I. C. 6884 MAY 1936

DEPARTMENT OF THE INTERIOR

UNITED STATES BUREAU OF MINES
JOHN W. FINCH, DIRECTOR

INFORMATION CIRCULAR

LIME

BY

OLIVER BOWLES AND D. M. BANKS

I.C.6884,
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By Oliver Bowles[2] and D. M. Banks[3]

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INTRODUCTION

The manufacture of lime is one of the oldest industries. Plants are distributed widely and furnish an essential raw material for numerous industries. The use of lime by the building trades, in agriculture, and in hundreds of manufacturing and chemical processes has created demands for a large production and has necessitated exhaustive research on methods of manufacture and uses. The bibliography of lime is an extensive one, but for the most part each publication has dealt with only certain operations.

The purpose of this paper is to present a general picture of the industry as a whole. The abundant literature has been abstracted and quoted freely, and the National Lime Association has rendered valuable assistance in furnishing data for certain sections. Publications containing more detailed information on the various branches of the industry are referred to in the footnotes and in the bibliography.

DEFINITION

Lime may be defined as calcium oxide resulting from heating calcium carbonate to a temperature at which the carbon dioxide is removed. A hundred pounds of pure calcium car-

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[1] The Bureau of Mines will welcome reprinting of this paper, provided the following footnote acknowledgment is used: "Reprinted from U.S. Bureau of Mines Information Circular 6884."

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bonate will yield 56 pounds of lime. The most common form of calcium carbonate in nature is limestone, which is therefore the chief raw material used in the manufacture of lime. In many places limestone is associated with varying quantities of calcium-magnesium carbonate (the mineral dolomite), or a deposit may consist of virtually pure dolomite. Calcination of such rocks produces mixed oxides of calcium and magnesium, which also are regarded as lime. Limestone almost always is associated with impurities, also, such as silica and oxides of iron and aluminum. The product resulting from the burning of such rock therefore may vary widely from pure lime. Commercial limes, however, usually contain not more than 5 percent total silica, ferric oxide, and alumina. Magnesia is not considered an impurity except in certain exacting chemical or industrial processes.

Varieties

Limes are classified according to their composition as follows:

High-calcium lime contains not less than 90 percent calcium oxide and 0 to 5 percent magnesia.
Low-magnesium lime contains 5 percent to 25 percent magnesia.
Dolomitic, or high-magnesium, lime contains 25 percent to 45 percent magnesia.

A content of 45 percent magnesia is the maximum that can be obtained by calcining a pure dolomite. To obtain more than that amount a mixture of dolomite and magnesite ($MgCO_3$) must be calcined, and, except in California and Washington, such material rarely occurs in the United States.

Hydraulic lime is the variety that results from the calcination of limestone containing enough argillaceous matter to form a substance that will set under water. Its action is similar to that of natural cement, but it contains more calcium and less aluminum.

Chemical and Physical Properties

Commercial limes are composed of oxides of calcium, anywhere from 0 to 45 percent magnesium oxide, and generally more or less impurities, such as silica and oxides of iron and aluminum. When properly burned and fresh from the kiln, lime should contain no water and less than 0.5 percent carbon dioxide. If the impurities formed by the contact of lime with the lining of a kiln are disregarded, the chemical composition of any lime will be the same as that of the stone from which it was burned, minus the carbon dioxide; but because of the loss of about half the weight of the stone as carbon dioxide during burning, the proportion of every other constituent of the stone will be nearly doubled in the lime. A chemical analysis of a limestone therefore is a very good criterion of the grade and commercial utility of the lime it will produce.

Lump lime retains the same form as the stone after calcination, but the porosity is increased greatly. When water is added to lime a chemical reaction takes place, and calcium hydroxide ($Ca(OH)_2$), also known as hydrated lime, is formed. This process is known as slaking or hydrating. Considerable heat is generated during the reaction. The reactions of dolomitic lime and calcium lime differ somewhat in the slaking process. A high-calcium lime expands greatly when water is added, and much heat is generated. Dolomitic lime slakes much more slowly, generates less heat, and expands less, which results in a correspondingly smaller yield. Other things being equal the less magnesium oxide present in a lime the more quickly will it slake, and the greater will be the amount of heat generated.

The rate of hydration depends also on the porosity of the lime. Water penetrates the more porous limes rapidly, and the chemical reaction takes place quickly. Indeed, in some cases the porosity of a lime seems to be a greater factor than the chemical composition; for instance, a very porous dolomitic lime may slake more quickly than a dense lime with a much higher content of calcium oxide.

When lime is underburned the calcium carbonate left in it acts as inert matter for most uses. Overburned lime also contains relatively inactive matter consisting of a mixture of lime and impurities, which forms a semivitrified mass. When overburned, lime is inclined to slake slowly because of the diminution of pore space. The appearance of underburned lime varies with that of the stone and can be distinguished only by one who has had experience in burning the particular kind of stone. Overburned lime generally is yellow or black and can be separated readily from good lime.

When quicklime is exposed to air it absorbs carbon dioxide and water and "air-slakes." Such reaction takes place in two more or less distinct stages - first, the absorption of water and, second, displacement of the water by carbon dioxide. As these reactions are slow, lime may air-slake to almost any degree, and this has led to great confusion in the literature regarding the properties of air-slaked lime. For instance, at one stage of the process, when the water has been absorbed and has not been displaced to any extent, the product is similar in composition to "water-slaked" or hydrated lime. At the other extreme, recarbonation may be so nearly complete that the lime virtually has reverted to limestone. Absorption of water during the process of air-slaking involves a large increase in volume, and the lumps of lime therefore fall to pieces. Limestone may fall to pieces in the kiln under several circumstances. The stone may be so soft that it is broken by abrasion; its pores may be filled with water at the time of burning, which shatters the stone when heated; or its component crystals may be bound together by organic matter that is consumed in the kiln. Sometimes over 50 percent of the output of a kiln is finely divided lime, which is as good for most purposes as lump lime and is easier to handle.

The chemical and physical properties of a lime determine its adaptability for certain uses. The requirements for the various processes and products in which lime is used therefore have been the subject of much scientific study. It has been found that properties may be adjusted to some extent in the various processes of production. The ratio of calcium to magnesium depends largely on the market in the particular locality. When the lime is sold for chemical purposes, this ratio generally will be specified. Specifications for the various uses are discussed under the section on Uses.

HISTORY OF THE INDUSTRY

The art of burning limeand the use of lime can be traced back through the ages of Roman, Greek, and Egyptian civilizations to times of remote antiquity. The use of kilns for burning was mentioned by Cato in 184 B.C. Lime mortar was used in the pyramids of Cheops and older monuments, and references have been found indicating that lime was used at this early time in the chemical as well as in the building industries. Recent investigations of a Roman water conduit, A.D. 70-100, running from Eifel to Cologne show that the concrete was made with hydraulic lime, Rhine sand, and crushed high-calcium limestone.[4] Something of the manufacture and use of lime may be traced from passages in the Old Testament, from the writings of Dioscorides and Pliny (circa A.D. 75) and of Vitruvius (circa 50 B.C.), and from references in literature to its employment in war and by alchemists during the Middle Ages. Joseph Black and Lavoisier (circa 1777) dispelled the old theory that calcination was attrib-

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[4] Quarry Manager's Journal. Ancient Lime Mortar Concrete: Vol. 18, June 1935, p. 81.

utable to the introduction of phlogiston. The first measurements of the dissociation pressure of calcium carbonate were made in the latter part of the nineteenth century by Debray and Le Chatelier.

Although machinery and methods of preparing limestone for burning were developed to keep pace with the growth of an industry that has reached large proportions, comparatively little improvement was made during the centuries in the process of burning lime or in the type of kiln used until recent years. Within the past 35 years experimental work in the laboratory and field has resulted in the adoption of certain improvements. The outstanding feature in the development of the industry was the manufacture of hydrated lime, which began about 1900, and the rapid growth of its use. One of the more recent advances in lime manufacture was the introduction of pulverized quicklime. This product has been received favorably and used widely, especially in the construction field. New types of kilns and hydrators now have been evolved. The rotary kiln, well-known in the cement industry, has been adopted extensively for burning lime and produces what is commonly called pebble lime.

A very valuable contribution to the lime industry was a study by the National Bureau of Standards beginning in 1912. In cooperation with the lime-consuming industries, it conducted extensive research to determine what kinds of lime are most efficient and economical for each product or process of manufacture. The result of this work was the promulgation of many specifications. That Bureau also made detailed studies of typical lime plants and in 1913 published a paper on the manufacture of lime.[5] This was revised in 1927.[6]

Statistical records of the lime industry since 1894 are available in annual reports published, first, by the United States Geological Survey and later by the Bureau of Mines. A National Lime Association was organized in 1918 and incorporated in 1922 as a promotional and research organization, and its activities have had an important influence on the development of the industry. For many years before 1918 similar work was conducted by the National Lime Manufacturers Association and the Hydrated Lime Bureau, sponsored by progressive and far-thinking members of the industry.

RAW MATERIALS

The natural calcium and magnesium carbonates, limestone, marble, dolomite, and shell deposits, are the principal sources of commercial lime. Small quantities are made from similar carbonates produced as byproducts of chemical industries. Of these materials, limestone is the most abundant and is used most extensively for lime manufacture.

Limestone

Origin.- Limestone is formed in beds by the accumulation of calcareous shells and varying quantities of other substances, such as magnesium carbonate, silica, clayey material, salts of iron, and organic matter. These are consolidated gradually into rock by pressure, and through long geologic ages of surface adjustment occupy land areas and become available for commercial use.

Composition and varieties.- The chemical composition of limestone for making lime is important, as lime is used in many products and processes in which the chemical requirements are exacting. Physical properties have some influence on both methods of manufacture and costs. For instance, a friable stone is unsuitable for shaft kilns because it crumbles,

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[5] National Bureau of Standards, Manufacture of Lime: Technol. Paper 16, 1916, 130 pp.

[6] National Bureau of Standards, Manufacture of Lime: Circ. 337, 1927, 104 pp.

retards the draft, and furnishes a small proportion of lump lime. High porosity may retard the rate of heat conductivity and thus lower fuel ratios.

The essential chemical constituent of limestone is calcium carbonate ($CaCO_3$), the mineral calcite. Many commercial occurrences designated "high-calcium" limestone carry 93 to 99 percent calcium carbonate. When other substances occur in the stone it is classed according to the nature of the impurities. If 10 percent magnesium carbonate is present it is called "magnesium" or "dolomitic" limestone. Magnesium limestones may embrace several varieties texturally and if physically suitable may be burned to lime, which will be a mixture of calcium oxide (CaO) and magnesium oxide (MgO). When the amount of magnesium carbonate present approaches 45 percent the rock is known as "dolomite", which is the double carbonate of calcium and magnesium expressed by the formula $CaCO_3.MgCO_3$. The uses of dolomite and high-magnesium limestone are discussed in a recent Bureau publication.[7]

"Argillaceous" limestone contains a considerable proportion of clay, consisting mainly of aluminum silicate. If the clay is present in certain proportions, mortar made with the "hydraulic" lime burned from the stone has the property of setting under water. "Siliceous" or "cherty" varieties contain considerable silica; if present to the extent of 4 or more percent, the limestone rarely is suitable for making lime. "Ferruginous" limestone has considerable iron content. "Carbonaceous" or "bituminous" limestone contains carbonaceous matter, such as peat or other organic materials, which color the rock a dark gray or black. Moderate amounts of carbonaceous matter are not retained in the lime, as they are consumed during calcination.

Other varieties of limestone are based on texture or physical character. Common compact limestone is a fine-grained, dense, homogeneous aggregate, ranging in color from light gray to almost black. This variety, when of suitable chemical composition, is burned into lime in many places. Oolitic limestone is composed of small, rounded grains of lime carbonate with a concentrically laminated structure. Some limestone beds have been formed under conditions that have left many shells almost intact or, at least, in fragments sufficiently well-preserved to indicate their origin and character. These are known as "fossiliferous" limestones. Some of them are made up almost entirely of shells of one kind and are named accordingly. "Coral", "crinoid", and "coquina" are common types. Unconsolidated oyster-shell beds are related closely to fossiliferous limestone and are quite extensive. When sufficiently pure, fossiliferous limestone generally is suitable for making lime. Cherty limestone contains nodules and bands of chert or flint and is not suitable for lime manufacture unless the chert can be separated and removed at very little expense.

Impurities.- The common impurities in limestone are clay, which contains silica and alumina; sand or other forms of free silica; iron oxide; iron carbonate; pyrite or marcasite (sulphides of iron); gypsum; alkalies; and carbonaceous material. Clay is found most often along the bedding planes, but it is also disseminated through the rock. Silica occurs in hard limestone as nodules or masses of chert (flint) or combined with alumina as clay matter. In soft limestone, such as marl and chalk, it usually occurs as grains of sand, but certain beds of Cretaceous chalk, notably the deposits along the English channel and to a smaller extent the beds in Texas, carry an abundance of chert nodules. Alumina commonly is present in combination with silica as a silicate mineral or as clay matter. Iron compounds are disseminated with the original sediments, but they were brought in by percolating waters and resulted from chemical action with other minerals. Sulphur is present in combination with iron as a disulphide and in gypsum ($CaSO_4.2H_2O$), so that under ordinary conditions it is not free, but the disulphide yields easily oxidizable sulphur. Small quantities of the alkalies soda and potash are present in some limestones, probably in the form of carbonates or in the

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[7] Hatmaker, Paul, Utilization of Dolomite and High-Magnesium Limestone: Inf. Circ. 6524, Bureau of Mines ,1931, 18 pp.

clay impurities as silicates. Impurities are noted in greater proportions in weathered than in unweathered rock because they are less soluble than the limestone.

