# A STUDY OF CALCIUM CHLORIDE AS A STRENGTH ACCELERATOR IN PORTLAND CEMENT CONCRETE

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## SYNOPSIS

Although previous reports have disclosed the effectiveness of calcium chloride as a strength accelerator, there is a paucity of published data regarding the long-time effects of different percentages of this agent, not only on strength but likewise on volume change and durability under various weathering conditions; and no data on the comparative compressive strengths at earlier than 24 hr. Test data relating to effect on volume change is meager and conflicting and there is very little published data relating to the effect of $CaCl_2$ on flexural strength.

The report covers tests conducted throughout a period of over 25 yr. involving hundreds of specimens, over 20 different brands and types of California cements, variable test conditions, and repeat series to check the results of previous tests.

The results of the most recent tests may be summarized as follows:

1. There was a very definite acceleration in compressive strength for all California cements.
2. In no case was the compressive strength of the concrete at one year (regardless of the percentage of calcium chloride) less than without $CaCl_2$.
3. Under moist-room initial curing at 70 deg. F. the $CaCl_2$ increased the initial shrinkage as well as the subsequent volume change under wetting and drying cycles; the increase being relatively slight with two percent but sometimes excessive with four percent, particularly in the case of some of the Type III cements.
4. When stored at 100 deg. F. and 30 percent relative humidity immediately after fabrication, the setting shrinkage was less with the $CaCl_2$ than without, but the subsequent total shrinkage and wet-dry volume changes substantially paralleled the specimens in which no $CaCl_2$ had been used.
5. The compressive strengths were not materially affected by the initial and subsequent curing and wetting and drying procedure regardless of the type of cement or percentage of $CaCl_2$ except in one case where the volume change of one of the Type III cements with four percent $CaCl_2$ was the greatest.
6. When initially cured in the moist room for 7 days the modulus of rupture and modulus of elasticity during the subsequent wet-dry cycles was as a rule lowered by the $CaCl_2$, but the differential was not material except in the case of the Type III cements.
7. When initially cured under what may be considered adverse conditions, the $CaCl_2$ was apparently beneficial with relation to the modulus of rupture as well as compressive strengths.
8. The fact that under initial thorough water curing conditions $CaCl_2$ apparently increases the initial shrinkage and induces subsequent greater wet-dry volume changes, indicates the sparing use of this additive when high tensile strength is important, or severe rusting of reinforcing steel may be facilitated by the infiltration of moisture through surface cracks.

### EARLY STUDIES

*Concrete* magazine in September 1919 reported on an investigation on the use of calcium chloride started at least as early as 1918 by the U. S. Bureau of Standards for the U. S. Engineers Office at Memphis, Tennessee.

In the fall of 1920 a cooperative series of tests to study and report on accelerators for concrete was undertaken by ASTM Committee C-9, the Structural Materials Research Laboratory of the Lewis Institute in Chicago (forerunner of the Portland Cement Association), and a number of other cooperating federal, state, city and producer laboratories.

The first results on this cooperative series were a report by Committee C-9 in 1923 (*1*)[1],

[1] Numbers in parenthesis indicate references listed at the end of the paper.

and a more lengthy report by Duff A. Abrams in 1924 on the work done at the Lewis Institute (*2*). The report contained a bibliography of previous publications reporting studies on the effect of $CaCl_2$, starting with an article on "Influence of Calcium Chloride on Portland Cement" by E. Candlot in 1889. Obviously cement technicians had been aware of the attributes of $CaCl_2$ as an accelerator prior to 1889.

Also in 1923, Clemmer and Burggraf (*3*) reported on an extensive investigation begun in Illinois in 1921 on the use of $CaCl_2$ as a curing agent and as an accelerator in the setting of concrete. In 1926, Stewart (*4*) reported on tests to determine the effect of $CaCl_2$ on transverse strength of concrete cured at various temperatures. Later the Calcium Chloride Association established a fellowship at the U. S. Bureau of Standards to study the reactions of $CaCl_2$ with cements. Progress reports on these studies were presented at the Thirteenth Annual Meeting of the Highway Research Board, December 1933, and at the Fourteenth Meeting the following year by Rapp (*5*). A final report by Rapp was published in 1935 (*6*). Rapp's work dealt primarily with the effect of $CaCl_2$ on the compressive strength of concrete cured at several temperatures within the range 40 to 90 deg. F.

In order to study strengths of similar concrete stored at temperatures within the range 20 to 40 deg. F. and likewise the volume change resulting from wetting and drying, the Calcium Chloride Association Fellowship was re-established in 1939 with Jason C. Yates in charge. Yates reported on this later series in 1941 (*7*). Further studies on the effect of $CaCl_2$ as a curing medium and on the corrosion of steel were reported in 1946 by H. C. Vollmer (*8*).

The above projects cover the principal studies on the effects of $CaCl_2$ on concrete reported in the proceedings of national societies engaged in research. Numerous other articles have appeared in print, particularly in *Concrete,* describing the results of studies by state and other agencies. They were unanimous in reporting the compressive-strength accelerating effects of $CaCl_2$.

## CALIFORNIA STUDIES

In the work of the California Division of Highways occasionally a relatively high strength in a few hours is desired. Typical cases of this nature are: (a) maintenance patches or minor replacements of short sections of concrete pavements where it is desired to open to traffic in a few hours; (b) in winter where low or freezing overnight temperatures are anticipated; and (c) sea wall construction along the coastal shores where it is desired to construct relatively small units between tides.

TABLE 1

COMPOUND ANALYSES AND FINENESS DETERMINATIONS OF ALL CEMENTS IN THE 1944 CALCIUM CHLORIDE TEST SERIES

| Cement Number | $C_3S$ | $C_2S$ | $C_3A$ | Alk. as $Na_2O$ | Autoclave | Specific Surface: Wagner | Specific Surface: Air Perm. |
|---|---|---|---|---|---|---|---|
| GROUP I CEMENTS | | | | | | | |
| 1-I | 50 | 25 | 11 | 1.05 | .070 | 1845 | 3530 |
| 2-I | 29 | 46 | 11 | 0.31 | .048 | 1750 | 3520 |
| 3-I | 47 | 30 | 6 | 0.51 | .010 | 1865 | 3390 |
| 4-I | 34 | 40 | 13 | 0.58 | .115 | 1950 | 3700 |
| 5-I | 42 | 30 | 14 | 0.98 | .198 | 1880 | 3480 |
| Avg. | 40 | 34 | 11 | 0.69 | .084 | 1858 | 3524 |
| GROUP II CEMENTS | | | | | | | |
| 1-II | 45 | 33 | 6 | 0.49 | .003 | 1925 | 3430 |
| 2-II | 37 | 39 | 5 | 0.26 | −.031 | 1755 | 3300 |
| 3-II | 54 | 24 | 6 | 0.60 | .002 | 1730 | 3170 |
| 5-II | 36 | 42 | 3 | 0.43 | −.010 | 1905 | 3170 |
| 6-II | 49 | 23 | 6 | 0.62 | .048 | 1865 | 3320 |
| 7-II | 51 | 23 | 6 | 0.38 | .166 | 1850 | 3770 |
| 8a-II | 50 | 23 | 7 | 0.89 | .105 | 1965 | 3960 |
| 8b-II | 44 | 32 | 4 | 0.48 | .046 | 1915 | 3900 |
| 9-II | 67 | 9 | 5 | 0.56 | .157 | 1640 | 3240 |
| Avg. | 49 | 27 | 5 | 0.52 | .054 | 1838 | 3473 |
| GROUP III CEMENTS (HIGH EARLY STRENGTH) | | | | | | | |
| 1-III | 46 | 26 | 12 | 1.09 | .047 | 3080 | 5420 |
| 2-III | 51 | 26 | 6 | 0.32 | −.004 | 2035 | 3830 |
| 3-III | 62 | 17 | 7 | 0.35 | −.018 | 2895 | 4930 |
| 6-III | 61 | 17 | 6 | 0.37 | −.029 | 2460 | 5270 |
| 9-III | 53 | 25 | 7 | 0.50 | .066 | 2170 | 4310 |
| Avg. | 55 | 22 | 8 | 0.53 | .012 | 2528 | 4752 |

Mortar tests in 1929 and 1939 on a number of California cements, using up to five percent $CaCl_2$, confirmed earlier tests indicating that, in so far as compressive strengths are concerned, this amount can safely be used.

However, as the 1929 and 1939 tests had been to determine the effects of $CaCl_2$ in mortars only, and no studies had been made of other effects such as volume change and modulus of rupture, a more extensive 6-sack concrete series was started in 1944 including all California brands and types of cement being manufactured at that time. The 1944

series included ten California brands of Types I, II and III with a total of 19 cements.

All cement manufacturers in California were requested to submit samples of all of the types manufactured. On the basis of the manufacturers ratings the cements were grouped as Type I, II and III. Subsequent chemical analyses however, disclosed that the manufacturers classifications were in error in several cases. Thus of the Type I classified cements one (cement 3-I) was a true Type II cement, based on compound analysis, whereas the cement of the same manufacturer furnished as Type II was found to be high in $C_3S$. All of the rated Type II cements contained less than eight percent $C_3A$ but three contained over 50 percent $C_3S$. Therefore, in tabulating and illustrating the test data the original segregation has been left but with the designation "Group" instead of "Type". (Table 1).

TABLE 2

AVERAGE SHORT-TIME COMPRESSION STRENGTH TESTS ON 6- BY 12-IN. CYLINDER SPECIMENS OF CONCRETE FROM NINE BRANDS AND THREE TYPES OF CALIFORNIA PORTLAND CEMENTS (TOTAL 19 CEMENTS) AS AFFECTED BY FROM TWO TO FIVE PERCENT CALCIUM CHLORIDE. 1944 TEST SERIES

Short Time Compression Strength 6- by 12-in. Concrete Cylinders Cured in Moist Room

| Age | 4 Hours | | | | | 8 Hours | | | | | 24 Hours | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Percent Calcium Chloride | | | | | | | | | | | | | | |
| Cement | 0 | 2 | 3 | 4 | 5 | 0 | 2 | 3 | 4 | 5 | 0 | 2 | 3 | 4 | 5 |
| GROUP I CEMENTS | | | | | | | | | | | | | | | |
| 1-I | 0 | 190 | 365 | 485 | 595 | 0 | 685 | 915 | 1070 | 1160 | 980 | 1840 | 2350 | 2185 | 2200 |
| 2-I | 0 | 270 | 420 | 490 | 640 | 0 | 710 | 785 | 870 | 930 | 630 | 1435 | 1500 | 1500 | 1575 |
| 3-I | 0 | 110 | 225 | 190 | 230 | 0 | 555 | 750 | 780 | 860 | 1100 | 1710 | 1815 | 1820 | 1785 |
| 4-I | 0 | 210 | 345 | 355 | 410 | 0 | 710 | 810 | 795 | 760 | 815 | 1690 | 1685 | 1610 | 1430 |
| 5-I | 0 | 95 | 205 | 320 | 365 | 0 | 430 | 735 | 770 | 830 | 550 | 1540 | 1885 | 1670 | 1695 |
| Avg. . ... ... . | 0 | 175 | 312 | 368 | 448 | 0 | 616 | 799 | 857 | 908 | 815 | 1643 | 1847 | 1751 | 1737 |
| GROUP II CEMENTS | | | | | | | | | | | | | | | |
| 1-II | 0 | 180 | 310 | 410 | 410 | 0 | 620 | 805 | 950 | 900 | 685 | 1550 | 1760 | 1825 | 1795 |
| 2-II | 0 | 225 | 345 | 435 | 480 | 0 | 715 | 775 | 870 | 970 | 870 | 1730 | 1570 | 1615 | 1815 |
| 3-II | 0 | 110 | 230 | 320 | 205 | 0 | 555 | 795 | 890 | 765 | 1035 | 1745 | 1885 | 1845 | 1690 |
| 5-II | 0 | 0 | 0 | 0 | 0 | 0 | 145 | 210 | 445 | 475 | 470 | 1050 | 1560 | 1825 | 1555 |
| 6-II | 0 | 220 | 465 | 600 | 540 | 0 | 750 | 1070 | 1240 | 1040 | 1055 | 1995 | 2320 | 2370 | 2030 |
| 7-II | 0 | 155 | 330 | 505 | 485 | 0 | 570 | 985 | 1080 | 985 | 995 | 1690 | 1900 | 2040 | 1800 |
| 8a-II | 0 | 145 | 260 | 350 | 410 | 0 | 630 | 845 | 870 | 850 | 650 | 1815 | 1840 | 1760 | 1595 |
| 8b-II | 0 | 135 | 235 | 380 | 365 | 0 | 635 | 715 | 945 | 925 | 920 | 1655 | 1690 | 1980 | 1895 |
| 9-II | 0 | 225 | 405 | 540 | 565 | 0 | 885 | 1030 | 1215 | 1110 | 1015 | 1965 | 2070 | 2175 | 2120 |
| Avg. ... . . | 0 | 155 | 287 | 393 | 384 | 0 | 623 | 803 | 941 | 891 | 855 | 1688 | 1844 | 1937 | 1811 |
| GROUP III CEMENTS (High Early Strength) | | | | | | | | | | | | | | | |
| 1-III | 0 | 680 | 1040 | 1045 | 1330 | 570 | 1645 | 1785 | 1865 | 2000 | 1665 | 2705 | 2855 | 2905 | 3000 |
| 2-III | 0 | 260 | 540 | 735 | 705 | 185 | 1170 | 1270 | 1390 | 1405 | 1365 | 2355 | 2325 | 2555 | 2360 |
| 3-III | 0 | 455 | 890 | 1110 | 1190 | 325 | 1780 | 1965 | 2220 | 2060 | 2050 | 3160 | 3290 | 3600 | 3340 |
| 6-III | 0 | 480 | 1010 | 1425 | 1385 | 380 | 1735 | 2110 | 2520 | 2375 | 1815 | 2955 | 3500 | 3700 | 3385 |
| 9-III | 0 | 445 | 840 | 910 | 1335 | 330 | 1375 | 1850 | 1895 | 2105 | 1595 | 2630 | 2920 | 2710 | 3115 |
| Avg. ... ...... .. | 0 | 464 | 864 | 1045 | 1189 | 358 | 1541 | 1796 | 1978 | 1989 | 1698 | 2761 | 2978 | 3094 | 3049 |
| AVERAGES | | | | | | | | | | | | | | | |
| GROUP I | 0 | 175 | 312 | 368 | 448 | 0 | 618 | 799 | 857 | 908 | 815 | 1543 | 1847 | 1857 | 1737 |
| GROUP II | 0 | 155 | 287 | 393 | 384 | 0 | 623 | 803 | 941 | 891 | 855 | 1688 | 1844 | 1937 | 1811 |
| GROUP III | 0 | 464 | 864 | 1045 | 1189 | 358 | 1541 | 1796 | 1978 | 1989 | 1698 | 2761 | 2978 | 3094 | 3040 |
| Grand Avg. ......... | 0 | 265 | 488 | 602 | 674 | 119 | 927 | 1133 | 1259 | 1263 | 1123 | 2031 | 2223 | 2263 | 2196 |

