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Curing of Cement-Lime Mortars

by
J. I. Davison

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CURE DE MORTIERS CIMENT-CHAUX

SOMMAIRE

Les résultats sont rapportés d'un programme d'essais coopératifs conduit par le Comité C7 de l'ASTM sur la chaux, comparant les effets de la cure en laboratoire et de celle conduite à l'extérieur pour une variété de mortiers de ciment-chaux. Cinq participants ont produit six ambiances de cure extérieure dans des endroits vastement séparés de l'Amérique du Nord. Cinq variétés de mortiers décrits dans ASTM C270, un 1:3 ciment:sable et un 1:3 chaux:mortier de sable ont été inclus.

La durée de la cure a été estimée en comparant les valeurs de la force compressive de cubes de 2 po après 28 jours de cure en laboratoire avec des valeurs après 3, 6 et 12 mois de cure extérieure. La cure en laboratoire a inclus 3 méthodes acceptées – la cure trempe pour les mortiers de ciment, la cure humide pour les mortiers ciment-chaux et la cure à l'air pour les mortiers de chaux. Les cubes dont la cure a été faite à l'extérieur étaient protégés dans des abris de bois avec une seule face exposée. La moitié des cubes de laboratoire ont été analysés dans leur état naturel. Les autres et ceux de l'extérieur ont été étuvés avant les essais.

Curing of Cement-Lime Mortars*

REFERENCE: Davison, J. I., "Curing of Cement-Lime Mortars," *The Reaction Parameters of Lime*, ASTM STP 472, American Society for Testing and Materials, 1970, pp. 193-208.

ABSTRACT: Masonry mortars are assessed on the basis of tests on specimens prepared and cured in the laboratory. Curing procedures differ depending on the relative amounts of cement and lime in the mortar, and the relation between the end result and that attained in the field, where no concession is made for the composition of the mortar, is often questioned. Laboratory and outdoor curing of a series of cement-lime mortars were compared on the basis of compressive strength values. Outdoor curing reflects a variety of weather conditions typical of six geographical areas of the continent. Results indicate increasing discrepancies in values as the amount of cement in the mortars was decreased and the lime increased. Drying laboratory cured cubes before testing substantially reduced these discrepancies for cement and cement-lime mortars, but values for laboratory cured lime mortars remained well below those cured outdoors.

KEY WORDS: curing, environments, weather, laboratories, carbonation, moisture, mortars (material), cements, calcium oxide, compressive strength, assessments, evaluation, tests

The first recorded use of lime in masonry mortar was in the building of the Egyptian pyramids between 4000 and 2000 B.C.² From that time until the beginning of the present century lime remained the basic cementitious material in mortar.

Soon after the introduction of portland cement during the early part of the twentieth century, it was found that the addition of cement accelerated the curing process and provided the high early strength now required by

* This paper is a contribution from the Division of Building Research, National Research Council of Canada, and is presented with the approval of the director of the division.

¹ Research officer, Atlantic Regional Station, Division of Building Research, National Research Council of Canada, Halifax, N. S., Canada.

² Boynton, R. D., *Chemistry and Technology of Lime and Limestone*, Interscience, New York, 1966, p. 3.

the construction industry. The trend to replace lime with cement continued until, in the early 1930's, serious moisture penetration problems were encountered in masonry walls in which predominantly cement mortars had been used.

Since that time mortars containing lime and cement in varying proportions have been used extensively. These mortars combine two materials, each with desirable properties to contribute to the end product. Cement adds strength, particularly early strength, to the slow-setting lime mortars. Lime adds workability and good water retentivity to the harsh cement mortars, properties essential in ensuring maximum bond with the masonry units. Cement-lime mortars give the architect maximum versatility. He can adjust the cement and lime contents to meet his requirements: high strength on the one hand and the ultimate in workability and extent of bond on the other.

