths for the twenty-eight day specimens. This can be accounted for by the fact that the six-week specimens were made from an aggregate of a different shipment. However, all the twenty-five specimens for the six-week test were made from the same material so that even though the individual compressive strengths are lower than the twenty-eight day compressive strengths, we still have data that gives us relative comparisons between the curing methods at six-weeks.

AN INVESTIGATION OF THE
DAILY MOISTURE GAIN OR LOSS

INTRODUCTION

Twenty-five specimens were made for the purpose of establishing the rate of daily moisture gain or loss with each of the various types of curing employed. The same precautions were practiced in making these specimens as in the mixing of the concrete for the compressive strength tests specimens.

At various ages, the specimens were weighed. The rate of moisture gain or loss is expressed as a percent of the initial weight of the specimen, the weight at age one-day being the initial weight. The final daily percentage rate of moisture gain or loss is expressed as an average of the five individual specimen rates.

AIR CURING

(Initial wt.)					
Identification	Age 1 day				
	Grams	%	2 days	3 days	5 days
M 1-1	12,470	100	12,340--98.95	12,295--98.59	12,286--98.52
M 1-2	12,873	100	12,740--98.96	12,702--98.67	12,687--98.55
M 1-3	12,870	100	12,717--98.81	12,680--98.52	12,647--98.27
M 1-4	12,587	100	12,433--98.78	12,397--98.49	12,365--98.24
M 1-5	12,712	100	12,585--99.01	12,547--98.71	12,517--98.47
% of initial wt.		100	98.98	98.60	98.41
% MOISTURE LOSS		0	1.02	1.40	1.59

Identification	6 days	7 days	9 days	12 days
M 1-1	12,260--98.31	12,252--98.25	12,239--98.14	12,215--97.95
M 1-2	12,670--98.42	12,656--98.31	12,646--98.23	12,633--98.13
M 1-3	12,638--98.20	12,620--98.06	12,614--98.01	12,590--97.82
M 1-4	12,351--98.13	12,342--98.06	12,328--97.95	12,316--97.85
M 1-5	12,518--98.48	12,510--98.42	12,482--98.20	12,475--98.14
% of initial wt.	98.31	98.22	98.11	97.98
% MOISTURE LOSS	1.69	1.78	1.89	2.02

Identification	20 days	26 days	34 days	42 days
M 1-1	12,193--97.78	12,189--97.74	12,183--97.70	12,175--97.63
M 1-2	12,605--97.92	12,595--97.84	12,590--97.80	12,570--97.64
M 1-3	12,575--97.71	12,557--97.57	12,545--97.47	12,532--97.37
M 1-4	12,287--97.62	12,275--97.52	12,285--97.60	12,249--97.32
M 1-5	12,456--97.99	12,443--97.89	12,438--97.85	12,415--97.67
% of initial wt.	-----97.80-----	-----97.71-----	-----97.68-----	-----97.53-----
% MOISTURE LOSS	-----2.20-----	-----2.29-----	-----2.32-----	-----2.47-----

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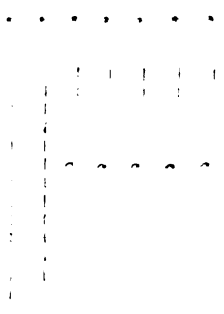
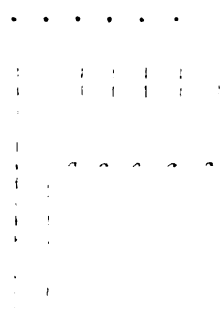
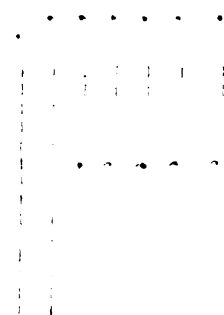
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CaCl₂ ADMIXTURE

Identification	Age 1 day	2 days	3 days	5 days
M 5-1	12,831--98.100	12,730--99.22	12,690--98.91	12,665--98.71
M 5-2	12,857--98.100	12,748--99.15	12,715--98.90	12,687--98.68
M 5-3	12,782--98.100	12,692--99.30	12,650--98.97	12,625--98.78
M 5-4	12,783--98.100	12,695--99.31	12,638--98.87	12,600--98.57
M 5-5	12,714--98.100	12,600--99.10	12,575--98.90	12,548--98.69
% of initial wt.	100	99.22	98.91	98.69
% MOISTURE LOSS	0	.78	1.09	1.31

Identification	6 days	7 days	9 days	12 days
M 5-1	12,635--98.48	12,558--98.66	12,625--98.40	12,620--98.36
M 5-2	12,679--98.62	12,670--98.55	12,663--98.49	12,642--98.33
M 5-3	12,610--98.66	12,605--98.62	12,590--98.50	12,591--98.51
M 5-4	12,612--98.66	12,596--98.54	12,578--98.40	12,575--98.37
M 5-5	12,543--98.65	12,530--98.55	12,510--98.39	12,496--98.28
% of initial wt.	98.61	98.58	98.44	98.37
% MOISTURE LOSS	1.39	1.42	1.56	1.63

Identification	20 days	26 days	34 days	42 days
M 5-1	12,585--98.09	12,579--98.04	12,576--98.02	12,554--97.85
M 5-2	12,615--98.12	12,604--98.03	12,592--97.94	12,578--97.83
M 5-3	12,553--98.21	12,549--98.18	12,525--98.00	12,513--97.90
M 5-4	12,538--98.08	12,535--98.06	12,520--97.94	12,505--97.83
M 5-5	12,475--98.12	12,467--98.05	12,458--97.98	12,438--97.82
% of initial wt.	98.12	98.07	97.98	97.85
% MOISTURE LOSS	1.88	1.93	2.02	2.15