The test specimens in the 1944 series consisted of (a) 6- by 12-in. cylinders of 6-sack concrete, and zero to five percent $CaCl_2$ (one set stored in the moist room and another set in the open on the roof of the laboratory); and (b) 2- by 2- by 6¼-in. bars (5 in. between gage points; max. ¾-in. aggregate and two

percent and four percent $CaCl_2$) for length change, modulus of rupture and compression tests. The percent of cement in the bars was the same as in the minus ⅜-in. portion of the 6-sack concrete mix, or the equivalent of 6.75 sacks of cement per cu. yd.

F. and 30 percent R.H. immediately after fabrication and kept there for 7 days after which exposure was in the open as with the first set.

Bar specimens were removed from the molds and initial length measurements were made at 24 hr. on the moist-room initially-cured specimens and at 6 hr. on the oven-initially-cured specimens. Pressure of other work delayed starting the wet-dry cycles until late summer of 1945, at which time the bars averaged 320 days age. Seventeen alternate wet-at-70 deg. F. and dry-at-110 deg. F. cycles of variable

TABLE 3

AVERAGE ONE YEAR COMPRESSION STRENGTH TESTS ON 6- BY 12-IN. CYLINDER SPECIMENS OF CONCRETE FROM NINE BRANDS AND THREE TYPES OF CALIFORNIA PORTLAND CEMENTS (TOTAL 19 CEMENTS) AS AFFECTED BY FROM TWO TO FIVE PERCENT CALCIUM CHLORIDE. 1944 TEST SERIES

| | One Year Compressive Strength 6- by 12-in. Conc. Cylinders | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Moist Rm Entire Period | | | | | Moist Room 10 Days Air 353 Days Water 48 Hr. | | | | | Moist Room 10 Days Air 355 Days Tested Dry | | | | |
| | Percent Calcium Chloride | | | | | | | | | | | | | | |
| Cement | 0 | 2 | 3 | 4 | 5 | 0 | 2 | 3 | 4 | 5 | 0 | 2 | 3 | 4 | 5 |
| GROUP I CEMENTS | | | | | | | | | | | | | | | |
| 1-I | 4965 | 5155 | 5985 | 6250 | 6125 | 4215 | 4180 | 4960 | 5210 | 5580 | 4860 | 5160 | 5750 | 5640 | 6370 |
| 2-I | 4220 | 6395 | 5925 | 6990 | 6825 | 3045 | 3850 | 4135 | 3915 | 4170 | 3325 | 4650 | 4425 | 5115 | 5285 |
| 3-I | 5635 | 6405 | 6085 | 6160 | 5745 | 4340 | 4510 | 4745 | 4340 | 4010 | 5140 | 4410 | 4980 | 5210 | — |
| 4-I | 4955 | 5520 | 6130 | 5900 | 6665 | 3705 | 4385 | 4825 | 4005 | 4500 | 4150 | 5190 | 5635 | 5195 | 5480 |
| 5-I | 5690 | 5600 | 6125 | 6495 | 6435 | 3840 | 3650 | 4455 | 4230 | 4495 | 3975 | 4335 | 4685 | 4970 | 4955 |
| Avg. | 5094 | 5815 | 6050 | 6359 | 6359 | 3829 | 4115 | 4624 | 4340 | 4551 | 4290 | 4749 | 5095 | 5226 | 5523 |
| GROUP II CEMENTS | | | | | | | | | | | | | | | |
| 1-II | 4395 | 6715 | 7095 | 6765 | 7365 | 4205 | 4735 | 4910 | 5345 | 5150 | 5290 | 5270 | 5500 | 6225 | 5820 |
| 2-II | 5410 | 6380 | 6605 | 7220 | 7055 | 4755 | 4175 | 3990 | 3990 | 4315 | 5580 | 5015 | 5385 | 4850 | 5375 |
| 3-II | 5885 | 5830 | 6350 | 6025 | 6300 | 4385 | 4245 | 4385 | 4170 | 4805 | 5455 | 4915 | 5605 | 5115 | 5285 |
| 5-II | 4945 | 6445 | 6710 | 7335 | 6985 | 4265 | 4820 | 4870 | 5260 | 4465 | 4390 | 5505 | 5565 | 4550 | 5490 |
| 6-II | 5180 | 6315 | 6240 | 5795 | 5485 | 4490 | 4490 | 4760 | 5160 | 4705 | 5460 | 5630 | 5485 | 5520 | 5830 |
| 7-II | 6320 | 6455 | 6985 | 7610 | 6510 | 4960 | 4370 | 4390 | 4845 | 4255 | 5075 | 5340 | 5860 | 5530 | 5735 |
| 8a-II | 4395 | 5915 | 6420 | 6400 | 5820 | 3950 | 4220 | 4720 | 3645 | 4355 | 4400 | 4945 | 5240 | 4975 | 5260 |
| 8b-II | 4735 | 5110 | 6270 | 6645 | 6455 | 4390 | 4945 | 4845 | 5330 | 4975 | 4540 | 5790 | 5280 | 6065 | 5525 |
| 9-II | 4990 | 6630 | 6525 | 6310 | 6870 | 4570 | 4885 | 5670 | 5365 | 5210 | 5405 | 5280 | 5350 | 5470 | 6250 |
| Avg. .... ... ...... | 5139 | 6288 | 6577 | 6678 | 6538 | 4441 | 4543 | 4727 | 4790 | 4693 | 5066 | 5299 | 5474 | 5371 | 5619 |
| GROUP III CEMENTS (High Early Strength) | | | | | | | | | | | | | | | |
| 1-III | 4535 | 6125 | 6155 | 6605 | 6665 | 4165 | 4355 | 5230 | 4930 | 5070 | 4565 | 5085 | 5435 | 5785 | 5775 |
| 2-III | 4960 | 6915 | 7400 | 7480 | 6780 | 3610 | 4510 | 4305 | 4835 | 4355 | 5215 | 5610 | 5355 | 5290 | 5390 |
| 3-III | 6260 | 6850 | 7090 | 6885 | 6525 | 5355 | 5095 | 5370 | 5745 | 6095 | 4960 | 6155 | 5745 | 6800 | 5450 |
| 6-III | 5215 | 6710 | 6460 | 6575 | 6955 | 4125 | 4460 | 4955 | 4870 | 4870 | 4735 | 4975 | 5240 | 5720 | 5795 |
| 9-III | 5390 | 6110 | 6290 | 6570 | 6570 | 4700 | 5030 | 4960 | 5070 | 5425 | 5615 | 6005 | 5895 | 6580 | 5580 |
| Avg.................. | 5276 | 6542 | 6679 | 6823 | 6699 | 4391 | 4690 | 4964 | 5094 | 5163 | 5018 | 5566 | 5534 | 6035 | 5598 |
| AVERAGES | | | | | | | | | | | | | | | |
| GROUP I | 5094 | 5815 | 6050 | 6359 | 6359 | 3829 | 4115 | 4624 | 4340 | 4551 | 4290 | 4749 | 5095 | 5226 | 5523 |
| GROUP II | 5139 | 6288 | 6577 | 6678 | 6538 | 4441 | 4543 | 4727 | 4790 | 4692 | 5066 | 5299 | 5474 | 5371 | 5619 |
| GROUP III | 5276 | 6542 | 6679 | 6823 | 6699 | 4391 | 4690 | 4964 | 5094 | 5163 | 5018 | 5566 | 5534 | 6035 | 5598 |
| Grand Avg. . | 5169 | 6215 | 6435 | 6620 | 6532 | 4220 | 4449 | 4772 | 4741 | 4802 | 4791 | 5205 | 5368 | 5544 | 5580 |

To study the effects of $CaCl_2$ under good and bad initial curing and subsequent atmospheric weathering, one set of the bars was cured in the moist room for 7 days and then exposed on the roof of the laboratory until the start of the wet-dry length change tests. A second set was placed in an oven at 110 deg.

length (Fig. 4 to 14) were then started and continued for a period of approximately 200 days, after which the bars were tested for modulus of rupture and the ends of the broken bars in compression at an average age of 520 days.

In general all previous tests to determine the effect of $CaCl_2$ on compressive strength were confirmed; i.e., higher compressive strength at all ages, up to 520 days at least. (Tables 2, 3, 4 and 5). The results on volume change and modulus of rupture are contained in Tables 4 to 8 and Figures 4 to 16. The $CaCl_2$ generally induced greater length changes in the initially moist-room cured specimens which with some cements (particularly the finely ground Type III) became excessive under the 17 wet-dry cycles.

TABLE 4

AVERAGE OF ALL TESTS FOR DYNAMIC MODULUS OF ELASTICITY, MODULUS OF RUPTURE AND COMPRESSIVE STRENGTH OF 2- BY 2- BY 6¼-IN. CONCRETE BARS (¾-in. max. size aggregate) CONTAINING ZERO, TWO, AND FOUR PERCENT CALCIUM CHLORIDE BY WEIGHT OF CEMENT 1944 TEST SERIES[a]

| Cement Group | Avg. Age | Dynamic $E \times 10^{-6}$ | | | Mod. of Rupt. | | | Compr. Strength | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | PERCENT CALCIUM CHLORIDE | | | | | | | | |
| | | 0 | 2 | 4 | 0 | 2 | 4 | 0 | 2 | 4 |
| (a) Bars initially stored in moist room at 70 deg. F. 7 days, then on Lab. Roof and subsequent wet and dry cycles | | | | | | | | | | |
| I | 512 | 5.34 | 5.43 | 5.21 | 1170 | 1156 | 1042 | 5778 | 6890 | 6976 |
| II | 536 | 5.66 | 5.55 | 5.43 | 1312 | 1147 | 1017 | 6794 | 7658 | 7399 |
| III | 527 | 5.51 | 4.95 | 4.34 | 1120 | 964 | 788 | 6798 | 7164 | 6826 |
| Avg. | 525 | 5.50 | 5.31 | 4.99 | 1201 | 1089 | 949 | 6456 | 7237 | 7067 |
| (b) Bars initially stored in oven at 110 deg. F. 7 days, then on Lab. Roof and subsequent wet and dry cycles | | | | | | | | | | |
| I | 514 | 5.07 | 5.22 | 5.60 | 1028 | 1008 | 1116 | 4974 | 6750 | 6728 |
| II | 537 | 5.19 | 5.50 | 5.57 | 992 | 1127 | 1076 | 5406 | 7030 | 7083 |
| III | 530 | 5.64 | 5.60 | 5.62 | 1184 | 1154 | 1120 | 6630 | 7890 | 7924 |
| Avg. | 527 | 5.30 | 5.44 | 5.60 | 1068 | 1096 | 1104 | 5670 | 7223 | 7245 |

[a] One set of bars cured in moist room for 7 days and the other set in an oven at 110 deg. F. at an average humidity of 30 for the same period (7 days). Both sets then stored in the open on the Laboratory roof for an average of approximately 320 days, then to 17 alternate cycles of immersion in water at 70 deg. F. and drying in the oven at 110 deg. F. over a period of approximately 200 days until breaking test at an average age of 526 days. (Fig. 4).

