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CEMENT-LIME MORTARS

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By H. V. Johnson

ABSTRACT

Tests were made upon cement-lime mortars in which the percentages of cement, lime, and sand were varied considerably. It was found that the addition of lime to cement mortars increased the water requirement for the same consistency, very nearly in proportion to the percentage of lime added, that shrinkage is increased by the addition of extra water; therefore, where low shrinkage is of prime importance, lime should be limited in cement mortars. The addition of lime can not be expected to increase the strength of cement mortars richer than 1 : 2 by weight; with leaner cement mortars the maximum increase in strength which may result from the proper addition of lime is greater the leaner the mortar. The addition of lime in small amounts increased the density of lean cement mortars. The principal advantages resulting from the use of lime in cement mortars are an increase in workability and a reduction in cost. While a cement-gauged lime plaster retains much of the workability of straight lime plaster, the presence of the cement gives it greater strength and a shorter time of set.

When one is about to prepare a mortar, it is well to consider what are its requirements for the work in question. It may be found that a desirable change in one property results in disadvantages in others. That choice of proportions then must be made which will result in the best possible compromise.

Exact duplications of results are not to be expected where other brands of materials or differently graded sands are used, with different manipulation and different storage conditions.

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I. INTRODUCTION

1. REASONS FOR FURTHER STUDY OF CEMENT-LIME MORTARS

For a considerable period of time it has been common practice to add lime to Portland cement mortars, on the ground that it increased the workability and lessened the cost of the mortars; on the other hand, Portland cement has been added to lime mortars for the purpose of increasing the strength and reducing the time of set. Numerous experiments have been conducted in order to determine

the effect of these admixtures to mortars, but usually there were only a few properties of the mortars studied by each individual. Therefore, it seemed advisable to give further study to cement-lime mortars, in order that more properties of the same mortars might be considered and that the work might include mixes of widely different proportions.

2. MATERIALS

The mortars under consideration were made from three brands of Portland cement, two brands of high calcium mason's hydrated lime, and Potomac River sand. The sieve analysis of this sand appears in Table 1. On account of the greater ease of securing a uniform mixture, dry hydrated lime was used rather than lime paste made from quicklime. While several cements and limes were used, it should be noted that only one brand of cement and only one brand of lime were used in the series of tests for a given property.

TABLE 1.—*Sieve analysis of Potomac River sand*

Sieves	Per cent sand	Sieves	Per cent sand
8 to 16	18.4	70 to 100	6.3
16 to 30	20.4	100 to 200	3.3
30 to 50	36.4	Passing 200	1.5
50 to 70	13.7		

The proportion of each material was varied in amounts of 5 per cent by weight, based on total dry weight of mix. This made 231 possible combinations. All of these were used in tests for compressive strength and for plasticity. For tests of other properties only 105 different mixes were used, which included all those with 50 per cent of sand and over and, in addition, the mixes represented by the remaining points on the border of each diagram.

3. TEST METHODS

The materials for each batch were proportioned by weight, mixed thoroughly while dry, then wetted and worked well. The same consistency (one-half inch slump) was used in all the tests except for plasticity. The consistency was measured by filling a 2 by 4 inch brass cylinder with wet mortar, removing the cylinder vertically, and measuring the slump. (For plasticity tests a wetter consistency was used—a slump of one-fourth inch when the standard rubber ring (108)[1] was substituted for the brass cylinder.) The water was calculated as per cent of the dry materials to which it had been added. These percentages were used in plotting the curves in Figure 1.

[1] The figures given in parentheses here and throughout the text refer to the reference numbers in the bibliography at the end of this paper.

Specimens for tensile-strength tests were molded in the standard cement briquet molds. The briquets, as well as the other test specimens, were removed from the molds after 24 hours and placed on shelves in the laboratory. Eighteen briquets of each mortar were made, in order to have 6 of each for a test at the end of the aging periods of 7, 28, and 90 days.

Compressive-strength tests were made on 2-inch cubes and 2 by 4 inch cylinders, three of each. The principal series of tests for compressive strength was made on specimens aged for one year in the air of the laboratory.

Volume shrinkage and density of mortar when fresh and after drying (in grams per cubic centimeter) were determined on two specimens for each mortar. The brass molds were 3 by 3 by ¾ inch in size. A comparatively shallow mold was chosen in order to secure rectangular prisms after shrinkage rather than frustrums of four-sided pyramids; the latter shapes resulted when deeper molds were tried. The measurements which were taken for these determinations were: The volume of the molds, the weight of the fresh mortar filling them and the volume and weight of the mortar after drying in air for 10 days.

The three dimensions of the dry specimens were taken by the use of micrometer calipers, the average of five readings being taken for depth and the average of three readings for each of the lateral dimensions. Volume shrinkage was computed as percentage decrease in the original volume.

In making these specimens, a glass plate was placed under each mold. Therefore the volume shrinkage was greater than that occurring in those mortars which are applied to an absorbent base and which receive thorough troweling by the mason. Nevertheless, the results are all relative, and they show the inherent tendency of each mortar to shrink.

The time of set was determined with the usual rubber rings as molds and the Vicat needle. "Time of set" is here taken to mean the time which elapsed before the mortar was able to sustain the needle without leaving a visible depression in the mortar when removed.

Plasticity tests were made on these mortars by means of the Bureau of Standards plasticimeter (107). It seemed best to treat all samples alike, and since those which contained Portland cement could not be soaked overnight the lime-sand mortars of this series were not soaked. The consistency for plasticity tests was mentioned above.

4. USE OF TERMS

The term "mortar" is used in this paper to include all of the various mixes, regardless of the percentages of cement, lime, and sand. When considering some of these mortars as a covering for interior walls or exterior walls, they are termed "plaster" or "stucco," respectively

The term "density" is here taken to mean weight per unit volume, and throughout this paper it is expressed in grams per cubic centimeter.

5. PRESENTATION OF DATA

In order to simplify this paper, many of the tables have been omitted, and the same information is given in the various figures. In 11 of the figures are given four curves, in dotted lines, marked 1:4, 1:3, 1:2, and 1:1. These numbers express the ratios of cement to sand by weight, for all mortars represented by points on these curves, without regard to the percentage of lime present. These curves will enable the reader to see at a glance the effect of adding various amounts of lime to these mortars. As one proceeds from left to right along the dotted curves, each mortar of the fixed cement-sand ratio has a greater and greater addition of lime. By noting how the solid curves cross the dotted curves, it can be seen readily what effect additions of lime had upon the properties of the cement mortars.

A fifth dotted curve will be found in these same figures, and it represents all mortars in which 15:85 expresses the ratio of lime to sand by weight, without including the cement. This curve will enable one to see the effect of adding cement to a lime mortar of this ratio. (Exact duplications of results are not to be expected where other brands of materials or differently graded sands are used with different manipulation and different storage conditions.)

This paper deals with mixes proportioned by weight, and in order to avoid confusion the lime must be understood to be an addition to the cement mortars, where reference is made to its effects. The only exception to be noted is in Figure 13, where the given ratios are volume ratios which include the lime as well as the cement. Mortars of the ratios in Figure 13 are represented by curves drawn in solid lines, the object being to show the effect upon the compressive strength of substituting lime for cement or cement for lime by volume.

Figure 14 has been constructed as a result of close study of the figures on strength, time of set, plasticity, and shrinkage. It is conservative, and it is believed that one will not go far astray in following it. It should be noted that the region marked "good in strength" includes the lime mortar of the proportions 15:85 by

weight. To illustrate the meaning, it may be said that a lime mortar of the above ratio is good in strength for all purposes for which lime mortars are to be recommended, but that a cement mortar of the same strength is not to be placed in this group of mortars.

In order to be consistent with the previous part of the paper, recommendations for practice have been made on a weight basis for dry materials. To recommend by volume proportions would be uncertain, on account of the differences in the volume which unit weight of any of the ingredients might occupy merely by a change in the amount of packing. A very noteworthy source of error would be the bulking of sand when moistened. This is shown by the fact that 1 cubic foot of Potomac River building sand when tamped and dry weighed 96 pounds, while the cubic foot contained the equivalent of only 78 pounds of dry sand when measured moist without tamping.

II. MIXING WATER

In addition to cement, lime, and sand, water was one of the ingredients used in the mortars for this research. Variations in the amounts of mixing water have important effects upon all the properties of mortars. The kind and proportions of the ingredients of a mortar limit the range in the percentage of mixing water which can be used to produce a workable mortar, but within these limits the optimum amount of water to add must be determined by the usage for which the mortar is intended and by the practice to be followed in its application.