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MEMBRANE

Identification	Age 1 day	2 days	3 days	5 days
M 4-1	12,633--100	12,600--99.74	12,592--99.68	12,549--99.34
M 4-2	12,761--100	12,749--99.90	12,745--99.87	12,708--99.58
M 4-3	12,786--100	12,770--99.87	12,730--99.56	12,722--99.50
M 4-4	12,685--100	12,672--99.89	12,646--99.69	12,600--99.33
M 4-5	12,847--100	12,838--99.93	12,815--99.75	12,790--99.56
% of initial wt.	100	99.87	99.71	99.46
% MOISTURE LOSS	0	1.13	0.29	0.54

Identification	6 days	7 days	9 days	12 days
M 4-1	12,535--99.23	12,525--99.15	12,505--98.99	12,496--98.92
M 4-2	12,708--99.58	12,700--99.52	12,690--99.44	12,680--99.36
M 4-3	12,698--99.31	12,700--99.33	12,685--99.21	12,657--98.99
M 4-4	12,598--99.31	12,600--99.33	12,587--99.22	12,580--99.17
M 4-5	12,780--99.48	12,785--99.52	12,770--99.40	12,751--99.25
% of initial wt.	99.38	99.37	99.25	99.14
% MOISTURE LOSS	0.62	0.63	0.75	0.86

Identification	20 days	26 days	34 days	42 days
M 4-1	12,470--98.71	12,447--98.53	12,430--98.40	12,408--98.22
M 4-2	12,640--99.05	12,625--98.93	12,608--98.80	12,583--98.60
M 4-3	12,634--98.81	12,616--98.67	12,598--98.53	12,583--98.41
M 4-4	12,529--98.77	12,515--98.66	12,498--98.52	12,485--98.42
M 4-5	12,718--99.00	12,696--98.83	12,695--98.82	12,678--98.69
% of initial wt.	98.87	98.72	98.61	98.47
% MOISTURE LOSS	1.13	1.28	1.39	1.53

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NETTED BURLAP

Identification	Age 1 day	2 days	3 days	5 days
M 3-1	12,627--100	12,721--100.75	12,723--100.77	12,720--100.74
M 3-2	12,734--100	12,815--100.64	12,825--100.71	12,832--100.77
M 3-3	12,604--100	12,688--100.67	12,695--100.72	12,700--100.76
M 3-4	12,605--100	12,681--100.60	12,700--100.75	12,690--100.67
M 3-5	12,665--100	12,743--100.62	12,762--100.77	12,763--100.78
% of initial wt.	-----100-----	-----100.66-----	-----100.74-----	-----100.74-----
% MOISTURE GAIN	-----0-----	-----66-----	-----74-----	-----74-----

Identification	6 days	7 days	9 days	12 days
M 3-1	12,725--100.78	12,720--100.74	12,740--100.90	12,725--100.78
M 3-2	12,833--100.78	12,837--100.81	12,827--100.73	12,840--100.83
M 3-3	12,699--100.75	12,703--100.79	12,700--100.76	12,700--100.76
M 3-4	12,703--100.77	12,698--100.73	12,700--100.75	12,702--100.76
M 3-5	12,753--100.70	12,764--100.78	12,765--100.79	12,755--100.71
% of initial wt.	-----100.76-----	-----100.77-----	-----100.79-----	-----100.77-----
% MOISTURE GAIN	-----76-----	-----77-----	-----79-----	-----77-----

Identification	20 days	26 days	34 days	42 days
M 3-1	12,730--100.82	12,735--100.86	12,735--100.86	12,740--100.90
M 3-2	12,820--100.68	12,840--100.83	12,830--100.75	12,830--100.75
M 3-3	12,695--100.72	12,697--100.74	12,700--100.76	12,693--100.71
M 3-4	12,695--100.71	12,707--100.80	12,690--100.67	12,680--100.59
M 3-5	12,744--100.63	12,748--100.66	12,765--100.79	12,733--100.54
% of initial wt.	-----100.71-----	-----100.78-----	-----100.77-----	-----100.70-----
% MOISTURE GAIN	-----71-----	-----78-----	-----77-----	-----70-----