Compressive strengths and moduli of elasticity (compressive and dynamic) were determined at 4, 8, and 24 hr.; 7 and 28 days; and 6 months and 1 yr. on the 6- by 12-in. cylinders in the 1944 series. Some of the cylinder specimens were cured in the moist room for the entire period and others exposed to the atmosphere on the roof of the laboratory after 7 days in the moist room. (Tables 2, and 3, and Fig. 1 and 2). Six-sack concrete mixes (1½-in. maximum size coarse aggregate) were used with an average slump of 1½ in.

An effort was made to determine the setting as well as long time shrinkage of the 2- by 2-in. bars. To accomplish this, the screws holding the accurately spaced pins at each end of the specimens were loosened shortly after the specimens were fabricated. Regardless of precautions, however, the setting measurements were very erratic, in many cases indicating disturbance and hang-up of the pins. However, by discarding the obviously erroneous readings and averaging the others, it is believed that certain trends are indicated with sufficient accuracy (Table 6 and Fig. 3).

The subsequent long-time length-change measurements (Tables 7 and 8 and Fig. 4 to 14) were based on the initial set length as zero. Because of the pressure of other work, no fixed wet-dry schedule was followed, this phase of the operations being conducted as opportunity afforded.

All outdoor exposure specimens were stored on the roof of the laboratory throughout the winter following fabrication and until late in the following summer, length-change measurements being made at infrequent intervals to determine the effect of moisture from rain and the maximum shrinkage from thorough drying during the hot, dry weather of the summer. (The humidity on hot days was usually less than 20 percent.)

Before the second winter, and when the specimens were thoroughly dry, the series of wetting and drying cycles was started, the time intervals conforming to the demands of other work—first at 28 days, then at 7 days, and finally several cycles of 14 to 17 days (a total of 17 cycles) just prior to the final measurements. These included Dynamic E, modulus of rupture, and compressive strength at an average age of 520 days.

As will be noted from Table 6 and Figure 3, the initial or setting shrinkage was increased by the $CaCl_2$ under 100 percent humidity and normal temperature (70 deg. F.) storage; whereas when the storage conditions are what may be considered adverse, such as

TABLE 5

DYNAMIC MODULUS, MODULUS OF RUPTURE AND COMPRESSIVE STRENGTH OF 2- BY 2- BY 6¼-IN. CONCRETE BARS (¾-in. max. size aggregate, 6.75 sacks cement per cu. yd.) CONTAINING ZERO, TWO, AND FOUR PERCENT CALCIUM CHLORIDE; TESTS AT AVERAGE AGES INDICATED AFTER WET AND DRY CYCLES

| Cement Number | Age Days | Dynamic E × 10⁻⁶ | | | Modulus of Rupt. | | | Compr. Strength | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | PERCENT CALCIUM CHLORIDE | | | | | | | | |
| | | 0 | 2 | 4 | 0 | 2 | 4 | 0 | 2 | 4 |
| **(a) GROUP I CEMENTS** | | | | | | | | | | |
| (1) Bars stored in moist room at 70 deg. F., 7 days, then on Laboratory Roof and subsequent wet and dry cycles | | | | | | | | | | |
| 1-I | 595 | 5.43 | 5.71 | 5.29 | 1340 | 1330 | 970 | 6000 | 7580 | 7000 |
| 2-I | 519 | 5.57 | 5.48 | 5.58 | 1370 | 1240 | 1240 | 6080 | 6640 | 7430 |
| 3-I | 505 | 5.41 | 5.39 | 5.43 | 1180 | 1100 | 1110 | 5890 | 7030 | 6790 |
| 4-I | 471 | 5.21 | 5.20 | 5.05 | 850 | 1110 | 1080 | 5340 | 6480 | 6650 |
| 5-I | 469 | 5.09 | 5.35 | 4.69 | 1110 | 1000 | 810 | 5580 | 6720 | 7010 |
| Avg. | 512 | 5.34 | 5.43 | 5.21 | 1170 | 1156 | 1042 | 5778 | 6890 | 6976 |
| (2) Bars stored in oven at 110 deg. F. first 7 days, then on Laboratory Roof and subsequent wet-dry cycles | | | | | | | | | | |
| 1-I | 590 | 4.80 | 5.20 | 5.80 | 900 | 1190 | 1240 | 4720 | 7100 | 7320 |
| 2-I | 521 | 5.53 | 5.48 | 5.50 | 1220 | 1170 | 1032 | 5230 | 7360 | 6710 |
| 3-I | 507 | 5.54 | 5.54 | 5.51 | 1080 | 1110 | 1260 | 5870 | 6350 | 6930 |
| 4-I | 478 | 4.78 | 4.63 | 5 31 | 850 | 1030 | 920 | 4130 | 6110 | 6680 |
| 5-I | 476 | 4.68 | 5.26 | 5.87 | 1090 | 1040 | 1130 | 4920 | 6830 | 6000 |
| Avg. ... | 514 | 5.07 | 5.22 | 5.60 | 1028 | 1008 | 1116 | 4974 | 6750 | 6728 |
| **(b) GROUP II CEMENTS** | | | | | | | | | | |
| (1) Bars stored in moist room at 70 deg. F., 7 days, then on Lab. Roof and wet and dry cycles. | | | | | | | | | | |
| I-II | 589 | 5.83 | 5.91 | 5.74 | 1370 | 1230 | 1100 | 6480 | 7650 | 7450 |
| 2-II | 518 | 5.66 | 5.71 | 5.76 | 1300 | 1190 | 1220 | 6690 | 7950 | 7910 |
| 3-II | 504 | 5.59 | 5.47 | 5.64 | 1250 | 1170 | 1150 | 6030 | 7710 | 7330 |
| 5-II | 477 | 5.68 | 5.67 | 5.52 | 1280 | 1080 | 910 | 7140 | 7030 | 7450 |
| 6-II | 574 | 5.63 | 5.53 | 5.40 | 1420 | 1180 | 1137 | 6710 | 7820 | 7160 |
| 7-II | 471 | 5.64 | 5.51 | 5.58 | 1420 | 1240 | 1070 | 6840 | 7650 | 7450 |
| 8a-II | 575 | 5 63 | 5.43 | 5 16 | 1340 | 1250 | 1000 | 7110 | 7700 | 6780 |
| 8b-II | 581 | 5.51 | 5.49 | 5.44 | 1300 | 1050 | 830 | 8620 | 7460 | 7960 |
| 9-II | 532 | 5.78 | 5 23 | 4.66 | 1130 | 930 | 740 | 7330 | 7950 | 7080 |
| Avg. . | 536 | 5.66 | 5.55 | 5.43 | 1312 | 1147 | 1017 | 6794 | 7658 | 7399 |
| (2) Bars stored in oven at 110 deg. F., 7 days, then on Laboratory Roof and subsequent wet and dry cycles. | | | | | | | | | | |
| 1-II | 588 | 5.18 | 5.88 | 5 93 | 880 | 1320 | 1020 | 5270 | 7430 | 7860 |
| 2-II | 520 | 5.63 | 5.59 | 5.82 | 1150 | 1200 | 1210 | 5390 | 6960 | 6820 |
| 3-II | 506 | 5.26 | 5.52 | 5.54 | 1130 | 1400 | 1180 | 6060 | 7710 | 7540 |
| 5-II | 475 | 4.48 | 5.52 | 5.48 | 840 | 1060 | 990 | 4600 | 6360 | 6530 |
| 6-II | 576 | 5.37 | 5.42 | 5.56 | 750 | 1130 | 1140 | 5750 | 6950 | 7200 |
| 7-II | 477 | 5.27 | 5 47 | 5 54 | 1300 | 1240 | 1060 | 5380 | 7110 | 6230 |
| 8a-II | 577 | 4.46 | 5 10 | 5.02 | 700 | 1040 | 890 | 5210 | 6880 | 7260 |
| 8b-II | 583 | 5 44 | 5 47 | 5.61 | 990 | 960 | 1130 | 5210 | 6510 | 6980 |
| 9-II | 534 | 5 66 | 5.57 | 5.63 | 1190 | 1050 | 1060 | 5780 | 7360 | 7330 |
| Avg. | 537 | 5.19 | 5.50 | 5.57 | 992 | 1127 | 1076 | 5406 | 7030 | 7083 |

TABLE 5—*Continued*

| Cement Number | Age Days | Dynamic E × 10⁻⁶ | | | Modulus of Rupt. | | | Compr. Strength | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | PERCENT CALCIUM CHLORIDE | | | | | | | | |
| | | 0 | 2 | 4 | 0 | 2 | 4 | 0 | 2 | 4 |
| **(c) GROUP III CEMENTS (High Early Str.)** | | | | | | | | | | |
| (1) Bars stored in M.R. at 70 deg. F., then on Lab. Roof and subsequent wet-dry cycles | | | | | | | | | | |
| 1-III | 582 | 5.44 | 5.22 | 4.54 | 1170 | 1040 | 750 | 6450 | 7590 | 7770 |
| 2-III | 513 | 5.70 | 5.49 | 5.37 | 1140 | 960 | 890 | 6690 | 6680 | 7000 |
| 3-III | 484 | 5.47 | 5.38 | 5.33 | 1220 | 1150 | 1030 | 6560 | 7340 | 6970 |
| 6-III | 533 | 5.43 | 3.56 | 2.05 | 930 | 560 | 430 | 6970 | 7020 | 5890 |
| 9-III | 525 | 5.52 | 5.11 | 4.43 | 1140 | 1110 | 840 | 7320 | 7190 | 6500 |
| Avg. | 527 | 5.51 | 4.95 | 4.34 | 1120 | 964 | 788 | 6798 | 7164 | 6826 |
| (2) Bars stored in oven at 110 deg. F. first 7 days, then on Lab. Roof and subsequent wet-dry cycles | | | | | | | | | | |
| 1-III | 584 | 5.27 | 5.46 | 5.83 | 1010 | 1180 | 1250 | 6010 | 7860 | 8270 |
| 2-III | 514 | 5.66 | 5.63 | 5.57 | 1160 | 1070 | 1180 | 6990 | 7810 | 7890 |
| 3-III | 485 | 5.91 | 5.55 | 5.54 | 1400 | 1280 | 1070 | 6810 | 7900 | 7870 |
| 6-III | 542 | 5 82 | 5.79 | 5.60 | 1230 | 1160 | 1020 | 7500 | 8660 | 7940 |
| 9-III | 526 | 5.53 | 5.59 | 5.57 | 1120 | 1080 | 1080 | 5840 | 7220 | 7650 |
| Avg. | 530 | 5.64 | 5.60 | 5.62 | 1184 | 1154 | 1120 | 6630 | 7890 | 7924 |

TABLE 6

INITIAL (SETTING) LENGTH CHANGES OF 2- BY 2- BY 6¼-IN. MORTAR BARS CONTAINING ZERO, TWO, AND FOUR PERCENT CALCIUM CHLORIDE. 1944 TEST SERIES

Average setting shrinkage of all bars, Cement Groups I, II and III

| Percent $CaCl_2$ | CEMENT GROUP I | II | III | Average |
|---|---|---|---|---|
| (a) Initially cured in moist room at 70 deg F. Bars removed from molds and measured at 24 hr. | | | | |
| 0% | −122 | −134 | −178 | −145 |
| 2% | −220 | −199 | −224 | −214 |
| 4% | −275 | −235 | −260 | −257 |
| (b) Initially cured in oven at 110 deg. F., 30 percent R.H. Bars removed from molds and measured at 6 hr. | | | | |
| 0% | −554 | −527 | −724 | −602 |
| 2% | −166 | −320 | −216 | −234 |
| 4% | −160 | −387 | −298 | −282 |

*Note:* The pins for measuring length changes were very accurately spaced between gage points and held rigid by set screws prior to fabricating the concrete. As soon as the concrete had stiffened the set screws were loosened in an effort to free the pins from all restraint. The effort was only partially successful, but as there were over 340 specimens in all groups it is believed that the average of the measurements in each group and for the whole indicates the trend of initial or setting shrinkage as influenced by the $CaCl_2$ and the initial storage conditions.

relatively low humidity (30 percent) and moderately high temperatures (110 deg. F.) the initial or setting shrinkage was materially retarded by the $CaCl_2$. Subsequent shrinkage on thorough drying over a long period (300+ days) and under variable atmospheric conditions was about the same, with or without the $CaCl_2$, for the specimens initially stored in the moist room for 7 days; there was a moderate increase in shrinkage of the specimens initially stored in the oven for 7 days (Fig. 4 to 14).

