DEPARTMENT OF COMMERCE

CIRCULAR
OF THE
BUREAU OF STANDARDS

S. W. STRATTON, DIRECTOR

No. 30

LIME: ITS PROPERTIES AND USES

[2d Edition]
JULY 6, 1920

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LIME: ITS PROPERTIES AND USES[1]

CONTENTS

I. INTRODUCTION

Since the first edition of this circular was published in 1911 the lime industry has made rapid advances. A great deal of experimental work has been accomplished in both the laboratory and

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[1] Prepared by Warren E. Emley, chief, lime section of the Bureau of Standards.

the field. This has formed the basis for numerous articles in the technical press.

Two books on the subject of lime contain general information of value to the industry: Bureau of Standards Technologic Paper No. 16, Manufacture of Lime, by Warren E. Emley, can be obtained from the Bureau; and The Source, Manufacture, and Use of Lime, by Burchard and Emley, was published by the United States Geological Survey as a part of the volume on Mineral Resources of the United States, calendar year 1913. This is now out of print, but may be consulted in any public library.

The outstanding feature in the development of the industry is the rapid growth of the manufacture of hydrated lime in comparison with quicklime. Hydrated lime has found a wide market for addition to concrete in the construction of both buildings and roads. The practice of adding it to cement mortar for laying brick is almost universal. As a plastering material, its greater convenience has made it a serious competitor with lump lime, especially in the large cities where space and time are important considerations. As a fertilizer, it has gained in favor over lump lime because the farmer has found he can spread it more evenly, and can keep it from one season to the next with less danger of deterioration. Even in the chemical industries there is a marked tendency toward the use of hydrated lime rather than quicklime.

The past few years' experience has resulted in the permanent adoption of certain new types of equipment for the manufacture of lime, and the permanent rejection of other proposed types. Two new kilns and two new hydrators have been developed. The rotary kiln is gradually being abandoned, and producer gas is coming to be the favorite fuel where wood or oil is not available.

During the war the manufacture of lime was declared to be an essential industry. Large quantities of lime were used in the buildings erected by the United States Housing Corporation. The use of lime as a fertilizer was decided to be an economic necessity. Of far greater importance, however, was its use as a chemical reagent in the manufacture of guncotton, leather, sugar, paper, etc.

II. LIMESTONE

Limestone is one of our commonest rocks. It is of sedimentary origin, having been deposited originally from solution by living organisms, or by chemical or physical processes not related to changes in living matter. It consists essentially of calcium carbonate, but, as may be expected from its origin, is never found pure. The impurities generally present are magnesia, iron, alumina, and silica.

On the basis of chemical composition, limestones may be divided into several classes. Very pure crystallized limestone is known as calcite. As the content of magnesia increases, the stone is called magnesian limestone until the ratio of calcium carbonate to magnesium carbonate becomes 100 to 84, when the name is changed to dolomite. If the magnesia content remains low, but the other impurities increase, the rock is known as argillaceous (clayey) limestone, natural cement rock (with suitable clay content for cement manufacture), and calcareous shale.

Limestones may also be classified according to their physical properties, as hard or soft, porous or dense, coarsely crystalline or fine grained. When metamorphosed—that is, when through the agency of heat limestone has been recrystallized after deposition—it is known as marble.

III. LIME

1. METHOD OF MANUFACTURE

In the manufacture of lime, limestone is quarried, broken into convenient sizes, and burned in a kiln. There are three types of kilns in common use, the pot kiln, the patent kiln, and the rotary kiln. All consist essentially of shafts lined with fire brick. The stone is fed in at the top and the lime drawn out at the bottom. In the pot kiln fuel is fed in with the stone in alternate layers; the patent kiln is provided with external fire boxes, so that only the gases of combustion come into contact with the stone; the rotary kiln is of the ordinary type used in the cement industry. Of the three, the patent kiln is much the best for the production of lime, because where the fuel is in actual contact with the stone the ashes of the fuel will contaminate the lime produced. This objection does not, of course, apply to rotary kilns fired with gas. Rotary kilns, while useful for the calcination of small pieces of stone, have not proven satisfactory from an economic standpoint. Their fuel efficiency is too low and their original cost too high to enable them to compete successfully with the modern patent kiln.

Some limestones are composed of coarse crystals, loosely bound together, and others contain so much silica that dicalcium silicate is formed during the burning. This substance increases in volume on cooling,[2] thus causing disintegration of the lime. If either of these kinds of stone is used the fine powder produced will choke the draft in a shaft kiln, and consequently a rotary kiln must be

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[2] Day and Shepherd, The Lime-Silica Series of Minerals, Jour. Am. Chem. Soc., p. 1089; 1906.

used. It is well to note that the quantity of silica is not so important as is its relative position in the stone. If the silica is concentrated in the planes bounding the crystals of calcite, it will be much more apt to cause trouble than if it is distributed throughout the stone. Chemical analysis will give no information on this subject, and it is the part of wisdom, when investigating a newly opened quarry, to insist upon having some of the stone actually burned in a lime kiln.

Limestone consists essentially of calcium and magnesium carbonates. During the burning process enough heat is supplied to break up these compounds. The carbon dioxide is driven off as a gas, leaving the lime, which consists of a mixture of oxides. The amount of heat to be supplied depends on the character of the stone, and may vary within rather wide limits. Under ordinary conditions calcium carbonate will break up at 898° C (1648° F).[3] At about 1200° C (2192° F) the impurities form chemical combinations with the calcium oxide. This results in incipient vitrification on the outside of the lump, so that when water is added it can not penetrate so readily, and the lime slakes more slowly. Therefore the temperature at which lime is burned may vary from about 900° C to 1200° C, or a little higher if the stone is very pure. The amount of heat supplied depends upon the temperature used, and also upon the duration of the burning. Consequently it is optional with the manufacturer whether he shall use a high temperature for a short time or a lower temperature for a long time. His choice depends on the economic relation between interest on investment and cost of fuel. However, the activity of the impurities becomes noticeable much below 1200° C, and therefore the lower the temperature at which the lime is burned the better will be its quality. This is the reason why wood-burned lime generally commands a higher price than that burned with coal. Moreover, the minimum temperature for the decomposition of calcium carbonate may be decreased from 898° C to 790° C (1454° F) by the introduction of steam into the kiln.[4] Thus the presence of steam in the gases of combustion from wood tends to the production of a better quality of lime.

