PROPERTIES AND USES OF THE CARBONATES

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Kansas Geological Survey
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CHAPTER XV

PROPERTIES AND USES OF THE CARBONATES

Frederic R. Siegel[1]

ABSTRACT

Carbonate rocks are raw materials indispensible to industrial development. In recent years, limestone, dolomite, and marble constituted more than 70 percent of all rocks quarried in the United States. Statistics on production and dollar value for 1961, 1962, and 1963 are presented, by uses. The uses to which carbonate rocks and minerals can be put is a function of their physical and/or chemical properties. This chapter contains listings of selected chemical analyses and important physical properties of carbonate rocks. More than 100 uses for carbonate rocks and minerals are given together with the users' general chemical and physical requirements. Because of space limitations, only three of the many areas of active research on carbonate properties are discussed: solid solution and subsolidus relations, thermoluminescence, and infrared absorption.

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Some Aspects and Statistics of Carbonate Economics

A myriad of uses exist for carbonate minerals and rocks or products derived from them. Indeed, industrial development in the United States and other areas of the world is often reflected in the number of tons of carbonate raw material produced and sold each year. If, for example, there were a cut-back in steel production or a lag in building construction, there would generally be a concomitant drop-off in the quarrying of carbonate rock. Similarly, a reduction in funds for state and federal highway development programs would cause a great drop in carbonate quarrying. During 1962, more than 70 percent of all rock quarried in the United States was limestone, dolomite, and marble. Crushed and broken stone comprised a major part of the carbonate rock production and 93 percent of almost 500 million short tons (representing about $600 million) was used for concrete and road stone, cement (Portland and natural), flux, agriculture, and lime and dead-burned dolomite. In Table 1 there is a categorization of statistics on production and dollar value for most of the carbonate rock sold or used by producers in the United States in 1961, 1962, and 1963, by uses. No such detailed data are available on a world basis. However, cement production figures have been published and are presented in Table 2; they show that in 1962, 30 countries accounted for about 90 percent of the world production of 353 million long tons of cement. During 1962, seven countries (China, France, Federal Germany, Japan, the United Kingdom, the U.S.S.R., and the United States) produced over 75 percent of the world total of 618 million long tons of steel ingots and castings, pig iron, and ferro-alloys; if one can extrapolate from this to the amount of carbonate rock (or derivatives) used in the siderurgical industry, an extremely conservative estimate would be well over 1000 million long tons.

In addition to their direct and indirect applications in many industrial processes, limestones and dolomites are reservoir rocks for more than one-half of the known petroleum reserves of the world (Imbt, 1950) and act as host rock for numerous important metalliferous ore deposits. Equally impressive is the fact that in many areas, the major source of water is from limestone aquifers.

Although the practical (economic) value of the carbonates are emphasized in the later paragraphs of this chapter, one must not forget their meaning to the academician. In his study of fossils and other features commonly associated with the carbonate rocks, the geoscientist can often find clues for solving economic problems by delving into the geologic past, reconstructing environments that existed at the time of their formation, developing fundamental concepts, and establishing parameters which could show trends important to successful exploitation.

Properties

Introduction: The physical, chemical, optical, and other properties of carbonate rocks influence (within certain limits) their economic potential, that is, the maximum number of uses they might serve. Because these properties are in great part determined by those of the carbonate mineral(s) in the rock and because the carbonate minerals themselves can be very valuable, selected physical, optical, and crystallographic properties of the economically important carbonate minerals are presented (Tables 3, 4, and 5). These properties can be significantly altered by cationic substitution, especially in calcite and dolomite. In fact, much recent research has concerned the solid solution and subsolidus relations within the calcite group minerals. This aspect is discussed in another part of the chapter.

Physical Properties

Factors which most affect carbonate economics are the physical properties of the quarried material. For example, to be suitable for building stone, limestone, dolomite, or marble must be strong, durable, and reasonably workable; in addition, stone which has these qualities and is aesthetically pleasant to view, will have greater dollar value.