1. EFFECT OF LIME ON WATER REQUIREMENT

A record was kept of the percentages of mixing water required for the same consistency by the various mortars used. Each curve in Figure 1 represents the composition of all mortars requiring the same percentage of mixing water. A study of these curves indicates that when lime is added to cement mortars the additional amount of water required to bring the mortars to the same consistency is very nearly proportional to the amount of lime added. (In the region approaching straight sand there is an exception to this rule, for with a deficiency of cement paste or of lime paste it becomes necessary to add more water in order to produce the same amount of slump in the mortar.) The mortar which required least water to bring it to the same consistency as the others was the 1:3 cement mortar without lime, requiring 16.3 per cent water.

In practice, when a cement mortar works too poorly, it has been found that this difficulty can be met by adding lime or other finely divided material to the mortar; this will necessitate adding more water, but not to the extent of greatly reducing the strength of the mortar.

2. EFFECT OF WATER ON TIME OF SET

The percentage of mixing water is doubtless an important factor influencing time of set. It is to be expected that a greater amount of water will require more time than less water to dry out and will affect the time of set of mortars containing lime. The amount of water present is also a determining factor in the rate of carbonation of lime. Landis (86) has shown that when the mortar is fresh there is too much water present for it to absorb carbon dioxide, and that

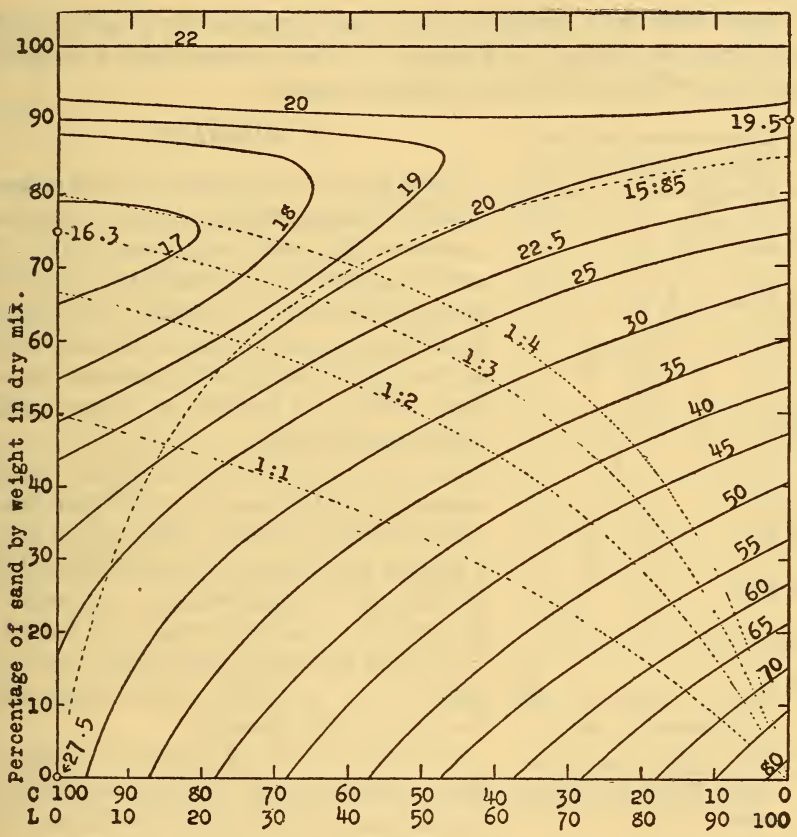

FIG. 1.—*Percentages of mixing water in cement-lime mortars*

if the mortar is dried completely it does not absorb carbon dioxide. Richardson (87) went further and set 5 to 0.7 per cent moisture as the limits within which carbonation of lime mortar can occur.

3. RELATION OF WATER TO DENSITY

The effect of varying percentages of water upon the density in grams per cubic centimeter was determined for neat lime paste only. The results are shown in Figure 2, where percentage of mixing water

is plotted against density. For neat-lime paste of the hydrate used, the amount of water that resulted in greatest density was found to be 63 per cent of the dry weight of hydrated lime. The water used for normal consistency of the same hydrate was 82 per cent. With only that water which gives greatest density, a mortar is too stiff. More water swells the mixture and acts as a lubricant, making it workable.

4. EFFECT OF WATER ON SHRINKAGE

Some tests on a hydrated lime made plastic by grinding with quicklime (see section 1 of Chapter VI) show a remarkable increase in shrinkage with an increase in mixing water.

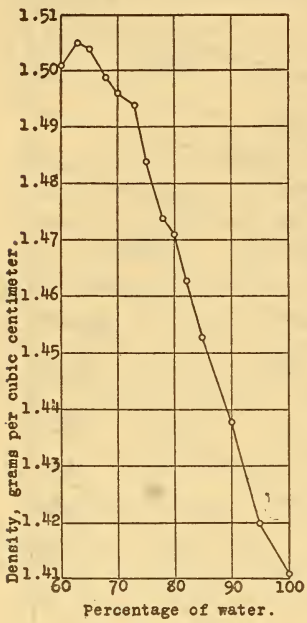

FIG. 2.—*Effect of water content on density of neat lime paste*

5. SUMMARY

From the above discussion it will be seen that the addition of lime to cement mortars increases the water requirement for the same consistency very nearly in proportion to the amount of lime added. Shrinkage in mortars increases with an increase in the percentage of mixing water present; therefore, additions of lime are an indirect cause of greater shrinkage.

Since the density of lime paste can be reduced by additions of water, and since the lime paste fills the voids in the sand, it follows that excesses of water will reduce the density of mortars also. A mortar of the greatest possible density is too stiff to be used and must have more water in order to be workable, even though this does reduce the density.

The time of set of mortars containing lime is influenced by the amount of water which must dry out, and the amount of water retained in the mortar influences the rate of carbonation of the lime.

III. PLASTICITY

1. TESTS WITH THE PLASTICIMETER

It is well known that a variation in the amount of mixing water is not sufficient to give all mortars the same workability and that differences in this property are largely dependent upon the nature of the ingredients composing the mortar. This led to the practice of adding finely divided materials to those mortars which did not work smoothly under the trowel. The improvement in workability

is one of the principal arguments advanced in support of the practice of adding lime to Portland cement mortars. In order to determine by mechanical measurement whether or not lime increases the workability of cement mortars, the Bureau of Standards plasticimeter was used in measuring the plasticity of various mortars; the plasticity as thus determined was taken to be an index of the workability of each mortar.

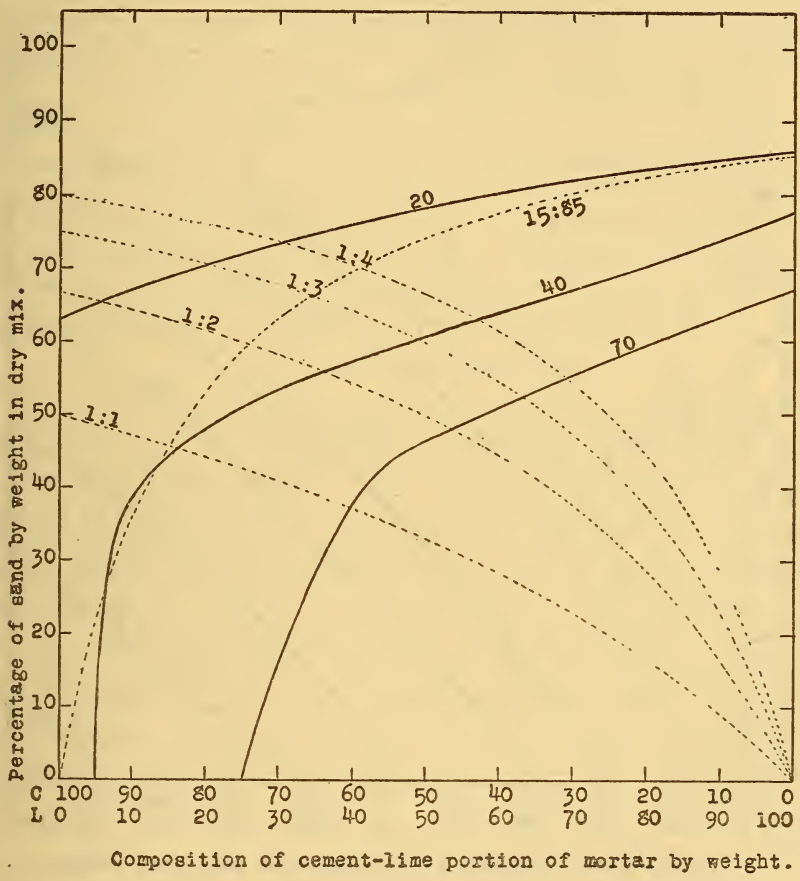

FIG. 3.—*Plasticity of cement-lime mortars*

An increase in plasticity is indicated by an increase in the numerical value of the plasticity figures obtained for the 231 mixtures. These values were used in locating the curves in Figure 3, which show the compositions of the mortars with plasticity figures of 20, 40, and 70. Though some of the figures were over 100, there was not a sufficient regularity to warrant plotting any curves above 70.