Impurities in the stone have various effects on the properties of the lime. Small amounts of silica tend to decrease the plasticity, sand-carrying capacity, and yield of a lime but have no apparent effect on its hardness or strength. The same may be said of iron, except that lime containing large amounts is much stronger and harder. Kaolin seems to act in a manner similar to silica and iron. Gypsum shows detrimental effects, even when only 1 percent is present.

Dolomite

Dolomite is next in importance to limestone as raw material for lime. Magnesium limestone containing 20 percent or more magnesium carbonate is designated "dolomitic" or "high-magnesium" limestone. When the amount of magnesium carbonate present approaches 45 percent, the rock is virtually a pure dolomite and is then regarded as a distinct mineral composed of calcium and magnesium carbonates combined in proportions expressed by the formula $CaMg(CO_3)_2$.

Other Raw Materials

The crystalline form of limestone known as marble also is a common source of lime. As shown later in more detail, marble is used for lime manufacture in New England, Maryland, Tennessee, Washington, and several other States. The waste of many quarries that produce building and monumental marble also is utilized in this way. Vein deposits of calcite also are used to a limited extent for lime.

Oystershells are one of the purest forms of calcium carbonate that occurs in commercial quantities. They therefore are well-suited for making chemical lime, for which purity and uniformity of composition are necessary. Easily accessible shell reefs large enough and of a character to warrant their use for lime are few, but their utilization for this purpose has increased in recent years.

Travertine or calc sinter, a massive, porous to compact limestone, is formed as deposits from solution at calcareous springs. It does not occur extensively in the United States. Several quarries for building stone have been developed, and the waste of one has been utilized for lime.

Marl, a fine-grained, loose, earthy material containing a large proportion of calcium carbonate, occurs commonly in this country, notably in the Southern Peninsula of Michigan, in northern Indiana, and in western New York; but, because of its high content of water and the difficulty experienced in burning, it is not used for making lime.

Distribution in the United States

Deposits of limestone occur in every State. In some States they are very extensive and are quarried in hundreds of places for various uses. The location of every limestone quarry and limekiln in the United States east of the Mississippi River is shown in a series of seven maps in the chapter on Stone of Mineral Resources of the United States for 1911, part II, published by the United States Geological Survey; the location of every such plant in the States between the Mississippi and the western boundary of Montana is shown in the corresponding chapter of the volume for 1912; and the quarries and kilns in the remaining Western States and in the Pacific Coast States are shown in the volume for 1913. Although some lime plants have been abandoned and new ones built since these reports were published, the general locations are unchanged, and the reports are valuable sources of information on occurrences of limestone suitable for burning lime.

The distribution of lime plants in the States, with the kinds of lime produced in each plant, based on the most recent information furnished this Bureau, is shown in the section on Production. Distribution of raw materials suitable for lime manufacture, with chief emphasis on deposits now or recently in use, is covered briefly in the following paragraphs.

New England States.- Most of the limestones in the New England States are so highly crystalline as to be classed as marble. In Maine the lime industry is centered at Rockland, where vertically dipping beds of crystalline limestone are utilized extensively. An occurrence of noncrystalline limestone in Aroostock County has been utilized for lime. In Vermont noncrystalline limestone is found principally in the northwestern counties, where moderate-size lime plants are operated. Waste marble from quarries in Rutland County is an important raw material. Commercial limestone occurring in the northern part of Rhode Island in the vicinity of Lime Rock is used for the manufacture of low-magnesium lime. Large lime plants in western Connecticut and Massachusetts utilize crystalline limestones and dolomites. Small outcrops of limestone in New Hampshire have no commercial importance at present.

New York, New Jersey, and Pennsylvania.- New York and Pennsylvania are especially rich in limestones. In New York they occur extensively in a group of counties between the Adirondacks and Lake Ontario. They also outcrop to the south in Herkimer, Saratoga, Washington, and Warren Counties and in a small area in the Champlain Valley. Another formation, containing stone of 95 percent or more calcium carbonate, outcrops at various points in the eastern Adirondacks from Saratoga County northward to the Canadian boundary. Along the lower Hudson a formation outcrops near Poughkeepsie. Limestone beds extend from Otsego County northwestward to Oneida Lake and westward to the Niagara district. A belt of great economic importance extends from Buffalo in Erie County eastward to Oneida County and southeastward to Albany County, where it curves south toward the Delaware River. Stone suitable for lime manufacture is found in the Finger Lakes district. Much of the limestone of New York, especially of the western half of the State, is high in calcium carbonate. Lime is burned in many sections.

In Pennsylvania the high-grade limestones of greatest commercial importance are confined to the central and southeastern counties and to an area north of Pittsburgh near the western border. Extensive deposits of both high-calcium and high-magnesium stones occur, the magnesium rock being especially abundant in the valleys of the southeastern section and the high-calcium variety in the central part. Pennsylvania has more lime plants than any other State. Lime is manufactured most extensively in the central and southeastern sections, though stone is used locally for this purpose also in the southwestern counties. Commercial high-calcium and magnesium limestone is found in the northwestern border counties of New Jersey, and dolomitic limestone occurs in Somerset County.

Maryland, Delaware, Virginia, West Virginia, North Carolina, and South Carolina.- The limestones of this area fall physically into three groups: (1) The nonmetamorphosed limestones of the Appalachian valleys; (2) the metamorphosed or crystalline limestones of the Piedmont region, both of which are hard limestone; and (3) the soft limestones of the Coastal Plain.

The great limestone deposits of the Shenandoah Valley of Virginia and of similar valleys lying northwest of the Blue Ridge Mountains are the most noteworthy in this area. The stone of the two western tiers of counties throughout the entire length of Virginia has great commercial value. It is accessible easily and is used extensively for lime. Limestone of variable composition occurs also in the Alleghany Mountains of Virginia. Occurrences in the Piedmont district of the State, especially in Loudoun County, have been utilized for lime. The soft limestones of the Coastal Plain of Virginia consist largely of shell marl and have little value.

Deposits of hard limestone are found west of the Alleghanies in eastern West Virginia, but few approach in purity those of the northeastern Panhandle, where the large lime plants of the State are located. Beds of both high-calcium and magnesium limestone extend from the Valley of Virginia into the central and northern counties of Maryland. Crystalline limestones in an area north of Baltimore are utilized for lime.

Small areas of crystalline limestone, mostly dolomitic but with variable magnesium content, occurring in the extreme northern part of Delaware have no commercial importance as sources of lime. Both high-calcium and magnesium limestones occur in many counties of the western section of North Carolina, mostly in valleys, but they are so covered with soil that careful surveying and prospecting are required to determine their extent and quality. Few of them have been utilized for lime. Small deposits of crystalline limestone occur in western South Carolina, and soft limestones and marls are found on the Coastal Plain. They have not been used in recent years for lime manufacture.

Tennessee, Mississippi, Alabama, Georgia, and Florida.- Limestone abounds in Tennessee, particularly in the eastern and central parts. The Holston marble of Knox County is the principal source of lime. The limestone of middle Tennessee, which is pure to argillaceous and low in magnesium, is used extensively for lime manufacture in the counties of the central basin. The most prominent formation in the northern and western counties of middle Tennessee contains high-grade limestone in places, which also is utilized for lime. Small beds of limestone and larger deposits of chalk occur in Mississippi, but they are not used to produce lime.

Limestone sufficiently pure for lime occurs in the river valleys of northern and central Alabama, and stone of a high degree of purity outcrops along the sides and bases of plateaus in the same general region. An unusually pure high-calcium marble occurs in Talladega County. Formations suitable for lime occur also in the north-central counties of the State. The Selma Chalk extending across central Alabama and the Vicksburg limestone farther south are not used for lime. Lime is produced principally in Blount, Shelby, and other counties of the Birmingham area and in the northern counties.

In Georgia sources of raw material for lime are confined to the marble belt of Pickens and adjacent counties and the abundant limestones of the Appalachian Valley district to the west. Recent production has been confined to Bartow County.

Limestone is distributed widely in Florida. High-calcium stone, some of which is soft and chalklike, occurs in Jackson County and over a wide area of central Florida. A compact, white rock, quite hard in places, is found in northwestern Florida. Tampa limestone, a fairly hard, compact, light-gray to yellow rock, occurs in parts of the west-central counties. Coral and oolitic limestones form the foundation of the keys from Miami to Key West and border the east side of the Everglades. Coquina and related shell varieties occupy a large part of southern Florida as well as sections of several northern counties, particularly along the coast. Most Florida limestones are too soft for the manufacture of lime by ordinary methods, and at present the industry is confined to Marion and Dade Counties.

Wisconsin and Michigan.- Limestones occupy the north-central and northern sections of Wisconsin, appear in a broad belt along the eastern border of the State, extend across the southern part, and are available in certain areas along the western side. Nearly all of them are dolomites well-adapted for making high-magnesium and special limes. The lime industry, however, is confined chiefly to the east-central counties.

In Michigan limestones border the northern part of the Southern Peninsula along Lakes Michigan and Huron and cross the southeastern part. The largest area is near Rogers City, Presque Isle County. Another important formation outcrops on the east side of Saginaw Bay, on Charity Island in Saginaw Bay, and in Arenac, Eaton, and Jackson Counties. Limestone also occurs along the southern border of the Northern Peninsula. The lime centers are in the northern part of the Southern Peninsula and in Menominee and Schoolcraft Counties. The rock is shipped to Menominee from Rogers City. Large quantities of Michigan limestone are shipped also to lime-manufacturing plants in other States.

Illinois, Indiana, Ohio, and Kentucky.- Commercial limestones of both the high-calcium and magnesium varieties occur in about a third of the area of Illinois, including the northern end and a belt along the western and southern borders, and scattered deposits of minor economic importance are found in the remaining two-thirds of the State. Lime production is centered chiefly near Quincy and Cordova, in the western section, and in Chicago. Some of the stone burned in and about Chicago, however, is obtained from Calcite, Mich.

Limestones occur widely in Indiana, the most important beds forming a belt about 20 miles wide extending northwestward through the central part of the State. In this belt is the famous oolitic limestone quarried in Lawrence and Monroe Counties for building. Waste from the quarries is used for lime. Owen, Crawford, Harrison, and Washington Counties also contain high-calcium oolitic limestone, which is burned into lime at several places. Farther north magnesium limestone occurs in several counties and is now used for lime in Huntington County. Lime is produced also in Cass County in the north.

Limestone underlies a large portion of Ohio and is used extensively for the manufacture of lime. Exceedingly pure dolomite prevails in the Toledo district, including Wood, Sandusky Ottawa, and several other counties, and most of the lime plants are in this area. In a second area farther south, extending as far as Columbus, both high-calcium and low-magnesium limestones abound and are used for lime in many places. High-calcium limestone in eastern Ohio and dolomite in Adams County, southern Ohio, also are used for lime.

Kentucky is underlain with the same formations of limestones as occur in Illinois, Indiana, and Ohio, and they appear in many eastern, southeastern, central, north-central, and western counties. A notable outcrop of high-calcium oolitic variety is in Warren County. The manufacture of lime has been confined almost exclusively to Rockcastle and Franklin Counties.

States West of the Mississippi River.- In Minnesota commercial limestone occurs only in the suotheastern part. The beds generally are highly magnesian, and many are nearly pure dolomites. They are used for lime in several counties. The only limestone formation in North Dakota is a soft, chalklike rock intermixed with clay, which is unsuitable for the manufacture of lime. Hard limestones occur in the Black Hills district of South Dakota, and recent production of lime in the State has been confined to this district. Except for small local quarries in the southeastern counties, the chalky limestone occurring in the eastern part of the State has no commercial use at present.

Limestone is plentiful in Iowa. Formations in the eastern counties are generally high in magnesium, those in the east-central area are magnesium in the northern part and high-calcium in the south, and those of the central and southern parts have some fairly high-calcium stone. Chalk beds occur in the western part of the State. Lime production is relatively unimportant and is confined almost exclusively to Jackson County. The limestones of greatest economic value in Nebraska outcrop chiefly in the southeastern counties, where lime has been produced. Another formation is exposed along the Missouri River in northeastern Nebraska and in the Republican Valley in the southern part.

In Missouri dolomite or magnesium limestone is found in the southeastern part, except the corner counties. Limestones low in magnesium and mostly of a high degree of purity outcrop near the Mississippi River north of Cape Girardeau and extend to the northern part of Jefferson County; they are exposed again near the Mississippi in Lincoln, Pike, Ralls, and Marion Counties. High-calcium limestone also covers extensive areas along the Mississippi and Missouri Rivers and in southwestern counties. In all these areas it is used widely for the manufacture of lime. Limestone also occurs in the northern and western parts of the State.

Commercial limestones occur in the eastern third of Kansas, but only those of Bourbon County have been used for lime. Rocks in the central area contain limestones, but little economic use has been found for them. The principal limestone area of Arkansas lies in the Ozark Plateau region in the northern part of the State. High-calcium rocks suitable for the manufacture of lime are found in several formations.