Basic properties are given in Table 6. These are generally sufficient for the builders' (architectural and engineering) needs, but there are many other physical properties which have been measured and reported, and which must be known before a carbonate rock may be considered for specialized use. A classic compilation of quantities important for the physics and physical chemistry of geological materials was published by Birch, Schairer, and Spicer (1942) in the "Handbook of Physical Constants." Selected data from this publication are presented in Table 7.

Methods of testing rock materials for several of their physical properties have been fairly well standardized by the American Society for Testing and Materials (ASTM). Many of these tests, however, were not directly applicable to samples obtained, for example, by diamond drilling techniques. Therefore, in a program designed to determine the petrographic and physical properties of mine rock and establish correlations between these properties and the costs of various mining operations, U. S. Bureau of Mines scientists began by developing or adapting methods for measuring the physical properties of rock to core specimens obtained by diamond drilling (Obert, Windes and Duvall, 1946). The standardization of testing methods was necessary first to demonstrate that the size of the sample or the testing conditions did not affect the results; second, to establish a correlation factor so that values obtained which were influenced by size or testing methods could be made to correspond to values obtained by a recognized standard technique. The physical properties treated were the following:

Apparent specific gravity, apparent porosity, compressive strength, tensile strength, modulus of rupture (flexural strength), impact toughness, abrasive hardness, scleroscope hardness, Young's modulus (modulus of elasticity), modulus of rigidity, specific damping capacity, longitudinal bar velocity, apparent Poisson's ratio, and grindability.

This initial phase of the U. S. Bureau of Mines program was followed by a systematic investigation of the physical properties of mine rock from all parts of the United States. Results were published in a series of four papers (Windes, 1949, 1950; Blair, 1955, 1956), the last of which contains a complete index of all the rocks examined. These papers, titled Physical Properties of Mine Rock, Parts I, II, III, and IV, probably present the most complete data on the important physical properties of the carbonate (and other) rocks. Selected information from these papers are shown in Table 8 where they can be compared with values given by other authors.

Gillison (1960) briefly reviewed testing methods and physical properties given by Kessler and Sligh (1927) and Woolf (1953). Woolf's paper is especially interesting because in it are described physical tests crushed stone must undergo before it can be evaluated for use as road building aggregate for state and federal highway development programs. A test treated by Woolf but often omitted by other authors is that of soundness, that is, response of the rock to alternate freezing and thawing. One manner of determining whether material is "sound", "questionable", or "unsound" is by immersing several fragments or blocks of the material in a saturated solution of Na_2SO_4 for 16 to 18 hours, drying them in an oven, repeating the test five times, and noting the damage to the fragments or blocks.

Research on newer testing methods is continuously in progress. Crow (1963) presented an easy and precise optical method for determining Poisson's ratio. Durelli and Ferrer (1963) have developed a simple and somewhat novel way of determining Young's modulus and Poisson's ratio which could be practical when speed is required or when measurements have to be made inside furnaces; these authors expect the method to be especially useful for materials used in three dimensional photoelastic studies.

Chemical Composition

The chemical property of the carbonates which most influences their potential usefulness is the chemical composition. Iron content, for example, is undesirable in limestones to be used as dimension stone, because with weathering the iron will alter to the oxide and stain the stone surface a reddish or brownish color. The American Society for Testing and Materials, the U. S. Bureau of Standards, the British Standards Institution, and similar organizations publish results of their investigations and give recommendations as to the limits of impurities that can be tolerated in carbonates for industrial use.