PONDING

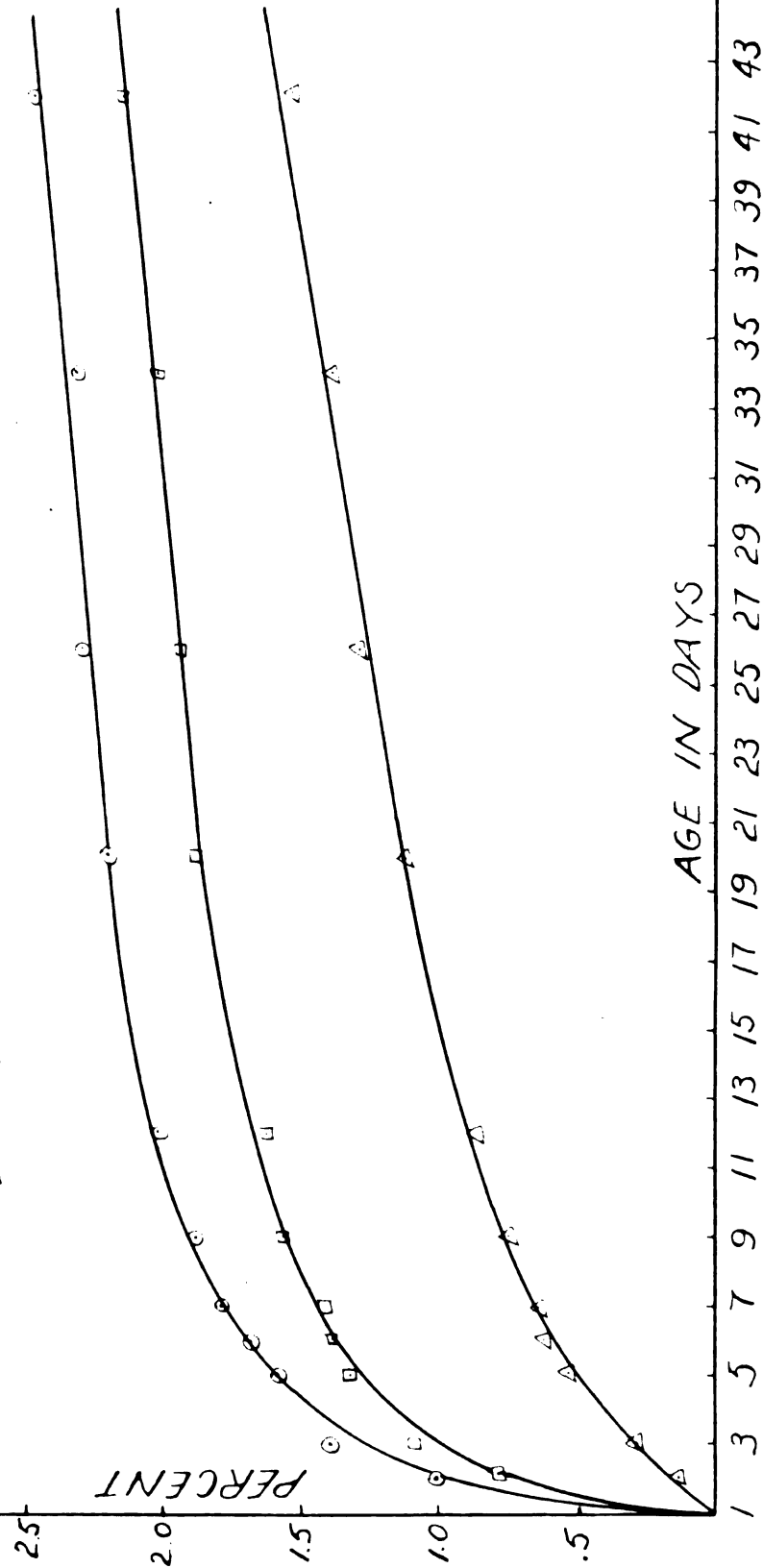
Identification	Abs 1 day	2 days	3 days	5 days
M 2-1	12,818--100	12,912--100.74	12,902--100.66	12,917--100.78
M 2-2	12,693--100	12,772--100.62	12,767--100.58	12,782--100.70
M 2-3	12,506--100	12,591--100.68	12,581--100.60	12,595--100.71
M 2-4	12,481--100	12,581--100.80	12,562--100.65	12,567--100.69
M 2-5	12,684--100	12,761--100.61	12,752--100.54	12,792--100.85
% of initial wt.	-----100	-----100.69	-----100.61	-----100.75
% MOISTURE GAIN	-----0	-----.69	-----.61	-----.75

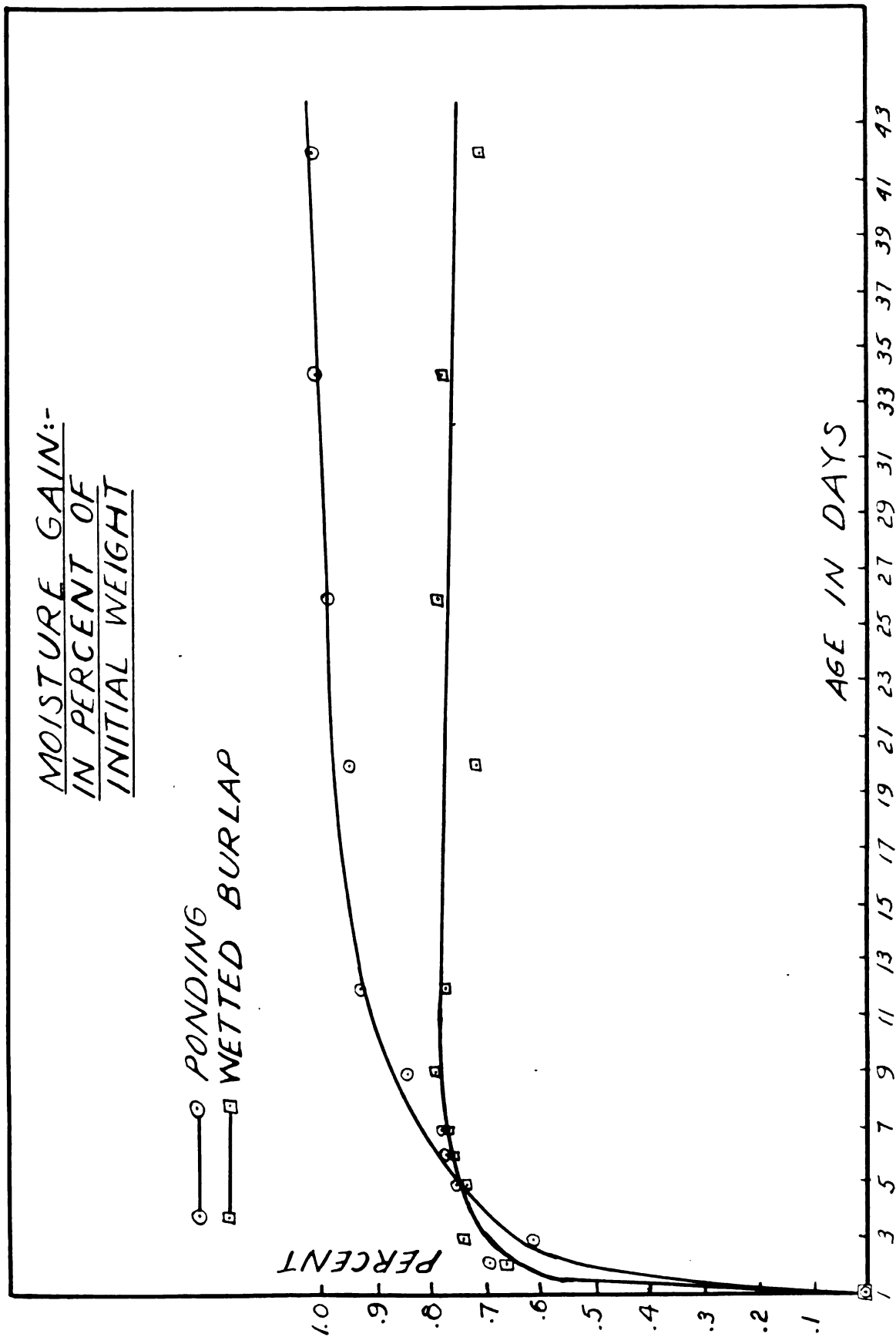
Identification	6 days	7 days	9 days	12 days
M 2-1	12,930--100.88	12,931--100.89	12,937--100.93	12,940--100.96
M 2-2	12,782--100.70	12,788--100.74	12,790--100.76	12,815--100.96
M 2-3	12,599--100.74	12,595--100.71	12,600--100.75	12,616--100.89
M 2-4	12,581--100.80	12,570--100.71	12,594--100.90	12,592--100.89
M 2-5	12,777--100.73	12,790--100.84	12,792--100.85	12,800--100.92
% of initial wt.	-----100.77	-----100.78	-----100.84	-----100.92
% MOISTURE GAIN	-----.77	-----.78	-----.84	-----.92