There were two interesting developments from the wetting and drying cycles: (1) the specimens initially cured for 7 days in the moist room developed substantially greater subsequent volume change in the wetting and drying cycles than the specimens initially oven-cured; and (2) the $CaCl_2$ specimens initially cured in the moist room had a greater wet-dry length change than those without $CaCl_2$, while the initially oven-cured specimens developed relatively low subsequent volume change whether with or without $CaCl_2$. The $CaCl_2$ specimens, which developed greater wet-dry length changes when initially moist-room cured than those without $CaCl_2$, showed about the same length changes with $CaCl_2$ as without when initially oven-cured. The Type III cement specimens initially moist-room cured for 7 days developed excessive expansion during the wet-dry cycles ultimately leading to lower strength (particulraly lower modulus of rupture) and even to failure (Fig. 16(a)) with $CaCl_2$, particularly with four percent.

It would appear from the results of these tests that the $CaCl_2$ minimizes the initial (setting) shrinkage under adverse high temperature–low humidity initial weathering, but has little effect on the subsequent shrinkage under normal atmospheric weathering conditions.

The wet-dry length changes of 2- by 2- by $6\frac{1}{4}$-in. bars of concrete (max. $\frac{3}{4}$-in. aggregate, 6.75 sacks of cement per cu. yd.) when subjected to alternate cycles of immersion at 70 deg. F. and oven-drying at 110 deg. F. are shown in Figures 4 to 14. Initial measurement was made on the specimens on removal from forms after 24-hr. storage in moist room at 70 deg. F. ("Series A"), and on the specimens on removal from forms after 6 hr. in the oven at 110 deg. F., relative humidity 30 percent ("Series B"). After an initial curing period of 7 days in the moist room for the Series A specimens and 7 days in the oven for the Series B specimens all specimens were stored in the open on the roof of the Labora-

TABLE 7

AVERAGE FINAL DRY AND WET BAR LENGTHS IN THE 1944 CALCIUM CHLORIDE TEST SERIES JUST PRIOR TO FINAL TEST AT AVERAGE AGES INDICATED

Figures Millionths of an Inch per Inch

| 1 | 2 | 3[a] | 4[a] | 5[a] | 6[a] | 7[a] | 8[a] | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| Cement Group | Avg. Age Days | Oven 17 Days at 110 deg. F. | | | Water 16 Days at 70 deg F. | | | Final Range Dry to Sat. | | |
| | | PERCENT CALCIUM CHLORIDE | | | | | | | | |
| | | 0 | 2 | 4 | 0 | 2 | 4 | 0 | 2 | 4 |
| (a) Bars initially stored in moist room at 70 deg. F. then on Lab. Roof and subsequent wet-dry cycles. Based on initial measurement at 24 hr. | | | | | | | | | | |
| I | 512 | −604 | −493 | −123 | −325 | −148 | +307 | 279 | 346 | 451 |
| II | 536 | −530 | −433 | −190 | −273 | −104 | +209 | 257 | 329 | 399 |
| III | 527 | −421 | +187 | +860 | −113 | +736 | +1643 | 308 | 549 | 783 |
| Avg. ... ..... | 525 | −518 | −246 | +182 | −237 | +161 | +720 | 281 | 408 | 544 |
| (b) Bars initially stored in oven at 110 deg. F. first 7 days then on Lab. Roof and subsequent wet-dry cycles. Based on initial measurement at 6 hr. | | | | | | | | | | |
| I | 514 | −576 | −641 | −708 | −347 | −376 | −423 | 229 | 265 | 285 |
| II | 537 | −484 | −619 | −708 | −269 | −386 | −452 | 216 | 234 | 256 |
| III | 530 | −528 | −520 | −539 | −304 | −212 | −187 | 224 | 308 | 352 |
| Avg. ..... ....... | 527 | −529 | −593 | −652 | −307 | −325 | −354 | 223 | 269 | 298 |

[a] Length changes shown in Columns 3 to 8 are with relation to the initial measurement on removal from molds at 24 hr. for the (a) and 6 hr. for the (b) group specimens.

## TABLE 8
## FINAL DRY AND WET LENGTHS OF ALL BARS IN THE 1944 SERIES

(a) GROUP I CEMENTS

| 1 | 2 | 3[a] | 4[a] | 5[a] | 6[a] | 7[a] | 8[a] | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| Cement Number | Avg. Age Days | Oven 17 Days at 110° F. | | | Water 16 Days at 70° F. | | | Range—Dry to Sat. | | |
| | | PERCENT CALCIUM CHLORIDE | | | | | | | | |
| | | 0 | 2 | 4 | 0 | 2 | 4 | 0 | 2 | 4 |
| (1) Bars initially stored in moist room at 70 deg. F. 7 days. Then on Lab. Roof and subsequent wet-dry cycles | | | | | | | | | | |
| 1-I | 595 | −600 | −467 | −460 | −340 | −153 | −113 | 260 | 314 | 347 |
| 2-I | 519 | −633 | −613 | −400 | −360 | −260 | +13 | 273 | 353 | 413 |
| 3-I | 505 | −640 | −660 | −587 | −360 | −313 | −193 | 280 | 347 | 394 |
| 4-I | 471 | −627 | −367 | +187 | −353 | −20 | +633 | 274 | 347 | 554 |
| 5-I | 469 | −520 | −360 | +647 | −213 | +7 | +1193 | 307 | 367 | 546 |
| Avg. | 512 | −604 | −493 | −123 | −325 | −148 | +307 | 279 | 346 | 451 |
| (2) Bars initially stored in oven at 110 deg. F. first 7 days then on Lab. Roof and subsequent wet-dry cycles | | | | | | | | | | |
| 1-I | 590 | −460 | −547 | −680 | −213 | −267 | −420 | 247 | 280 | 260 |
| 2-I | 521 | −580 | −607 | −680 | −380 | −393 | −420 | 200 | 214 | 260 |
| 3-I | 507 | −580 | −767 | −900 | −367 | −520 | −640 | 213 | 247 | 260 |
| 4-I | 478 | −713 | −673 | −627 | −473 | −360 | −287 | 240 | 313 | 340 |
| 5-I | 476 | −547 | −613 | −653 | −300 | −340 | −347 | 247 | 273 | 306 |
| Avg. | 514 | −576 | −641 | −708 | −347 | −376 | −423 | 229 | 265 | 285 |

(b) GROUP II CEMENTS

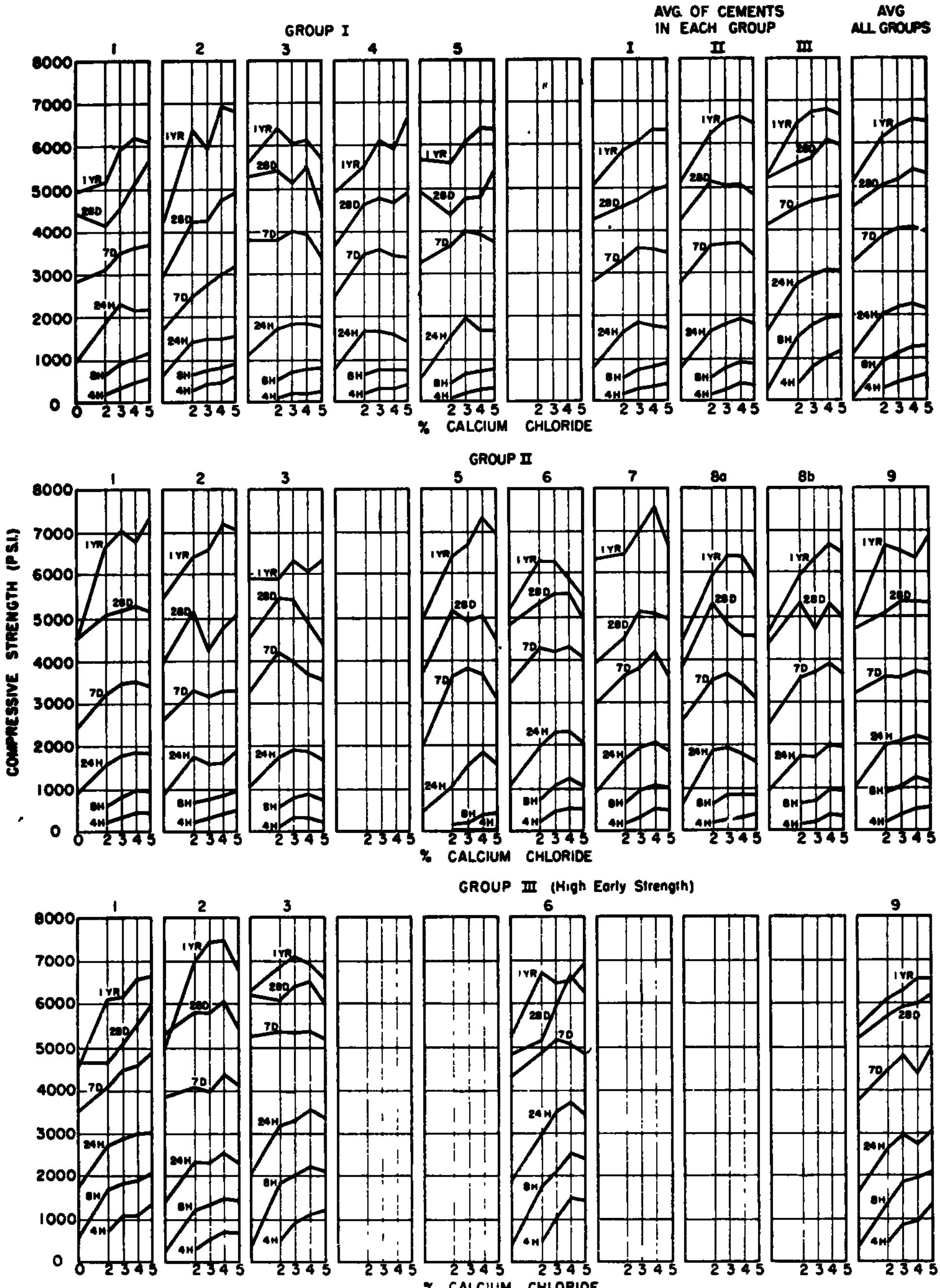
| 1 | 2 | 3[a] | 4[a] | 5[a] | 6[a] | 7[a] | 8[a] | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| (1) Bars initially stored in moist room at 70 deg. F., 7 days, then on Lab. roof and subsequent wet-dry cycles | | | | | | | | | | |
| 1-II | 589 | −607 | −587 | −593 | −353 | −313 | −313 | 254 | 274 | 280 |
| 2-II | 518 | −533 | −540 | −140 | −280 | −247 | +220 | 253 | 293 | 360 |
| 3-II | 504 | −567 | −560 | −547 | −307 | −233 | −153 | 260 | 327 | 394 |
| 5-II | 477 | −507 | −413 | −187 | −240 | −80 | +253 | 267 | 333 | 440 |
| 6-II | 574 | −573 | −480 | −60 | −333 | −160 | +287 | 240 | 320 | 347 |
| 7-II | 471 | −473 | −427 | −80 | −193 | −53 | +367 | 280 | 374 | 447 |
| 8a-II | 575 | −553 | −520 | −380 | −313 | −220 | −20 | 240 | 300 | 360 |
| 8b-II | 581 | −487 | −413 | −293 | −253 | −113 | +33 | 234 | 300 | 326 |
| 9-II | 532 | −473 | +40 | +567 | −187 | +480 | +1207 | 286 | 440 | 640 |
| Avg. | 536 | −530 | −433 | −190 | −273 | −104 | +209 | 257 | 329 | 399 |
| (2) Bars initially stored in oven at 110 deg. F., 7 days, then on Lab. roof and subsequent wet and dry cycles | | | | | | | | | | |
| 1-II | 588 | −453 | −600 | −773 | −253 | −393 | −553 | 200 | 207 | 220 |
| 2-II | 521 | −547 | −687 | −860 | −320 | −453 | −560 | 227 | 234 | 300 |
| 3-II | 506 | −573 | −827 | −780 | −360 | −567 | −500 | 213 | 260 | 280 |
| 5-II | 475 | −467 | −573 | −760 | −200 | −340 | −493 | 267 | 233 | 267 |
| 6-II | 576 | −473 | −613 | −707 | −307 | −413 | −493 | 166 | 200 | 214 |
| 7-II | 477 | −453 | −587 | −687 | −160 | −313 | −407 | 293 | 274 | 280 |
| 8a-II | 577 | −427 | −660 | −673 | −260 | −453 | −433 | 167 | 207 | 240 |
| 8b-II | 583 | −500 | −547 | −653 | −313 | −335 | −420 | 187 | 214 | 213 |
| 9-II | 534 | −467 | −480 | −500 | −247 | −207 | −213 | 220 | 273 | 287 |
| Avg. | 537 | −484 | −619 | −708 | −269 | −386 | −452 | 216 | 234 | 256 |