Stringent control must be maintained on the chemical composition of the limestone used in the manufacture of many economically important products. Thus, for the production of the better grades of glass, a maximum of only 0.2 percent iron oxide is allowable in the limestone used in the manufacturing process, and for flint glass this impurity must not exceed 0.03 percent (Johnstone and Johnstone, 1961). It must be remembered, however, that the economics of industrial operations often dictates that a raw material less pure than that recommended be used so that the end product is obtained at a maximum profit. This is true in the metallurgical industry in which both the economics and the processes affect the acceptibility of a carbonate rock considered as a fluxing agent for the removal of silica, alumina, and other undesirable impurities from the ore rock. For the production of pig iron from iron ore in the blast furnace process, the limestone flux should contain less than 1.5 percent silica, and less than 0.1 percent each of sulfur and phosphorus; but because the logistics of individual operations, more silica and up to 0.5 percent sulfur might be tolerated. Several large companies use a limestone with 4 to 15 percent magnesia as a flux although a purer limestone, if it were available at the same cost as that being used, would contribute to a more efficient process. Similarly, for basic open-hearth smelting, the flux should be ideally at least 98 percent $CaCO_3$ with only 2 percent of impurities such as alumina, silica and magnesium carbonate and but a trace of phosphorus; however, in areas where the purer material is not available, the flux might contain 5 to 10 percent magnesium carbonate, 1.5 percent alumina and 1 percent silica. The capacity for phosphorus removal is lessened bv the higher magnesia content and more flux must be used, but transportation costs involved in bringing a purer fluxing agent from a distant area would cut profit margins so that the less efficient material is employed.

Table 9 contains individual and composite analyses of selected carbonate rocks. There does not exist a standard list of components that should be determined in the chemical analysis of a carbonate rock. The analyses that are made are dependent in some cases upon the needs of the person requesting them and, in others, by the availability of facilities and equipment. Some of the differences in the compounds reported as part of a carbonate analyses are demonstrated in Table 9. An obvious difference can be found in the method of reporting the loss of ignition in weight percent; some laboratories will equate this percentage with the CO_2 content of a carbonate rock, but investigations made by Galle and Runnels (1960) and Waugh and Hill (1960) demostrate that this is not so. By accurately controlling the temperature of a muffle furnace at 550 C and 1000 C, values were obtained for carbonate and non-carbonate portions of the loss on ignition. In samples which contain small amounts of pyrite, the loss on ignition is complicated by the oxidation of the pyrite. Upon oxidation the pyrite forms Fe_2O_3 and oxides of sulfur which in turn react with $CaCO_3$ below the intermediate temperature to form $CaSO_4$ and cause a premature evolution of CO_2. It is possible to obtain a true CO_2 value by applying corrective measures as outlined by Waugh and Hill (1960). It is evident that the results of a chemical analysis, however technically perfect, are representative of a carbonate rock only in so far as the sample supplied to the analyst is representative of the unit being studied. Galle (1964) has shown that on samples taken along an outcrop, channel samples give more reliable and consistent analytical results than spot samples, and indicated that analyses of carbonate rock to be presented to a possible user should be made on channel samples.

Clarke (1924) gave an extensive listing of chemical analyses of carbonate rocks. Graf (1960a) presented tables of isotopic compositions and chemical analyses of carbonate rocks and sediments and (1960b) of minor element distribution in these materials. Several analyses have also been presented by Gillison et al. (1960). Ingerson (1962) noted that compilations of carbonate rock analyses were being made at least at two places: H. R. Gault began such a compilation at Lehigh University and his program is being continued by K. Chave. The collection of analyses of all types of sedimentary rocks was begun by W. W. Rubey of the U. S. Geological Survey and continued by H. A. Tourelot who reports (personal communication) that for Kansas, Nebraska, North Dakota, South Dakota, Montana, Wyoming, and Colorado, it has already been completed.

Other Properties

The number of measurable properties of carbonate minerals is great (e.g., Graf and Lamar, 1955) and increasing as systematic advances in theory and instrument technology are made (e.g., electron spin resonance, nuclear magnetic ~~spin~~ resonance, Mössbauer effect, microwave, and exo-electron emission studies). Some of the properties of a physical-chemical nature are summarized in Table 10 (melting and transformation temperatures and solubilities of selected carbonate minerals), and Table 11 (magnetic susceptibilities of certain carbonate minerals). For the most part, the data given are for pure compounds, but as noted previously, properties will vary with the presence of impurities. Among the properties most affected by the presence of foreign ions in the crystal lattice are thermoluminescence, infrared absorption, and those properties related to solid solution.