Identification	20 days	26 days	34 days	42 days
M 2-1	12,950--101.04	12,955--101.07	12,960--101.11	12,962--101.13
M 2-2	12,802--100.85	12,800--100.84	12,804--100.87	12,817--100.97
M 2-3	12,618--100.89	12,625--100.95	12,630--100.99	12,637--101.05
M 2-4	12,605--100.99	12,600--100.95	12,605--100.99	12,612--101.05
M 2-5	12,800--100.92	12,820--101.07	12,815--101.03	12,810--100.99
% of initial wt.	-----100.94	-----100.98	-----101.00	-----101.04
% MOISTURE GAIN	-----.94	-----.98	-----1.00	-----1.04

MOISTURE LOSS:-
IN PERCENT OF
INITIAL WEIGHT

○ AIR CURING
□ CaCl_2 ADMIXTURE
△ MEMBRANE





CONCLUSION: In observing the foregoing graphs, it is noticed, as might be expected, that the wetted burlap and ponding methods of curing allowed the concrete to absorb any moisture it desired. In the case of wetted burlap, the saturation point according to the curve was at approximately the ninth day. In the case of ponding, the saturation point was reached at about the nineteenth day. As seen from the seven day compressive strength results, the ponding method produced a stronger concrete than that obtained by wetted burlap, and from the foregoing graphs it is evident that the concrete had gained more moisture by ponding curing than by wetted burlap curing. From this first observation, it might be stated that during early ages it is beneficial to allow concrete to absorb moisture. This, however, can not be true since the concrete produced by membrane curing was higher in seven day strength than either that produced by ponding or wetted burlap, and it is evident from the graph that the membrane curing actually allows some moisture to escape.

At the end of twenty-eight days, the percent moisture gain for the ponding method was some what higher than that for the wetted burlap. For the membrane at twenty-eight days, as might be expected, there was a slight moisture loss.

From the results obtained, I am forced to conclude that as far as I am capable of figuring, there seems to be no definite correlation between moisture gain or loss and the compressive strength of concrete. It is noticed from the graphs that the membrane curing compound actually does check the evaporation of water from the concrete, and thus is serving its primary purpose.

ACCELERATED FREEZE-THAW TESTS

INTRODUCTION: The specimens for this test consisted of cubes of mortar two inches on a side.

The specimens were cured by the various methods for six days and then placed in a rubber boot and immersed in a fifteen per cent calcium chloride solution.

The boots containing the specimens were then placed in the glycerine bath of the refrigerator, which was maintained at a temperature below -10° F., for a period of at least ten hours. At the end of the freezing period, the boot was removed from the refrigerator, wiped off with a sponge, and placed in the thawing tank. After the thawing was completed, the calcium chloride solution in the boot was thoroughly stirred. The boot was then placed in the refrigerator for a repetition of the cycle. A satisfactory and convenient schedule for this procedure consisted in placing the specimens in the refrigerator at about four-thirty p.m. to allow freezing overnight and removal at eight a.m. the next morning for thawing during the day. Week ends were considered as one cycle.

CONCLUSION: The examination of the specimens at frequent intervals was based on visual inspection to note development of scale on the surfaces.

After the completion of ten cycles, the specimens cured by air, ponding, and wetted burlap failed completely by showing one-hundred per cent scaling. The specimens cured by calcium chloride admixture gave anti-scaling properties to the specimens that were some what better than those given by air, ponding, or wetted burlap. The important result obtained was that the specimens cured with the membrane compound showed absolutely no signs of scaling. These membrane cured specimens were continued to be subjected to the freeze-thaw cycles. Even after twenty cycles the specimens showed no signs of scaling.

GENERAL CONCLUSIONS

After the breaking of a total of seventy-five test specimens, cured by the five different methods I conclude that for short curing periods membrane curing produces the highest compressive strength concrete, except in the case of a calcium chloride admixture which gives a high early strength. For the longer curing periods ponding and wetted burlap give the best concrete.