These curves show that a greater amount of lime is required in the leaner cement mortars than in the richer mortars to produce the same plasticity. About 16 per cent of the total dry weight in the

1:1 cement mortar gave a plasticity figure of 70, while the amount of lime necessary to produce this result in the 1:4 cement mortar increased to about 30 per cent of the total dry weight.

Plasticity, as measured, was a determination of the relative resistance of the mortar to spreading when on an absorbent base. The less this resistance, the higher was the plasticity figure. This is not to be interpreted as a measure of the effort required to spread a

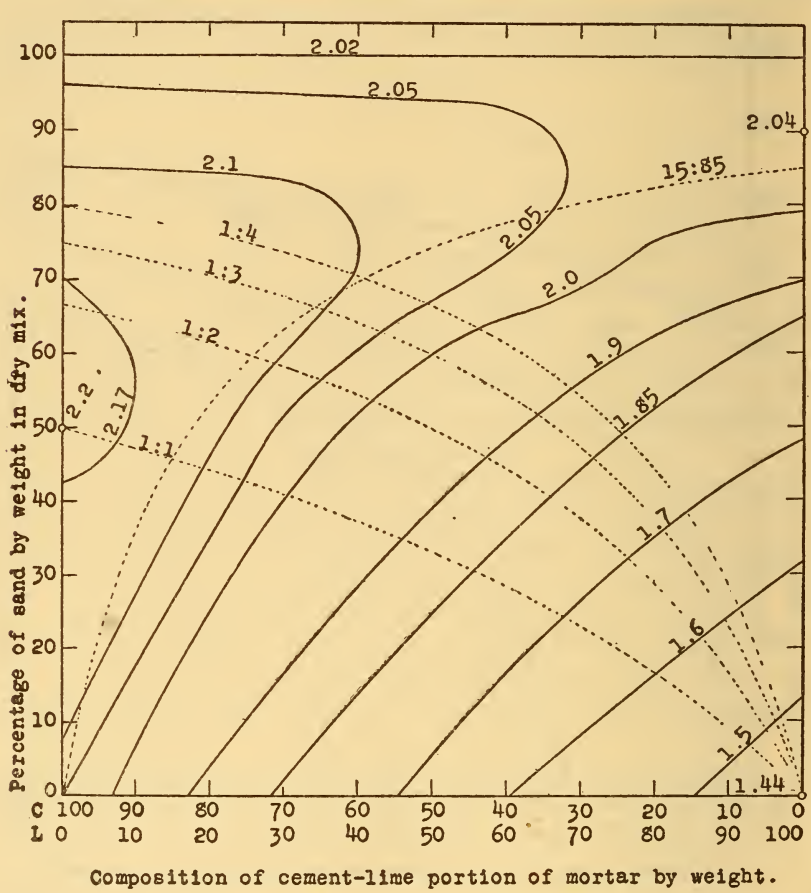

FIG. 4.—*Density of fresh cement-lime mortars (in grams per cubic centimeter)*

mortar under all circumstances, for it is relatively severe. The workability of the freshly-mixed mortar is often noticeably increased by the addition of a fine material, such as a "short-working" mason's hydrate, which does not have the ability to retain water against suction to any great extent. In laying stone and brick that have been wet the mason experiences no interference from an absorbent base.

The experimental evidence leads to the conclusions that, for a given plasticity, where more lime is added more sand can also be added,

but at the expense of strength. Lime increases the plasticity of cement mortars, so that a 1 : 1 : 6 cement-lime mortar by volume is more easily worked than a 1 : 3 cement mortar. The plasticity of two materials, when mixed together, is not an additive function of their plasticities when measured separately.

IV. DENSITY

The density of a plaster is important in relation to the acoustic properties of a wall. Also it is known to affect thermal conductivity, fire resistance, and the total weight of plaster on walls and ceilings. Considering density to be weight per unit volume, it will be seen by a study of the curves in Figures 4, 5, and 11 that the 1 : 1 cement mortar had greatest density, while the mortars approaching neat cement had greatest strength. However, when dealing with a mortar of a fixed cement-sand ratio, a definite relation will be found to exist between density and strength. Any change which reduces the voids, without loss of any of the materials present in unit volume of mortar, will increase both the density and the strength.

1. EFFECT OF ADDING LIME

A study of the curves in Figure 4 shows that the addition of lime did not increase the density of fresh cement mortars which were much richer than 1:6 by weight. This is in agreement with results obtained by Scofield (53) for fresh mortars. (This reference to Scofield's results on density appears to be warranted, for, by the use of the values for specific gravities which he gives, it was found that the changes in the solidity ratios corresponded to the changes in the density when expressed as grams per cubic centimeter.) However, a comparison of Figures 4 and 5 shows that the addition of lime increased the density of richer mortars which had dried; in this case the additions of 21, 44, 60, and 90 per cent of lime, by weight of cement, increased the density of 1:3, 1:4, 1:5, and 1:6 cement mortars, respectively.

Although shrinkage tended to increase the density of the mortars, this effect was more than offset by loss of water which evaporated; this loss in weight was dependent upon the percentage of mixing water in the mortar, and an increase in lime increased the percentage of water required for the same consistency. The effect of additions of lime on the density of cement mortars, both wet and after drying, are shown by the curves in Figures 4 and 5.

2. RELATION OF CEMENT TO VOIDS AND DENSITY

The voids occupied 35 per cent of the volume of the dry Potomac River sand, and yet greatest density of mortar was obtained with cement and sand mixed in equal proportions by weight (approximately

equal by volume also). (See figs. 4 and 5.) It is impossible to fill the voids in sand with just the amount of cement theoretically required, for in the mixing some fine particles of cement lodge between the sand grains and hold them apart.

From a study of Figure 5 in conjunction with Figure 11, it is seen that the volume of cement must exceed the volume of voids in the sand in order to obtain the greatest density of mortar, and that while

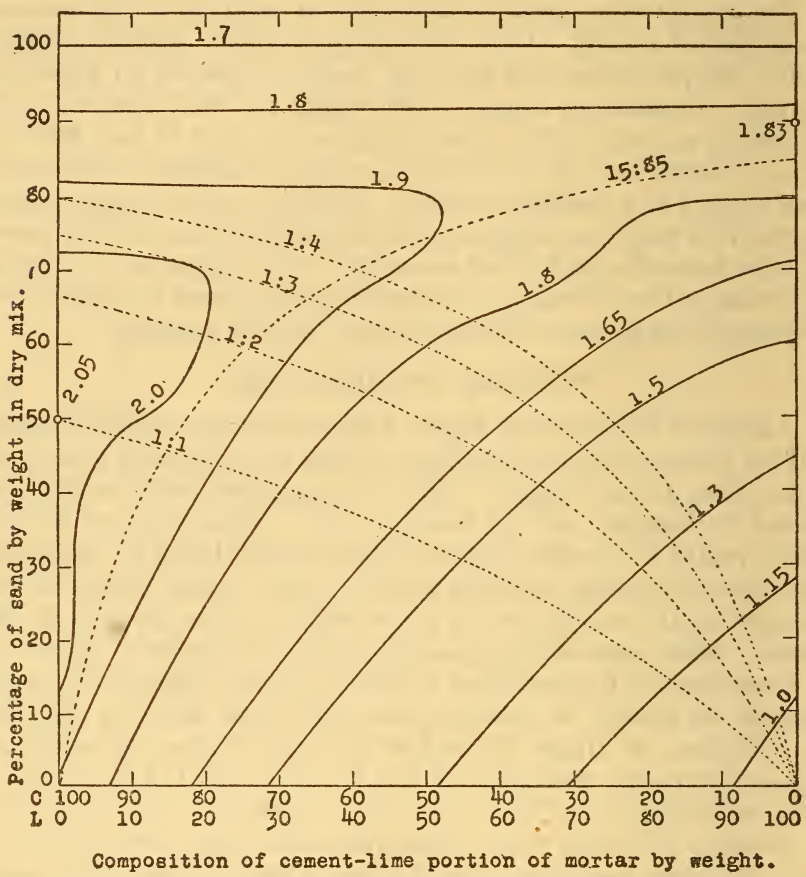

FIG. 5.—*Density of cement-lime mortars after drying (in grams per cubic centimeter)*

there is a limit to the amount of cement which can be added to produce greatest density, the strength continues to increase with further additions of cement. This statement concerning the cement ratio is based on the weights of unit volumes of different mixes.