For an assessment of the relative merits of the various cement-lime mortars, the architect relies on laboratory tests described in mortar specifications, such as ASTM Specification for Mortar for Unit Masonry (C 270). Many students of masonry have observed that current laboratory curing procedures do not reflect adequately the end result attained in the field with mortars containing high percentages of lime. The excellent durability of lime mortars, as evidenced by the performance of many old buildings (for example, Independence Hall in Philadelphia) along the northeast coast of the Continent, would not be predicted on the basis of laboratory test results. Staley³ noted an increasing discrepancy in the ratio of compressive strength values for cylinders, cured 6 months and 28 days, as the percentage of lime increased in cement-lime mortars. Others have⁴ noted the lack of a satisfactory method for curing cement-lime mortars and suggested an accelerated curing in a carbon dioxide (CO₂) atmosphere.

Interest in improving curing procedures for mortars containing lime, in ASTM Committee C-7, resulted in a preliminary study to compare current laboratory procedures with outdoor curing. The program, which was developed in the Research Subcommittee of Committee C-7 and coordinated in the DBR Atlantic Regional Laboratory of the National Research Council of Canada, compares the two methods of curing on the basis of compressive strength values for 2-in. mortar cubes. There were five participants, and they provided outdoor curing environments typical of six widely separated locations on the North American continent.

³ Staley, H. R., "Volume Changes in Mortars and Strength Characteristics of Brick Masonry," *Proceedings*, National Lime Association, Washington, D. C., 1939, pp. 37-65.

⁴ Private communication.

TABLE 1—*Mortar proportions by volume.*

Mortar Type	Parts by Volume		
	Portland Cement Type 1	Hydrated Lime	Volume Aggregate
C.....	1	..	3
M.....	3	1	12
S.....	2	1	9
N.....	1	1	6
O.....	1	2	9
K.....	1	3	12
L.....	...	1	3

The Mortars

The mortars included in the study are listed in Table 1. In addition to the five mortars listed in ASTM Specification C 270, two others, a 1:3 cement:sand, and a 1:3 lime:sand mortar are included. All participants used cement and lime available in their respective areas. All used hydrated lime; one participant also included a lime putty. The hydrated limes were all dolomitic; the lime putty was high calcium. The aggregate was a combination of equal parts graded and 20:30 Ottawa sand. The mixing of the mortars and the molding of the cubes followed procedures outlined in ASTM Specification C 270-64 T, with the following exceptions: (1) the weight of hydrated lime used in calculations to determine the amount to be used was taken as 50 lb/ft³ (a recommendation from ASTM Committee C-7); and (2) the waiting period as stated in Section 6. Subsection 5, was increased from 1½ to 3 min. Thirty-six cubes were molded for each mortar. As the cubes were removed from the molds they were numbered; one-third (12 cubes) were designated for laboratory curing and the remaining two-thirds (24 cubes) for outdoor curing. The numbering and selection of the cubes was done according to a predetermined pattern carefully set out in the instructions.

Curing Procedures

Laboratory

Laboratory curing was of 28 days' duration and followed the procedures designated in ASTM Specification C 270-64 T.

Types C, M, and S—The "cement" mortars. After molding, these cubes were kept in molds in a moist cabinet maintained at a relative humidity of 90 percent or more for 48 to 52 h. After their removal from the molds,

those cubes designated for laboratory curing were returned to the moist cabinet. At the end of seven days they were immersed in clean water where they remained for the duration of the curing period.

Types N and O—The “cement-lime” mortars. After being molded these cubes also were placed in the moist cabinet for 48 to 52 h. Upon removal from the molds the cubes designated for laboratory curing were returned to the moist cabinet for the duration of the curing period.

Types K and L—The “lime” mortars. After being molded these cubes were left in molds in laboratory air at a temperature of 70 ± 5 F for 48 to 52 h, and after their removal from the molds they were stored in the laboratory air for the entire curing period.