From the above discussion it is apparent that both manufacturer and consumer are interested in having the lime burned at the proper temperature. This is recognized in all specifications by the statement that the lime must be well burned. A closer definition

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[3] J. Johnston, Thermal Dissociation of Calcium Carbonate, Jour. Am. Chem. Soc., p. 938; 1910.

[4] Orton and Peppel, Limestone and Lime Industry in Ohio, Geological Survey of Ohio, Bull. No. 4, p. 294; 1906.

of this property may be based on the fact that both underburned lime and overburned lime will slake more slowly than that which is properly burned. The rate of hydration, therefore, indicates the burning temperature.

2. DEFINITION AND CLASSIFICATION

A consideration of the burning process, as just described, shows that lime is merely limestone from which the carbon dioxide has been removed by heat. This, then, must constitute a definition of lime. The wide variation in the chemical and physical properties of limestone necessitates a similarly great difference in the kinds of lime. Therefore some system of classification becomes necessary. That adopted by the American Society for Testing Materials [5] is as follows:

High calcium: Not less than 90 per cent calcium oxide.

Calcium: Not less than 85 per cent nor more than 90 per cent calcium oxide.

Magnesian: Not less than 10 per cent nor more than 25 per cent magnesium oxide.

High magnesian: Not less than 25 per cent magnesium oxide.

The total amount of impurities (exclusive of carbon dioxide) shall not be more than 5 per cent in selected lime, or 7½ per cent in run-of-kiln lime. This Bureau has found it convenient to use a system based on the purpose for which the lime is best fitted, as building, finishing, chemical, or agricultural lime. Both systems of classification will be used in this circular.

3. GENERAL PROPERTIES

Since lime has such an indefinite commercial meaning, any description of its properties must be very general. There are, however, several properties which are common to all limes in a greater or less degree. Thus it may be said that lime is a white or nearly white substance which will slake when water is added to it. When lime slakes it enters into chemical combination with the water. This reaction generates heat and is accompanied by an increase in volume. Slaked lime when exposed to air will set. First the excess water evaporates, and then carbon dioxide from the air combines with the lime, converting it back to calcium carbonate. Setting is always accompanied by a decrease in volume, or shrinking.

The degree in which any lime possesses the above properties is more or less dependent on its chemical composition. For example,

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[5] Standard Specifications for Quicklime, C 5–15.

a dolomitic lime will slake more slowly, combine with less water, generate less heat, undergo less increase in volume, set more slowly, and shrink less than a high-calcium lime. This statement must be taken as a generalization, for the properties are decidedly influenced by the impurities, the temperature of burning, and many other factors.

When lime is exposed to the air it absorbs carbon dioxide and water. This air-slaking is accompanied by the generation of heat, so that if lime is to be stored it must be in an air-tight receptacle, or else precautions must be taken to prevent the outbreak of fire. Completely air-slaked lime is practically identical with finely ground limestone, and therefore has no value, as lime, for building or chemical purposes.

Underburned lime is produced when the temperature of burning is too low or the time is too short. The calcium carbonate which is then retained in the lime acts merely as an inert filler. Such lime can be used for certain purposes. Since underburned lime does not contain so much of the active calcium oxide, its reactions will be much slower than if it were burned in the proper manner. It is possible, therefore, to produce a lime having many of the properties of a dolomitic lime from a high-calcium limestone merely by underburning it.

Overburned lime is produced when the temperature of burning is too high or the time too long. The impurities which cause the trouble [6] may be contained in the stone itself, they may be introduced by the slagging action of the lime on the brick lining of the kiln, or they may be due to contamination with ash from the coal. Overburned lime will react similarly to lime burned in the proper manner, except that the reactions will take place much more slowly. There is no reason why it can not be used instead of good lime for many purposes, provided sufficient care is taken to insure its complete hydration before using. However, some of the compounds formed by the impurities in lime hydrate very slowly, so that it is hardly practicable to use an impure overburned lime for the final coat of plastering.

4. COMMERCIAL FORMS AND THEIR PREPARATION FOR USE

Lime is put on the market as either lump or ground lime. Lump lime is shipped in bulk, or in wooden barrels holding 180 or 280 pounds net.[7] Ground lime is lump lime which has been

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[6] Bleininger, Burning Temperature of Limestone, Proc. Nat. Lime Mfrs. Assn.; 1911.

[7] Federal lime-barrel law, Public, No. 228, Sixty-fourth Congress.

ground and screened, generally through 60-mesh. It is shipped in air-tight iron casks.

To prepare lime for use in building or plastering operations, it must first be slaked. This is accomplished merely by the addition of water, but there are several points to be noted in this connection. Calcium oxide generates so much heat during slaking that unless this heat is removed or some means provided to prevent too great a rise in temperature the lime will burn. It is not known just what this reaction is, but the resultant product, burned lime, will not slake, and acts very similarly to ground limestone. Therefore it is necessary, when slaking a high-calcium lime, to watch it and stir it continually. If every particle of lime is in intimate contact with plenty of water, this water will absorb the heat generated and prevent burning.