A reference to Figure 5 will show that the density of 1:1 cement mortar after drying was 2.05 g per cubic centimeter, which was considerably more than the density of either cement or sand alone after being wetted and then allowed to set and dry. This shows that the

volume of the mixture was less than the sum of the volumes of the sand and cement measured separately; therefore, it is to be noted that the 1:1 cement mortar contained more than 50 per cent as much cement as was contained in the same volume of neat-cement mortar. This is of interest, since specimens which are tested are usually of equal volumes.

3. CONCLUSIONS

In order to obtain a workable consistency, more water must be added to a mortar than that amount which results in greatest density; additions of lime in small amounts can increase the density of lean cement mortars—the leaner they are the more effective is the lime in this respect; and the volume of cement must exceed the volume of voids in the sand in order to obtain maximum density.

In evaluating density of a mortar with reference to its various uses it is found that where the density is low the thermal conductivity of a plaster is less, the total weight of plaster on walls and ceilings is reduced, and the fire resistance of a mortar is only slightly affected, but the permeability is greater and the strength is less than where the density of the mortar is high.

V. TIME OF SET

Slow-setting plasters have a disadvantage in practice, for the scratch coat made from them hardens so slowly that considerable delay is often experienced before the other coats can be applied. It therefore, will be a question of practical interest to consider some factors influencing the time of set of cement-lime mortars.

1. EFFECT OF CEMENT

The curves of Figure 6 show the time of set for various mortars. Where the cement content is high the most rapid setting occurs. The cement was not varied in the mortars by less than 5 per cent of the total dry weight; this difference in cement content was sufficient to reduce the time of set even in mortars containing the greatest proportion of lime. Lime mortar, 15:85 by weight, set in 60 hours, and the curves in Figure 6 show that when cement was added to the extent of 43 per cent of the weight of the lime the time of set was reduced to 30 hours, and when the added cement equaled the lime in weight the mortar set in about 18 hours.

2. EFFECT OF LIME

It is seen from the curves in Figure 6 that, in general, the addition of lime will retard the setting of cement mortars. In the case of mortars containing 10 per cent or less of cement a small addition of lime decreased the time of set, as measured by the Vicat needle,

but these mortars are too lean for practical use in situations where a reduction in time of set would be of any consequence.

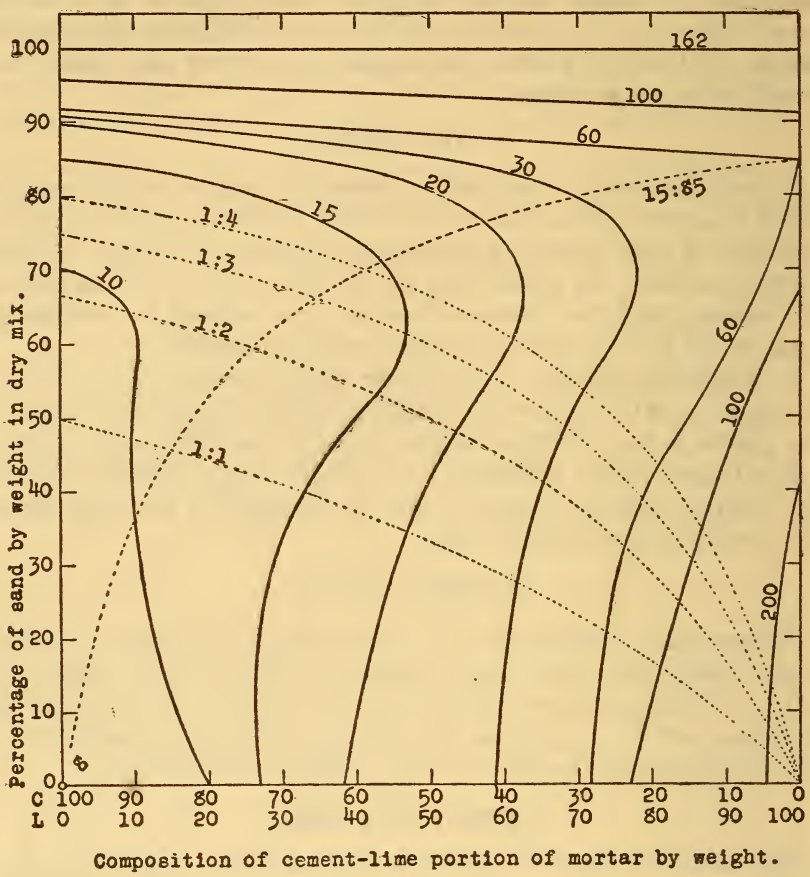

FIG. 6.—*Time of set of cement-lime mortars, in hours*

The effect of water on time of set and the relation of water content to the rate of carbonation have been mentioned in Chapter II.

VI. VOLUME SHRINKAGE

The experiments with fresh mortars show that when they dry out there is a certain amount of shrinkage. According to Figure 7 the volume shrinkage varied from practically 0 per cent for sand up to 3.2 per cent for neat cement paste and 9 per cent for neat lime paste. This shrinkage tends to result in cracks in the plaster or in the separation of the mortar from the brick or stone. The ingredients of a mortar are factors which largely determine how much the mortar will shrink, therefore a study of these factors is necessary in order to control shrinkage. The absorption of the base upon which the mortar is applied, the amount of troweling, and atmospheric conditions immediately after application also have some effect on shrinkage.

1. EFFECT OF A VARIATION IN MIXING WATER

In connection with some work on plastering sands at this bureau tests were made on mortars in which a plastic hydrated lime was used, the lime being prepared according to Welch's patent (106). These mortars contained various percentages of sand; but the variable of special interest was the percentage of mixing water used, this being varied by two different amounts for each mortar. The shrink-

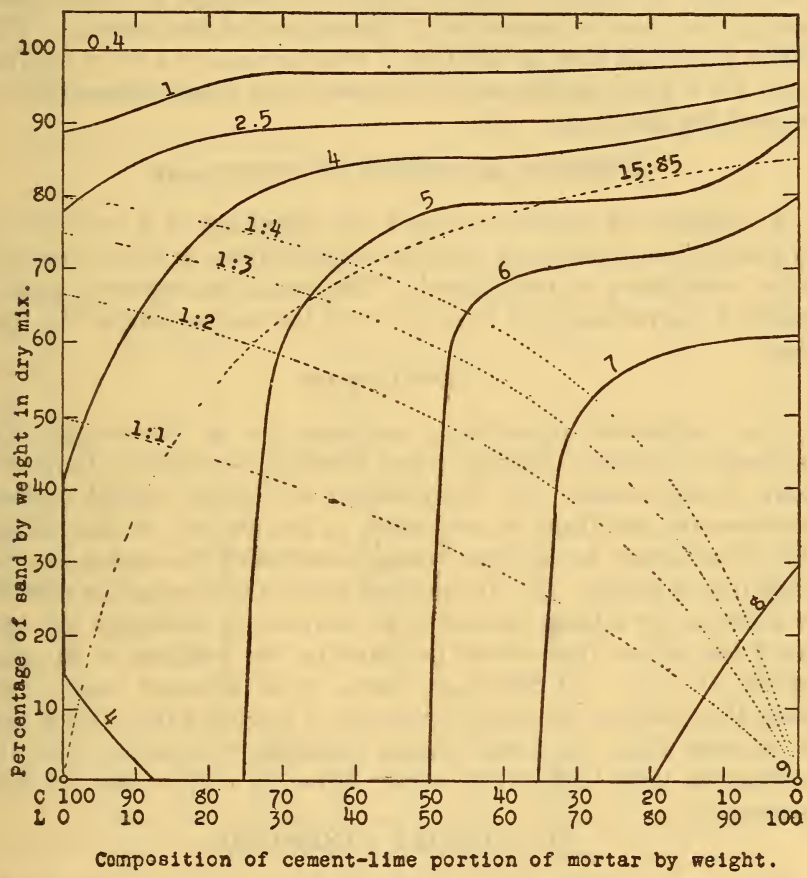

FIG. 7.—*Shrinkage of cement-lime mortars (percentage decrease in volume of wet mortar on drying)*

age of each of these mortars was much greater where extra water was used. The mixing water required by the neat lime paste for normal consistency, without soaking, was 68.3 per cent, and the shrinkage was 15.9 per cent, but when soaked overnight the water required for the same consistency was 85 per cent and the shrinkage was 27.7 per cent. The increase in shrinkage is seen to be very sensitive to the addition of extra water.

The mason's hydrate used in this research on shrinkage required 82 per cent of water for normal consistency, nearly as much as the soaked plastic hydrate, but the shrinkage was only 9 per cent. This shows that the percentage of mixing water is not the only factor influencing shrinkage.