Solid Solution and Subsolidus Relations

Much of the initial impetus for these studies was provided by Harker and Tuttle (1955) and Graf and Goldsmith (1955) who investigated the solid solution and subsolidus relations in the system $CaCO_3$-$MgCO_3$. It was found that the percentage of Mg in calcite could be determined from various cell parameters (e.g., $d_{10\bar{1}4}$, a or c). Similar results were given by Chave (1952) who found a linear variation in the $d_{10\bar{1}4}$ spacing with varying percentages (2 to 16 percent) of $MgCO_3$ in shell material from living organisms. At the elevated temperatures and pressures used by Harker and Tuttle (1955), the solubility of $MgCO_3$ in $CaCO_3$ increased from 5 mol percent at 500°C to 27 mol percent at 900°C. Corroborating figures were given by Graf and Goldsmith (1955). Because of these and similar relations, it was suggested that when a rock contains dolomite in equilibrium with magnesian calcite, the amount of solid solution constituted a geologic thermometer. Harker and Tuttle also found that at 900°C, dolomite will take only 1 percent excess $MgCO_3$ in solid solution indicating that the miscibility gap in the system $CaCO_3$-$MgCO_3$ is almost complete and that at this same temperature magnesite would take only about 2 percent (by weight) $CaCO_3$ into solid solution. Graf (1960c) citing unpublished data of Goldsmith wrote that at 800°C dolomite will hold 2 mol percent excess $CaCO_3$ in solid solution and that this would increase to 4 percent at 900°C. In 1958a Goldsmith and Graf were able to determine the mol percent of $CaCO_3$ in dolomites from various rocks by X-ray diffraction techniques.

The most comprehensive study on the properties of the calcium and magnesium carbonates was presented by Graf and Lamar (1955), with a bibliography of 524 references. Further advances in understanding this $CaCO_3$-$MgCO_3$ system were made by Goldsmith and Graf who published data on structural and compositional variations in some natural dolomites (1958a) as well as on the relation between lattice constants and composition in the Ca-Mg carbonates (1958b). More recently, Rosenberg and Holland (1963) gave a preliminary report on the stability of calcite, dolomite, and magnesite in chloride solutions at elevated temperatures and CO_2 pressures.

The solid solution relations existing between calcite and rhodochrosite were reported on by Goldsmith and Graf in 1957 who have shown experimentally that a complete series exists above 550°C at CO_2 pressure sufficient to prevent decomposition, but that there is a solubility gap at lower temperatures in the manganese half of the system. Bodine and Holland (1963) have provided additional data on the coprecipitation of manganese with calcite at elevated temperatures to complement data presented by Goldsmith and Graf (1957) who were able to precipitate the complete Ca-Mn carbonate solution series at room temperature.

Rosenberg and Harker (1956) worked on the subsolidus phase relations in the $CaCO_3$-$FeCO_3$ system and found a miscibility gap between calcite and siderite at temperatures from 350°C to 550°C. Experiments run at CO_2 pressure high enough to prevent dissociation showed that a solid solution of 5 mol percent siderite in calcite is stable at 400°C and that at 500°C, about 14 mol percent siderite can be taken into solid solution by calcite. Under similar CO_2 pressure conditions, Goldsmith (1959) reported that a solid solution of up to 8 mol percent siderite in calcite is stable at 400°C and at 700°C this increases to 37 mol percent. In a more recent study at elevated temperatures (Rosenberg, 1963) (using small CO partial pressure to maintain iron as Fe^{+2}), a solvus between $CaCO_3$ and $FeCO_3$ was determined between 300°C and 550°C. With CO_2 pressures sufficient to prevent dissociation of the carbonates, solid solutions containing up to 9 mol percent siderite in calcite and 7 mol percent calcite in siderite were stable at 400°C. At 500°C the solvus passed through points at 17 mol percent siderite in calcite.