(c) GROUP III CEMENTS (High Early Strength)

| 1 | 2 | 3[a] | 4[a] | 5[a] | 6[a] | 7[a] | 8[a] | 9 | 10 | 11 |
|---|---|---|---|---|---|---|---|---|---|---|
| (1) Bars initially stored in moist room at 70 deg. F., then on Lab. roof and subsequent wet-dry cycles. | | | | | | | | | | |
| 1-III | 582 | −453 | −180 | +293 | −193 | +227 | +793 | 260 | 407 | 500 |
| 2-III | 513 | −540 | −253 | +60 | −233 | +153 | +587 | 307 | 406 | 527 |
| 3-III | 484 | −420 | −313 | −113 | −87 | +87 | −327 | 333 | 400 | 440 |
| 6-III | 533 | −293 | +1520 | +2880 | +47 | +2540 | +4567 | 340 | 1020 | 1687 |
| 9-III | 525 | −400 | +160 | +1180 | −100 | +673 | +1940 | 300 | 513 | 760 |
| Avg. | 519 | −421 | +187 | +860 | −113 | +736 | +1643 | 308 | 549 | 783 |
| (2) Bars initially stored in oven at 110 deg. F. first 7 days, then on Lab. roof and subsequent wet-dry cycles. | | | | | | | | | | |
| 1-III | 584 | −533 | −460 | −667 | −287 | −153 | −327 | 246 | 307 | 340 |
| 2-III | 514 | −513 | −700 | −700 | −300 | −413 | −420 | 213 | 287 | 280 |
| 3-III | 485 | −587 | −567 | −513 | −353 | −273 | −147 | 234 | 294 | 366 |
| 6-III | 542 | −500 | −327 | −300 | −300 | +13 | +93 | 200 | 340 | 393 |
| 9-III | 526 | −507 | −547 | −513 | −280 | −233 | −133 | 227 | 314 | 380 |
| Avg. | 530 | −528 | −520 | −539 | −304 | −212 | −187 | 224 | 308 | 352 |

[a] Length changes shown in Columns 3 to 8 are with relation to the initial set length at 24 hr. for specimens initially cured in the moist room at 70 deg. F. and at 6 hr. for specimens initially cured in the oven at 110 deg. F.

At the end of the wet-dry cycles and just prior to test for dynamic modulus of elasticity, modulus of rupture and compressive strength, all specimens were stored in the oven at 110 deg. F. for 17 days—measured and then stored in water for 16 days at 70 deg. F.




Note
Erratic results for individual cements probably due to the fact that breaks represent single specimens Three specimens were cast for each mix but one specimen in each set was cured 10 days in the moist room, 353 days on the roof of the laboratory and 48 hours in water The third specimen was cured 10 days in the moist room and 355 days on the roof at the laboratory, then broken dry See Table 3 and Fig 2 for test data

**Figure 1. Effect on Compressive Strength of Zero to Five Percent Calcium Chloride in a Six-Sack Concrete Mix. All Specimens 6- by 12-in. Cylinders, Cured in the Moist Room at 70 deg. F. for Entire Period. 1944 Test Series**

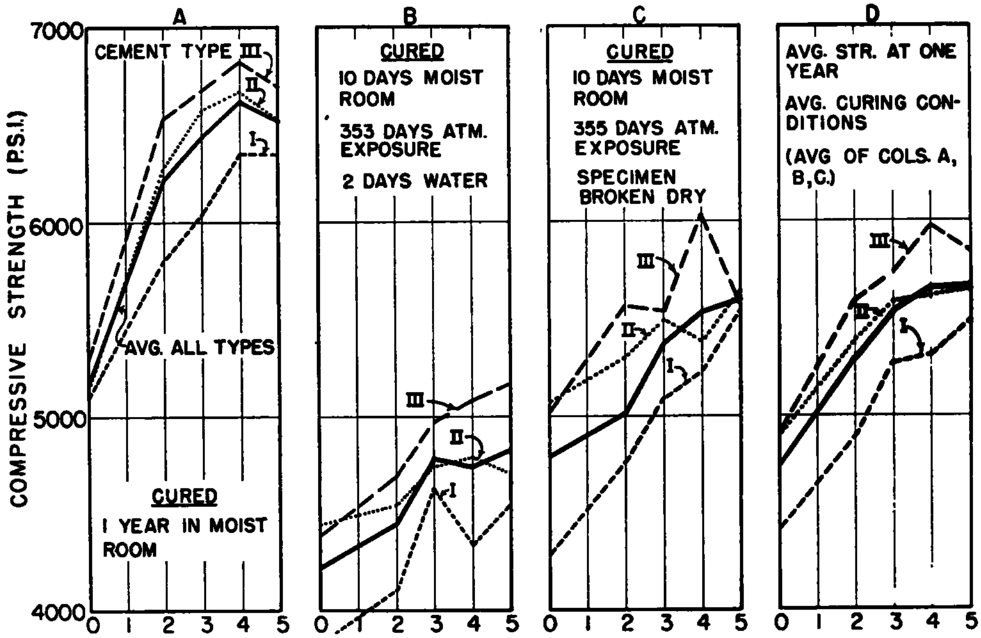



**Figure. 2. Average One-Year Compression Strength Tests on 6- by 12-in. Cylinder Specimens of Concrete from Nine Brands and Three Types of California Portland Cements (Total 19 Cements) as Affected by from Two to Five Percent Calcium Chloride**

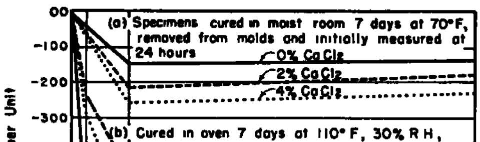



**Figure 3. Initial and Seven-Day Shrinkage of 2- by 2- by 6½-in. Concrete Bars with Zero, Two, and Four Percent Calcium Chloride Additions. 1944 Test Series, Average of 19 Cements, All Types. (See Table 6.)**

tory until the start of the wet-dry cycles. The first measurement indicates the shrinkage during this outdoor exposure period. All measurements starting at average age of 320 days indicate departure from the initial set measurements. Figures 5 to 14 show length changes for each brand and type cement, for which the averages are shown in Figure 4. Figure 7 illustrates a minimum effect of $CaCl_2$ on a Type III cement as well as a negligible effect on the Type I and Type II cements of the same brand. Brand 5 (Fig. 9) shows the greatest effect on a Type I cement, and Brand 9 (Fig. 14) the greatest effect on a Type II cement. Brand 6 (Fig. 10) is affected the greatest of the Type III cements.

All bar specimens were tested for modulus of rupture and modified cube compressive strength at the conclusion of the wet-dry cycles, the average age being shown on the respective figures. The modulus of rupture and compressive test data are shown in the two columns to the right of the plotted length change data.

The length changes in the wet-dry cycles in the case of the specimens initially cured for 7 days in the moist room were greater with the $CaCl_2$ additions than without. The final expansion was substantial with four percent $CaCl_2$ regardless of type of cement, but par-

ticularly so in the case of the Type III cements, where, as will be noted, a material reduction in flexural strength developed.

The initial oven cure at 110 deg. F., however, seemed to temper the concrete, with the result that the wet-dry length changes were of a low order, even with four percent $CaCl_2$,

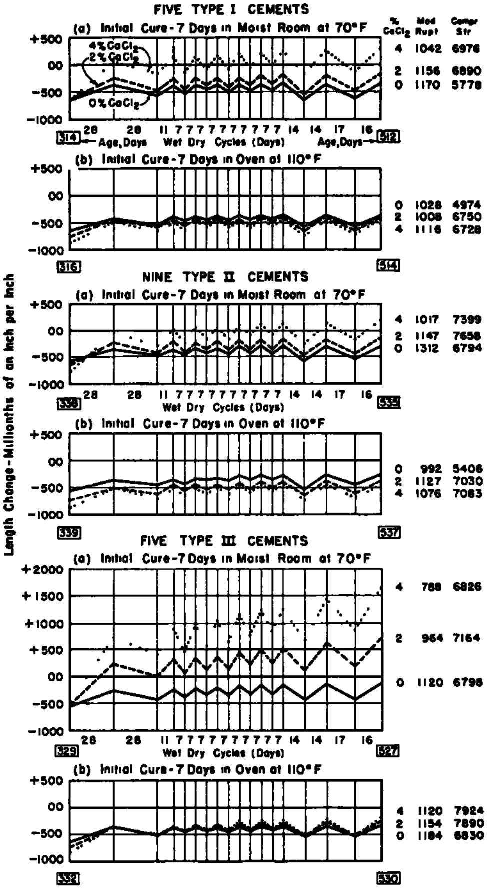



**Figure 4. Average Length Changes of 2- by 2- by 6¼-in. Bars (5 in. between gage points) with Zero, Two, and Four Percent Calcium Chloride Additions**

and there was little if any reduction in flexural strength induced by the $CaCl_2$. The effect of any high ultimate expansion of the initially moist-room cured specimens was reflected in lower modulus of rupture. There was little adverse effect, however, on the compressive strength; the ultimate compressive strengths of the four percent $CaCl_2$ additions was almost invariably higher than without $CaCl_2$ regardless of initial cure.

That these results are not accidental is evident from a study of the data which show the test results for each brand and type cement. The same pattern is apparent throughout although some cements are affected to a greater extent than others.

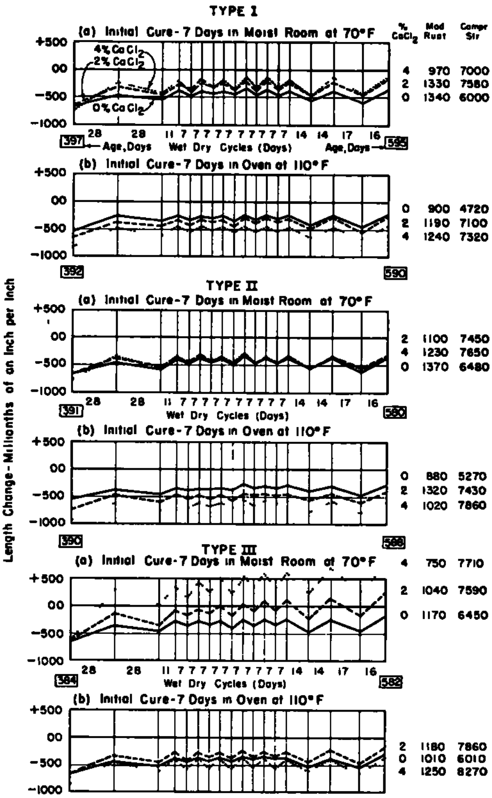



**Figure 5. Length Changes with Calcium Chloride Additions. Cement Brand 1, 2, 3, 4, 5, 6, 7, 8a, 8b, 9**

The indications from this series are that under normal construction operating conditions where, particularly in hot weather, the concrete temperature and moisture conditions during the early curing periods may on occasion more nearly conform with the treatment of the Series B specimens than the ideal moist-room cure of the Series A, the actual concrete performance will probably fall somewhere between the two extremes.

*1945 Series*—Because the 1944 series was necessarily limited in scope through the large number of cements tested (nineteen) a new series was started in 1945 on one standard cement of the 1944 series (Cement 1-I) with variable cement content and water-cement ratio.