Outdoor

All cubes designated for outdoor curing were placed on an exposure site in wooden shelters facing toward the south immediately after their removal from the molds. The shelters (Figs. 1 and 2) were designed in such a way that five sides of the cubes were protected, while the sixth side was exposed to the weather. The design also permitted free circulation of air around the cubes. The shelters were supported on frames 18 in. above ground level to prevent their being buried in snow. Outdoor curing periods were three months, six months, and one year.

FIG. 1—Shelter and rack for mortar cubes.

FIG. 2—Cubes curing on exposure site: (a) close-up of shelter and rack; (b) general view.

Compressive Strength Tests

ASTM Specification C 270-64 T directs that compressive strength tests be conducted on cubes in the condition in which they were cured. Thus the cement mortars (Types C, M, and S) are tested wet, the cement-lime mortars (Types N and O) are tested damp, and the lime mortars (Types

K and L) are tested air dry. This procedure was questioned on the grounds that results would not be comparable. It was noted also that the moisture content of cubes removed from the outdoor curing site for testing would vary with weather conditions at the end of the respective curing periods. Therefore, it was decided to test all cubes in an oven-dry condition and to compare the results with those for laboratory-cured cubes tested, as directed, in their as-cured condition. Thus, half the laboratory-cured cubes were tested in the normal manner, while the remainder and all the outdoor cured cubes were dried upon completion of the curing period and prior to compressive strength tests.

The procedure outlined in ASTM Test for Drying Shrinkage of Concrete Block (C 426-66T) was selected for drying the cubes. Although this procedure applies specifically to concrete blocks, it was selected because it was adequate for the study, and it seemed more logical to use a recognized ASTM test rather than draw up a new one. Under its provisions, the cubes were dried in an oven for 48 h at a temperature of 122 ± 2 F and a relative humidity of 17 ± 2 percent. The cubes were then cooled to room temperature (70 ± 5 F) and compressive strength tests carried out. The cubes tested in the dry condition were thus two days older than the indicated curing period, that is, laboratory-cured cubes tested dry were tested at $28 + 2$ days and compared with as-cured cubes tested at 28 days.

Variables

There were a number of major variables in the program that should be recognized before considering the results:

1. The use of different cement and lime by each participant. This was not considered important as the object of the study was a comparison of curing procedures and not absolute values.

2. An unexpected variable, as a result of variable No. 1, appeared in the form of a range in the water requirements for each mortar in the different laboratories. The differences can be seen in Fig. 3 where the amounts of water required to produce a flow of 110 to 115 percent are shown. It will be noted that results from Laboratory 6 were quite different than those from the other laboratories. This appears to relate to the lime since the water requirement for the cement mortar was similar to the other laboratories, and the discrepancy widened as the percentage of lime in the mortar was increased.

3. A third major variable was the weather conditions which governed the outdoor curing, and reflected typical conditions in various parts of the continent: Henderson, Nev.; Chicago, Ill.; Gibsonburg, Ohio; New Orleans, La.; Philadelphia, Pa.; and Halifax, Canada (Fig. 4). Records of

FIG. 3—Water required to produce mortars in flow range 110 to 115 percent.

monthly average temperature, relative humidity, and rainfall were compiled from weather summaries published by meteorological stations nearest the exposure sites and are plotted in Fig. 5. The data indicate that: (a) highest relative humidity occurred at Halifax and by far the lowest at Henderson; (b) Highest temperatures occurred at Henderson and New Orleans. In New Orleans the high temperatures were associated with the second highest relative humidity. Lowest temperatures were recorded at Halifax; (c) Lowest rainfall totals were at Henderson. The most distinctive features of the weather data are the low rainfall and humidity recorded at Henderson.

FIG. 4—Locations of curing sites.

FIG. 5—Weather data for the six curing environments.

Results

Average values obtained by each laboratory for the different mortars are shown in Table 2. The overall averages, listed in Table 3 and shown graphically in Fig. 6, reveal large differences in values for the different laboratories. Contributing to these differences are the major variables listed above plus the inevitable variations in laboratory techniques despite the use of uniform procedures.