Related studies on ternary systems have been made. Goldsmith and Graf (1960) investigated the subsolidus relations in the system $CaCO_3$-$MgCO_3$-$MnCO_3$ in the temperature range of 500°C - 800°C with special emphasis being given to the $CaMg(CO_3)_2$-$CaMn(CO_3)_2$ join; above 650°C, a complete solid solution series extends between the two members.

In his work on the system $CaCO_3$-$MgCO_3$-$FeCO_3$, particularly on the join $CaMg(CO_3)_2$-$CaFe(CO_3)_2$, Rosenberg (1959) found that at 450°C this join is binary from $CaMg(CO_3)_2$ to 75 mol percent $CaFe(CO_3)_2$. Goldsmith, Graf, Witters, and Northrop (1962) studied the phase relations in this same system at temperatures ranging from 600°C to 800°C and 15 kilobars total pressure.

More recently Goldsmith and Northrop (1964) have reported the results of their research on the subsolidus phase relations in the ternary systems $CaCO_3$-$MgCO_3$-$CoCO_3$ and $CaCO_3$-$MgCO_3$-$NiCO_3$.

Although emphasis has been on the minerals of the calcite or dolomite groups, Chang (1964a) worked on the subsolidus phase relations in the binary systems $BaCO_3$-$CaCO_3$, $SrCO_3$-$CaCO_3$, and $BaCO_3$-$SrCO_3$ between 400°C and 1000°C and at CO_2 pressures high enough to prevent decomposition of the carbonates. He observed that for the system $BaCO_3$-$CaCO_3$, there is a complete solid solution above 850°C; at 400°C, $CaCO_3$ was 3.5 mol percent soluble in $BaCO_3$; and at 700°C, 5 mol percent soluble. The maximum amount of calcium taken up by $SrCO_3$ is about 47 mol percent at 550°C.

Thermoluminescence

Certain minerals possess the ability to store energy in the form of electron energy. An electron, displaced by some external source of energy such as natural alpha radiation, can be moved from its normal lattice position and become "trapped" by some type of imperfection in the crystal lattice structure. Some of the common types of possible electron traps are described by Daniels, Boyd, and Saunders (1953): 1) imperfections and vacancies in the crystal lattice produced at the time of crystal formation, or later by mechanical stress or thermal agitation; 2) lattice vacancies (Schottky defects); 3) distortions produced by impurity ions of larger or smaller radius than is normal in a given crystal lattice; and 4) dislocations produced by radioactive bombardment. In addition, Frenkel defects are produced when an atom is transferred from a lattice site to an interstitial position and can serve as electron traps (Kittel, 1956, Chapter 17) and color centers (F, F', R and N centers) may act as traps for electrons, whereas V centers may act as traps for holes (Kittel, 1956, Chapter 18). Any excess energy associated with the electron becomes "frozen" in the trap; when released by the application of heat, the excess energy is dissipated in the form of heat and light. The light thus produced is termed thermoluminescence.

The thermoluminescence of calcite, aragonite, dolomite, and magnesite has been studied by many workers and attempts have been made to use observed effects in the solution of certain geologic problems involving carbonate rocks. For example, limited success was achieved in correlation and zonation of carbonate sediments by Saunders (1953), Parks (1953), Bergstrom (1956), Lewis (1956), and Brooks and Clark (1961) while Siegel (1963) was able to relate artificially induced thermoluminescence of sedimentary dolomites to their probable environment of deposition. Zeller (1957), Pearn (1959), Albissin, Fornaca-Rinaldi and Tongiorgi (1962) and Zeller and Ronca (1962) have applied thermoluminescence techniques to direct age determinations and the dating of tectonic and thermal events. Temperature (including paleoclimatology) and pressure histories of carbonate rocks have been revealed by thermoluminescence investigation (Zeller, 1957; Angino, 1961; Ronca, 1964). Handin et al. (1957) have used thermoluminescence in deformation studies of calcite and dolomite as have Roach, Johnson, McGrath, and Spence (1961) in their investigation of the effects of impact on marble. Geochemical prospecting using thermoluminescence has been reported by MacDiarmid (1960a, 1960b). The above represent only a fraction of the studies completed using thermoluminescence. Angino and Grogler (1962) have compiled an extensive bibliography of thermoluminescence research containing more than 600 entries. This is an excellent reference work for scientists intending to do thermoluminescence research on carbonates and other rocks.