From the moisture tests I can conclude that when concrete is cured by the atmosphere, it will loose a considerable amount of moisture. A calcium chloride admixture doesn't allow the concrete to loose as much moisture as if it weren't in the mix. Also, I verified the statement made by its producers that a membrane compound will check the evaporation of moisture from the concrete, although it doesn't check it completely. As might be expected, it was shown that curing by ponding or wetted burlap allows the concrete to absorb moisture.

In the investigation of the action of accelerated freeze-thaw tests, it was definitely displayed that a membrane curing compound definitely has valuable anti-scaling properties.

In final conclusion, I might add that there are grounds for another thesis project in the investigation of the effects of the combination of curing methods on concrete. Such combinations as calcium chloride admixture plus membrane curing, or calcium chloride admixture plus wetted burlap might make an interesting project.

BIBLIOGRAPHY

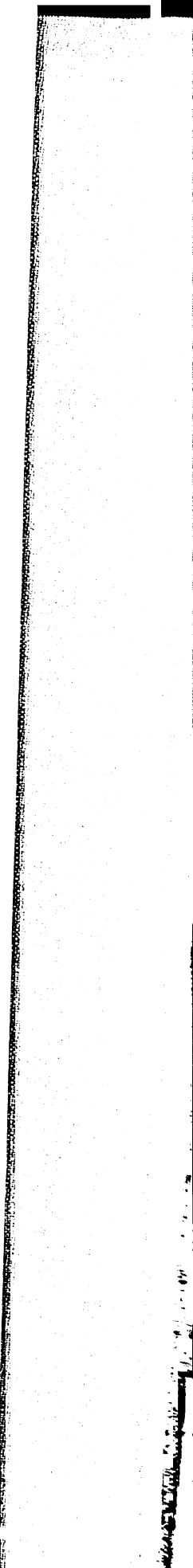
1. General Engineering Handbook

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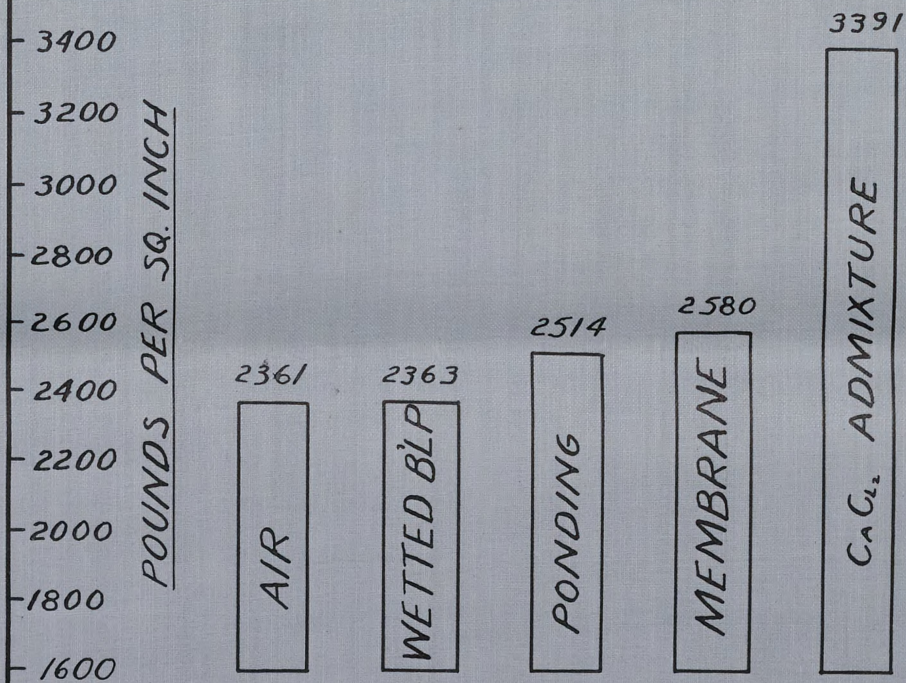
2. Concrete Practice

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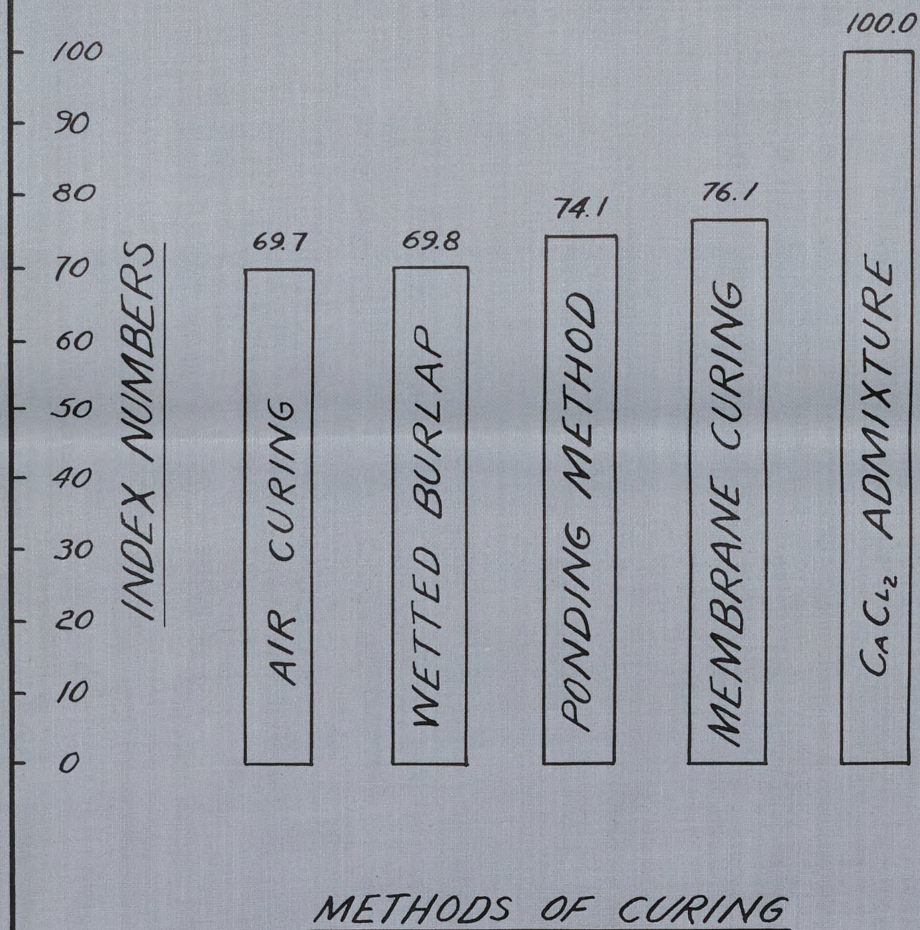