The commercial limestones of Louisiana are limited to two occurrences - one in Winn and the other in Evangeline Parish - and both have been utilized for lime. On the Gulf coast oystershells are used for making chemical lime. The largest limestone area in Oklahoma is in the Arbuckle Mountain District; smaller areas occur in the foothills of Wichita Mountains, in the northern and southeastern sections, and in the Ozark uplift. Lime has been burned in several counties.

Limestones are distributed widely in Texas, particularly in the eastern half of the State. A belt runs from Red River in the northeastern part westward across the central part of the State and extends south and southwest, terminating a little southwest of San Antonio. Analyses of the stone show a content of 70 to more than 90 percent calcium carbonate and very little magnesium. West and parallel to this formation is another group of limestones, and still larger areas are exposed in the Edwards Plateau west of San Antonio. Several lime plants are operated in the east-central district, chiefly in Comal, Travis, and Williamson Counties. Other occurrences are in western Texas near El Paso, where a group of lime plants is located. A plant near Houston and one in Corpus Christi utilize oystershells for lime.

In Montana limestone occurs chiefly in massive beds along the flanks of the mountain ranges in the western part of the State. It is used for lime in several counties in this district; some of the high-calcium variety, containing very little impurity, is burned into lime for refining sugar. Smaller deposits throughout the eastern two-thirds of the State have been used locally for lime burning.

Limestones are found in many parts of Wyoming but have not been developed extensively. The best-known deposits are in Albany, Laramie, and Platte Counties in the southeast and in Weston County in the northeast. Most of them are of the high-calcium type and supply stone for sugar factories.

The Colorado limestone deposits may be divided into two groups - an eastern division forming a belt immediately east of the Front Range and a second division lying west of the range. Limestone of the first division outcrops continuously from north of Fort Collins to the middle of Douglas County, passing a little west of Denver. The best rock contains more than 90 percent total carbonates, but most of the formation is mixed with shale. Stone for lime manufacture is obtained chiefly in El Paso, Pueblo, and Chaffee Counties in central Colorado. Some of the limestones west of the range are pure enough for the highest-grade uses, but their location has discouraged commercial development. Other deposits outside these areas that are exploited for the manufacture of lime are in Larimer County in the north-central part of the State and in La Plata County near the southwest corner. Waste travertine from the building-stone quarries at Salida, Chaffee County, also is utilized for lime. Very little is known of the chemical and physical properties of the limestone outcrops in New Mexico. Lime has been produced in San Juan and San Migual Counties.

Western and Pacific Coast States.- Limestone deposits are to be found in many parts of Idaho, those of chief value occurring in the southeastern and northwestern counties. Lime is produced in both sections. Pure limestone from Butte and Teton Counties is or has been shipped to sugar factories in Idaho and Utah. The most important limestones of Utah occur in many parts of the Wasatch Mountains in the northern and north-central counties. A good many of these are pure enough for the manufacture of lime, and a number of lime plants are located in this district. A plant at Garfield is unique in that it utilizes limestone sand as raw material. Lime is produced also in the western and southwestern parts of the State.

The Arizona limestones have been developed only in a small way, probably because of restricted markets rather than lack of raw materials. Lime is produced chiefly in Yavapai, Pima, Gila, and Maricopa Counties.

The principal lime plants of Washington are on Orcos and San Juan Islands, San Juan County, where an abundance of crystalline limestone is used for the manufacture of a very pure lime. Water transportation assists marketing. Lime is made from marble in Stevens County. Suitable limestones are available, and lime has been burned also in Chelan, Ferry, Okanogan, and Whatcom Counties. Deposits of limestone occur as well in the northeastern counties of Washington. In Oregon, limestone pure enough for lime manufacture occurs principally in the southwestern and northeastern counties, and lime plants are located in these sections. Some of the stone in the southwestern area contains only 5 percent or less impurities. Limestones occur also in the northwestern corner of the State but generally are too impure for making lime. Both high-calcium and magnesium limestones are available in various places in the eastern third of Nevada. The chief developments for lime manufacture are in Clark County.

Few extensive limestone deposits comparable with those in many of the Eastern States occur in California. Most of them are irregular bodies of variable magnesium content. Lime is manufactured chiefly in the central part of the State. The extreme northern parts and the desert regions in the south have larger deposits of limestone than the more populous parts of the State, but because of the distance from markets and inadequate transportation facilities they have little commercial value. Lime has been produced, however, in Siskiyou and Shasta Counties in the northern section and in San Bernardino County in the south. Oystershells are used as raw material in Alameda and Tulare Counties.

USES

Lime is an essential raw material for numerous industries. It enters three large fields of utilization - the building industries, agriculture, and the chemical and manufacturing industries. For many years the building trades consumed the largest quantity, but a more or less steady trend toward wider use by the chemical and manufacturing industries has taken place. In 1906, the first year in which sales by uses were reported, 86 percent by value was consumed in building and only 8 percent in chemical and manufacturing processes; in 1934 only 27 percent by value was used in building and 64 percent in chemical and manufacturing processes. The quantity sold for agricultural purposes has shown only slight change; in 1906 about 6 percent and in 1934 about 10 percent was so used.

For each use of lime more or less rigid requirements of composition and quality must be met. Standard specifications for lime for certain industries have been developed by the American Society for Testing Materials in cooperation with the National Lime Association.[8] The National Bureau of Standards also has developed quite a number of specifications. The types of lime best fitted for certain uses are discussed in the following paragraphs.

Building

For lime used for building purposes physical properties, such as plasticity, sand-carrying capacity, strength when mixed with sand, time of set, and color have primary importance. Either high-calcium or magnesium lime, in the form of quicklime or hydrated lime, is used in structural work, though for some uses one type may be preferred to the other.

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[8] Copies of such specifications may be obtained from the American Society for Testing Materials, 1315 Spruce Street, Philadelphia, Pa., or from the National Lime Association, 927 Fifteenth Street, N.W., Washington, D.C.

If quicklime is used, it must be made into lime putty by proper slaking; it is also desirable to soak hydrated lime before use.

According to accepted specifications, quicklime for mortar, plaster, and masonry cement must have the following chemical requirements, calculated to the nonvolatile basis:[9]

	Calcium lime	Magnesium lime
	Percent	Percent
Calcium oxide, minimum	75	....
Magnesium oxide, minimum	....	20
Calcium and magnesium oxides, minimum	95	95
Silica, alumina, and oxide of iron, maximum	5	5

If sample is taken at the kiln 3 percent is the maximum permissible CO_2 content; if taken at any other place 10 percent is allowable.

The specifications for hydrated lime for structural purposes cover two kinds - masons' hydrated lime and finishing lime. Masons' hydrated lime may be used for scratch or brown coat of plaster, stucco, and mortar, and it may be added to portland-cement concrete. According to the specifications for this type of lime, calcium and magnesium oxides shall constitute not less than 95 percent of the nonvolatile portion, and carbon dioxide shall not exceed 5 percent if sample is taken at place of manufacture or 7 percent if it is taken at any other place. The percentages in both cases are based on the nonvolatile portion. The sample shall leave a residue of not more than 0.5 percent on a 30-mesh sieve and not more than 15 percent on a 200-mesh sieve. Finishing hydrated lime is used, in addition to the purposes for which masons' lime is employed, as an ingredient in the final or white coat of plaster, and it must have a plasticity figure of not less than 200 as tested with an Emley plasticimeter.[10]

Mortar.- Mortar is made by mixing lime putty with sand and water. Lime putty for this use is made by slaking quicklime properly or by soaking hydrated lime for an adequate period of time; the lime may be either high-calcium or dolomitic. The quality of a mortar depends on the method by which it is prepared as well as on the characteristics of the lime used. The type of lime used usually depends upon economic factors and local custom.

The quantity of mortar a lime will produce varies widely with the properties of the lime. A properly burned high-calcium lime will yield the greatest volume provided the mortar is prepared properly. The presence of impurities or of magnesium will decrease the yield of paste. Probably the most important difference in the mortar-making properties of various types of lime depends more on whether the lime putty was prepared from a properly slaked quicklime or from hydrated lime than on whether a high-calcium or a dolomitic lime was used.

As to the actual strength of lime mortars, tests conducted by the National Bureau of Standards indicate that mortar made of dolomitic lime is stronger than that made of high-calcium lime.[11] The strength of a mortar, however, may be controlled by the method of mixing and by the use of different kinds of sand. Properly made mortars, however, are so strong that for ordinary building the question of strength usually need not be considered. Where

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[9] American Society for Testing Materials, Standard Specifications for Quicklime for Structural Purposes: C5-26.

[10] American Society for Testing Mateials, Standard Specification for Hydrated Lime for Structural Purposes: C6-31.

[11] Emley, W. E., and Young, S. E., Strength of Lime Mortar: Proc. Am. Soc. Test. Mat., vol. 14, pt. 2, 1914, pp. 339-58.

factors of design or unusual conditions of service require high-strength mortar, portland cement may be added to lime mortar. The quantity of cement to be added is determined largely by the physical properties of the building units and the conditions of service.

Masonry cement.- Lime has properties that make it eminently desirable in cement mortars for masonry. It has been found that hydrated lime mixed with cement increases the plasticity of a mortar and makes it denser, thereby increasing its imperviousness to water. A cement mortar in which lime is used also adheres better to the brick. Experiments have shown that cement can be replaced by hydrated lime without material diminution of strength if the ratio of hydrate to cement is less than 1 to 3 by weight.[12] Cement mortar, however, is much stronger than is necessary for ordinary buildings, and this feature ordinarily is not a factor to be considered. Either high-calcium or magnesium lime may be used in masonry cement.

Plaster.- Lime plaster is made by mixing lime putty and sand, with or without hair. A coarse sand, often mixed with gravel, is used for exterior work, as for stucco, while fine sand is preferred for plaster for interior walls and ceiling. A highly plastic grade of lime is required for the finishing coat. It must be very nearly white, must work smoothly, and must not "pop" or "pit" or shrink too much in setting. The cause of popping and pitting is attributed to impurities in the lime or in the sand used, improper burning, or incomplete slaking. Many builders prefer hydrated lime for the finishing coat of plaster.

Concrete.- The addition of hydrated lime to concrete increases its plasticity, smooth-working quality, and resistance to water absorption. It is added to the batch as it goes into the mixer.

Natural cement.- The addition of lime to natural cement increases the strength and plasticity of the mortar made from it. A hydrated high-calcium lime is used; magnesia is objectionable because it is likely to hydrate after the cement has set, which weakens it. The lime may be added either during the grinding of the cement or when the mortar is mixed.

Artificial stone.- Lime is used as a binder in the manufacture of artificial stone made of various sizes and types of aggregates. It produces a whiter and more pleasing product than that in which ordinary portland cement is used. Various colors may be secured by adding appropriate quantities of mineral oxides.

Agriculture

Fertilizer.- Lime is applied to land extensively, primarily, as a soil corrective and conditioner and, secondarily, to supply the plant-food elements calcium and magnesium. Soil is a complex material, possessing a number of chemical, biological, and physical properties, and lime applied to it may affect these properties by any or all of the following actions: (1) Neutralizing soil acidity, (2) replenishing the supply of calcium and magnesium, (3) promoting the activity of beneficial bacteria and depressing injurious soil organisms, (4) improving the texture and permeability of heavy soils by flocculating the colloids and clay particles, (5) hastening the decay of organic matter and the formation of nitrates, (6) rendering iron and aluminum insoluble, thereby preventing the phosphorus in the soil from combining with them in unavailable form, and also preventing toxicity, (7) combining with nitrogen and phosphorus in easily available form, (8) acting as a germicide in certain soil-borne plant-disease organisms, and (9) leaving the soil in a well-balanced, productive condition.

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[12] Emley, W. E. The Use of Hydrated Lime in a Portland Cement Mortar: Proc. Nat. Lime Assoc. vol. 12, 1914 pp. 258-70.

Lime acts differently on various soils. The effects of the various types of limes on soils and plants and their use as quicklime, hydrated, or air-slaked lime, methods of application, and other factors for obtaining the best results have been subjects of careful investigation by agriculturists and chemists for many years. Their conclusions may be found in several publications listed in the bibliography.

Insecticides, fungicides, and disinfectants.- Lime, dry or as whitewash, may be used as a mild disinfectant. It also enters a number of insecticides, fungicides, and disinfectants used for spraying farm crops, gardens, orchards, and buildings.

Calcium arsenate, one of the more important insecticides, is used for controlling the cotton boll weevil, tobacco worm, potato beetle, and codling moth. A cold solution of arsenic acid is added to a diluted milk of lime, and calcium arsenate is formed as a white precipitate; this is filtered and dried, and the lumps are disintegrated to a fine powder. In this process a slow-setting, free-slaking quicklime with an available lime content of not less than 85 percent is used. Oxides of iron and alumina should be low, and the lime should be as free as possible from carbonates and other inert substances. Hydrated lime often is added to dry calcium arsenate at the time of use, and this also should have a low-magnesium content.[13]

Commercial lead arsenate, containing small quantities of calcium arsenate and hydrated lime, is used for the same purposes as calcium arsenate. Lime sulphur, one of the best fungicides and insecticides for fruit trees, is prepared by heating sulphur with milk of lime. Bordeaux mixture is a basic sulphate of copper made by the reaction of copper sulphate with lime. Lime used in these mixtures is the high-calcium type with a low iron and alumina content.[14]

Industrial and Chemical Processes

Lime is one of the most widely used chemical reagents in the industrial world. It is utilized in many manufacturing processes and enters directly into the manufacture of hundreds of articles. The processes involved in the manufacture of products in which lime is used include neutralization, coagulation, distillation, precipitation, solution, hydrolysis, dehydration, high-temperature processes, high-pressure processes, gas absorption, saponification, and causticization.