The use of too much water is also apt to be detrimental to the quality of the product. By keeping the temperature of the mass too low the excess water slows down the reaction, and this, through some unknown mechanism, impairs the plasticity of the product. This phenomenon is known as "drowning."

A high-calcium lime must be watched to prevent burning; a high-magnesian lime to prevent drowning. In either case the slaking of quicklime should be done by a skilled operator, preferably one who has had experience with the particular kind of lime he is called upon to slake.

After lime has been slaked sand is added to it. A lime putty, used without sand, will shrink so much on setting that it will crack to pieces and have no strength. The sand decreases the cost by making the same amount of lime cover a larger surface. It improves the spreading quality, decreases the shrinking when the lime sets, and produces a more porous mass into which the carbon dioxide can penetrate more readily, so that the setting takes place more rapidly.

The setting of lime is caused first by the evaporation of excess water, and finally by the absorption of carbon dioxide, causing the lime to revert into calcium carbonate.[8] Therefore, setting will take place more rapidly if the amount of carbon dioxide in the air is increased, as, for example, by the use of salamanders.[9] Dry carbon dioxide will not react with dry slaked lime,[10] so that it is

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[8] Emley, Hardening of Lime Mortar, Trans. Nat. Lime Mfrs. Assn.; 1914.

[9] Ashley, Trans. Nat. Lime Mfrs. Assn.; 1910.

[10] Wolters, Dinglers Poly. Jour., **196**, p. 344.

necessary for the air to be moist. Indeed, it is advisable to soak the mortar thoroughly at frequent intervals during the setting process.

The final, or "skim," coat in plastering is often put on without sand in order to obtain a better color.

IV. HYDRATED LIME

1. MANUFACTURE

Lime that has been slaked is an article of commerce under the name of hydrated lime. This substance is prepared by adding to quicklime just sufficient water to insure complete slaking, and under such conditions that the heat generated will evaporate all the excess water, leaving the product dry. Since slaking is accompanied by an increase in volume, the lumps of lime fall into powder during the process. Any impurities in the lime will not slake, will not fall into powder, and consequently any large particles of them can be removed from the finished product by screening.

2. PROPERTIES

Hydrated lime is a fine, dry powder, consisting essentially of calcium hydrate and magnesium oxide, for it is generally conceded that the magnesia does not slake during the ordinary process of manufacture. The quantity of water contained varies from 24.3 per cent for pure high-calcium hydrate to 11.3 per cent for impure dolomitic hydrate. The proportion of impurities is generally less than that in the lime from which it was made.

In building operations hydrated lime may be used for any purpose in place of lump lime, with precisely similar results. The consumer must pay the freight on a large amount of water, but the time and labor required for slaking lime is eliminated, and there is no danger of spoiling it either by burning or by incomplete slaking.

Hydrated lime will keep better than lump lime, because the powder packs together into a dense mass, rendering the penetration of carbon dioxide very difficult. It can be stored with absolutely no danger of fire.

3. COMMERCIAL FORMS AND THEIR PREPARATION FOR USE

Hydrated lime is put on the market in paper sacks of 50 pounds each. The Urschel-Bates valve bag is used almost universally. There are many varieties of hydrated lime, depending on the fineness of the grain. It can be obtained screened through any mesh from 10 to 200.

To prepare hydrated lime for use the mere addition of water is all that is necessary. It is a rather difficult powder to wet, however, so that it is advisable to let the hydrated lime and water stand for 24 hours before using. Or it can be used immediately if the hydrated lime is added to the water, rather than water to the hydrated lime.

V. USES OF LIME

1. LIME AND HYDRATED LIME

(*a*) BUILDING LIME.—By far the greatest use of lime is as a mortar for building purposes. Whether a dolomite or a high-calcium lime is best suited for this purpose has long been an important question for both lime manufacturers and builders. In considering this question the points of difference between the two limes should be noted.

A high-calcium lime slakes quickly and generates a large amount of heat, hence it is apt to burn if it is not watched carefully. A magnesian lime slakes slowly, generates comparatively little heat, and is never in danger of burning. A high-calcium lime increases in volume much more than a magnesian lime, and requires more water, both for the hydration and the formation of a paste. Magnesian mortars generally work smoothly and freely under the trowel, while high-calcium mortars are apt to be sticky and work "short." When laid in the wall, both limes set by absorbing carbon dioxide from the air. During this process a high-calcium lime shrinks noticeably, while the change of volume of a magnesian lime is much less. It must be borne in mind that the above properties are subject to radical modifications, due to different porosities of the stones or to different conditions of burning.

The usefulness of lime as a bonding agent probably depends more on the method in which it is handled than on its content of magnesium. Aside from the larger cities, where machine-mixed mortar can be had, the slaking of lime is generally left to unskilled labor. In such cases the kind of lime to be used is the kind the laborer is accustomed to handle. Thus a laborer used to high-calcium lime will probably not be able to get good results with a dolomite lime, and vice versa. Moreover, a high-calcium lime will give a much larger volume of putty than a magnesian lime, hence the laborer is deceived into adding an extra quantity of sand. However, this is not an unmixed evil, for the sand improves the spreading qualities of the mortar and lessens shrinkage. Masons generally prefer magnesian lime because it works more smoothly and sets more slowly. This latter property permits of a larger batch of mortar being made up and gives the mason plenty of time to spread it. On the other hand, the contractor prefers a quick-slaking lime, so that the job can be finished as soon as possible. The fact that a high-calcium lime gives a larger volume of putty and carries more sand is also of advantage to him.

As to the actual strength of the two mortars, recent tests conducted [11] by this Bureau indicate that mortars made of dolomitic limes are stronger than those made of high-calcium limes.