2. EFFECT OF LIME ON SHRINKAGE

A study of Figure 7 shows that the shrinkage of cement-lime mortars increased in proportion to the amount of lime present. This is due to the fact that an addition of lime increases the water requirement for a given consistency. No point was found where lime decreased the shrinkage.

3. EFFECT OF CEMENT ON SHRINKAGE

An increase in cement increases the shrinkage of a mortar, but to a much less extent than does the same increase in lime, where the same consistency is maintained. This would be expected after a study of the shrinkage of neat pastes of the cement and of the lime used.

4. CONCLUSIONS

The conclusions concerning shrinkage are as follows: (1) The tendency of mortars to shrink when drying is increased by the use of extra mixing water. (2) The addition of lime to cement mortars increases the shrinkage in proportion to the amount of lime added; this is due largely to the extra mixing water which the mortar requires when lime is added. (3) The general effect of increasing the richness of a mortar by adding cement is an increase in shrinkage but to a much less extent than would be noted by the addition of an equal weight of lime. (4) Shrinkage varies with different limes, even when they contain the same percentage of mixing water; this is true of cements also. (5) Sand acts as a stabilizer in mortars, for the decrease in their tendency to shrink is nearly proportional to their leanness.

VII. TENSILE STRENGTH

Without a certain amount of strength mortars would not be capable of resisting the various strains and stresses which occur in them when in place. For this reason it became customary to include a strength test among the specifications for cement and for mortars. Tensile-strength tests were supposed to give a general indication of the resistance of a mortar, and were the tests usually specified, since they are much easier to make than compression tests. Tensile-strength tests were made in this research in order to compare the results with those obtained in the compression tests.

1. EFFECT OF LIME ON TENSILE STRENGTH

The slope of the curves in Figure 9 shows that there was a gradual decrease in the tensile strength of cement mortars with the addition of lime to all mortars richer than 1:3; but the tensile strength of leaner cement mortars was increased by the addition of lime. Adding 25 per cent of lime, by weight of cement, to the 1:3 cement mortar

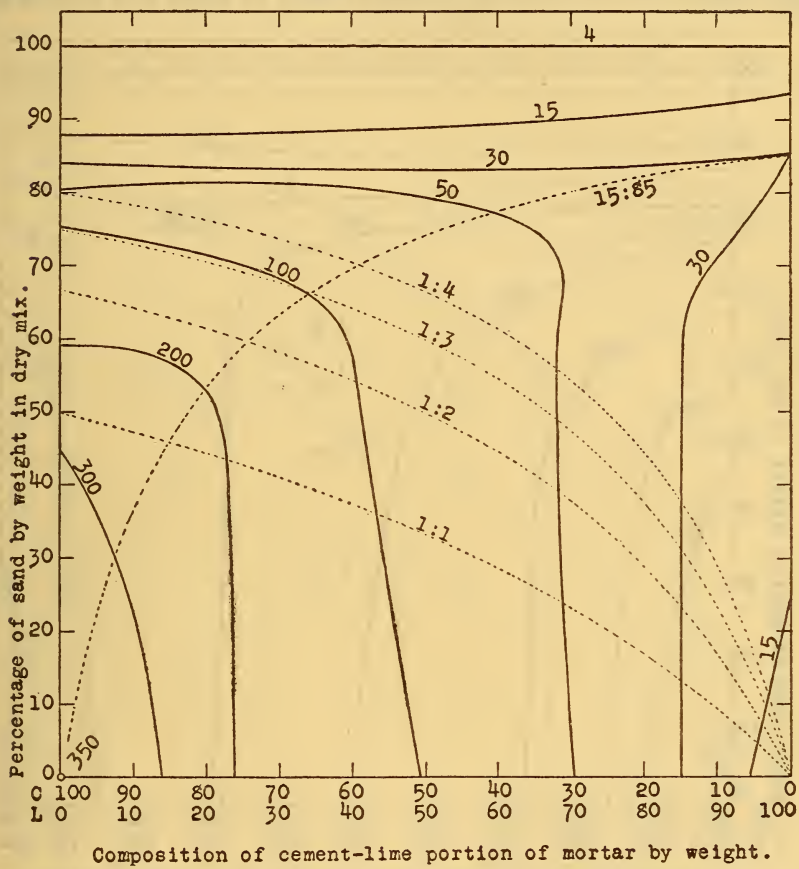

FIG. 8.—*Tensile strength of cement-lime mortars in seven days (pounds per square inch)*

resulted in only a trifling reduction in tensile strength when aged for 28 days. Adding lime to the same extent to the 1:4 cement mortar resulted in maximum increase in tensile strength at the same age. In straight lime mortars the greatest tensile strength resulting in 28 days was obtained when the lime was 20 per cent of the combined weights.

2. EFFECT OF CEMENT ON TENSILE STRENGTH

From the curves in Figure 9 it is seen that the addition of cement to neat lime increased the tensile strength, but the increase in strength

is not so rapid as that noted when cement is added to sand. (The latter case is merely the reciprocal of adding sand to cement.) One reason for this difference in the rate of increasing strength must be the fact that lime has greater bulk than the same weight of sand, so that lime resulted in distributing the cement throughout a greater volume. On the other hand, the sand had larger voids into which the cement could be worked, which tended to make still greater the

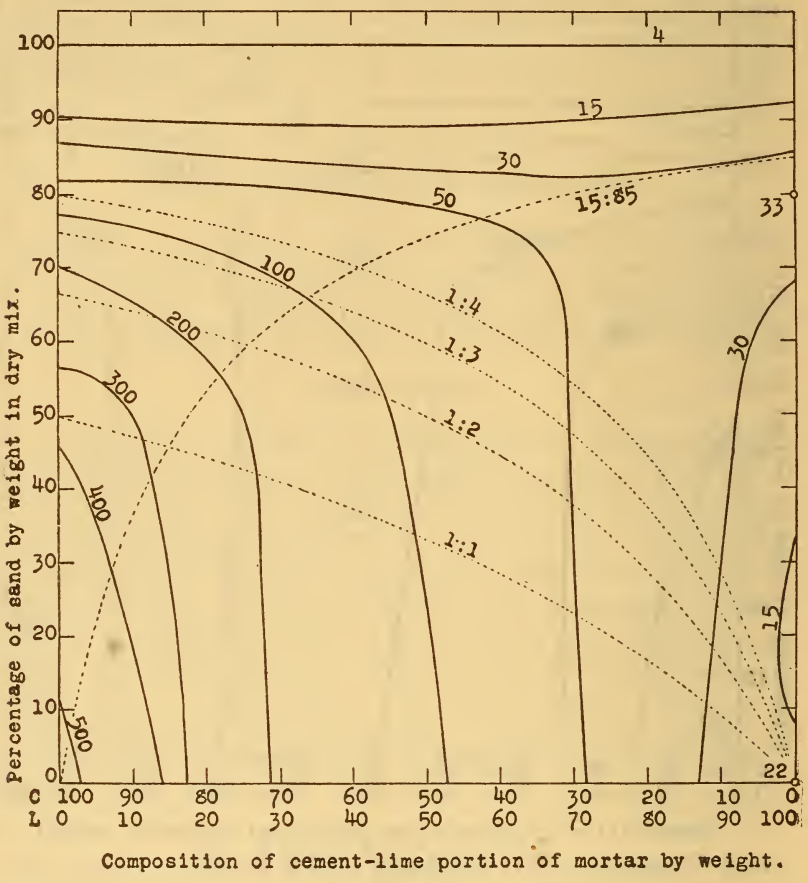

FIG. 9.—*Tensile strength of cement-lime mortars in 28 days (pounds per square inch)*

difference in the resulting volumes of lime and of sand to which the same weight of cement had been added. The general effect of increasing the cement content of cement-lime mortars was an increase in strength. However, in the lime mortar of the proportions 15:85 by weight, no appreciable increase in strength was noted until the added cement was over 25 per cent of the lime by weight, which is shown by the curves in Figure 9.