Obviously the kind of lime depends on the purpose for which it is to be used: Under some conditions either high-calcium or magnesium lime can be used with equal success; under others, magnesium is objectionable. Quicklime is preferred for some processes, hydrated lime or ground limestone for others. Some of the industries and processes in which large tonnages of lime are consumed are discussed in this paper, and general specifications of lime best-adapted for each are given. Lime, however, is employed in so many processes that all of them cannot be included.

Metallurgy.- Large quantities of lime are used in the metallurgical industries. The process of refining pig iron to make steel has as its object the elimination from the iron of certain materials that are undesirable or present in excessive quantities. Lime finds its principal use as a fluxing agent in the basic open-hearth process. It forms a basic slag for the removal of phosphorus and other impurities. The amount of lime used depends upon the quantity and nature of the impurities to be removed. In some localities limestone is used instead of lime. The proportion of scrap metal in the charge offsets the quantity of lime required. High-calcium lime low in silica and sulphur is preferred. Magnesia is

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[13] National Lime Association, Lime—Its Use and Value in the Industrial and Chemical Processes: 1930, p. 38.

[14] Work cited, pp. 40, 41, 44.

undesirable, as it is not effective in eliminating phosphorus.[15]

Lime is used also in a number of processes in the manufacture of iron and steel products. The molds in which pig iron is cast are limed to prevent the iron from sticking, either by spraying them with a wash or by passing the molds through milk of lime. The requirements of lime for this purpose are not very rigid, but it should form a slow-settling suspension and not contain too high a percentage of waste.[16]

Lime is employed to neutralize the "pickling" liquor used to remove rust and scale from iron and steel before it can be discharged into streams. As it is employed in the form of milk of lime, it should not settle rapidly and should not contain a high percentage of core or overburned material.[17]

In the process of wire drawing, lime is used for several purposes. The rods of iron or coils of wire are dipped in milk of lime to neutralize the acid remaining after pickling. The lime coating thus obtained serves as a lubricant in the drawing process and protects the finished wire from oxidation. Lime for this process must be absolutely free from grit and ash and must form a slow-settling suspension.[18]

Refractory brick.- Large tonnages of lime also are sold for the manufacture of silica brick, which is used chiefly for lining furnaces. Milk of lime is added to silica in quantities ranging from 1.5 to 4 percent CaO. The mixture is molded in forms, dried, and burned under carefully controlled conditions. The lime serves as a bonding agent and also acts as an accelerator in the conversion reaction. Either quicklime or hydrated lime may be used for the milk of lime. It must be substantially free from ash, dirt, and core and must conform to the following requirements as to chemical composition, calculated on a nonvolatile basis.[19]

	Percent
Calcium oxide (CaO), minimum	92.0
Magnesium oxide (MgO), maximum	3.0
Combined iron and aluminum oxides (Fe_2O_3 and Al_2O_3), maximum	1.5
Silica (SiO_2) and insoluble matter, maximum	3.0
Carbon dioxide (CO_2), maximum:	
If sample is taken at place of manufacture	5.0
If sample is taken at any other place	10.0

Dead-burned dolomite, used extensively as furnace refractory, is not a true lime but sometimes is classed as refractory lime.

Paper.- The manufacture of paper is another large lime-consuming industry. Lime serves in several chemical processes of preparing the raw materials. In what is known as the sulphite process it is combined with sulphur dioxide to form an acid liquor that at high temperature and pressure dissolves and removes all the constituents of the wood chips except the cellulose. Either quicklime or hydrated lime may be used, but in either case a dolo-

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[15] Work cited, p. 9.

[16] Work cited, p. 10.

[17] Work cited, p. 11.

[18] Work cited, p. 11.

[19] American Society for Testing Materials, Standard Specifications for Quicklime and Hydrated Lime for the Manufacture of Silica Brick: C49-24.

mitic lime is preferred because magnesium bisulphite is more soluble than calcium bisulphite, its decomposition products also are more soluble, and it produces a softer, whiter pulp. The ratio of magnesium oxide to calcium oxide should be reasonably constant and the lime moderately free from impurities. The chemical composition of quicklime must conform to the following requirements, calculated on a nonvolatile basis.[20]

	Calcium lime		Magnesium lime	
	Maximum	Minimum	Maximum	Minimum
Calcium oxide, percent	....	94.3	....	56.5
Magnesium oxide, percent	2.6	....	....	40.4
Oxides of silicon, iron, and aluminum, percent	3.1	....	3.1	....

In the soda pocess wood and other fibers are digested with a caustic-soda solution. Lime is used as a causticizing agent in recovering the caustic soda from the wash by liberating the sodium hydroxide. It serves the same purpose in recovering the sodium sulphate in the sulphate process. Either quicklime or hydrated lime can be used, but quicklime generally is preferred because the heat generated by its slaking hastens the reactions. It must be low in magnesia, highly reactive chemically, quick settling, and quick slaking and have an available lime content of 85 or more percent.[21]

Rags for the manufacture of paper are cooked in a digester under steam pressure with lime or with lime and soda ash. They are then washed to eliminate as much of the noncellulose material as possible. The standard quicklime for use in cooking rags shall contain 90 percent available lime calculated on the basis of the weight of the sample taken at point of manufacture. Hydrated lime must contain 64.3 percent available lime calculated on the same basis.[22]

Water treatment.- Lime, or a mixture of lime and soda ash, is used extensively for softening water. When water contains considerable quantities of the bicarbonates and sulphates of calcium and magnesium it is "hard." The carbonates of calcium and magnesium are very slightly soluble in pure water, but when carbon dioxide comes in contact with the water containing these compounds the weak carbonic acid formed dissolves and holds in solution calcium and magnesium as bicarbonates, thus producing hardness. When an excess of lime is added to hard water it immediately combines with the carbon dioxide present and forms calcium carbonate, and as the solvent is thus removed the bicarbonates held in solution are precipitated. Thus, lime in suspension removes lime in solution. The precipitation of lime also assists in clarifying water and removing bacteria.

The character of treatment depends on the nature of the raw water and the purpose for which it is to be used - whether for hman consumption or for use in industrial processes. The essential features of the process involve preliminary settling of the water in large reservoirs and the addition of lime and other materials, such as soda ash, iron, or alum, to coagulate the impurities and remove temporary or permanent hardness.

The only useful constituent of lime for the treatment of water is the calcium oxide capable of reacting with the chemicals which are already in the water or which are added to

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[20] American Society for Testing Materials, Standard Specifications for Quicklime for Use in the Manufacture of Sulphite Pulp: C46-27.

[21] National Lime Association, Lime—Its Use and Value in the Industrial and Chemical Processes: 1930, p. 15.

[22] American Society for Testing Materials, Standard Specifications for Quicklime and Hydrated Lime for Use in Cooking of Rags for the Manufacture of Paper: C45-25.

it. Inert material makes more sludge to be disposed of and thus reduces the capacity of the equipment in which it is used. The lime therefore must be substantially free of core, ash, and dirt and capable of disintegrating in water into a suspension of finely divided material. Standard quicklime for use in water treatment must contain 90 percent available lime calculated on the basis of the weight of the sample taken at the point of manufacture.[23] Hydrated lime for this use must contain at least 68.1 percent available lime.[24]

Glass.- There are many kinds of glass, and raw materials and processes used in their manufacture vary. Lime is used as a raw material of plate, sheet, and bottle glass and of a large proportion of the pressed or blown glass. Silica in the form of sand is admixed in carefully weighed amounts with an alkali metal compound, usually sodium carbonate or sodium sulphate, and an alkaline earth compound, usually granulated quicklime.

The chemical requirements of the lime depend upon the kind of glass to be produced. The National Lime Association gives the following requirements.[25]

> For optical glass the iron oxide should be practically zero, whereas in bottle glass 0.5 percent is permissible, with nearly the same limits for blown or sheet glass. The silica or alumina may run as high as 15 percent for bottle glass, but it should be very much less for the other grades of glass. The sulphuric and phosphoric anhydride should be low, not exceeding 1 percent for bottle glass and diminishing through the other kinds to about 0.2 percent for optical glass. The combined CaO and MgO preferably should be at least 89 percent for bottle glass, 91 percent for sheet glass, 93 percent for blown glass, 96 percent for rolled glass, and 99 percent for optical glass.
>
> Quicklime should not contain more than 3 percent and hydrated lime not more than 5 percent carbon dioxide. The requirements regarding the state of division of the quicklime are variable, depending upon the conditions under which it is to be used, but, unless otherwise specified, it should pass a 12-mesh sieve.

Hydrated lime in varying percentages is used in admixture with plaster of paris for bedding plate glass on grinding tables.

Leather.- In the leather industry lime is used in the depilation process. The skins are soaked in vats containing lime water to which such "sharpening agents" as arsenic sulphide, sodium sulphide, and sodium hydroxide sometimes are added. The action of the lime is to swell up and soften the epidermal cells and dissolve the mucous layer, thereby so loosening the hair from the hide that it may be removed mechanically.

Either quicklime or hydrated lime may be used. It should have an available lime or calcium hydroxide content of at least 85 percent and lime should settle very slowly in suspension.[26] 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; iron oxides, though quite soluble, may become fixed mechanically in the grain of the hide and cause stains.[27] The use of hydrated lime would remove the objections to magnesia but not those to iron. In making morocco leather, however, high-magnesium lime is used.

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[23] American Society for Testing Materials, Standard Specifications for Quicklime for Use in Water Treatment: C53-27.

[24] American Society for Testing Materials, Standard Specifications for Hydrated Lime for Use in Water Treatment: C54-27.

[25] National Lime Association Lime—Its Use and Value in the Industrial and Chemical Processes: 1930, p. 23.

[26] Work cited, p. 27.

[27] Proctor, H. R., Principles of Leather Manufacture: 2d ed., S. Van Nostrand Co., New York, 1922, p. 121.

Calcium carbide and cyanamide.- Calcium carbide is made by heating a mixture of lime and carbon, in the form of coke, charcoal, or anthracite, to a very high temperature. Calcium cyanamide is made by treating this fused mass with nitrogen, in which process lime facilitates the reaction of the nitrogen with the carbide.

High-calcium quicklime is required for this use. Magnesia and alumina are undesirable, and the phosphorus and arsenic content especially should be low to avoid acetylene explosion.[28]

Alkali works.- In the manufacture of sodium hydroxide, or caustic soda, lime is added as a causticizing agent to a solution of sodium carbonate (soda ash). The caustic liquor thus formed is then filtered or settled to obtain a clear alkali liquor, which upon evaporation forms the sodium hydroxide.

Since the function of lime in this process is to furnish soluble alkali, a high-calcium lime must be used. Quicklime having an available lime content of at least 85 percent is preferred. Magnesia is inactive as a causticizing agent, and its content preferably should be not more than 3 percent.[29]

Lime is added to crude coal gas to concentrate crude ammonia liquors, and it is used also in the distillation of these liquors to produce aqua ammonia, anhydrous ammonia, or ammonium salts. The quicklime used in these processes should contain not less than 90 percent available calcium oxide, and at least 95 percent of the lime after being slaked should pass a 50-mesh sieve and not more than 10 percent be retained on a 200-mesh sieve.[30]

Sugar.- Milk of lime is used in clarifying and purifying juice extracted from either beets or cane to be used in the manufacture of sugar. When added to the juice and heated almost to boiling it combines with the acids, breaks up and precipitates other organic compounds, and forms insoluble salts. When beets are used it forms an insoluble compound with the sugar, and the juice is treated with carbon dioxide to disintegrate the lime and sugar and throw off the lime as calcium carbonate. This precipitate carries off all suspended matter, leaving a clear solution of sugar. In the Steffen process ground quicklime is used to precipitate sugar from impure molasses. For the reason that carbon dioxide is used in clarifying beet sugar, factories using beets produce their own lime and use the carbon dioxide obtained from the kilns for the carbonation process. Manufacturers of cane sugar buy their supplies of lime. Lime also is used in small amounts in refining sugar. The raw sugar is reduced to a syrup, which is treated with milk of lime and phosphoric acid to carry off impurities as a precipitate.

This industry requires the purest grade of high-calcium lime that can be obtained. Except in the Steffen process it may be used as quicklime or hydrated lime. According to specifications recommended in National Bureau of Standards Circular 207, issued in 1925, the hydrated lime should be of such size that 98 percent of it will pass a 200-mesh sieve; lime powder, or ground quicklime, should be of the same fineness but not so fine that it will "ball" when rotated in a 40-mesh bolter at 20°C. The lime must meet the following chemical requirements:

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[28] National Lime Association, Lime-Its Use and Value in the Industrial and Chemical Processes: 1930, p. 31.

[29] Work cited, p. 57.