It has been shown [12] that the strength of a lime-sand mortar may be changed 25 or 30 per cent by different methods of adding the water or by using different kinds of sand. Thus the crushing strength of lime-sand mortar (1 part lime to 3 parts of sand by weight) when one year old was found to vary with the method of slaking, as follows:

	Kilograms per square centimeter
Water added a little at a time, with constant stirring	28.1
Water added all at once, no stirring	26.0
Slaked with large excess of water	32.1

The influence of the size and uniformity of the sand grains is shown by comparison of the crushing strength of lime-sand mortars (1 part lime to 3 of sand) when six months old, using different kinds of sand. The results are:

	Kilograms per square centimeter
Normal sand	26.6
Building sand	30.6
Fine sand	24.2

The sizes of grains of these sands are shown in the following table:

TABLE 1.—Per Cent of Sand Remaining on Sieve

Meshes per square centimeter	1	4	9	20	60	120	324	900	Through 900
Normal				0.0	0.5	89.4	0.6		
Building		0.0	0.8	5.2	19.5	19.0	31.0	17.0	7.5
Fine		.0	.1	.1	.9	1.9	28.5	61.0	7.5

These results, therefore, agree with the conclusions reached by Feret,[13] that a mixture of two grades of sand of different sizes

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[11] Emley and Young, Proc. Am. Soc. Test. Mat., **14**, p. 339; 1914.

[12] H. Butchartz, Luftkalke und Luftkalk-mörtel, Materialprüfungsamt; 1908.

[13] Feret, Les Matériaux de Constructions, **1**, p. 139; 1904.

gives a stronger mortar than when any particular size is used alone, and also that if the sand used is of one size only, the larger that size the stronger will be the mortar.

The strength of a lime morter, therefore, depends on a variety of conditions, chief of which is the method of preparing it. Magnesian limes give a stronger mortar for several reasons: (1) The greater shrinking of a high calcium mortar is apt to cause a weakening of the bond; (2) magnesian mortars contain less water and, therefore, there is more actual binding material contained in them; (3) the common practice of overloading the high-calcium mortars with sand tends to give a weaker material. However, the previous experience of the men who handle the lime may outweigh the advantage of the high content of magnesia.

For all building purposes hydrated lime is to be preferred to lump lime. By its use the time and labor involved in slaking the lime may be saved, and the experience of the laborer is eliminated as a factor in the problem. In this event the mortars will stand on their own merits, and dolomitic hydrate is therefore to be preferred.

This question of the strength of a mortar is apt to be given undue weight. Since masonry is assumed to weigh 150 pounds per cubic foot, then the compressive load (in pounds per square inch) at the bottom of a wall will be $\frac{150}{144}$ times its height in feet. A mortar with a compressive strength of 100 pounds per square inch, should, according to this reasoning, be able to carry a wall $100 \times \frac{144}{150} = 96$ feet high, or about nine stories. The compressive strength of the mortar is usually measured by crushing 2-inch cubes. For a homogeneous material the unit compressive strength varies with the shape of the specimen, being dependent upon the ratio between the least horizontal dimension and the height. In a cube, this ratio is one. A mortar joint in a wall may possibly be 9 inches wide by 30 feet long by ½ inch thick. In this joint the ratio is $9 \div \frac{1}{2} = 18$. If a mortar has a strength of 100 pounds per square inch when tested in the form of a cube, it should theoretically have a strength of 1800 pounds per square inch when laid up in the wall.

The decision between two limes should be made on the basis of previous experience and cost rather than upon strength.

(*b*) PLASTERING.—Lime to be used for plastering must work smoothly under the trowel, must not "pop" or "pit," and must not undergo too great a change of volume during setting, and, if it is to be used for the finish coat, it must have a good color.

It was noted above, when discussing the properties of the two kinds of lime, that magnesian limes work more smoothly under the trowel and shrink less on setting than high-calcium limes.

Cracking of plaster is in most cases traceable to faulty bracing of the building, settling of foundations, or similar causes. Sometimes it is due to the swelling of wood lath which had not been wetted sufficiently before the plaster was applied. In the undercoats of plaster the shrinking of the lime is counteracted by diluting it with sand. In the finishing coat, calcined gypsum is mixed with the lime. This sets before the lime has begun to shrink, and thereby prevents cracking.

The cause of popping or pitting is not very well understood. In some cases it has been attributed to the impurities in the lime, such as clay, iron oxide, silicates, and pyrites. These seem to form various chemical compounds during the burning, which hydrate very slowly and expand during the process. For this reason it is generally conceded that lime to be used for plastering must be more nearly pure than that for any other purpose. Another probable cause of popping is the slow hydration of particles of calcium oxide which have been burned during the slaking. This is one more reason for the preference of magnesian lime for plastering, although extraordinary care must be taken to slake the lime properly, whichever kind is used. Recent experiments lead to the belief that impurities in the sand are frequently responsible for popping.

Magnesian limes are also to be preferred because they are generally more nearly white than high-calcium limes.

On the other hand, a given weight of high-calcium lime yields a larger volume of putty than the same weight of magnesian lime, and hence will cover a larger surface.

The time of setting is an important item, since it regulates the time required between coats. High-calcium limes set more quickly than magnesian limes, but both are rather slower than the contractor would like. It is suggested that some accelerator might be added to the lime to hasten its setting, or an atmosphere of carbon dioxide might be created for the same purpose.[14]

For plastering, also, hydrated lime will generally be found more economical and convenient to use than lump lime. Moreover,

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[14] H. E. Ashley, The Spreading Quality of Mortars, Trans. Nat. Lime Mfrs. Assn.; 1910.

it has the important advantage of containing less impurities than the lime from which it was made.

(*c*) HYDRATED LIME AND PORTLAND CEMENT.—For both building and plastering purposes, hydrated lime may be used interchangeably with quicklime and is often preferred, especially for the final coat in plastering. Hydrated lime is added to Portland cement mortars to make them impervious in water. Quicklime will produce a similar effect, but from the nature of the substance it is obvious that hydrated lime is much more suitable.