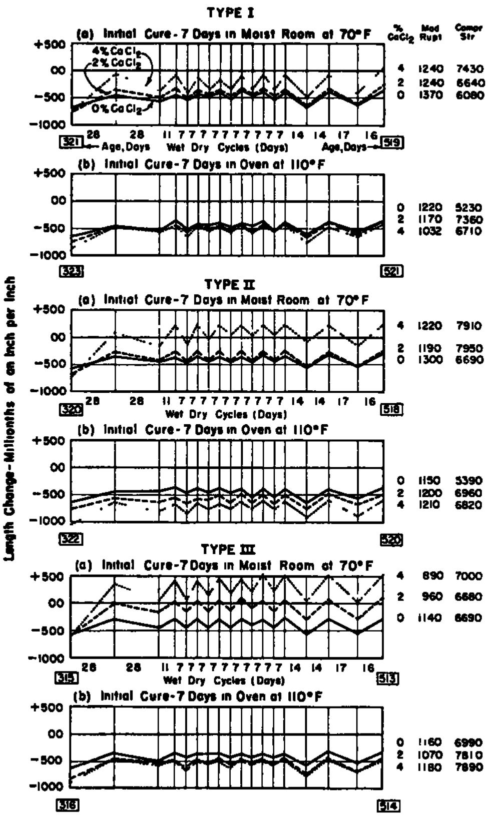



**Figure 6. Length Changes with Calcium Chloride Additions. Cement Brand 2**

These later tests were further limited to 2- by 2- by 6¼-in. bars, ¾-in. maximum size aggregate, the proportions of cement being on the basis of 4.50 sacks, 6.75 sacks and 9.00 sacks per cu. yd. of the ¾-in. top size aggregate portion of standard 4-, 6-, and 8-sack concrete mixes.

Two slumps, 1½ and 3 in., were used. One set of specimens was initially cured in the moist room for 24 hr. and then in the oven for an additional 6 days. The other set was in the oven for 7 days from the start. Both sets were then stored at normal laboratory temperature and relatively low humidity for 84 days until opportunity presented for a

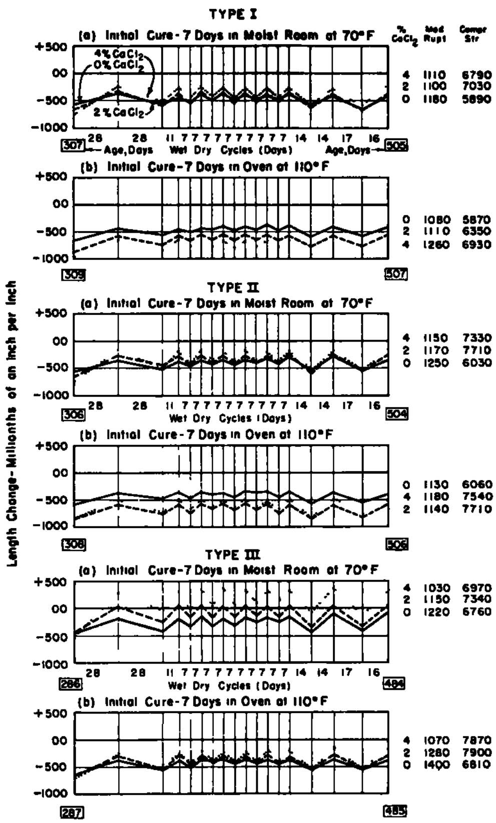



**Figure 7. Length Changes with Calcium Chloride Additions. Cement Brand 3**

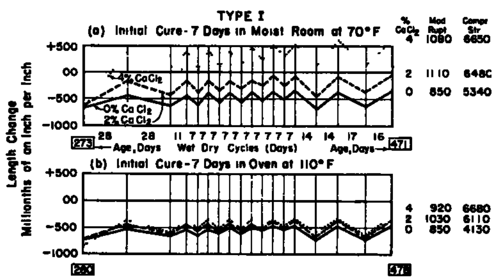



**Figure 8. Length Changes with Calcium Chloride Additions. Cement Brand 4**

long time series of 28-day wet (70 deg. F.) and dry (110 deg. F.) cycles (19 total) after which (age 616 days) all specimens were

tested for modulus of rupture, dynamic modulus and compressive strengths, as well as for wet-dry length changes.

Some results of this 1945 series of tests on the Type I cement were:

(1) No cracking, spalling, or evidences of disintegration was seen in any of the specimens.

(2) The effect of $CaCl_2$ upon the initial drying shrinkage was very apparent. For all mixes and storage conditions, the initial drying shrinkage increased with increasing percentages of the salt.

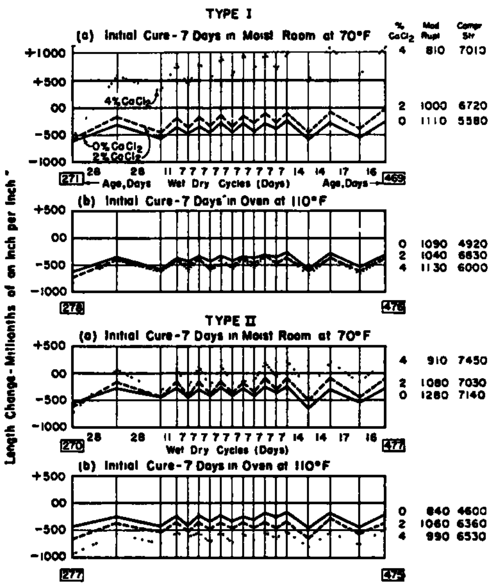



Figure 9. Length Changes with Calcium Chloride Additions. Cement Brand 5

(3) Subsequent wet-dry length changes were less with the $CaCl_2$ in the 4.5-sack mixes but greater in the case of the 6.75- and 9.0-sack mixes.

(4) Compressive strengths at 616 days after the wet-dry cycles were substantially greater for the $CaCl_2$ additions.

(5) The modulus of rupture and dynamic modulus of elasticity averaged moderately lower for the $CaCl_2$ additions than without.

*1950 Series*—The results of the 1944 and 1945 tests indicated greater shrinkage and greater wet-dry volume change of concrete containing $CaCl_2$ when initially cured under moist-room conditions at 70 deg. F., but less differential shrinkage and less wet-dry volume change when initially exposed to relatively high tem-

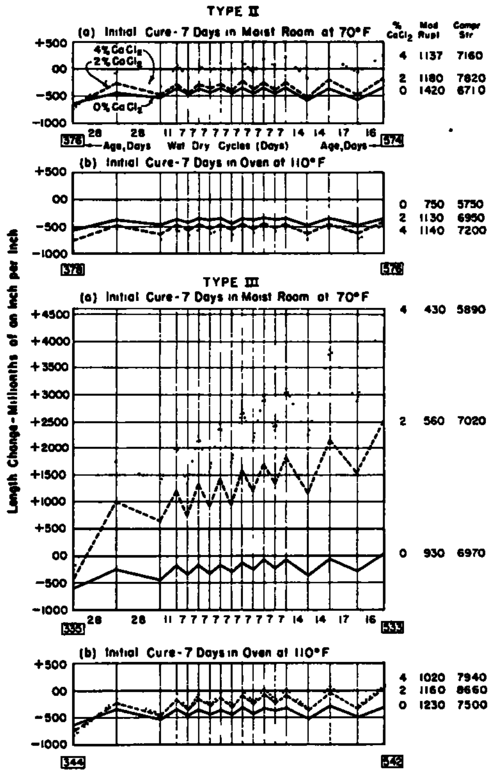



Figure 10. Length Changes with Calcium Chloride Additions. Cement Brand 6

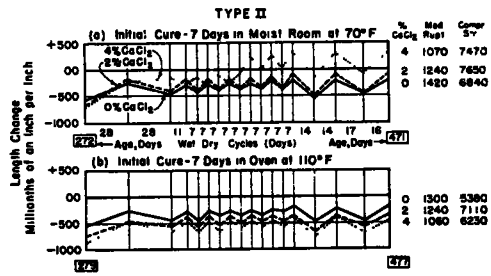



Figure 11. Length Changes with Calcium Chloride Additions. Cement Brand 7

peratures (100 to 110 deg. F.) and relatively low humidity conditions (30 percent R.H.). At the same time, although the compressive strengths were not adversely affected by the

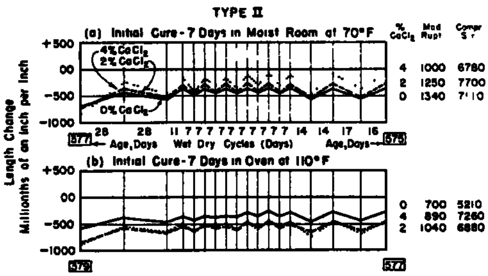



**Figure 12. Length Changes with Calcium Chloride Additions. Cement Brand 8a**

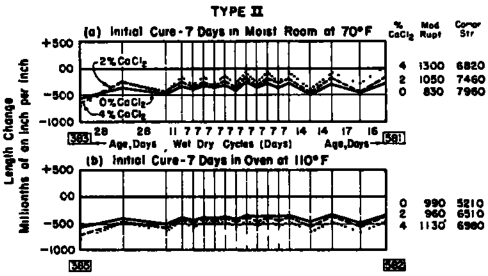



**Figure 13. Length Changes with Calcium Chloride Additions. Cement Brand 8b**

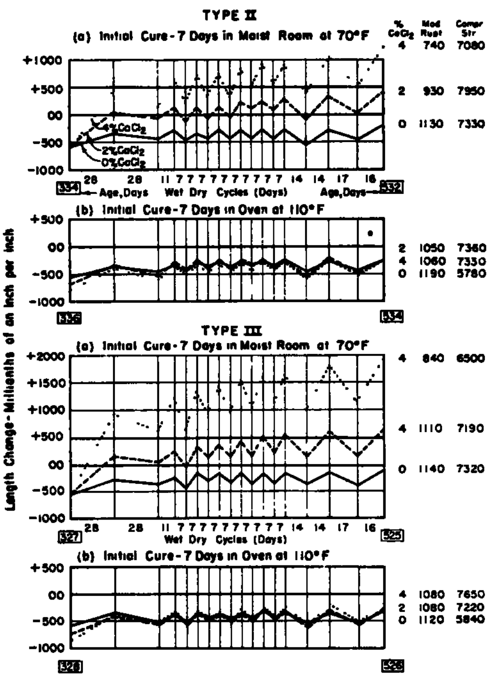



**Figure 14. Length Changes with Calcium Chloride Additions. Cement Brand 9**

addition of two to four percent $CaCl_2$ regardless of curing conditions, the modulus of rupture was apparently adversely affected to an extent depending on the volume change under alternate wet-dry cycles.

It was therefore deemed desirable to make a check of this tendency through a supplementary series of tests. It did not appear necessary to repeat all the cements included in the original series, particularly for the reason that, except for the fine ground Type III cements which are infrequently used (and seldom, if at all, in combination with $CaCl_2$), no substantial differences in performance between the different brands of cements had been observed in the 1944 tests.

The check series of tests was started in 1950 using Brand 1—Type I, five- and six-sack mixes, with zero, two, and four percent $CaCl_2$, and with a modified curing or storage procedure. The test specimens in this series consisted of 6- by 12-in. cylinders for standard compression tests and 3- by 3- by 11¼-in. beams for modulus of rupture, compression (modified cube on beam ends) and length-change measurements.

Storage of different sets of specimens prior to and during the test periods was as follows: (1) 6- by 12-in. cylinders and 3- by 3-in. bars continuous moist-room storage at 70 deg. F.; (2) bars moist-room 60 days, then alternate wet (70 deg. F.) and dry (100 deg. F.) cycles; (3) cylinders and bars at 100 deg. F. protected from moisture loss for 7 days, then stored on Laboratory roof until final test; and (4) bars same as in (3) until age 60 days, then alternate wet (70 deg. F.) and dry (100 deg. F.) cycles.

The results of this series are shown in Figures 18. to 20. The conclusions derived from the 1944 Series were essentially confirmed, i.e.:

1. Wet-dry volume changes of the 60-day moist-room-cured specimens were in proportion to the percentage of $CaCl_2$.

2. Early drying shrinkage and subsequent volume change of the specimens initially cured at 100 deg. F. under good moisture conditions were also increased by the $CaCl_2$, but with less range than in the case of the moist-room-cured specimens, thereby confirming the results of the 1944 Series with regard to the effect of initial curing conditions on the subsequent performance.