[30] National Bureau of Standards, Recommended Specifications for Quicklime for Use in the Distillation of Ammonia from Ammonia Liquors Obtained in Coke and Gas Manufacture: Circ. 373, 1929, 6 pp.

	Sugar soluble lime, minimum	Magnesium oxide, maximum	Loss on ignition, maximum
Quicklime for Steffen process	90	3	2
Quicklime for other purposes..	85	3	5
Lime powder..................................	90	3	2
Hydrated lime................................	85	3	....

Glycerine, soap, and lubricating greases.- Correct proportions of lime and animal or vegetable fat, mixed with a little water, are heated until the chemical reaction is complete. The glycerine in the fat is liberated and, after settling, is neutralized with lime and evaporated to crude glycerine. The soapy jelly remaining is mixed with mineral oil to form lubricating grease, or it may be treated with sulphuric acid and used in the manufacture of soap and allied products.

A high-grade, high-calcium lime is necessary in this process. It should contain less than 2 percent magnesia and less than 1 percent insoluble material, and the available lime content of quicklime or the available calcium hydroxide content of hydrated lime should be at least 90 percent.[31]

Paint and varnish.- The simplest form of paint is whitewash prepared by mixing lime and water. Various formulas now are used in preparing water paint for various applications, but the essentials are lime, pigment, and casein. Lime performs several functions in paint. As a protecting agent, soluble lime penetrates wood and there carbonates, protecting it against weathering and increasing its fire resistance. As an alkaline material lime, or carbonate, prevents rusting of iron and corrosion of other materials. Because it is white and possesses good covering and working qualities, hydrated lime serves as an excellent, economical, and readily available pigment. Lime also functions as a cementing or bonding agent in paints just as in plasters and mortars. It probably also improves the disinfecting properties of paint and makes it more suitable as a sanitary coating.[32]

In general, any hydrated lime that gives a smooth, fine-grained, and slow-settling suspension may be used in paint. The selection of a particular lime for a given formula must be governed by the other components of the mixture and the use to which the paint is to be put.[33]

In the manufacture of varnish, lime is added to melted resin to neutralize the acid in it and to clarify and harden the varnish. For this purpose lime must be hydrated completely and must conform to the requirements of the tung-oil-heat test. Not more than 10 percent must be retained on a 230-mesh sieve. It should have a minimum calcium oxide content of 94 percent, and to avoid undesirable color effects the iron oxide content must not exceed 0.4 percent.[34]

Bleaching powder and bleach liquor.- Bleaching powder, chloride of lime, or chlorinated liquor is formed by the action of chlorine on moist slaked lime. Liquid bleach is made by subjecting a milk-of-lime suspension to the action of chlorine. High-calcium quicklime or

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[31] National Bureau of Standards, Recommended Specifications for Quicklime and Hydrated Lime for Use in Soap Making: Circ. 372, 1929, 6 pp.

[32] National Lime Association, Lime--Its Use and Value in the Industrial and Chemical Processes: 1930, p. 74.

[33] Work cited, pp. 74-75.

[34] American Society for Testing Materials, Standard Specification for Hydrated Lime for the Manufacture of Varnish: C47-27.

hydrated lime is used for these products. It should have no appreciable amounts of impurities, including magnesia, as they accelerate decomposition of the bleach.[35]

Sand-lime brick.- Sand-lime brick is made by mixing sand and lime, pressing the admixture into brick form, and treating it with high steam pressure. The lime, reacting with a portion of the silica on the surface of the sand grains, forms calcium silicate, which binds the rest of the sand grains together. The lime must be completely hydrated before the mixture is pressed, otherwise subsequent hydration will cause expansion and rupture of the brick. For this reason many manufacturers find it better to have their own hydrating plants. A high-calcium lime is required to insure proper hydration. The MgO content preferably should be less than 5 percent, and the lime must be highly reactive chemically.[36]

Vienna lime.- Vienna lime is made from high-magnesium limestone or dolomite, with traces only of iron, silica, and alumina. The rock is grayish white and fine-grained and contains certain characteristic fossils (gastropods), which are said to affect its qualities materially. The stone is calcined carefully by a secret process, and the lime is cleaned, ground, packed in sealed containers, and sold to manufacturers of buffing compounds. Eardley-Wilmot states that the most important use of Vienna lime is for "coloring" nickel after it is plated to give it the deep "under-surface" blue peculiar to the metal.[37]

PRODUCTION

Statistics

Lime statistics include refractory lime (dead-burned dolomite). Table 1 has been compiled to show the growth of the lime industry in the United States since 1904. Available data indicate that production in 1935 was about 35 percent of total plant capacity.

TABLE 1.- Quantity and value of lime sold in the United States, 1904-34

Year	Short tons	Value	Year	Short tons	Value
1904	2,707,809	$9,951,456	1919	3,330,347	$27,643,000
1905	2,984,100	10,941,680	1920	3,570,141	37,543,840
1906	3,198,087	12,480,653	1921	2,532,153	24,895,370
1907	3,092,524	12,656,705	1922	3,639,617	33,255,039
1908	2,766,873	11,091,186	1923	4,076,243	39,993,652
1909	3,484,974	13,846,072	1924	4,072,000	39,596,423
1910	3,505,954	14,088,039	1925	4,580,823	42,609,141
1911	3,392,915	13,689,054	1926	4,560,398	41,566,452
1912	3,529,462	13,970,114	1927	4,414,932	38,638,413
1913	3,595,390	14,648,362	1928	4,458,412	36,449,635
1914	3,380,928	13,268,938	1929	4,269,768	33,478,848
1915	3,622,810	14,424,036	1930	3,387,880	25,616,486
1916	4,073,433	18,509,305	1931	2,707,614	18,674,000
1917	3,786,364	23,807,877	1932	1,959,990	12,302,231
1918	3,206,016	26,808,909	1933	2,269,280	14,253,659
			1934	2,397,087	17,164,024
			1935[1]	2,955,000[1]	21,438,000[1]

[1] Estimated.

Table 2 shows sales of lime, by States, for a series of years.

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[35] National Lime Association, Lime—Its Use and Value in the Industrial and Chemical Processes: 1930, p. 50.

[36] Work cited, p. 29.

[37] Eardley-Wilmot, V. L., Abrasives--Part I, Siliceous Abrasives: Canada Dept. Mines, Mines Branch Publication 673, 1927, p. 97.

TABLE 2. - Lime sold by producers in the United States 1925-34, by States

(All quantities in short tons)

	1925	1926	1927	1928	1929	1930	1931	1932	1933	1934
Alabama	207,699	220,732	206,010	192,364	209,260	164,822	137,423	92,359	107,810	123,881
Arizona	39,045	42,757	41,859	36,244	42,971	35,642	22,567	11,061	8,587	16,003
Arkansas	24,791	31,346	35,375	40,438	33,647	30,349	22,520	(1)	(1)	(1)
California	70,805	67,421	64,934	60,751	49,753	51,302	41,371	29,925	35,754	34,733
Colorado	(1)	12,470	11,900	8,114	7,046	6,777	4,646	(1)	2,887	3,712
Connecticut	58,449	61,742	53,304	48,152	35,180	28,489	(1)	(1)	(1)	(1)
Florida	17,793	9,424	5,317	4,748	(1)	(1)	(1)	10,841	(1)	14,207
Georgia	(1)	18,526	13,533	12,890	10,757	7,455	5,139	3,567	3,898	2,664
Hawaii	(1)	5,717	5,679	6,284	6,384	7,591	7,332	6,292	5,995	6,053
Idaho	(1)	(1)	(1)	(1)	(1)	2,463	880	(1)	(1)	(1)
Illinois	96,066	103,180	115,803	115,523	119,382	89,709	96,105	62,436	81,888	86,679
Indiana	127,878	126,005	116,171	107,209	116,795	87,965	81,925	58,440	64,479	72,606
Iowa	(1)	(1)	(1)	(1)	(1)	......	(1)	......	......	......
Kentucky	9,433	8,550	6,862	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Louisiana	......	(1)	......	......	......	......	......	......	......	(1)
Maine	115,571	128,120	116,566	123,023	92,428	66,775	28,157	23,354	(1)	(1)
Maryland	64,518	63,639	55,405	59,508	54,029	53,090	36,445	26,536	26,469	28,167
Massachusetts	197,732	202,065	189,343	171,944	133,644	107,502	123,607	68,959	56,941	52,518
Michigan	95,036	107,671	101,172	104,917	91,468	80,241	46,716	38,610	43,959	32,844
Minnesota	(1)	28,522	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Missouri	273,348	263,467	267,776	303,014	316,579	265,771	224,416	174,427	230,051	272,236
Montana	6,269	8,099	11,607	(1)	(1)	(1)	2,028	1,016	1,251	(1)
Nevada	(1)	23,162	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
New Jersey	(1)	(1)	(1)	(1)	1,644	(1)	(1)	(1)	(1)	720
New Mexico	1,329	2,032	2,042	2,002	(1)	2,369	(1)	990	(1)	(1)
New York	104,829	107,326	98,071	93,354	104,614	83,078	49,574	29,391	36,369	36,050
North Carolina	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Ohio	1,089,385	1,056,589	987,726	1,013,676	962,415	736,305	656,441	475,441	558,901	562,041
Oklahoma	(1)	257	(1)	......	(1)	(1)	......	......	......	......
Oregon	(1)	785	1,105	2,090	2,486	1,741	(1)	......	(1)	(1)
Pennsylvania	794,951	794,196	813,571	834,050	782,915	633,520	497,258	374,244	433,795	434,519
Puerto Rico	9,988	7,116	7,516	9,405	10,114	9,764	11,302	9,366	5,631	6,255
Rhode Island	(1)	2,857	2,937	2,589	1,885	2,638	2,042	1,927	1,503	1,884
South Dakota	(1)	(1)	(1)	(1)	(1)	(1)	2,682	(1)	(1)	(1)
Tennessee	175,685	173,363	181,385	183,541	172,936	147,648	113,268	106,706	119,587	122,818
Texas	74,638	78,293	80,796	82,325	97,332	74,081	45,553	35,903	36,286	36,620
Utah	22,062	29,953	48,882	47,662	46,581	27,522	18,192	9,092	8,557	9,611
Vermont	66,245	56,378	61,024	52,445	53,128	45,963	30,226	29,187	28,509	31,218
Virginia	192,429	188,696	178,426	174,067	153,170	146,996	100,659	78,771	84,597	94,041
Washington	29,636	23,783	23,959	24,529	31,598	26,913	20,619	18,862	17,214	22,764
West Virginia	270,895	267,464	244,950	279,947	308,600	228,230	170,420	82,757	121,473	143,071
Wisconsin	244,903	216,414	197,667	163,965	130,902	64,989	42,621	27,283	28,909	33,856
Wyoming	......	(1)	30	......	......	(1)	......	......	......	......
Undistributed	99,415	22,281	66,229	97,642	90,125	70,180	65,480	72,203	117,980	115,316
	4,580,823	4,560,398	4,414,932	4,458,412	4,269,768	3,387,880	2,707,614	1,959,990	2,269,280	2,397,087

1/ Included under "Undistributed."

Table 3 shows sales of lime for a series of years by major uses. The tonnages sold for each use indicate trends in market demands.

An analysis of sales of lime by users and by districts over a period of years, a discussion of the relation of sales to general conditions and to allied activities, and the extent to which consumption of lime is keeping pace with related products are given in another Bureau report.[38]

Economics of Plant Location

The main factors to be considered in locating a lime plant are quality and extent of raw materials, conditions for quarrying, fuel supply, markets, and transportation facilities. The importance of considering carefully the character of raw materials available in relation to the type of lime in demand should be emphasized. The adaptability of limes for various products has been discussed already.

Table 4 has been compiled to show the lime-producing districts of the country and the kinds of lime produced in each.

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[38] Hatmaker, Paul, Trade Trends in the Lime Industry: Rept. of Investigations 3227, Bureau of Mines, 1934, 17 pp.