In a series of experiments in which the Portland cement in a mortar was replaced by varying amounts of hydrated lime it was found: (1) That hydrated lime up to 15 per cent (by weight) of the cement does not materially affect the strength of the mortar, even when stored under water; (2) this amount of hydrated lime will materially increase the imperviousness to water of even a 1:5 cement-sand mortar; (3) the addition of hydrated lime increases the plasticity of the mortar and makes it easier to work.[15]

2. LIMESTONE, LIME, AND HYDRATED LIME IN THE CHEMICAL INDUSTRIES

Under this head are grouped all the uses of these substances which depend principally on their chemical properties. The three materials are discussed together because in some industries they may be used interchangeably.

Wherever in the following discussion it is stated that "the impurities are not harmful," it is meant simply that their presence is of no importance chemically. It must be remembered that they reduce the amount of the useful constituents of the lime, and may cause mechanical difficulties by forming a sludge which must be removed.

As stated in the section on hydrated lime, this product should contain fewer impurities (especially calcium carbonate) than the lime from which it was made. Moreover, it will keep better and is easier to handle than lump lime. In some industries the lime is used in a hydrated condition, and in all such cases, unless the heat generated by the slaking can be utilized, hydrated lime will prove more economical. It will cost more for freight per unit of available oxide because of its water content, but this will generally be counterbalanced by the saving in time, labor, and apparatus necessary when quick lime is used.

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[15] E. W. Lazell, Hydrated Lime and Cement Mortars, Am. Soc. Test. Mat., 8, p. 418; 1908. Also, Wig, Proc. Nat. Lime Mfrs. Assn.; 1911.

(*a*) Natural Cement.—Lime plays an important part in the natural cement industry. These cements, whether made from rock or from blast-furnace slag, are much more acid in character than Portland cement. It is to be supposed, therefore, that an addition of lime, by increasing the basicity, will increase the strength. Experiments have shown that the addition of 5 per cent of lime to some natural cements increases the tensile strength from 100 to 200 per cent.[16]

A hydrated lime high in calcium must be used. Magnesia is objectionable because it is apt to carbonate after the cement has set, which weakens it. Other impurities are of little importance. The lime may be added either during the grinding of the cement, or when mixing the mortar. The former time is to be preferred, since it permits more thorough mixing.

Lime improves the spreading qualities of the mortar, as well as increases the strength.

(*b*) Sand-Lime Brick.—Sand-lime brick, although a rather new material, is of some importance in the building industry. The process of manufacture consists in forming bricks of a mixture of sand and hydrated lime by means of pressure. The bricks are then treated with high-pressure steam, which causes chemical combination between the sand and lime. The lime may be hydrated before or after adding the sand, but hydration must be complete before the bricks are pressed, in order to prevent any further change of volume.

High-calcium lime must be used. Any large amount of magnesia is dangerous, because it will probably not be hydrated until after the brick is pressed into shape. The steam treatment will hydrate the magnesia, which will expand and either weaken or completely disintegrate the brick. The impurities generally present are not harmful, except in so far as they may cause the lime to slake more slowly. In fact, kaolin, up to 2½ per cent, may be considered beneficial.[17] Hydrated lime is to be preferred to quicklime because it is more easily mixed with the sand. This statement is made on the assumption that the hydrated lime is perfectly and completely hydrated. Most sand-lime brick manufacturers prefer to buy quicklime and hydrate it themselves, because they must be absolutely certain that the hydration is complete.

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[16] A. V. Bleininger, Manufacture of Hydraulic Cements, Geol. Sur. of Ohio, Bull. 3, p. 191.

[17] S. V. Peppel, Sand-Lime Brick, Geol. Sur. of Ohio, Bull. No. 5.

(*c*) GLASS.—Calcium oxide is a necessary constituent of plate, sheet, and bottle glass, and of a large portion of pressed and blown glass. It acts as a flux. Magnesia makes the glass more difficult to melt,[18] but is sometimes a valuable constituent when particular optical properties are to be obtained.

The calcium oxide is generally introduced as ground limestone, but in this industry also, the use of lime or hydrated lime is sometimes necessary in order to avoid the evolution of gas at high temperatures.

The ordinary impurities of limestone are, in general, of no importance to the glass manufacturer. For white glass, however, the content of oxide of iron must be less than three-tenths of 1 per cent of the stone.[19]

(*d*) CERAMICS.—Lime and magnesia, generally, however, as carbonates, are used to some extent as fluxes in the manufacture of pottery and porcelain. It has been found that for wares burned at moderate temperatures, calcium oxide tends to bring the points of vitrification and fusion close together, while magnesia tends to separate them, to lower the temperature of vitrification, and to decrease the change of shape due to burning.[20] On the other hand, if the ware is to be burned at higher temperatures, magnesia has little effect on the points of vitrification and fusion and increases the shrinkage.[21] In a series of experiments to determine the values of different bases when used as fluxes for a mixture of feldspar, flint, and clay, it was found that magnesia gave the best results of the five bases tried (oxides of calcium, magnesia, barium, strontium, and zinc). It gave an excellent color, high tensile strength, and only moderate shrinkage.[22]

The above results all indicate that magnesia is better than calcium oxide as a flux for ceramic bodies.

The carbonates are generally used, since they are the cheapest forms. Levigated natural whiting is preferred on account of high colloidal content.[23] In some cases, however, vitrification sets in before the carbonates are all decomposed, and further evolution of gas may cause pinholing or internal strain. Under

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[18] Gelstharp, Fallacies and Facts Pertaining to Glass Manufacture, Trans. Amer. Ceram. Soc., **12**, p. 327; 1910.

[19] Walter Rosenhain, Glass Manufacture, p. 45.