3. EFFECT OF AGE ON TENSILE STRENGTH

A comparison of Figures 8, 9, and 10 will show how the tensile strength of all the mortars changed with age. While sand probably remains neutral with the passage of time, and lime tends to increase in strength as carbonation progresses, another phenomenon was noticed in the aging of these cement-lime mortars. In most cases

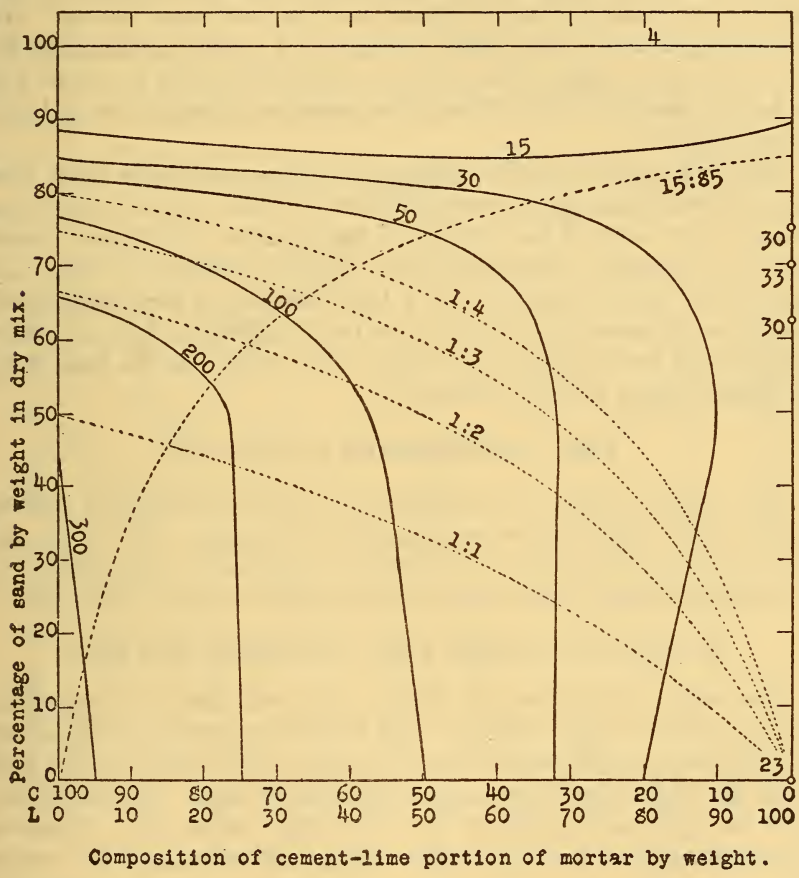

FIG. 10.—*Tensile strength of cement-lime mortars in 90 days (pounds per square inch)*

where the mortars contained cement the tensile strength was less at 90 days than at 28 days. This result is attributed to a retrogression in the tensile strength of the cement which was used.

The effect of age on lime mortars can be seen from the results below, which include the maximum tensile strengths obtained for any mixtures of sand and lime at the ages of 7, 28, and 90 days.

Age in days	Lime, by weight	Sand, by weight	Tensile strength
	Per cent	*Per cent*	*Lbs./in.²*
7	15	85	30.6
28	20	80	33.0
90	30	70	33.5

This result is typical of many others recently obtained in this laboratory. The leaner lime-sand mortars are more porous, and, air having better access, they carbonate at a more rapid rate, and invariably the mortar which gives greatest strength at seven days is leaner than the one which gives greatest strength for a longer aging period.

In a 1:3 cement mortar, additions of lime will have little effect on the tensile strength, provided that the lime added is not more than 25 per cent of the weight of the cement. In leaner cement mortars, increases in strength result from the addition of lime, and more lime can be added. In a lime mortar of any proportions, additions of cement will increase the tensile strength, but the cement added must be 25 per cent or more of the weight of the lime if any noticeable effect is to be attained.

VIII. COMPRESSIVE STRENGTH

The reasons given for studying the tensile strength of mortars apply also to this chapter on compressive strength. For some purposes mortars of a certain strength are desirable; it is therefore well to know what effect lime has on the strength of cement mortars.

1. EFFECT OF ADDING LIME TO CEMENT MORTARS

The slope of the curves in Figure 11 shows that each percentage of lime added to neat cement (until the lime approached 80 per cent of the total weight) reduced the strength of the cement much more than the addition of the same percentages of sand. This difference is to be explained as follows: The resulting volume of a 1:1 cement-lime mixture was more than three times the volume of the cement alone, and the cement content per unit volume was less than one-third that of neat cement. On the other hand, the volume of a 1:1 cement-sand mixture by weight was a little less than twice the volume of the cement alone; therefore, when equal volumes are considered, in this cement-sand mixture there was more than half as much cement as in neat cement.

A further study of Figure 11 shows that the compressive strength of cement mortars was not increased by the addition of lime when they were richer than 1:2. By interpolating from the curves, it is found that when the added lime was 10 per cent of the weight of the

cement the strength of this 1:2 cement mortar was increased by about 100 lbs./in.^{2}; and when 33 per cent of lime had been added, the strength was still equal to that of the cement mortar without lime.

As to the leaner cement mortars, an addition of 29 per cent of lime, based on weight of cement, gave a maximum strength of 1,165 lbs./in.^{2} to the 1:3 cement mortar, where the strength was 1,030

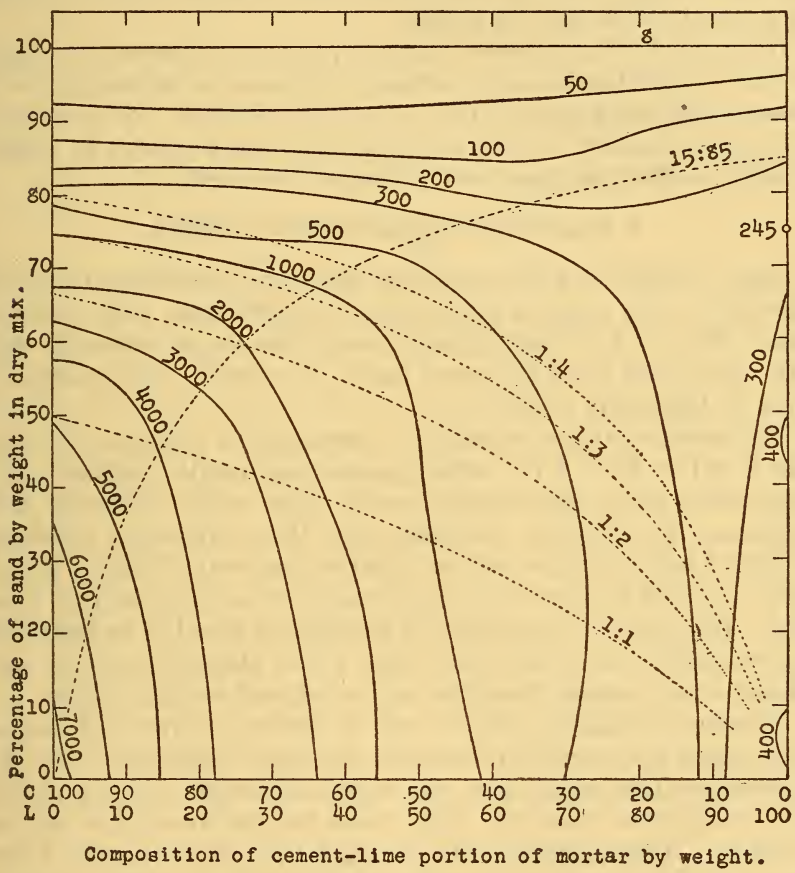

FIG. 11.—*Compressive strength of cement-lime mortars aged for one year. (Tests on 2 by 4 inch cylinders, with results in pounds per square inch)*

lbs./in.^{2} without lime. The strength of 1:4 cement mortar was 359 lbs./in.^{2}, and a maximum strength of about 700 lbs./in.^{2} resulted when the added lime was 80 per cent of the weight of the cement. These results refer to mortars which had aged in air for one year. The fact must be emphasized that the above results were obtained with one brand of cement and one brand of lime; results should be expected to vary with different brands of materials.

2. CEMENT ADDED TO LIME MORTARS

There is to be noted in Figure 11 a critical range in the compressive strength of cement-lime mortars aged for one year, for all of those mixes in which the cement constituted 5 per cent of the total weight were uniformly weaker than the corresponding lime mortars without any addition of cement. There was no increase in the strength of any lime mortar where the cement was added in quantities less than 22 per cent of the lime by weight.

It appears to be necessary to add 25 per cent of cement, by weight of lime, before there is any noticeable increase in the strength of a lime mortar; and where the lime mortar is as lean as 1:3 by volume, it may be necessary to add as much as 50 per cent cement, by weight of lime, to effect an appreciable increase in strength.

3. RELATION OF CYLINDERS TO CUBES

Since cylinders and cubes are each used quite extensively in testing mortars, in this research compressive strength tests were made on both. Three 2 by 4 inch cylinders and three 2-inch cubes for each mix were made from the same batch of mortar. The results are given in Figures 11 and 12.

The average ratio of compressive strengths of cylinders to cubes was found to be 1:1.157, which means that results obtained from cubes were about one-seventh greater than results obtained from cylinders. It is usually estimated that the compressive resistance of 2 by 4 inch cylinders will be about 80 per cent of that of 2-inch cubes. In this research the average value for the cylinders is 86.4 per cent. However, the value for the cylinders is found to be nearer 80 per cent of the strength of the cubes if only those mortars are considered which contain about the amount of sand ordinarily used.