TABLE 3.- Lime sold by producers in the United States, 1912-34, by major uses

(All quantities in short tons)

Year	Total (quick and hydrated)	Total hydrated	Building	Metallurgy	Refractory	Glass works	Sand lime and slag brick
1912	3,529,462	416,890	1,556,446	...	...	...	...
1913	3,595,390	493,269	1,358,099	...	...	...	...
1914	3,380,928	515,121	1,163,433	...	...	...	...
1915	3,622,810	581,114	1,149,733	...	...	...	...
1916	4,073,433	717,382	1,509,968	180,018	...	...	...
1917	3,786,364	709,157	1,313,493	209,976	...	60,624	...
1918	3,206,016	620,216	914,186	253,778	318,896	34,051	7,417
1919	3,330,347	777,408	1,191,434	295,622	222,036	44,618	5,096
1920	3,570,141	853,116	1,305,412	344,921	316,293	54,747	19,520
1921	2,532,153	792,970	1,239,486	164,245	107,664	43,851	5,464
1922	3,639,617	1,106,063	1,845,208	200,799	348,838	62,187	28,612
1923	4,076,243	1,225,928	2,131,533	373,020	357,642	78,942	14,854
1924	4,072,000	1,316,664	2,169,700	336,813	328,659	72,822	26,549
1925	4,580,823	1,560,848	2,387,267	411,190	392,147	73,011	25,144
1926	4,560,398	1,606,811	2,320,323	408,234	386,715	84,263	39,821
1927	4,414,932	1,596,906	2,148,840	406,063	374,415	78,994	43,064
1928	4,458,412	1,612,818	1,986,465	504,248	448,761	76,161	47,527
1929	4,269,768	1,550,771	1,640,827	578,488	488,032	75,283	42,540
1930	3,387,880	1,329,562	1,204,614	415,692	351,740	62,912	29,506
1931	2,707,614	1,119,266	947,085	290,352	243,769	59,148	17,530
1932	1,959,990	852,251	596,825	170,518	135,733	51,142	13,524
1933	2,269,280	840,407	533,088	265,963	261,812	82,634	4,349
1934	2,397,087	829,340	511,419	334,406	324,868	76,232	8,446

Year	Agriculture	Paper mills	Water purification	Tanneries	Sugar refineries	Total accounted for by major uses	Total not so accounted for
1912	604,607	290,347	...	40,595	30,988	2,522,983	1,006,479
1913	590,229	284,090	...	49,591	32,236	2,314,245	1,281,145
1914	684,348	242,998	...	49,393	31,931	2,172,103	1,208,825
1915	673,260	216,819	...	47,104	34,025	2,120,941	1,501,869
1916	613,527	353,187	...	59,919	21,923	2,738,542	1,334,891
1917	488,297	355,768	...	66,629	47,546	2,542,333	1,244,031
1918	391,047	325,172	...	74,350	36,494	2,355,391	850,625
1919	438,632	335,813	...	59,978	13,111	2,606,340	724,007
1920	351,851	365,897	90,533	61,162	14,145	2,924,481	645,660
1921	284,722	235,855	74,201	47,841	12,225	2,215,554	316,599
1922	272,726	310,229	87,432	42,978	16,393	3,215,402	424,215
1923	240,551	311,309	92,406	53,906	13,044	3,667,207	409,036
1924	248,336	300,101	113,577	53,349	17,061	3,666,967	405,033
1925	298,976	376,670	115,776	62,933	19,089	4,162,203	418,620
1926	297,010	423,322	139,478	66,536	15,379	4,181,081	379,317
1927	322,893	429,606	124,212	63,666	16,086	4,007,839	407,093
1928	333,910	429,334	145,757	64,464	22,678	4,059,305	399,107
1929	338,329	411,017	156,117	67,046	20,758	3,818,437	451,331
1930	343,111	378,721	161,805	56,526	18,905	3,023,532	364,348
1931	297,312	286,745	160,384	54,604	18,185	2,375,114	332,500
1932	244,574	259,418	142,594	45,943	22,628	1,682,899	277,091
1933	246,110	304,729	174,694	70,662	17,372	1,961,413	307,867
1934	222,077	293,798	183,581	62,745	20,528	1,304,604	358,987

[1] Quantities listed under the several uses include both quick and hydrated lime.

TABLE 4.- Kinds of lime produced in the United States, by States and counties

State or Territory	County		
	High-calcium lime	High-magnesium lime	Low-magnesium lime
Alabama	Blount	Jefferson	Colbert.
	Colbert		Shelby.
	Shelby		
Arizona	Cochise		Yavapai.
	Yavapai		
Arkansas	Independence		
	Izard		
	Washington		
California	Alameda		Eldorado.
	Eldorado		
	San Bernardino		
	Santa Cruz		
	Tulare		
	Tuolumne		
Colorado	El Paso		
	Pueblo		
Connecticut		Litchfield	
Florida	Dade		
	Marion		
Georgia		Bartow	
Hawaii	Oahu Island		
Idaho	Clearwater	Kootenai	
	Kootenai		
Illinois	Adams	Cook	
	Cook	Rock Island	
	St. Clair		
Indiana	Cass	Huntington	Marion.
	Harrison		
	Lawrence		
	Marion		
	Washington		
Kentucky	Rockcastle		
Louisiana	Evangeline		
Maine	Knox	Knox	Knox.
Maryland	Baltimore	Baltimore	Frederick.
	Frederick	Frederick	Carroll.
			Washington.
Massachusetts	Berkshire	Berkshire	Berkshire.
Michigan	Cheboygan	Emmet	Emmet.
	Emmet	Menominee	
	Menominee		
Minnesota	Mower	Blue Earth	St. Louis.
	St. Louis	St. Louis	

TABLE 4.- Kinds of lime produced in the United States by States and counties - Continued

State or Territory	County		
	High-calcium lime	High-magnesium lime	Low-magnesium lime
Missouri	Greene		St. Genevieve
	Jefferson		
	Lawrence		
	Marion		
	St. Genevieve		
	St. Louis		
Montana	Deerlodge		
	Powell		
Nevada	Clark	Clark	White Pine.
	White Pine		
New Jersey	Sussex	Somerset	
		Warren	
New Mexico	San Miguel		
New York	Clinton	Dutchess	Clinton.
	Erie	Genesee	Herkimer.
	Herkimer		Ulster.
	Warren		
North Carolina	Henderson		
Ohio	Franklin	Clark	Delaware.
	Lawrence	Greene	Ottawa.
	Ottawa	Hardin	Stark.
	Stark	Ottawa	
		Sandusky	
		Seneca	
		Wood	
		Wyandot	
Oregon	Baker		
	Josephine		
	Wallowa		
Pennsylvania	Adams	Blair	Adams.
	Bedford	Chester	Blair.
	Blair	Dauphin	Cambria.
	Butler	Lancaster	Center.
	Cambria	Lebanon	Columbia.
	Center	Montgomery	Dauphin.
	Columbia		Lancaster.
	Cumberland		Lycoming.
	Dauphin		Mifflin.
	Lawrence		Somerset.
	Lebanon		Westmoreland.
	Lycoming		York.
	Mifflin		
	York		

TABLE 4.- Kinds of lime produced in the United States by States and counties - Continued

State or Territory	County		
	High-calcium lime	High-magnesium lime	Low-magnesium lime
Rhode Island			Providence.
South Carolina	Calhoun		Calhoun.
South Dakota	Custer		
	Pennington		
Tennessee	Coffee		Cumberland.
	Cumberland		Knox.
	Dickson		Montgomery.
	Franklin		
	Houston		
	Knox		
	Montgomery		
Texas	Comal		Coryell.
	Coryell		El Paso.
	El Paso		Harris.
	Dallas		
	Harris		
	Travis		
	Williamson		
Utah	Juab	Salt Lake	
	Salt Lake	Cache	
	Sevier	Tooele	
	Tooele		
Vermont	Addison	Windsor	Chittenden.
	Chittenden		
	Franklin		
	Rutland		
Virginia	Botetourt	Augusta	Botetourt.
	Frederick	Botetourt	Loudoun.
	Giles		Montgomery.
	Rockingham		Rockingham.
	Shenandoah		Shenandoah.
	Tazewell		Warren.
	Warren		
Washington	San Juan	Stevens	San Juan.
	Stevens		Stevens.
West Virginia	Berkeley	Jefferson	Berkeley.
	Preston		
	Wayne		
Wisconsin	Brown	Calumet	
		Dodge	
		Fond du Lac	
		Manitowoc	
		Ozaukee	
		Sheboygan	

QUARRYING LIMESTONE FOR LIME MANUFACTURE

Relatively few limestones are suitable for the manufacture of lime, for, as has been shown, they must possess certain chemical and physical properties. Not only are deposits variable in their properties, but individual beds within a deposit also differ. An operator contemplating the opening of a quarry for lime manufacture, therefore, must determine first the suitability of the stone for the major use to which the lime is to be put.

Methods of quarrying stone for the manufacture of lime are discussed only briefly in this paper. A detailed discussion of this subject may be found in Bureau of Mines Bulletin 269, Quarry Problems in the Lime Industry.

Prospecting.- After a stone suitable for the manufacture of lime has been found the next steps are to determine the extent of the deposit and to study the conditions affecting the development of a quarry or mine. To insure profitable operation a tonnage for at least 20 years' work should be proved. An idea of the extent may be had by a study of outcrops and by trenching and drilling. When the extent is known the tonnage may be estimated by multiplying the length, depth, and width in feet by 160 pounds (the average weight of 1 cubic foot of limestone) and dividing by 2,000.

Data on the composition, structure, and extent of the rock commonly are sought from surface conditions and trenching only. Such methods, however, frequently are inadequate for planning the development of a deposit. Prospect drilling is a valuable means of determining conditions at depth. Churn drilling generally provides adequate information on extent and quality.

Conditions governing open-pit and underground work.- The next problem is the proper method of development - whether an open-pit quarry would be more economical and how it should be developed, or whether underground mining should be resorted to. The chief factors involved are thickness of beds, position of beds - whether flat or tilted - strength and soundness of the rock, depth of overburden, topography of the region, and available area for waste disposal.

Open-pit quarrying usually is to be preferred when the rock has little or no overburden, because blasting by modern methods in deep holes back of an open face is more economical than the more confined drilling and blasting necessary in underground work. Where approximately horizontal beds are covered with a heavy overburden or where an opening in inclined beds must be carried beneath an ever-increasing burden of waste, underground methods are preferred. Underground methods are successful, however, only where the rock is strong enough to form a safe roof without timbering and with rock pillars spaced at moderate intervals.

Other important factors, as explained before, are the composition, structure, and physical properties of the various beds of a deposit. Certain beds may be unsuited for the manufacture of lime and should be discarded or diverted to other products. On the other hand, many deposits consist of a series of beds that, while varying somewhat in character, fall within the qualifications that permit their utilization for lime. Selection of stone for a special kind of lime may necessitate a method of quarrying different from the one followed when lime of another grade is to be produced. It therefore behooves an operator to study his deposit carefully and to plan his operations for the most efficient production of the kind or grade of lime desired.

Stripping.- The stone must be stripped clean, for silica and alumina, the chief constituents of a sand and clay overburden, are harmful impurities in lime. Mechanical stripping is the most economical method if conditions are favorable, but it is sometimes necessary to strip by hand irregular rock surfaces with large pockets of sand and clay or to shoot overburden and rock down together and separate them later on the quarry floor. This process, however, is tedious and wasteful unless a washing plant is available. The difficulty of stripping rough surfaces may prompt operators to resort to mining methods.

Drilling and blasting.- Most open-pit quarries are worked in single benches that may be 20 to over 100 feet high. Holes the entire depth of the face and about 6 inches in diameter are sunk with churn drills, and moderately heavy blasts loosen the rock. If charges are too heavy, an excessive proportion of fines is produced; if too light, much secondary blasting is required to reduce the large blocks of stone. If quarry conditions are unfavorable for churn drilling or if several ledges differ enough in quality to require quarrying separately, piston drills or hammer drills may be used on low benches. Holes may be drilled vertically from the top of the bench or horizontally at the base ("snake" holes). The spacing (distance apart in the row) and burden (distance back from the face) of drill holes is governed by the toughness of the rock and varies in different deposits. The proper spacing and burden can be determined only by experience.

Methods of underground operation, which are quite complex, are described in detail in a Bureau bulletin.[39]

Sorting and loading.- After the larger blocks are broken with dynamite they are reduced further to sizes suitable for charging into the kiln. Large unbroken rock may be loaded with mechanical shovels, but it must be crushed and screened later. Many operators prefer hand-sledging to mechanical crushing because it produces less fines; hand-loading, which involves hand-sorting, is advantageous because it permits selection according to quality. Hand-picked stone makes a higher-grade lime than unsorted material loaded with shovels and sized with mechanical equipment.

Quarrying to obtain a uniform grade of lime.- When the properties of stone at several levels or in several zones of a quarry face vary, rock of average quality with regular distribution of impurities that are not removable easily may be obtained only by mixing the stone from the various beds. In horizontal beds uniform quality may be obtained by shooting down all the ledges together in a mixed mass, loading the rock by hand, and distributing successive cars from each loading point to different kilns. The finished lime also is mixed during loading. When conditions are not favorable for single-bench operation, a quarry may be worked in a succession of comparatively low benches, but work must be carried on simultaneously on all benches. Carloads of rock from the several levels then must be taken to the kilns in regular order. When beds are inclined it is more difficult to maintain uniformity, and under some conditions underground methods offer advantages.

Quarrying to obtain special kinds of lime.- Whereas efforts formerly were directed chiefly toward producing a single uniform grade of lime increasing markets for special kinds or grades have made it necessary for operators to select and quarry beds having the desired properties, for the quality of a lime depends principally on the quality of the parent limestone. Each kind of lime - high-calcium, high-magnesium, low-magnesium, plastic, or nonplastic - is used in different processes and products. The impurities and the percentage of each impurity in the lime also govern the use to which it is put. As a rule, chemical uses demand greater purity than do agriculture or building; even small percentages of certain impurities may be decidedly harmful in some chemical processes. Some impurities in raw material for building lime actually may improve its quality, while for agriculture impurities generally are not harmful. For one use a certain impurity may be objectionable, while for aother the same impurity may cause no difficulty if present in reasonably small amounts.

Another feature that must be considered is that the percentage of each impurity in a stone is virtually doubled in the lime. There is little or no loss of the main impurities during calcination, although the weight of the limestone is reduced nearly half through loss of carbon dioxide. All impurities in each 100 pounds of limestone remain in the approximately 56 pounds of lime resulting from calcination. Therefore, if 4 percent is the maximum

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[39] Thoenen, J. R., Underground Limestone Mining: Bull. 262, Bureau of Mines, 1926, 100 pp.

permissible percentage of an impurity in a finished lime, the proportion of this impurity in the limestone should not exceed 2 percent.