[20] A. E. Hottinger, Influence of Magnesia on Clays, Trans. Am. Ceram. Soc., **5**, p. 130; 1903.

[21] L. E. Barringer, Influence of Magnesia on Clays, Trans. Am. Ceram. Soc., **6**, p. 86; 1904.

[22] Herford Hope, Comparative Effects of CaO, MgO, BaO, SrO, and ZnO on Some China Bodies, Trans. Am. Ceram. Soc., **11**, p. 494; 1909.

[23] Ashley, The Requirements of Pottery Materials, Trans. Am. Ceram. Soc., **12**, p. 445; 1910.

these circumstances it is necessary to use either the oxide or hydrate. It is sometimes desirable to use the carbonates in wares burned at low temperatures in order to obtain a porous body.[24]

Since the quality of carbonate used is generally small, and the chemical composition of the mixture may vary slightly, it follows that the impurities generally found in limestones are entirely negligible.

In glazes, magnesium oxide tends to absorb SO_3 from the kiln gases with production of a scum appearance. Although this can be overcome by skillful firing, it makes a low magnesia content desirable in most glazes.

(*e*) WATER PURIFICATION.—Temporary hardness of water is caused by the presence of calcium carbonate. This substance is practically insoluble in pure water, but is held in solution by the presence of carbon dioxide, which is found in practically all natural water. If this carbon dioxide is removed, the calcium carbonate will be thrown out of solution. The carbonic acid may be removed by boiling, but it is cheaper to neutralize it with lime. The lime reacts with the carbon dioxide to form calcium carbonate, and, since the carbon dioxide is thus removed, this calcium carbonate, together with that originally present, will be thrown down as an insoluble precipitate. While any magnesium carbonate present in the water will be removed by the same process, the magnesium oxide in the lime will take no part in the reaction and must be considered as an impurity.

The lime to be used should contain as much calcium oxide as possible. The generation of heat on slaking is of advantage in this process, for the reaction takes place more efficiently at elevated temperatures. Therefore the quantity of impurities should be low, and the use of hydrated lime is not advisable.

(*f*) SODA ASH AND CAUSTIC SODA.—Most of the soda ash sold in this country is made by the ammonia-soda process. A solution of common salt is saturated with ammonia and the mixture is treated with carbon dioxide. When the resultant solution is evaporated, the soda ash is obtained by crystallization. Ammonia is expensive, and consequently the gas must be recovered and used again. For this purpose the mother liquor is treated with lime and distilled. The lime replaces the ammonia in its compounds, and thus the gas is set free and may be distilled off.

It is evident that this industry demands limestone, for both the lime and the carbon dioxide are used. The impurities in the

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[24] Bourry, Treatise on Ceramic Industries, p. 79; 1901.

stone are not harmful. It would seem that magnesium oxide should be as effective as calcium oxide in breaking up the compounds of ammonia, yet Lunge makes the statement that "magnesium limestone is not suitable for this industry." [25]

Solutions of caustic soda, which are used in the purification of cotton, rags, and wood pulp in the manufacture of paper and explosives, are made by treating a solution of soda ash with lime. The reaction produces insoluble calcium carbonate, which settles to the bottom of the tank, and caustic soda remains in solution. The lime for this purpose should be as pure and as high in calcium as possible. Magnesia and other impurities are objectionable because they are slow in settling out after the reaction is completed. This results either in contamination of the soda or in a decrease in the daily output of the plant. In this industry quicklime is preferable to hydrated lime because it hastens the reaction.

(*g*) BLEACHING POWDER.—Bleaching powder is an oxychloride of calcium which is formed by the action of chlorine gas on moist slaked lime. The resultant product is sold on the basis of available chlorine. Any impurities in the lime will lower the amount of chlorine absorbed and consequently the value of the product. Magnesia is especially objectionable because it forms magnesium chloride.[26] This substance absorbs water from the air and makes the powder sticky and hard to handle.

Hydrated lime is better suited for this industry than quicklime, because it contains fewer impurities, is easier to handle, and requires no preparation before using.

(*h*) CALCIUM CARBIDE.—This substance, used as a source of acetylene, is made by heating a mixture of lime and coke in an electric furnace. For this purpose the only useful ingredient of the lime is calcium oxide.[27] Magnesia and other impurities are objectionable because the whole charge must be fused, and electric power is too expensive to waste it by heating useless material. For the same reason quicklime is preferable to either hydrated lime or limestone.

(*i*) ILLUMINATING GAS AND AMMONIA.—When illuminating gas is made by the distillation of coal the crude product contains, among other compounds, carbon dioxide, hydrogen sulphide, and hydrocyanic acid. All of these would be objectionable to the consumer. Their removal may be effected by passing the gas through

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[25] Lunge, Sulphuric Acid and Alkali, 3, p. 37.

[26] Lunge, Sulphuric Acid and Alkali, 3, p. 440.

[27] G. F. Thompson, Acetylene Gas and Calcium Carbide, p. 47.

layers of moist slaked lime. For this purpose calcium oxide only is useful, although the magnesia and impurities are not harmful.[28] Hydrated lime is to be preferred to quicklime because it is easier to handle and requires no preparation.

(*j*) CALCIUM CYANAMIDE AND CALCIUM NITRATE.—These substances, known technically as lime nitrogen and nitrate lime, have recently been put on the market as commercial fertilizers. They represent means of converting the nitrogen of the air into plant food.

Calcium cyanamide is prepared by heating a mixture of lime and coke in an electric arc furnace and treating the fused mass of calcium carbide with nitrogen. The nitrogen is obtained from the fractional distillation of liquid air. Pure, high-calcium quicklime is required for this industry.[29] Any impurities are undesirable on account of the expense required to heat them.