TABLE 2—Compressive strength values (psi) individual laboratory averages.

No.	Mortar Type						Curing Information	
	C	M	S	N	O	K		
1...	6 736	...	3 020	1 801	627	430	92	28-day laboratory curing
2...	6 563	...	...	...	...	...	...	
3...	7 233	...	4 715	2 324	1 002	563	93	
4...	6 389	4 358	4 186	2 499	1 150	299	88	
5...	...	4 225	3 756	2 275	940	469	125	
6...	5 883	4 220	3 244	1 458	408	448	151	
7...	4 604	...	2 029	1 219	638	522	..	
1...	7 732	...	3 710	2 288	1 120	517	94	28-day laboratory curing plus 48 h drying at 122 F and 17% RH
2...	9 247	...	...	...	...	...	...	
3...	9 025	...	6 104	2 971	1 650	701	126	
4...	7 105	5 506	5 095	3 210	1 561	374	104	
5...	...	5 455	4 973	3 323	1 625	537	139	
6...	7 500+	5 217	4 454	2 052	592	464	155	
7...	5 000+	...	2 850	1 477	754	438	...	
1...	7 629	...	4 118	2 495	1 004	477	97	3 months' exposure curing plus 48 h drying at 122 F and 17% RH
2...	7 273	...	4 255	2 896	1 531	958	289	
3...	7 653	...	4 724	2 998	1 498	899	257	
4...	7 854	5 796	5 125	3 036	1 375	990	276	
5...	...	5 318	4 735	2 965	1 148	932	418	
6...	5 166	4 118	3 425	1 808	700	426	199	
7...	7 215	...	2 461	1 801	833	694	..	
1...	8 632	...	4 396	2 900	1 207	637	147	6 months' exposure curing plus 48 h drying at 122 F and 17% RH
2...	7 934	...	4 636	3 493	1 684	1 250	400	
3...	8 247	...	5 224	3 467	2 009	1 324	400	
4...	8 075	6 025	5 790	3 750	1 779	1 203	527	
5...	...	5 670	5 015	3 280	1 245	1 015	376	
6...	5 419	4 213	3 549	1 825	817	524	253	
7...	7 202	...	2 855	1 714	1 303	1 045	...	
1...	9 046	...	4 389	2 907	1 343	698	163	12 months' exposure curing plus 48 h drying at 122 F and 17% RH
2...	8 416	...	5 103	3 223	1 701	1 244	430	
3...	9 017	...	6 016	4 016	2 402	1 574	730	
4...	8 350	6 220	6 118	3 898	1 890	1 555	465	
5...	...	5 608	5 238	3 103	1 130	1 044	354	
6...	6 511	4 604	3 420	2 000	801	515	223	
7...	8 084	...	3 025	2 517	1 551	1 272	..	

NOTES—Laboratory 3 prepared two sets of cubes for curing on two different outdoor sites; these values are listed as Nos. 2 and 3. Laboratory-cured values are listed under No. 3.

Laboratory 4 prepared two sets of cubes, one set of mortars containing hydrated lime (No. 4), the other set containing lime putty (No. 5).

Only Nos. 4, 5, and 6 included Type M mortar in their program. No. 7 did not test a Type L mortar.

TABLE 3—Summary of average compressive strength values (psi).

Type of Mortar	A	B	Improve- ment B over A, %	C	Improve- ment C over A, %	D	Improve- ment D over A, %	E	Improve- ment E over A, %
C 1:3 cement:sand	6 235	7 601+	21.9	7 132	14.4	7 585	21.6	8 237	32.1
M 1:1/3:4 C:L:S	4 268	5 393	26.4	5 077	18.9	5 303	24.2	5 477	28.3
S 1:1/2:4 1/2 C:L:S	3 492	4 531	29.7	4 120	18.0	4 495	28.7	4 758	36.2
N 1:1:6 C:L:S	1 929	2 553	32.3	2 571	33.3	2 918	51.2	3 095	60.4
O 1:2:9 C:L:S	794	1 217	53.3	1 155	45.5	1 435	80.7	1 545	94.6
K 1:3:12 C:L:S	455	505	11.0	768	68.8	1 000	119.8	1 129	148.1
L 1:3 lime:sand	112	124	10.7	256	128.6	350	212.5	394	251.8

NOTE—A. 28-day laboratory curing.