The physical as well as the chemical properties of a stone also influence the character of the lime produced. Limestones of identical chemical composition under the same burning conditions may give limes that differ in character. Some limestones crumble more readily than others during calcination. Certain beds chemically suitable may decrepitate or crumble so badly that it may be advisable to quarry and calcine them separately or, if lump lime is to be made, to reject them as raw material. Moreover, some beds are more refractory than others and require either a higher temperature or a longer time for calcination.

To obtain rock for special grades of lime, therefore, stone must be selected carefully in the quarry. Each bed may be worked as an independent unit, which may involve quarrying a succession of low benches with tripod or hammer drills and selecting and loading stone by hand. Underground mining sometimes is the better method. Rock from mines is not so liable to be mixed with impurities as that from open pits; this is particularly true of fines.

No general methods of quarrying can be given, for they must be varied to suit the peculiarities of the rock formation. Quarrying stone for specified types of lime usually costs more per ton than quarrying for a single uniform grade of lime, but the higher prices received for the lime may repay the increased cost of producing the raw material.

Transportation.- Stone usually is conveyed in three stages. It is removed from the quarry or mine, carried to the kiln or crusher, and elevated to the top of the kiln. The methods of conducting the work must be varied to suit the peculiar conditions of each quarry. The stone usually is loaded in tramcars. If the distance from quarry to kiln justifies, a locomotive is used for haulage. A cable draws the cars up a steep incline to the top of the kiln.

METHODS OF MANUFACTURE

Calcining Processes

Limestone or other raw material is converted into lime through the agency of heat. The process brings the stone into contact with a sufficiently high temperature long enough to dissociate the carbon dioxide and drive it off as gas. The quantity of heat required varies with the chemical and physical properties of the stone; small pieces of stone calcine more quickly than large ones; fine-grained stone conducts heat more readily than that which is coarsely crystalline and porous. Experimental work[40] has shown that the temperature of dissociation of calcium carbonate is 898°C. (1,648°F.) at atmospheric pressure. The corresponding temperature for magnesium carbonate has not been determined as accurately, but 756°C. (1,393°F.), obtained by Mitchell, probably is correct. After the dissociation temperature has been reached it must be maintained long enough to transfer the required amount of heat to the stone. A high temperature for a short time or a lower temperature for a longer time may be used, but the more nearly the heat approaches the minimum required the better the quality of the lime will be. To obtain a large output per kiln, however, a temperature of 1,050° to more than 1,100°C. commonly is carried.

It is well-known that the chemical reaction involved in burning lime is reversible; that is calcium carbonate may be decomposed into calcium oxide and carbon dioxide, or these substances may recombine to form calcium carbonate. The factor that determines the way the reaction shall go is the pressure of the carbon dioxide. If the gas is allowed to accumulate

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[40] Johnston, John, Thermal Dissociation of $CaCO_3$: Jour. Am. Chem. Soc., vol. 32, 1910, p. 938; Mitchell, A. E., Studies on the Dolomite System, Part I--Nature of the Dolomite: Jour. Chem. Soc. (London), vol. 123, 1923, pp. 1055-69.

its pressure may reverse the reaction, and the lime will recarbonate. Prompt removal of the gas therefore is essential to efficient calcination.[41]

Calcination, commonly known as "burning", is done in some form of kiln. Shaft kilns are used most generally, though the rotary type now is used extensively when hydrated lime is to be produced.

Shaft Kilns

Shaft kilns are built in various designs, but in general this type of kiln is a short, wide stack lined with refractory material. Stone is dumped into the upper part, called the hopper, where it is preheated slowly with the hot kiln gases. It gradually slides down into the middle section of the kiln, the shaft, which is the burning or calcining zone. The lime manufactured in this hot zone sinks downward into the third section, the cooler, from which it is drawn at intervals. The size of a kiln usually is governed by the demand for the lime because quicklime can be stored for only a short time. Hydrated lime, however, may be stored for longer periods. If there is a steady demand for a definite supply of lime, an operator may be justified in building a kiln large enough to supply the desired quantity; otherwise, it is better to build a number of small kilns so that production may be adjusted more easily.

Casing.- The casing, or outside of a kiln, may be of steel, stone, or a combination of steel with stone or some other material. It may be round, square, or elliptical. The casing performs three functions: It carries part of the weight of the kiln, protects the lining from changes in temperature, and minimizes the amount of heat lost by conduction and radiation.

Lining.- The lining usually is the same thickness throughout the kiln. If firebrick is used, about 8 inches (two courses) generally are considered enough; other materials may vary in thickness from 9 to 18 inches. The lining must be able to withstand reasonably well the chemical action of the lime as well as the temperature required for burning and the abrasion to which it is subjected. It is necessary to repair or replace the lining at intervals. Various grades of firebrick generally are used; mica schist, sandstone, and granite sometimes are employed. Often two grades of firebrick are used, for brick refractory enough to give good results in the burning zone may be too soft to withstand the abrasion to which it is subjected in the upper kiln.

Top of kiln.- The top of a kiln may be open, closed with flat steel plates or surmounted by a stack. A closed top, used in some systems of induced draft, should be kept virtually airtight so that the fan that removes the gas need not handle any unnecessary air. A closed top has two openings, one for charging the kiln with stone and one for removing the gas. The charging door usually is about 3 feet wide by 5 feet long, large enough to admit a carload of 2 or 3 tons of stone at once. The stack, which is the ordinary round-steel variety, aids combustion and assists in preventing recarbonation of the lime.

Hopper.- The hopper serves a twofold purpose; it provides space for storing enough stone to insure continuous operation, and it conserves fuel by utilizing the heat of waste gases to preheat the stone. It is shaped like an inverted cone; the large base is at the top, and the sides slope until the cross section becomes that of the shaft. The hopper usually is large enough to hold a 48-hour supply of stone.

Shaft and fireboxes.- The firebox consists of a grate spanned by an arch of firebrick, closed in front by a door and opening into the kiln in the rear. Two or more fireboxes are set into openings through the lining and casing in the lower part of the shaft, or, if gas

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[41] Burchard, Ernest F., and Emley, aarren E., The Source, Manufacture, and Use of Lime: U.S. Geol. Survey Mineral Resources of the United States, pt. II, 1913, p. 1569.

or oil are used as fuel ports through which they are hled into the kiln are used in place of fireboxes. The proper grate area depends on the quantity and quality of coal burned; it is customary to allow 1 square foot of grate surface for 12 to 15 pounds of bituminous coal an hour.

The draft caused by combustion of the fuel draws the flame up through the shaft in direct contact with the limestone, and the gases formed pass out the top of the hopper. The draft may be natural, forced by blowing air under the grates, or induced by a fan that draws the gas from the top of the kiln. By the Eldred process a fan takes the gas from the top of the kiln and forces it back under the grates. The carbon dioxide thus introduced is reduced to carbon monoxide (an endothermal reaction that tends to keep the grates cool); and as the carbon monoxide passes upward through the mass of stone it oxidizes (an exothermal reaction), thus extending the flame and promoting uniform calcination. Introduction of steam beneath the grates has the same effect.[42]

The stone is heated gradually as it passes down through the shaft until the temperature of calcination is reached, which usually is about 8 feet above the grates. The cross section of the shaft may be rectangular, elliptical, or circular; its diameter is limited by the distance the heat can be made to penetrate toward the center. The size and shape of the shaft depend very largely on the method by which the kiln is to be operated.

Cooler.- The top of the third compartment or cooler has the same cross section as the shaft. but its sides recede to form a steep cone, which terminates at the drawing door built 3 or 4 feet above the floor. The lime falls through the door into large iron barrows or into dump cars on tracks beneath the kiln. When a lined cooler is used the lime is removed hot and must be dumped to cool, which necessitates rehandling. When the lime is drawn cold, it may be dumped into a car for shipment. The most efficient coolers are provided with ducts through which the air used in burning the fuel is drawn and thus preheated.

All unburned stone must be kept above the level of the grates as heat from the fireboxes does not extend downward; enough lime, therefore, must be kept in the cooler to support the stone at the required height. Two methods of doing this are followed. When lime is drawn from the bottom of the kiln the remaining lime and stone slide down and fill up the space. Because the flame and hot gases tend to pass up the sides of the shaft rather than through the center, unburned stone extends down farther in the center than at the sides. It is obvious, therefore, that if the burned stone is allowed to fall to the burning level the unburned portion in the center falls below that level. By the "following" method enough lime is drawn so that the lowest part of the unburned material will reach to about grate level. The difficulty with this method is that the lime remaining above the grates may be overburned. By the "sticking" process the kiln is allowed to chill before drawing. The chilling causes contraction of the lining and solidification of the fused compounds resulting from the action of lime on the lining. These two processes prevent the stone from following and cause it to "stick" or "hang." The lime is knocked down with bars, and an even layer of fresh stone falls to grate level. In general, stone will follow in a shaft with sides sloping outward and will stick if the sides are straight, but any type of kiln may be operated by either process.

After lime has been burned it should be kept moving through the kiln, as further heating impairs its quality. The frequency with which it should be drawn depends on many conditions and can be determined only through experience. Lime is sorted to remove underburned stone and overburned lime; this is done either while the lime is being drawn or when it is taken from the cooling floor.

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[42] Berger, E. E., The Function of Steam in the Limekiln: Tech. Paper 415, Bureau of Mines, 1927, 43 pp.

Rotary Kilns

The rotary kiln is a steel cylinder resting on two heavy steel rings or tires that encircle it near each end and bear on steel rollers. It inclines 1/2 inch to 1 foot and revolves slowly on its axis. The driving mechanism, consisting of a series of gears, is placed at a point about a fourth the length of the kiln and is run by a variable-speed motor. The speed of the motor in turn is controlled automatically by the amount of stone fed into the kiln.

A few years ago kilns ranged from 6 to 8 feet in diameter and 100 to 125 feet in length, but the more recent trend is toward larger and longer kilns. Firebrick are used for the lining. The upper end of the kiln is located in a chamber, usually of brick, designed to collect and remove dust from the kiln. Beyond this chamber is located the stack, which produces the necessary draft through the kiln and chamber. The cooler, similar in construction and operation to the kiln, though shorter and smaller, is placed beneath the kiln. Because of the excessive amount of dust that may be swept into the flame, many coolers are divided into four segments.

For rotary kilns stone must be uniform in size, generally from 1/2 inch to 1 1/2 inches, which necessitates crushing and grading the rock after it is taken from the quarry. For efficient operation the stone also should be clean and dry. It is charged constantly from a bin into the kiln by an adjustable feeder. To produce lime of good quality the heat of a rotary kiln must be uniform. Coal, oil, or natural or producer gas may be used as fuel. The burned lime is discharged from the lower end of the kiln through an opening in the lower part of the hood into a chute that directs it to the cooler. At the lower end of the cooler it is discharged to a conveyor that takes it to a hydrate mill or to storage bins.

Sintering Machines

In 1925 and 1926 the Bureau of Mines, cooperating with a machinery company, conducted a series of tests to determine the feasibility of using sintering machines for calcining small stone. A sintering machine consists of traveling pallets with perforated floors. Limestone in small sizes is carried on the pallets and is calcined chiefly by hot gases from an external source, which are drawn through the layers of stone as the pallets pass over a suction box. Details of the operation have been described by Myers.[43] The equipment is, or has been, employed by lime companies to a limited extent, principally for making dead-burned dolomite.

Hydration Processes

Hydrated lime is prepared by crushing lime as it comes from the kiln, slaking it, and classifying the fine powder thus produced by screens or air separators to remove any core or overburned lime that would not slake. For hydrating, lime is crushed to about 1 inch or smaller because in these sizes it may be slaked mechanically, its reaction with water is quicker, and it produces a better hydrate than does lump lime.

Lime and water are mixed for slaking in a mechanical device called a hydrator. There are various designs of hydrators, but they are of two general types. The intermittent type consists of a circular iron pan, which revolves horizontally and is large enough to hold about 1 1/2 tons of hydrated lime, and a shaft with arms radiating from its lower end sus-

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[43] Myers, W. M., Manufacture of Lime from Small Stone with a Sintering Machine: Rept. of Investigations 2762, Bureau of Mines, 1926, 15 pp.

pended in the center of the pan; the arms carry plows that scrape the bottom of the pan as it revolves thus mixing the lime and water thoroughly. The pan is kept revolving until the evolution of steam ceases (indicating that hydration is complete) and the lime becomes light and dry. The machine is covered by a hood and stack. A continuous hydrator consists of long iron tubes, one above the other, in each of which is a screw conveyor. Lime is placed in the top tube, and water is added through a stack at one end of the tube. They are mixed by the screw conveyors and at the same time carried through the tubes. When the mixture reaches the end of the pipe it is completely hydrated.