7 DAY COMPRESSIVE
STRENGTH RESULTS
AFTER 6 DAYS
OF
CURING

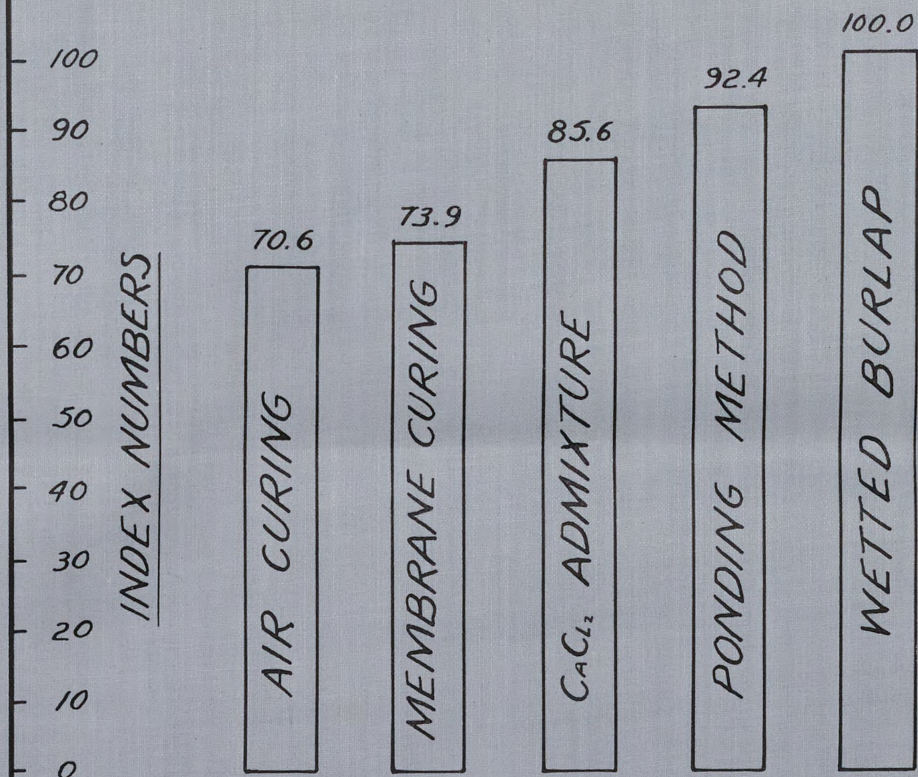


METHODS OF CURING

7 DAY COMPRESSIVE
STRENGTH RESULTS
COMPARED BY
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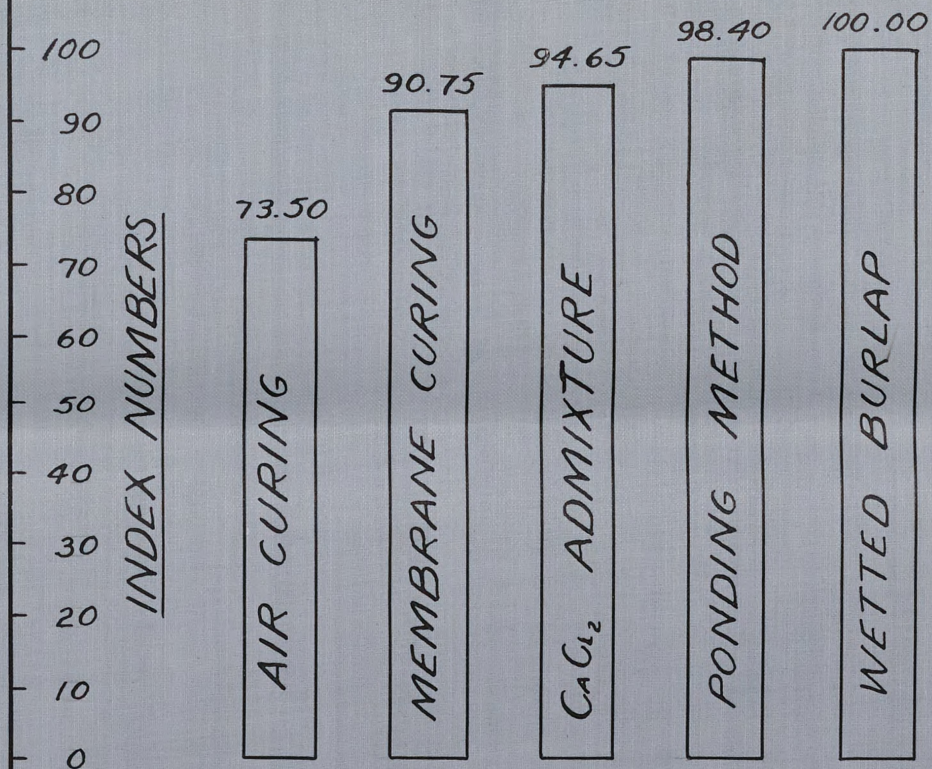