B. 28-day laboratory curing plus 48 h drying at 122 F and 17% RH.

C. 3 months' exposure curing plus 48 h drying at 122 F and 17% RH.

D. 6 months' exposure curing plus 48 h drying at 122 F and 17% RH.

E. 12 months' exposure curing plus 48 h drying at 122 F and 17% RH.

FIG. 6—Compressive strength values after different curing periods.

Laboratory Curing

There were great differences between the compressive strength values for the as cured and the dry cubes. Drying the wet cement mortars (Types C, M, and S) resulted in increases of 21.9, 26.4, and 29.7 percent of the as cured values. The biggest increases—32.3 and 53.3 percent—occurred with the cement-lime mortars (Types N and O), while the effect of drying was much less for the air-cured lime mortars (Types K and L) (Fig. 7).

Weight losses were checked in the control laboratory and results (Table 4) show that the moist cement-lime mortars contained more water than the wet cement mortars. Increasing weight losses in mortars Types C through O suggests an increasing capacity to hold water as the pore volume increases with increasing lime content. In addition, apparently the conditions of moist curing, at least in the control laboratory, were sufficient to maintain a high level of saturation in the pores of the cement-lime cubes. The

FIG. 7—Comparison of compressive strength values for different curing periods.

pattern of increasing weight losses on drying was broken by air curing for the lime mortars. Figures indicate that they contained very small amounts of moisture.

Outdoor Curing—Three Months

Increases in the values for dry cubes after three months of outdoor curing over 28-day laboratory-cured cubes tested in the as cured condition are shown in Figs. 6 and 7. The data indicate an increasing improvement as the amount of lime in the mortars is increased. The pattern changes if the comparison is made against the values for cubes dried before testing after

FIG. 7—(continued).

28 days' laboratory curing. In this case the values for the three-month cubes are below the 28-day cubes for mortar Types C to O, with the exception of Type N, where they are about equal. There is a sharp increase in values for the lime mortars (Types K and L) over the 28-day dry values.

Thus the results suggest that laboratory curing is superior to three months of exposure curing for cement and cement-lime mortars, but that it is inferior for lime mortars.

TABLE 4—Weight losses in mortar cubes (% dry weight) after drying for 48 h at $122 \pm 2^\circ \text{F}$ and $17 \pm 2\% \text{RH}$ determined in control laboratory.

Mortar Type	Laboratory Curing, 28 Days	Outdoor Curing		
		3 Months	6 Months	1 Year
C.....	2.8	2.1	1.8	0.1
M.....	4.7	1.9	1.5	2.0
S.....	5.2	1.6	1.9	0.9
N.....	7.4	2.9	2.7	1.1
O.....	10.6	0.8	6.9	1.1
K.....	0.5	1.7	1.3	1.0
L.....	0.2	0.2	0.6	0.6

Outdoor Curing—Six Months

Increases in the values for mortars after six months of outdoor curing over values for as cured mortars at 28 days are shown also in Figs. 6 and 7. There is a continuing and growing improvement over the original values as the percentage of lime in the mortars increases, as was noted in values for the three-month cubes. The increases range from 22 percent for Type C (cement) mortar to 212 percent for Type L (lime) mortar. When the comparison is made against values for dry cubes at 28 days, the values for cement mortars are about equal, but outdoor curing resulted in an 18 to 35 percent improvement for the cement-lime mortars and 110 to 200 percent for the lime mortars.