3. Greater wet-dry volume change occurred

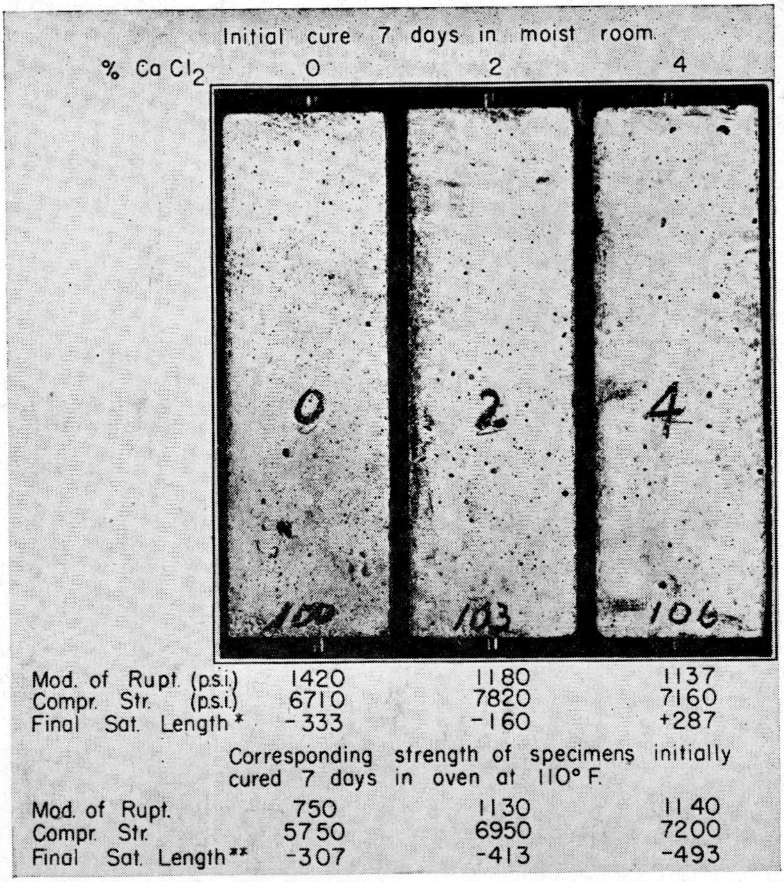



**Figure 15. Condition of Cement 6-II Bars at Age 574 Days, After Nine Cycles of Water Immersion at 70 deg. F. and Oven Drying at 110 deg. F.**
(Compare with corresponding high early strength cement of the same brand, Fig. 16)
* Based on zero at 24 hr.
** Based on zero at 6 hr.

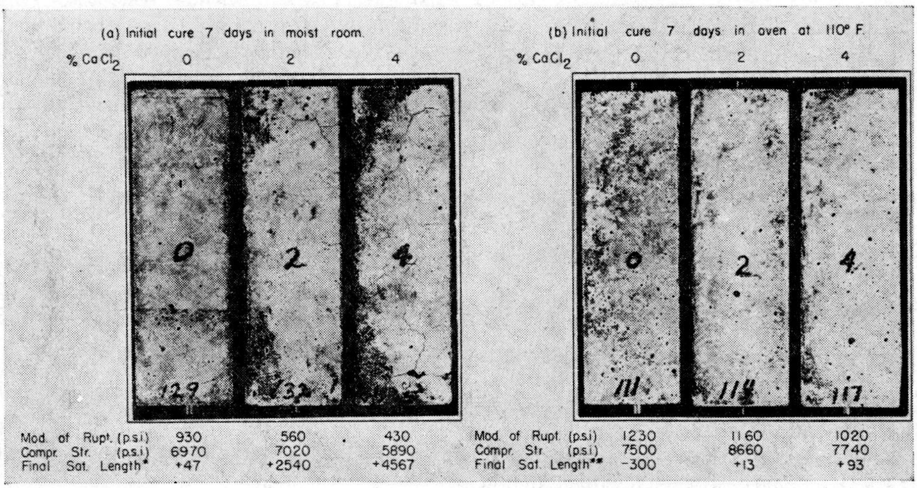



**Figure 16. Condition of Cement 6-III Bars at Age 533 Days, After Nine Cycles of Water Immersion at 70 deg. F. and Oven Drying at 110 deg. F.**
* Based on zero at 24 hr.
** Based on zero at 6 hr.

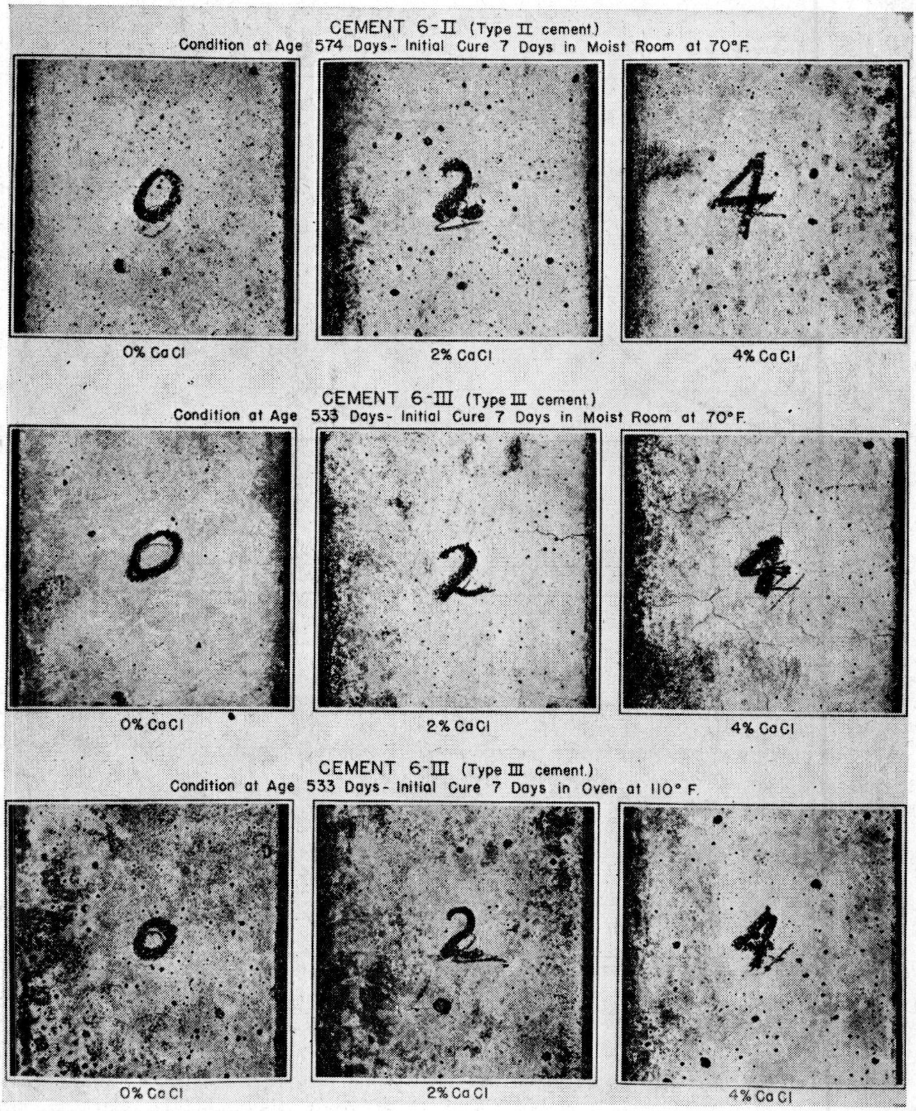



**Figure 17. Condition of Cement 6-II and 6-III Bars in the 1944 Test Series at Ages and Initial Curing Indicated, After 17 Alternate Wet-Dry Cycles as Shown in Fig. 10**

with the initially moist-room-cured specimens than with the specimens initially cured at 100 deg. F.

4. Lowered modulus of rupture was observed with specimens with $CaCl_2$ after a succession of wet-dry cycles when initially cured in moist room at 70 deg. F., but as a rule there was either increase in modulus or less differential with added $CaCl_2$ when initially cured at 100 deg. F.

5. Increase in compressive strength with $CaCl_2$ was obtained regardless of initial cure and subsequent treatment.

ACKNOWLEDGEMENT

The author wishes to express appreciation to the staff of the Materials and Research Department for their assistance, particularly to Associate Materials and Research Engineer W. E. Haskell for the excellence of his work

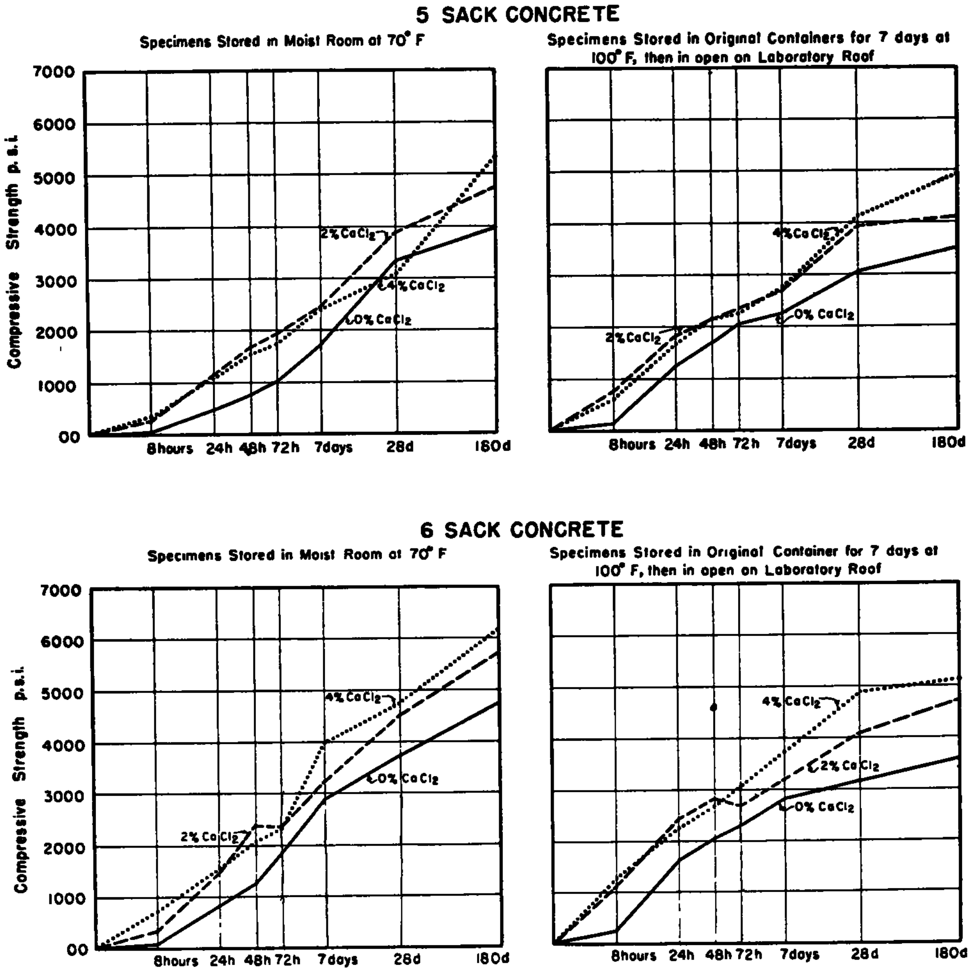



**Figure 18. Compressive Strength of 6- by 12-in. Concrete Cylinders (Cement 1-I), 1950 Calcium Chloride Test Series**

in designing the bar mixtures and his meticulous care in fabricating and performing the numerous tests on the bars; also to Associate Materials and Research Engineer L. P. Kovanda for work done in connection with the design and fabrication of the mixtures for the concrete cylinder tests.