28 DAY COMPRESSIVE
STRENGTH RESULTS
COMPARED BY
INDEX NO'S.



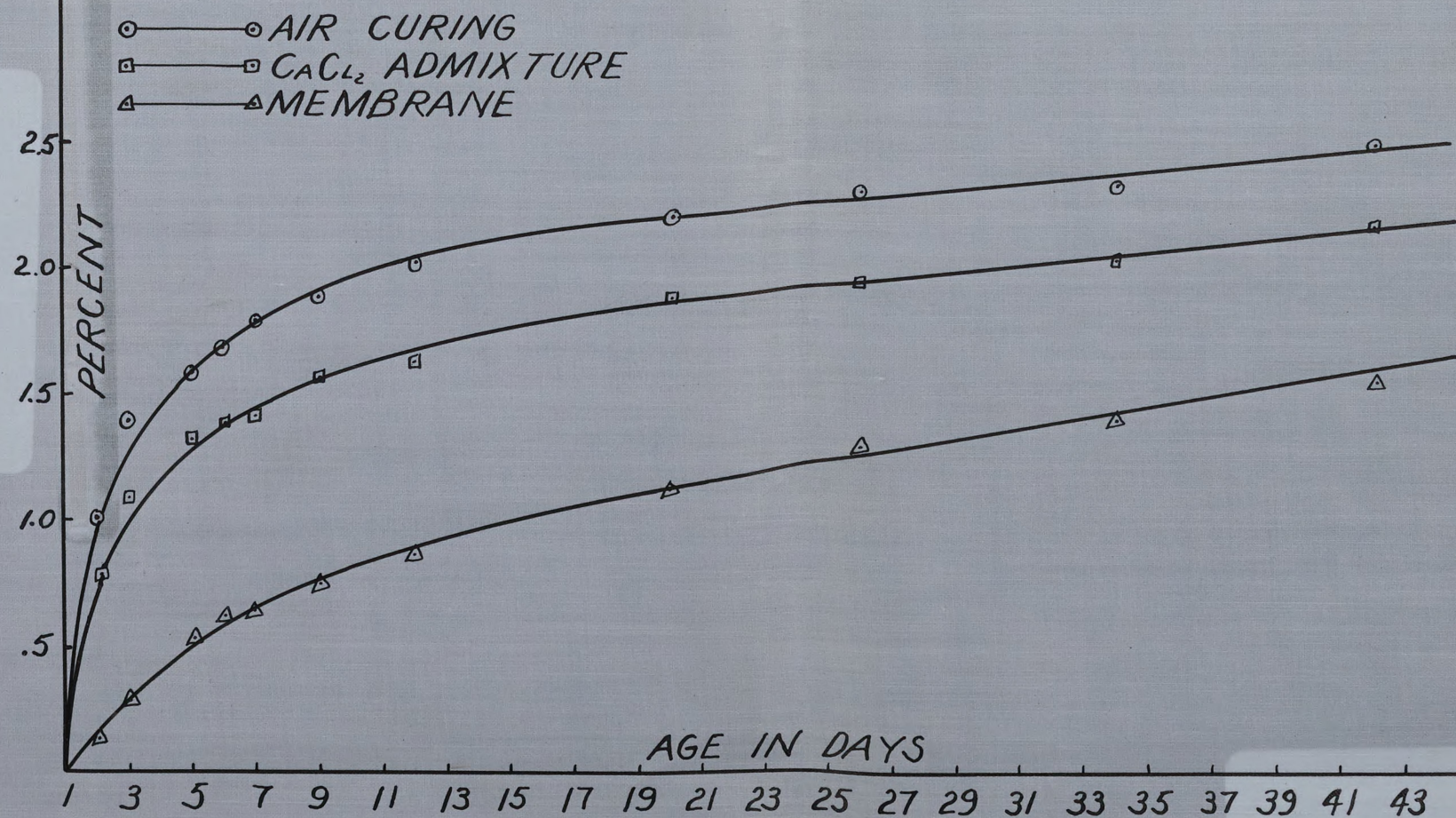
METHODS OF CURING

6 WEEK COMPRESSIVE
STRENGTH RESULTS
AFTER 41 DAYS OF
CURING
REPRESENTED BY
INDEX NOS.

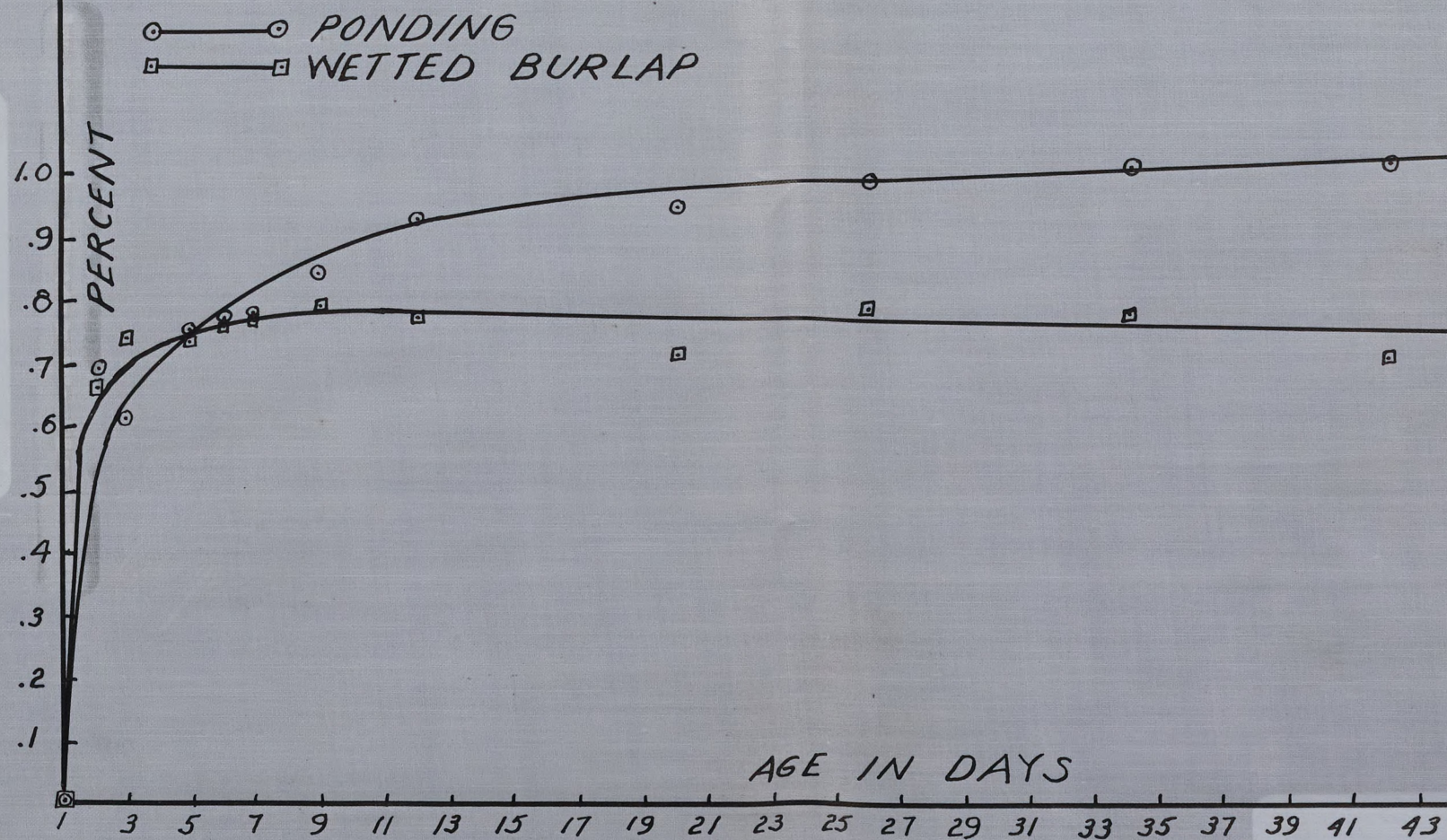


METHODS OF CURING