If air is passed through an electric arc, the nitrogen and oxygen contained in it will combine. The oxides of nitrogen thus formed, when dissolved in water, produce nitric acid, which may be combined with any base to form the corresponding nitrate. Since lime is the cheapest of all bases, and has fertilizing value of its own, it is obviously the best base to use. Hence calcium nitrate is produced commercially by this method. Magnesia acts in a similar manner. The presence of impurities in the lime is a matter of indifference, and quicklime, hydrated lime, or limestone will produce identical results. Hydrated lime is probably the most economical.

(*k*) FERTILIZER.—Lime is used extensively as a fertilizer. The Department of Agriculture and the various State agricultural experiment stations have carefully investigated the use of lime for this purpose and have published their conclusions in several bulletins.[30]

A correlation of these results will lead to the following general statements: (1) A plot of ground is in need of lime when it fails to produce a good crop of common red clover, or when the clover crop contains patches of sorrel. (2) Lime should never be used alone, but always in connection with some organic fertilizer. (3) Care must be taken not to use too much lime, as this will tend to waste the plant food stored in the soil. If the lime is coarsely ground, more must be used, but its effect will be more

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[28] Chas. Hunt, Gas Lighting, p. 136.

[29] J. B. C. Kershaw, Calcium Cyanamide, The Electrician, **60**, p. 548.

[30] Gardner, Fertility of Soils as Affected by Manures; U. S. Dept. Agri., Bur. of Soils, Bull. No. 48.

lasting. (4) Magnesia is at least equally as valuable as lime for use as a fertilizer. (5) Whether the lime should be applied as ground quicklime, hydrated lime, air-slaked lime, or ground limestone depends chiefly on the cost per unit of calcium oxide (it being assumed that the four substances are of the same fineness). Thus 500 pounds of ground quicklime, which is the quantity recommended for one acre, is equivalent to 950 pounds of hydrated lime or 1250 pounds of either ground limestone or air-slaked lime. (6) Lime is sometimes used to improve the drainage conditions in the soil, and for this purpose ground quicklime alone is suitable.

(*l*) SPRAYING.—Lime enters into the preparation of a number of insecticides used in spraying vegetation. For such purpose calcium oxide is the only useful constituent of the lime. Magnesia and impurities are not harmful. The physical quality of the lime is of paramount importance. The material is sprayed on the vegetation through some form of atomizer, and therefore must contain no coarse particles or grit. For this reason hydrated lime screened to pass 150 or 200 mesh (a commercial article) would certainly give better satisfaction than lump lime.

(*m*) SUGAR.—In the manufacture of sugar both carbon dioxide and lime are used. Therefore, sugar manufacturers prefer to buy limestone and burn their own lime.

The juice extracted from either beet or sugar cane contains various impurities. Some of these would discolor the sugar and others (organic acids) would invert it; that is, they would change the sugar into uncrystallizable glucose, and thus reduce the yield. In order to remove these impurities the juice is heated almost to boiling in the presence of an excess of lime. This combines with the acids and breaks up the other organic compounds forming insoluble salts, but it also forms an insoluble compound with the sugar itself. For this reason, after the lime has completed its action, carbon dioxide is forced into the liquid. This breaks up the combination between the lime and sugar and throws down all the lime as calcium carbonate. This precipitate carries with it all suspended matter, leaving a clear solution of sugar.

For the above purposes calcium oxide only is useful.[31] Impurities are apt to cause trouble. Thus, magnesium carbonate is more soluble in sugar solutions than calcium carbonate, and the salt so dissolved is later deposited on the tubes in the evap-

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[31] H. Classen, Beet Sugar Manufacture, p. 64.

orating pans, thus making it necessary to clean them more frequently. Any silica present is thrown down as a gelatinous precipitate. This becomes a general nuisance by coating the cloth in the filter presses.[32]

(*n*) DISTILLATION OF WOOD.—The destructive distillation of wood gives rise to four products: gas, pyroligneous acid, tar, and charcoal. Of these, pyroligneous acid is of most interest to the lime manufacturer. From this solution are prepared wood alcohol, acetic acid, and acetone, and lime is an essential ingredient in the manufacture of all of these. First, the crude acid is treated with an excess of lime and distilled. Wood alcohol passes over. The material remaining in the still is known as gray acetate of lime. From this, acetone may be produced by dry distillation, or it may be treated with sulphuric acid and the acetic acid distilled off. The wood alcohol is again treated with lime and redistilled in order to purify it.

For any of the above purposes calcium oxide is the only useful constituent of the lime.[33] Magnesia and impurities are not harmful. Hydrated lime may be used instead of quicklime for any of the above purposes except the final distillation of the wood alcohol. For the other purposes probably neither substance has any advantage over the other.

(*o*) PAPER.—Wood pulp for the manufacture of paper is prepared by one of three processes: Mechanical, soda, or sulphite, of which only the second and third interest the lime manufacturer.

In the soda process lime is used to causticize sodium carbonate, thus recovering the caustic soda used in cooking the wood. The quality of lime required for this purpose was discussed under "Caustic soda," quod vide.

Another solution which may be used in place of caustic soda for dissolving the cementing constituents of wood is bisulphite liquor. This is a mixture of calcium and magnesium bisulphites held in solution by an excess of sulphur dioxide. The liquor is prepared by one of two methods: Limestone may be subjected to the solvent action of sulphur dioxide and water, or milk of lime may be treated with sulphur dioxide. The resultant solution is the same in either case.

For the maker of sulphite pulp magnesia is a desirable constituent of the lime or limestone. Magnesium sulphite is more soluble than calcium sulphite, and consequently permits of making a

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[32] Manufacture of Sugar, Int. Lib. of Technology, Sec. 50, p. 36.