The process of hydrating must be manipulated so that the lime may be slaked properly. It is important that enough water be added to hydrate the lime completely, but an excess of water makes the lime wet and sticky and must be avoided. About 18 pounds of water must be added to 56 pounds of pure, high-calcium lime to make 74 pounds of hydrate. It is necessary, also, that the water and lime be mixed thoroughly, otherwise the heat generated by slaking may be localized and become so intense that the lime will "burn." High-calcium limes slake much faster than those containing considerable quantities of magnesia and consequently liberate a great amount of heat in a short time, which must be dissipated or the lime will burn. This may be accomplished by regulating the water in such a manner that the excess heat will be absorbed by evaporation. In general, magnesium limes hydrate less quickly than high calcium limes and do not burn so readily. It is important also that the proper design of hydrator be used, for no one type is suitable for all kinds of lime.

The chief advantages of hydrated lime to the consumer are that it is handled easily, keeps better than lump lime, does not require slaking, and has been screened to eliminate unburned or overburned lime. On the other hand, hydrated lime contains a considerable proportion of water, on which the consumer must pay freight.

STORAGE AND SHIPMENT

Quicklime cannot be stored for a long time, as it air-slakes readily and eventually becomes useless for most purposes. It is marketed as lump lime, just as it comes from the kiln, or as pulverized lime ground to any desired fineness. It may be shipped in bulk in airproof and moistureproof bags, in wooden barrels of 180 or 280 pounds capacity, or in steel drums. It sometimes is shipped by truck rather than by rail; but, whatever the method of shipment, care must be taken that moisture does not reach the lime and slake it in transit.

Hydrated lime is taken from screens or air separators, in which all unhydrated, lumpy material is eliminated, to dustproof storage bins, in which it may be aged if desired. Hydrated lime usually is shipped in 50-pound bags. Packing is done by means of an automatic machine that receives the lime from the bins and delivers it to the bags.

MARKETS AND PRICES

The principal markets for lime have been indicated in the section on "Uses" and by the table of sales of lime by uses under "Production." Study of these statistics reveals that major sales have been to the building industries, for agriculture, to the steel and other metallurgical industries for refractory and fluxing material, and to paper mills, glass works, tanneries, and water-treatment plants. These industries normally consume about 86 percent of domestic sales. The remaining 14 percent includes lime sold for use in the manufacture of alcohol, alkalies, bleaches, calcium acetate, calcium carbide, coke gas and byproducts, glue, insecticides, oils and fats, paints, rubber, and sand-lime, slag, and silica brick; in the disposal of sewage and garbage; in the textile industries; and in wood distillation. There are many other uses for which sales data are not available.

Cost of production is an influential factor in marketing. A plant that operates at low cost has a wider field than one that operates at high cost. The distance to which lime may be shipped depends also on the nature of the product. Lime peculiarly adapted for special uses may command a price that will justify shipment over long distances, and distant markets may be developed through an established reputation for reliability. Demands for lime conform in a general way to current conditions within the more important consuming industries. For example, sales of building lime conform generally to the floor space of new buildings or to the value of building contracts awarded, and sales of metallurgical and refractory lime to volume of steel-ingot production. Sales of lime are affected also by purely local conditions. Analyses of trends in sales, particularly of the causes for the fluctuations in quantities sold for the various uses, are valuable in forecasting future demands. Some of the findings of an analysis of market trends and prices of lime compared with those of other materials appear in another Bureau circular.[44]

The average price of lime began to decline in 1924 more or less in conformity with prices of other commodities. This trend was arrested in 1934, though the average was still considerably below values of pre-depression years. Table 5 shows average values of lime sold for building, agricultral, and chemical purposes and the total average for a series of years.

TABLE 5.- Average value per ton of lime sold in the United States 1914-34, by use[1]

Year	Agriculture	Building	Chemical	Total
1914..	$3.13	$4.36	$3.68	$3.92
1915..	3.21	4.26	4.03	3.98
1916..	3.63	5.21	4.17	4.54
1917..	5.07	6.63	6.35	6.29
1918..	7.42	8.51	8.58	8.63
1919..	7.63	9.64	8.49	8.84
1920.	8.80	11.70	9.98	10.52
1921..	7.86	10.70	9.19	9.83
1922..	7.35	10.01	8.32	9.14
1923..	7.59	10.57	9.18	9.81
1924..	7.51	10.61	8.90	9.72
1925..	7.12	10.10	8.64	9.30
1926..	7.25	10.01	8.33	9.11
1927..	6.93	9.76	7.94	8.75
1928..	6.85	8.91	7.70	8.18
1929..	7.06	8.72	7.33	7.84
1930.	6.92	8.34	7.17	7.56
1931.	6.47	7.33	6.70	6.90
1932..	5.59	6.45	6.33	6.28
1933..	5.36	7.18	6.11	6.28
1934..	6.66	8.33	6.87	7.16

[1] Figures do not include cost of package.

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[44] Hatmaker, Paul, Trade Trends in the Lime Industry: Rept. of Investigations 3227, Bureau of Mines, 1934, 18 pp.

FOREIGN TRADE

Very little lime is exported. Shipments are mainly to Peru, the West Indies, Mexico, and Canada. Virtually all imports are from Canada to the States of Washington and California. Table 6 shows total imports and exports from 1923 to 1933.

TABLE 6.- Lime imported and exported from the United States, 1923-34
(All quantities in short tons)

Year	Imports	Exports	Year	Imports	Exports
1923	25,407	11,789	1929	21,501	17,334
1924	20,480	14,905	1930	20,706	14,536
1925	15,323	14,800	1931	13,458	11,924
1926	18,702	12,960	1932	8,777	3,579
1927	19,567	15,478	1933	10,505	3,710
1928	18,321	18,188	1934	9,232	3,752

SELECTED BIBLIOGRAPHY

ADAMS, F. W. Effect of Particle Size in the Hydration of Lime. Jour. Ind. and Eng. Chem., Vol. 19, May 1927.

AMES, J. W., and SCHOLLENBERGER, C. J. Liming and the Lime Requirements of Soil. Ohio Agric. Exp. Sta. Bull. 306, 1916, pp. 279-396.

BERGER, E. E. The Function of Steam in the Limekiln. Tech. Paper 415, Bureau of Mines, 1927, 43 pp.

BLEININGER, A. V. The Physical Properties of Lime. Trans. Nat. Lime Mfrs. Assoc., 1909, pp. 365-69.

BLEININGER, A. V., and EMLEY, W. E. Burning Temperature of Limestones. Trans. Nat. Lime Mfrs. Assoc., 1911, pp. 68-78.

BOWLES, OLIVER. Utilization of Waste Rock at Lime Plants. Rept. of Investigations 2463, Bureau of Mines, 1923, 5 pp.

BOWLES, OLIVER, and BANKS, D. M. Limestone--Part I, General Information. Inf. Circ 6723, Bureau of Mines, 1933, 21 pp.

BOWLES, OLIVER, and MYERS, W. M. Quarry Problems in the Lime Industry. Bull. 269, Bureau of Mines, 1927, 97 pp.

BROWN, P. E., HOWE, F. B., and SOR, M. E. Soil Acidity and the Liming of Iowa Soils. Iowa Agric. Exp. Sta. Bull. 151, 1914.

BURCHARD, E. F. Stone. U.S. Geol. Survey Mineral Resources of the United States, pt. 2, 1911, pp. 782-831; 1912, pp. 754-815; 1913, pp. 1335-1408. Contain a series of maps showing the location of every limestone quarry and limekiln in the United States.

_____Lime. U.S. Geol. Survey Mineral Resources of the United States, pt. 2, 1911, pp. 645-718. Contains a table showing the chemical analyses of a large number of typical limestones and limes produced in various parts of the United States.

BURCHARD, E. F., and EMLEY, W. E. Source, Manufacture, and Use of Lime. U.S. Geol. Survey Mineral Resources of the United States, 1913, pt. 2, 1914, pp. 1509-93.

ECKEL, E. C. Cements, Limes, and Plasters. John Wiley & Sons, New York, 1928, 699 pp.

ELLSWORTH, C. E. Lime in Concrete: Nat. Lime Assoc., 1930, 19 pp.

EMLEY, W. E. Measurement of Plasticity of Mortars and Plasters. Nat. Bureau of Standards Technol. Paper 169, 1920, 27 pp.

_____The Use of Hydrated Lime in a Portland Cement Mortar. Proc. Nat. Lime Assoc., vol. 12, 1914, pp. 258-70.

_____Manufacture of Lime. Nat. Bureau of Standards Technol. Paper 16, 1913, 130 pp.

_____Kiln Design. Trans. Nat. Lime Mfrs. Assoc., 1910, pp. 90-107.

_____Tests of Lime. Trans. Nat. Lime Mfrs. Assoc., 1911, pp. 192-99.

FARNSWORTH, MARIE. An X-Ray Study of Limes Having Different Plasticities. Ind. and Eng. Chem., vol. 19, May 1927, p. 583.

FREAR, WILLIAM. Sour Soils and Liming. Pennsylvania Dept. Agric. Bull. 261, 1915, 222 pp.

HATMAKER, PAUL. Trade Trends in the Lime Industry. Rept. of Investigations 3227, Bureau of Mines, 1934, 18 pp.

_____Utilization of Dolomite and High-Magnesium Limestone. Inf. Circ. 6524, Bureau of Mines, 1931, 18 pp.

HASLAM, R. T., ADAMS, F. W., and KEAN, R. H. The Rate of Solution and Availability of Commercial Limes. Ind. and Eng. Chem., vol. 18, no. 1, 1926, pp. 19-23.

HERTY, C. H., Jr., Burnt Lime and Raw Limestone in the Basic Open-Hearth Process. Ind. and Eng. Chem., vol. 19, May 1927, p. 592.

HOOVER, C. P. Water Supply and Treatment. Nat. Lime Assoc. Bull. 211, 1934, 143 pp.

JOHNSON, JOHN. Thermal Dissociation of $CaCO_3$. Jour. Am. Chem. Soc., vol. 32, 1910, p. 938.

KNIBBS, N. V. S. Lime and Magnesia. Ernest Benn Ltd., London, 1924, 306 pp.

LOEW, OSCAR. Some Principles in Manuring with Lime and Magnesia. Puerto Rico Agric. Exp. Sta. Circ. 10, 1909, 12 pp.

_____On the Influence of the Ratio of Lime to Magnesia on Plants. Ind. and Eng. Chem., vol. 5, 1913, pp. 959-60.

McCOOL, M. M., and MILLER, C. E. Effect of Calcium Sulphate on the Solubility of Soils. U.S. Dept. Agric. Jour. Agric. Research, vol. 19, 1930, pp. 47-54.

MITCHELL, A. E., Studies of the Dolomite System, Part I--Nature of the Dolomite. Jour. Chem. Soc. (London), vol. 123, 1923, pp. 1055-69.

MINERALS YEARBOOK. Lime. These chapters contain statistical and general information. Published each year by the U.S. Bureau of Mines. Prior to 1932-33 these publications appeared under the title Mineral Resources of the United States, and prior to 1924 they were published by the U.S. Geological Survey.

MYERS, W. M. Manufacture of Lime from Small Stone with a Sintering Machine. Rept. of Investigations 2762, Bureau of Mines, 1926, 16 pp.

_____Production of Lime from Small Stone. Rept. of Investigations 2596, Bureau of Mines, 1924, 9 pp.

NATIONAL BUREAU OF STANDARDS. Standards and Specifications for Nonmetallic Minerals and Their Products. Misc. Pub. 110, 1930, 680 pp.

_____Lime--Its Properties and Uses. Circ. 30, 1920, 25 pp.

_____Manufacture of Lime. Circ. 337, 1927, 104 pp.

NATIONAL LIME ASSOCIATION. Lime--Its Use and Value in the Industrial and Chemical Processes. 1930, 88 pp.

_____Lime in Agriculture. Bull. 190, 1930, 53 pp.

_____Masonry Mortar. Bull. 321, 1934, 36 pp.

_____Whitewash and Cold Water Paints. Bull. 304-C, 1931, 6 pp.

_____Lime Mortar. Bull. 320, 1931, 35 pp.

_____Lime on Lawns and Flower Gardens. Bull. 180, 1930, 6 pp.

OHIO ENGINEERING EXPERIMENT STATION. Symposium on Lime. Bull. 35, 1927, 182 pp.

OLSON, G. A. High-Magnesium and High-Calcium Hydrates and Limestone Compared. Cement, Mill, and Quarry, vol. 25, no. 9, p. 62.

O'MEARA, R. G., GOW, A. M., and COGHILL, W. H. Compendium on Limes in Hydrometallurgy and Flotation. Inf. Circ. 6423, Bureau of Mines, 1931, 54 pp.

RUE, H. P. Use of Lime in a Salt Solution for Removing Hydrogen Sulphide from Natural Gas. Rept. of Investigations 3178, Bureau of Mines, 1932, 8 pp.

SEARLE, ALFRED B. Limestone and Its Products. Ernest Benn Ltd., London, 1935, 709 pp.

SHOREY, E. C. The Principles of Liming of Soils. U.S. Dept. Agric. Farmers Bull. 921, 1918, 30 pp.

THOENEN, J. R. Underground Limestone Mining. Bull. 262, Bureau of Mines, 1926, 100 pp.

UNITED STATES TARIFF COMMISSION. Lime, Gypsum, and Cements. Tariff Information Surveys, 1921, par. 73.

VOORHEES, J. H. The Physical Effect of Lime on Soils. Rock Products, vol. 22, Apr. 26, 1919, p. 30.

WHEELER, H. J. The Agricultural Lime Market. Rock Products, vol. 35, Sept. 10, 1932, pp. 28-33.

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