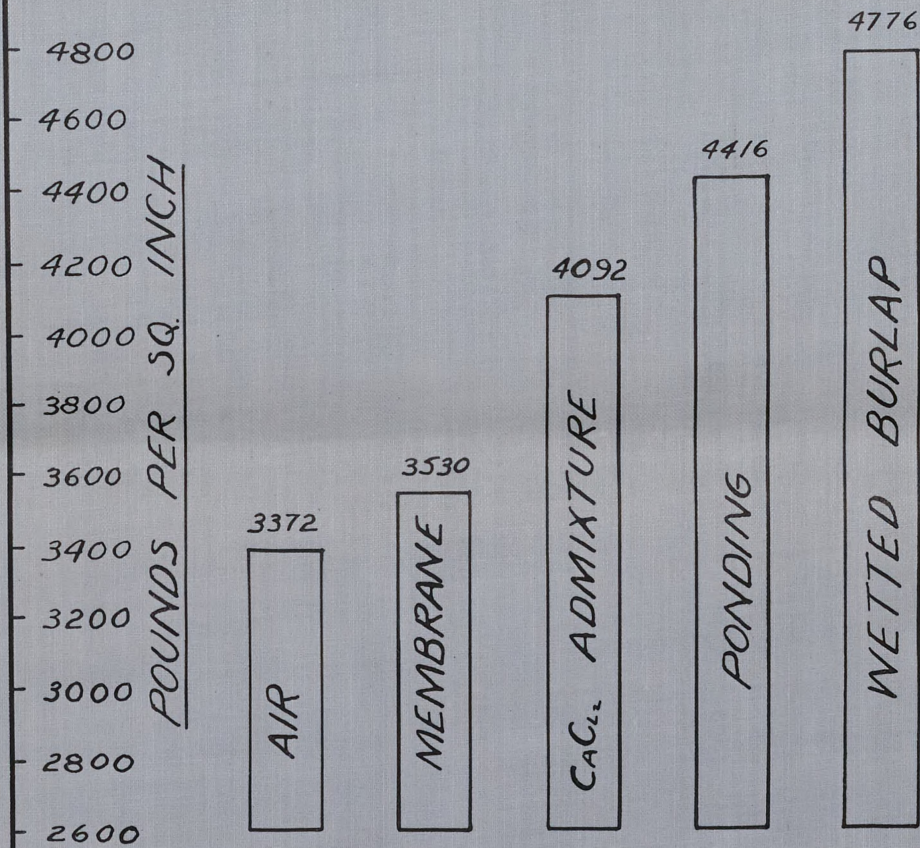
MOISTURE LOSS:-
IN PERCENT OF
INITIAL WEIGHT



MOISTURE GAIN:-
IN PERCENT OF
INITIAL WEIGHT



28 DAY COMPRESSIVE
STRENGTH RESULTS
AFTER 27 DAYS
OF
CURING



METHODS OF CURING

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