[33] P. Dumesny and J. Moyer, Wood Products, Distillates, and Extracts, p. 8.

stronger liquor. Moreover, the presence of magnesia in the liquor gives the pulp a better color and makes it softer to the touch, so that it will felt together better when made into paper. Therefore, dolomite, or magnesian lime, is much preferable to the high-calcium compound. The impurities are not harmful. If limestone is used it should be as porous as possible to permit of rapid solution. Hydrated lime is preferable to lump lime, because it is easier to handle and contains fewer impurities.

(*p*) PAINTS.—Ground lime, air-slaked lime, levigated chalk (natural whiting), and chemically precipitated calcium carbonate are used to a large extent in the paint and allied industries. For these purposes fineness of grain is essential, while sometimes the color or chemical composition is of equal importance. It is generally impossible to obtain a limestone of sufficient whiteness, or to grind it sufficiently fine to meet the requirements. It is therefore an advantage to use air-slaked lime or hydrated lime.

(*q*) GLYCERIN, LUBRICANTS, AND CANDLES.—Most of our common fats are compounds of glycerin with various organic acids. These compounds can be broken up by heating the fat with lime and water under pressure. The glycerin is liberated, while the lime takes its place in the compounds. Practically all of the glycerin used in this country (mostly in the manufacture of explosives) is made in this way. The lime soaps formed by this process are sometimes mixed with heavy mineral oils and sold as lubricants or greases. They are of especial value for the lubrication of heavy machinery, or for use at high temperatures. Or, the soaps may be treated with sulphuric acid, and the fatty acids recovered and used in the manufacture of soap and allied products.

Calcium oxide is the only useful constituent of the lime, although the magnesia and impurities are not harmful.[34] Quicklime is probably preferable to hydrated lime, because the heat of slaking can be used.

(*r*) TANNING.—In the leather industry lime is used in the depilation process. The hair is so loosened from the hide by soaking it in lime water that it can be removed by subsequent scraping. In regard to the quality of lime to be used, the following statement is made:

> The presence of magnesia and clay is injurious, not only by diminishing the amount of lime present, but by making the lime much more difficult to slake; and iron oxide,

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[34] S. P. Sadtler, Industrial Organic Chem., p. 58.

though quite insoluble, may become mechanically fixed in the grain of the hide, and may be the cause of subsequent stains.[35]

The use of hydrated lime would remove the above objections to magnesia, but not those to iron. Hydrated lime is probably preferable to quicklime for this reason and because it is easier to handle.

VI. TESTING LIMES

1. TESTS REQUIRED

General methods for testing lime should be devised to serve as a basis for mutual agreement between manufacturer and consumer. Such tests must ultimately depend on the physical and chemical properties of the lime. Unfortunately, our present knowledge does not permit us to define clearly the meanings of such terms as "plasticity" and "time of set." Researches are in progress to correlate these terms with definite measurable properties and thus to eliminate them from the standard specifications which the Bureau hopes to offer.

From a consideration of the general purposes for which lime is to be used, it is believed that the testing of lime for purchase should include the following determinations:

Carbon Dioxide.—To measure general conditions as affected by burning and air-slaking. Quicklime of good quality should not contain over 1 per cent of carbon dioxide.

Rate of Hydration.—Lime which has been burned properly will slake more rapidly than that which is underburned or overburned. Consequently, a knowledge of the rate of hydration furnishes a good indication of the burning conditions.

Chemical Composition.—Different limes have different rates of hydration. Therefore it is necessary to take the chemical analysis of the lime into consideration, or else to compare the sample with another of the same lime which is known to have been burned properly. It is sometimes desirable to know the quantity of water in hydrated lime, but this is not very important and is of no value unless a complete chemical analysis is made, which last is the only test required for limes that are to be used for chemical or fertilizing purposes.

For building and finishing limes, a number of physical properties are important. Chief among these may be mentioned plasticity, sand-carrying capacity, strength when mixed with sand, time of set, and color.

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[35] H. R. Proctor, Principles of Leather Manufacture, p. 121.

2. METHODS OF TESTING

It is not within the scope of this article to go into details about the testing methods which have been evolved. For this purpose reference to the articles cited must be made. Briefly, the carbon dioxide is determined according to standard methods for chemical analysis.[36] The rate of hydration can be measured in a calorimeter especially designed for the purpose.[37] Mixtures of the sample with varying proportions of water will produce pastes of different consistencies. These can be compared by means of the Southard viscosimeter.[38] The plasticity of a paste of normal consistency is measured in an instrument designed for the purpose.[39] To this paste varying proportions of a standard testing sand may be added, and the plasticities of the mortars measured. The quantity of sand required to produce a mortar of predetermined plasticity is recorded as the sand-carrying capacity of the lime. Pats of this mortar can be tested for time of set with a Vicat needle.[40] The mortar can be molded into 2-inch cubes, which, after ageing for 60 days, can be crushed to determine its compressive strength.

The color, acoustical properties, and fire resistance of plasters are subjects which are now being investigated.

Methods for measuring the proportion of waste in quicklime, and the fineness of hydrated lime, together with much more information of general interest, are embodied in the specifications adopted by the American Society for Testing Materials, as follows:

Standard specifications for quicklime	C5–15
Standard specifications for hydrated lime	C6–15
Tentative specifications for masons' hydrated lime	C6–17 T

WASHINGTON, December 15, 1919.

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[36] Report of Com. C–7, Am. Soc. Test. Mat.; 1919.

[37] Emley, Tests of Commercial Limes, Trans. Nat. Lime Mfrs. Assn.; 1913.

[38] Report of Com. C–11, Am. Soc. Test. Mat.; 1919.

[39] Emley, An Instrument for Measuring Plasticity, Trans. Am. Ceram. Soc.; 1917.

[40] Report of Com. C–1, Am. Soc. Test. Mat.; 1905.