Cylinders containing 50 per cent of cement or over approached more nearly the strength of cubes of the same composition than did cylinders containing less than 50 per cent of cement, which probably accounts for the relatively high value for the average of all the cylinders. This suggests rather strongly that the conversion factor should be determined for the mortars that are to be used, instead of assuming that the same factor will suit all mortars regardless of their composition. The effect of the test methods also must be considered.

4. EFFECT OF VOLUME SUBSTITUTIONS OF LIME FOR CEMENT

Throughout this paper the object has been to preserve clearness by referring to mortars which were proportioned by weight, in which the use of lime is taken to be a percentage addition based on the weight of the cement. However, in order to satisfy those who

prefer to study the effects of lime and cement as substitutions, Figure 13 has been prepared from mortars aged for 28 days.

The curves marked 1:4, 1:3, 1:2, 1:1, and 1:0 represent mortars having those ratios by volume of cement plus lime to sand. Proceeding from left to right along these curves, there is a greater and greater subsitution of lime for cement by volume. (The scale at the lower edge of Figure 13 represents weight proportions and was used for the

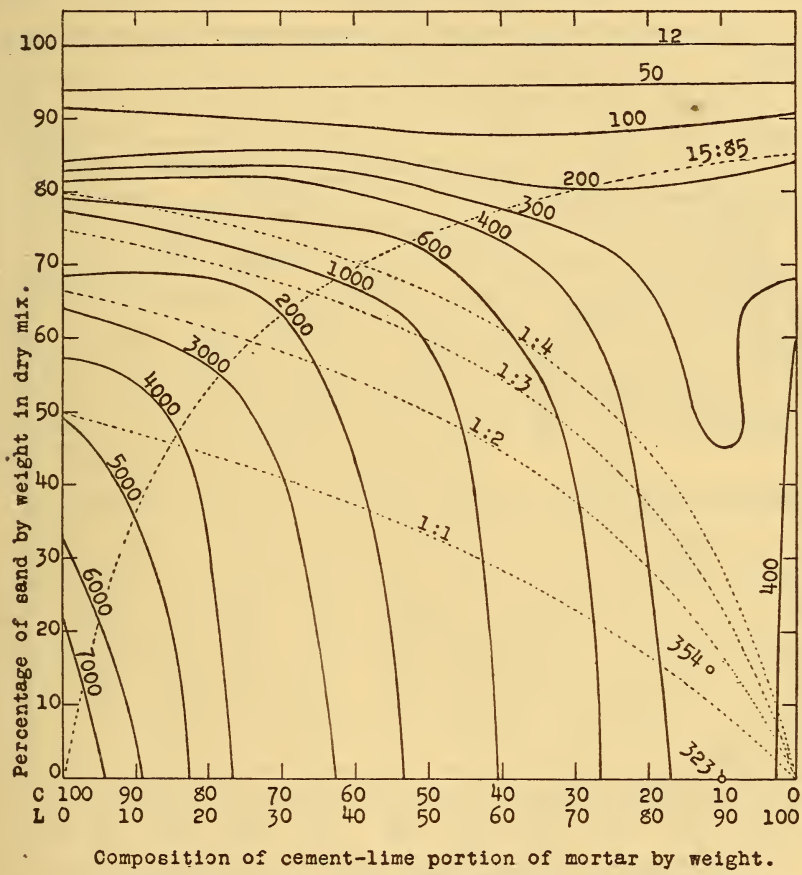

FIG. 12.—*Compressive strength of cement-lime mortars aged for one year. (Tests on 2-inch cubes, with results in pounds per square inch)*

sake of having all the figures uniform. It is not to be used as indicative of the corresponding volume substitutions.) The results show that all substitutions of lime for cement by volume resulted in a decrease in compressive strength. The result of the converse was an increase in strength. The addition of a certain percentage of lime to Portland cement mortar is much preferred to its substitution for a part of the cement. Addition rather than substitution is recommended by manufacturers of both cement and lime.

5. CONCLUSIONS

When lime was added to cement mortars not richer than 1:2, the compressive strength was increased. The maximum increase in strength, as well as the amount of lime required to produce this maximum, was found to increase with the leanness of the mortars.

Lime mortars to which cement has been added do not show noticeable increases in strength, unless the cement is added to the extent

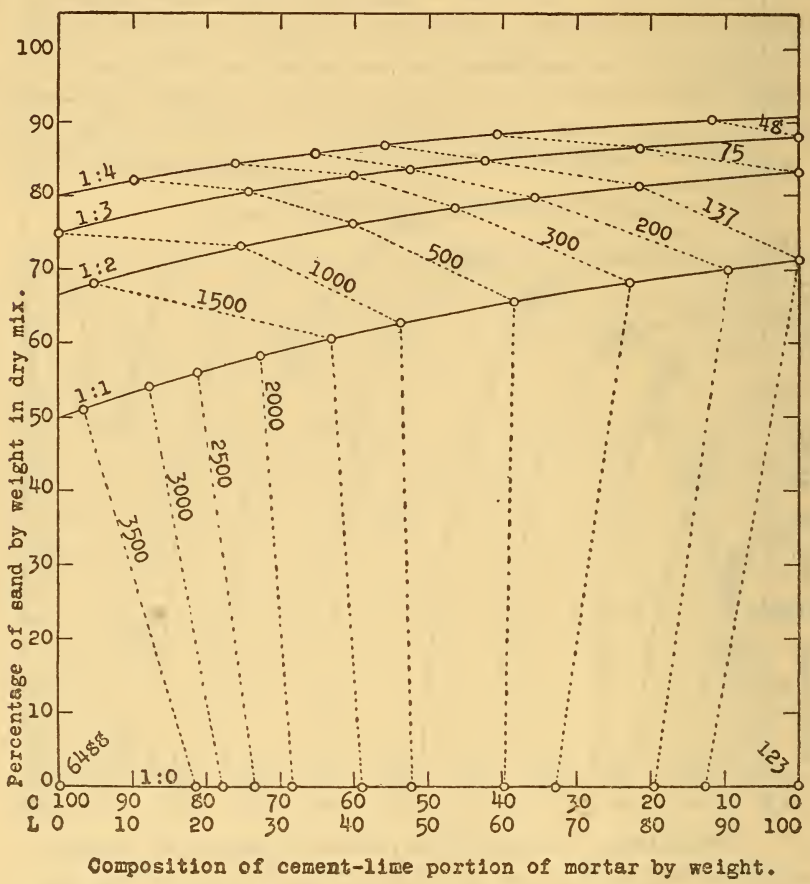

FIG. 13.—*Compressive strength of cement-lime mortars, proportioned 1:0, 1:1, 1:2, 1:3 and 1:4 by volume, with weight proportions given. (2 by 4 inch cylinders aged 28 days)*

of 25 per cent of the lime by weight and at least 5 per cent of the total dry weight of the mix.

It was found that results obtained for compression tests were somewhat higher for 2-inch cubes than for 2 by 4 inch cylinders, and that the ratio was not fixed, but varied somewhat with the composition of the mortars.

IX. RECOMMENDED PRACTICE

The preceding chapters have shown in detail how the properties of the mortar are affected by variations in its composition. This chapter embodies an attempt to evaluate the properites of a mortar, in order that the reader may be guided in giving due weight to the various conclusions reached.

1. INGREDIENTS OF A MORTAR AND CONSISTENCY

First, it should be remembered that the mortars under consideration consist, in general, of four ingredients—cement, lime, sand, and water. The proportions of the first three may be varied at the will of the operator. The percentage of water used is fixed within narrow limits by the composition of the mortar and by the fact that the consistency must suit the purpose for which the mortar is used. The effect of the composition of the mortar upon the water required for the same consistency may be expressed by the statement that, in general, lime paste will require much more water than will cement paste, but the water required by each will decline proportionally with increasing additions of sand. As to usage, a mortar of wetter consistency can be used for laying brick than for laying stone or for plastering, and the scratch coat of plaster for metal lath must be stiffer than the scratch coat for masonry.

2. COMPOSITION OF A MORTAR AFFECTS ITS PROPERTIES

A mortar having a high content of cement is characterized by high strength and by a short time of set; it is also fairly workable and shrinks some on drying. One having a high content of lime will have less strength, will be slower in setting, will be more workable, but will show more shrinkage. The chief characteristic which a high sand content gives to mortar is low shrinkage, but it also results in low strength and in poor workability. These principles are elaborated and shown graphically in Figure 14, where the mortars are divided into groups which are good, fair, or poor in respect to strength, time of set, plasticity, and shrinkage. An excessive amount of water may permit of easier application of a mortar, but at the expense of strength. The evaporation of this water may be accompanied by excessive shrinkage, or the mortar may be left porous. This high porosity is to be desired if light weight and low thermal conductivity are important; it is not desirable from the standpoint of strength or of permeability.