Outdoor Curing—Twelve Months

The trends noted above continue as the values of mortars cured outdoors for twelve months are compared with mortars cured in the laboratory and tested in the as cured condition (Figs. 6 and 7). There are increasing improvements as the amount of lime in the mortars is increased. If the comparison is made with the values for dry cubes at 28 days, all the mortars have improved beyond their original values. The cement mortars show an increase of 2 to 10 percent, the cement-lime mortars have increased 28 to 41 percent, and the lime mortars 137 to 141 percent.

Results for the twelve-month outdoor-cured mortars indicate a reduction in the curing rate for cement-lime and lime mortars in the six to twelve-month period as compared with the rate during the three to six-month period. This was not as evident for the cement mortars (except Type M where there were only three values). It should be noted that the six-month to one-year period included the winter months, and the slowdown in the curing rate during this period may reflect, in part, the adverse effect of winter weather conditions on the curing of the lime portion of the mortar.

Discussion

It is important to be realistic when considering the extent to which laboratory curing of masonry mortars should reflect the end result achieved in the field. Certainly laboratory curing of lime mortars cannot be expected to approach the condition of the mortar in buildings like Independence Hall. Lime cures very slowly by reacting with the CO_2 in the air, and its ultimate strength is not attained for many years. But the architect must specify a mortar that will acquire the strength required when the building is ready to assume its full load. In discussing this aspect, Voss⁵ suggests

⁵ Voss, W. C., "Exterior Masonry Construction," *Bulletin* 324, National Lime Association, Washington, D. C., p. 41.

that "occupancy involving the full loads of design is usually delayed by at least six months from the time of laying." It was probably on this basis that Staley compared compressive strength values for mortars cured six months with those cured 28 days. A comparison of his results with those obtained in the present study is as follows:

6 Month/28 Day Ratio					
Staley		ASTM Committee C-7			
Mortar		Laboratory Cubes	Laboratory Cubes		
		Mortar	As Cured	Dried	
	1:0:2.5 C:L:S	1.76	1:0:3 C:L:S	1.22	0.99
	1:1:5 C:L:S	1.82	1:1:6 C:L:S	1.51	1.14
	1:2:7.5 C:L:S	2.42	1:2:9 C:L:S	1.81	1.18
		1:3:12 C:L:S	2.20	1.98	

The same pattern of increasing discrepancies, in the six-month/28-day ratio, as the lime content of the mortars is increased, occurs in results of this study as observed by Staley, although the differences are not as great. Most significant, however, are the figures in the column comparing the six-month values with those for dry cubes at 28 days: the 28-day laboratory results equal those for the six-month cement mortar, but the increases in the 1:1:6 and 1:2:9 cement-lime mortars have been reduced sharply. The big increases remain with the lime mortars where, as noted previously, drying has no appreciable effect.

The weight loss data in Table 4 indicate that cement and cement-lime mortars cured on outdoor exposure had much lower moisture contents than those cured in the laboratory, while lime mortars were slightly higher. It is noted also that moisture contents generally became smaller as the curing period was lengthened. A notable exception to this is the value 6.9 percent for Type O mortar after six months' outdoor curing. It was raining on the day these cubes were removed from the exposure site, and had the cubes been tested in their as cured condition the resulting value would not have been representative. Drying the cubes eliminated the possibility of inconsistencies of this type. Weight loss data, as previously noted, indicate that cement-lime mortars remain near saturation during moist cabinet curing. The result of curing at lower relative humidities that would allow some air to enter the pore spaces and facilitate a more extensive carbonation of the lime might be studied.

Conclusions

Compressive strength values for mortars cured outdoors show increasing discrepancies, when compared with values for mortars cured and tested by conventional laboratory methods, as the percentage of cement in the mortar is decreased and the percentage of lime is increased.

These discrepancies are reduced greatly if laboratory-cured cement and cement-lime mortar cubes are dried before testing.

Big differences remain between values for outdoor- and laboratory-cured lime mortars even when they are compared on the basis of values for cubes that have been dried before testing.

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