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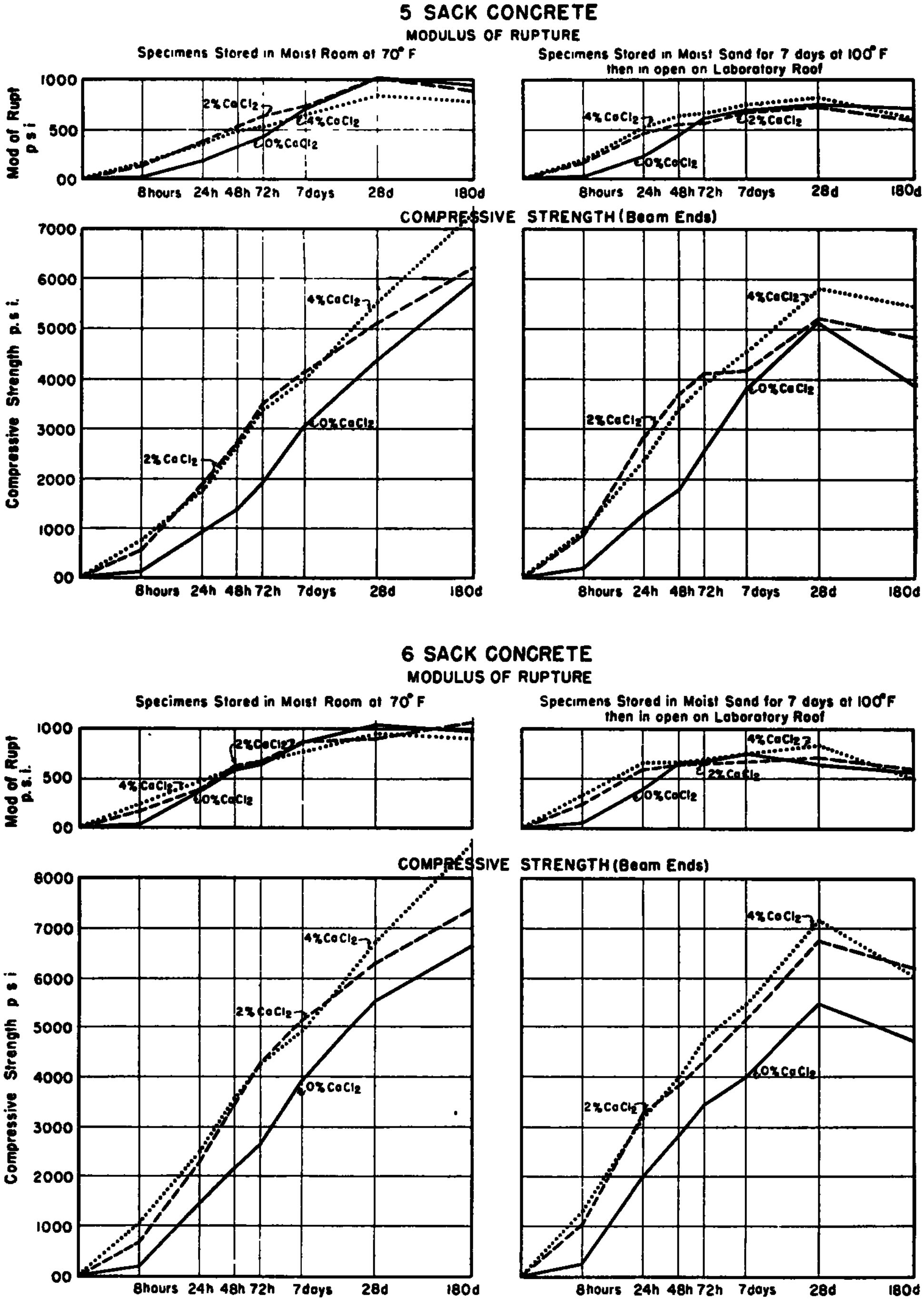
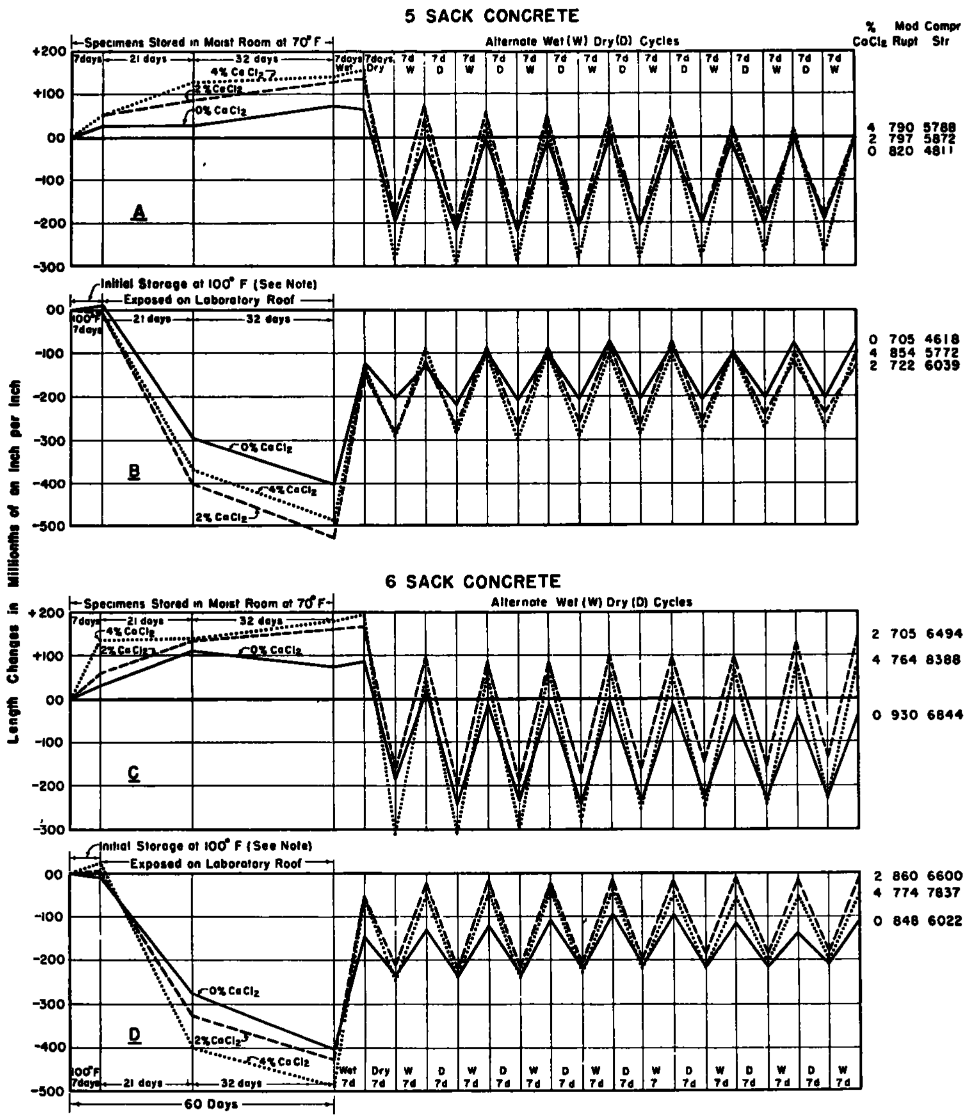



**Figure 19. Modulus of Rupture and Compressive Strength of 3- by 3- by 11½-in. Concrete Beams (Cement 1-I), 1950 Calcium Chloride Test Series**




Note

All specimens were removed from the molds and initially measured at 24 hours One set of each mix was then stored in the moist room for 60 days at 70° F and then subjected to 7 day cycles of alternate soaking at 70° F and drying in an oven at 100° F until test for modulus of rupture and compression at age of approximately 6 months The second set of each mix was stored at 100° F for 7 days in a moist sand bed and with impervious membrane surface seal, then in open on laboratory roof until start of wet-dry cycles at 60 days

**Figure 20. Wet-Dry Length Changes of 3- by 3- by 11¼-in. Concrete Beams (Cement 1-I), 1950 Calcium Chloride Test Series**

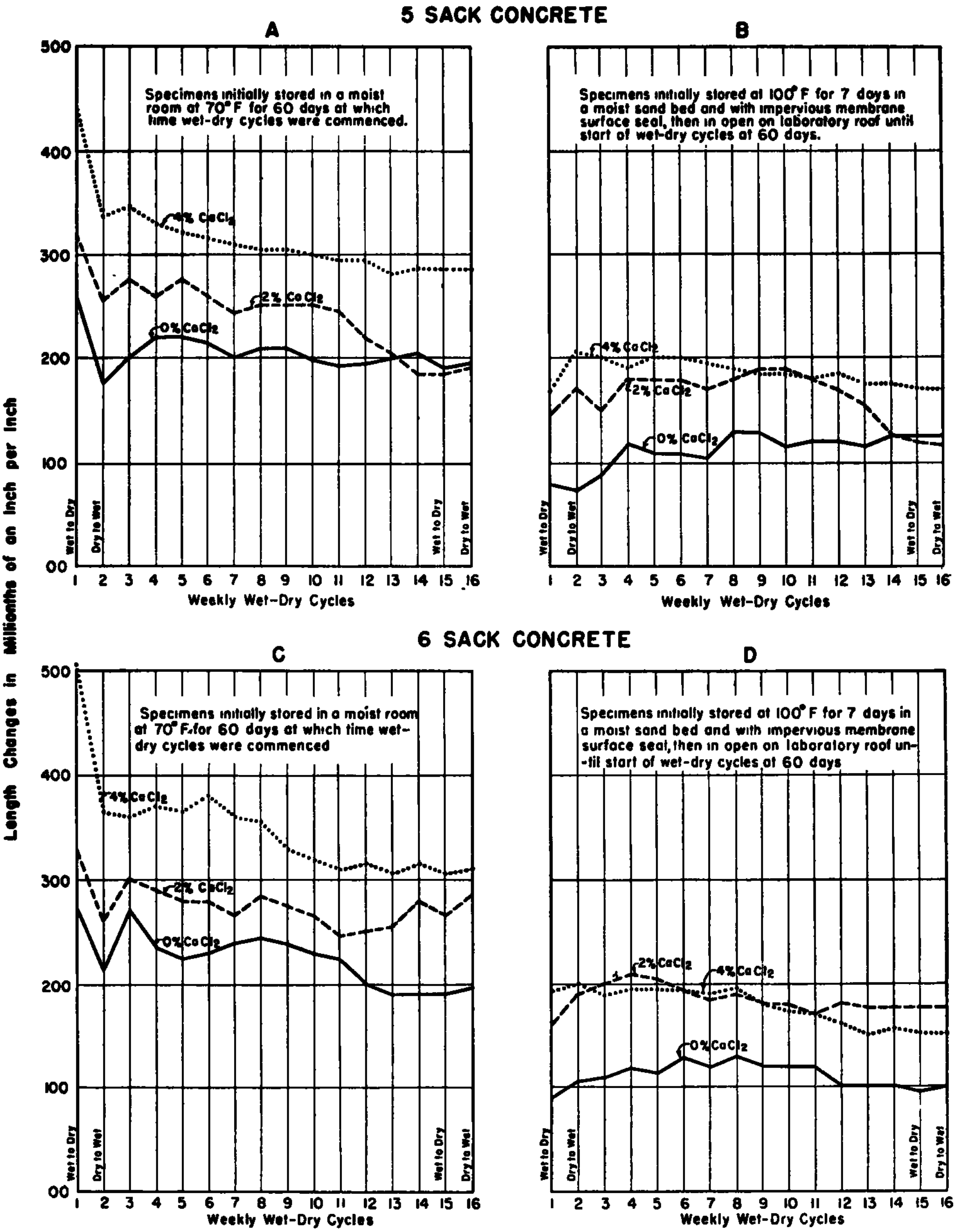



Figure 21. Wet-Dry Length Changes of 3- by 3- by 11¼-in. Concrete Beams (Cement 1-I), 1950 Calcium Chloride Test Series. Specimens Alternately Soaked in Water at 70 deg. F. and Dried at 100 deg. F., 30 percent R. H.

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# MICHIGAN'S EXPERIENCE IN THE USE OF WHITE-PIGMENTED MEMBRANE CURING COMPOUNDS

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## SYNOPSIS

Michigan, in 1949, adopted specifications for white-pigmented curing compounds in an attempt to minimize temperature cracking in concrete pavements built during the spring and summer months. Previous laboratory studies and field tests had demonstrated the effectiveness and practicability of this type of curing.

At first there was some difficulty encountered in applying the compound with the spraying equipment then in use, which led to a modification of pump design by the manufacturer. It was found that most operational troubles were caused by: (1) inadequate stirring of the compound before and during application; and (2) failure to clean the spraying equipment properly after use.

Whiteness and hiding power are important properties of white-pigmented compounds. Michigan specified a minimum apparent reflectance of 70 percent relative to magnesium oxide for the former and 100 sq. ft. per gal. for the latter. The method of determining color by means of a spectrophotometer is described and details of other tests and application requirements are given in the Michigan specifications appended to the report.

As a result of more than 4 years of research and cooperative development, Michigan in 1949 adopted specifications for white-pigmented membranes as an alternate method of curing concrete pavements. The use of clear, or transparent, membrane curing compounds had been permitted since the spring of 1942, but a subsequent appraisal (*1*)[1] clearly revealed the need for controlling heat pickup in pavements cured by this method. The first full-scale use of white-pigmented compounds in Michigan was in July of 1949, and white compounds have been required on all membrane-cured concrete paving projects authorized since that time.

While it is still too early to make a statistical evaluation of their performance in actual service, the benefits to be derived from the use of white-pigmented compounds appear to be well established and there is a definite trend toward their preferment over the transparent type of membrane. New materials bring new problems, however, and it is the purpose of this paper not so much to present the case for white-pigmented compounds as to transmit experience gained in handling, specifying and testing these materials.

[1] Italicized figures in parentheses refer to the list of references at the end of the paper.

### WHY USE WHITE-PIGMENTED COMPOUNDS?

That measures should be taken to prevent excessively high temperatures in immature concrete seems obvious, but it might be well to review briefly the basic reasons behind the use of white-pigmented curing compounds.

In the year A.D. 97 Sextus Junius Frontinus, Water Commissioner of Rome, wrote: "The proper time for masonry work is from the 1st of April to the 1st of November; but with this restriction: that the work be interrupted during the hottest part of the summer; —for the heat of the sun is no less destructive to masonry than is too violent frost." (*2*) Since that time, the wisdom of the Roman Commissioner's remarks has been demon-