3. PORTLAND CEMENT STUCCO

(*a*) Scratch Coat on Lath.—The property of prime importance for the scratch coat of stucco on lath is strength. The keys of this coat must be strong enough to hold the stucco in place and the set

material must be sufficiently rigid to prevent breaking these keys during the application of the succeeding coats. A fairly rapid set is also desirable under modern building conditions. These requirements may be met by a Portland cement mortar as rich as 1:3, which customarily is used for the scratch coat of stucco on lath.

(*b*) Scratch Coat on Masonry.—For scarch coat on masonry, plasticity comes in as an additional important property because of

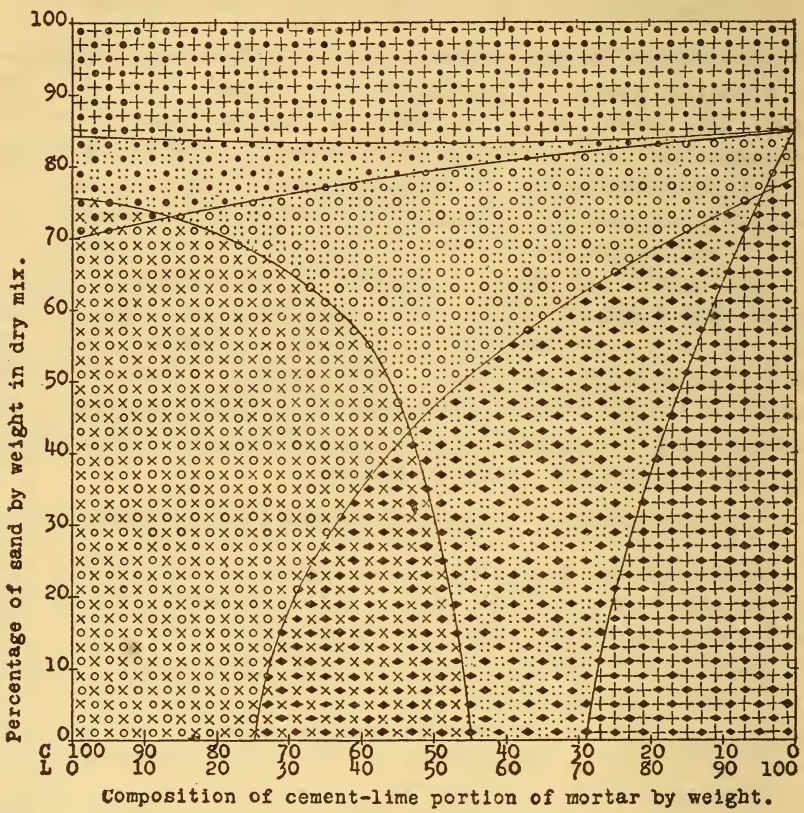

Fig. 14.—*Mortars which are good, fair, and poor in strength, time of set, plasticity and shrinkage, respectively*

Legend:
×=Hign strength, short time of set.
⁝⁝=Good strength and time of set.
+=Poor strength, long time of set.
✦=Good plasticity, high shrinkage.
○=Fair plasticity and shrinkage.
●=Poor plasticity and low shrinkage.

the difficulty in spreading the mortar over the more or less absorptive surface. In this case, where a 1:3 cement mortar is used, a concession may be made to the plasterer by permitting the addition of lime. The lime should be about one-tenth of the weight of the cement (one-fourth of the volume), since less than this would probably not be appreciably effective and more would increase the tendency to shrink and crack.

(*c*) Brown Coat.—In stucco work, where the scratch and finish coats are chiefly cement, the brown coat must also be made of cement, but lime may well be added to increase its plasticity. The proportions for this cement brown coat should be the same as for the scratch coat for cement stucco.

(*d*) Finish Coat.—The finish coat of stucco must be fairly plastic to permit of being spread over the set and dry brown coat. It must have low shrinkage to prevent the formation of cracks. If this coat sets with sufficient slowness to permit of thorough floating while the water is being absorbed by the brown coat, then the density of the finish coat can be increased and the shrinkage and cracking can be reduced. (While some absorption is thus a good property for the brown coat, it should not rob the finish coat of that water necessary for proper hydration of the cement.) Filling the surface pores leaves fewer lodging places for unsightly dust. This high density will also tend to prevent the penetration of water, which might cause the coat to expand and then to crack as the water dries out. Usual practice calls for a 1:3 cement mortar for this coat also. The plasticity can be improved somewhat by the addition of lime, which should not exceed 10 per cent of the weight of the cement. The addition of lime will necessitate the use of more water, which will tend to increase both the shrinkage and the porosity; but if thorough floating is applied while the water is being absorbed by the brown coat and before the set has begun, the finish coat may be even denser than if no lime had been added.

4. LIME PLASTER

(*a*) Scratch Coat On Lath.—For plaster, where strength is of somewhat less importance than it is for stucco, and where the succeeding coats are to be of straight lime mortar, a reduction in cost can be made by the use of a 1:5 lime mortar by weight for the scratch coat on wood lath. This mortar can be improved in respect to strength and time of set by adding cement, but the cement must be at least 40 per cent of the weight of the lime to be effective. This gauging with cement is necessary where the scratch coat is to be applied to metal lath, in which case even more cement would be advisable.

(*b*) Brown Coat.—The brown coat must be reasonably plastic to permit of spreading it over the set scratch coat. For plaster a low density is desirable, not only because it means less weight for the wall as a whole but also because a less dense plaster is a poorer conductor of heat. High shrinkage is objectionable; the resulting cracks can be closed when the finish coat is applied, but they are apt to reopen. The brown coat must have sufficient strength to resist a moderate impact, but this property is not very important (except in such places

as laundries, trunk rooms, hotel kitchens, etc., where impacts are more likely to occur). Time of set is likewise of little importance, for the finish coat usually is not applied until the brown coat is dry, and it takes much longer for the brown coat to dry than to set. The above considerations lead to the recommendation of a lean lime mortar, with 15 per cent of lime by weight, for a brown coat plaster. This lime mortar will be sufficiently plastic for use; and when the mixing water has dried out, the brown coat will have a high porosity. The high sand content is required to keep down the shrinkage. Since strength and time of set are of minor importance, cement is not required.

If the brown coat for plaster or stucco is gauged with cement, it is important that the scratch coat should also contain cement, and if either coat is to be the stronger this should be the scratch coat.

(*c*) Finish Coat.—The finish coat of plaster is usually of lime and gypsum, a mixture not considered in this paper.

5. MASONRY MORTAR

A mortar for masonry should be fairly plastic, for this permits the mason to spread out a longer bed and to "butter" the bricks more easily. Shrinkage is of some importance, for when the mortar shrinks it pulls away from the ends of the bricks, leaving vertical cracks through the wall. A rather lean mortar of either cement or lime seems to meet the above requirements, and a mixture of equal parts of 1:3 cement and lime mortars by volume possesses advantages not found in either one alone. The lime gives it plasticity and the cement gives it the ability to set quickly. This is the mortar usually known as 1:1:6. For continuously damp situations the cement mortar should be used alone, without any addition of lime; in such cases below grade, if greater strength is desired, a richer cement mortar (1:2) could be used, for it would not have a chance to dry out and crack. For a further discussion and recommendation of mortars for masonry the reader is referred to (7) and (8) in the bibliography.

6. FIRE RESISTANCE

Where resistance to fire is a matter of prime importance, the scratch coat of lime plaster should contain at least 5 parts of cement to 4 parts of lime by weight (1 volume of cement to 2 volumes of lime). The fire resistance of lime scratch coat will be very much improved if this coat contains twice this amount of cement. The use of cement and cement-lime mortars in masonry walls which are long and high and of minimum thickness increases the fire resistance, for the stronger mortars give the walls greater resistance to lateral strains and to the eroding action of water from the fire hose than they would have with straight lime mortar.

7. SEA WATER AND ALKALI

Lime should be entirely omitted from plasters or mortars which are likely to be exposed to the action of sea water or alkalies.

The rôle of the mixer of cement-lime mortars should be that of an intelligent workman who secures the desired changes in the properties of his mortars by varying the proportions of his four materials—cement, lime, sand, and water. The properties are variables which can not all be changed favorably for a given purpose at the same time. The problem, then, consists in altering the proportions of a mortar until one obtains the most suitable combination of these variables for the purpose in view. The reader is referred to the preceding chapters for a discussion in detail of the ways in which each property of a mortar is made to vary by changes in composition.

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