Infrared Absorption Spectra

Huang and Kerr (1960) described the infrared spectra of 27 common and rare carbonates and found that each one shows characteristic absorption bands, some of which differ from published curves. In the calcite group and in the aragonite group there was a noteworthy shift of absorption bands with longer wave lengths which corresponds to an increase in cation radius or mass, a phenomenon also observed by Keller, Spotts, and Biggs (1952). Huang and Kerr (1960) believed that the spectral difference between the more common groups may be related to crystal structure and that infrared active groups of CO_3^{-2}, HCO_3^-, H_2O, OH^-, and SO_4^{-2}, dominate the absorption characteristics.

Although the emphasis of infrared studies has been on mineral identification (Table 13), Adler and Kerr (1962) began applying the method to geologic problems. In a detailed study on aragonite and calcite, they found that in artificial mixtures, the intensity ratio of the bands at 11.41μ (specific for calcite) and 11.65μ (specific for aragonite) is approximately proportional to the ratio of concentration of aragonite and calcite in a given sample. This relation held for recent and fossil invertebrates and suggested application of the method to the study of the composition of calcareous shells. Later empirical studies of infrared absorption spectra of isomorphous anhydrous carbonate minerals (Adler and Kerr, 1963) demonstrated that shifts in the frequencies of carbonate-ion vibrations are primarily related to differences in the radius of cations in the external lattice positions. They believed that this relationship may be conditioned by the electronic periodicity of the cations, and although mass effects are suggested, they are not definitely shown. In addition, they interpreted spectral differences among the calcite group and aragonite group minerals in terms of coordination change between the two groups and the mineral composition within each group. Adler (1963) presented some basic considerations in the application of infrared spectroscopy to mineral analysis and affirmed that the infrared absorption spectra may be used in various ways to gain information of minerals and mineral aggregates such as composition, structure, and mode of combination of molecular ions (anionic radicals) in unidentified materials.

USES

The most recent compilation of uses in which the carbonate rocks are employed directly (e.g., dimension stone) or indirectly in a manufacturing process (e.g., glass manufacture or sugar refining) was made by Lamar (1961). In this paper, Lamar gave more than 70 uses for limestone and dolomite and general physical and/or chemical specifications for each job; he also included an excellent bibliography of 156 entries. Similar presentations have been made by other authors. Johnstone and Johnstone (1961) wrote about minerals for the chemical and allied industries, with a chapter devoted to limestone, chalk, and whiting; carbonates are also considered in separate chapters on iron ores, lead, magnesium, manganese, sodium carbonate, and strontium. These authors included many British and Canadian specifications in addition to the American Society for Testing and Materials requirements. In the American Institute of Mining, Metallurgical, and Petroleum Engineers 1960 edition of Industrial Minerals and Rocks (Nonmetallics other than fuels), Gillison treats physical and chemical properties of the carbonate rocks and discusses some of the uses for limestone and dolomite; this fine symposium also contains chapters on specific carbonate products (e.g., cement materials, chalk and whiting, crushed stone, dimension stone, lime, magnesite and related materials, mineral fillers, refractories, sodium carbonate from natural sources in the United States, and strontium minerals). Gamkosian, Jansson, and Umlandt (1961) listed the chemical specifications of carbonate rocks to be used for specific industries of Argentina, and it was noted that Gamkosian is preparing a publication titled Tecnologia Mineral in which he will present various physical and chemical requirements followed not only in the Argentine Republic but probably in other republics of Central and South America.

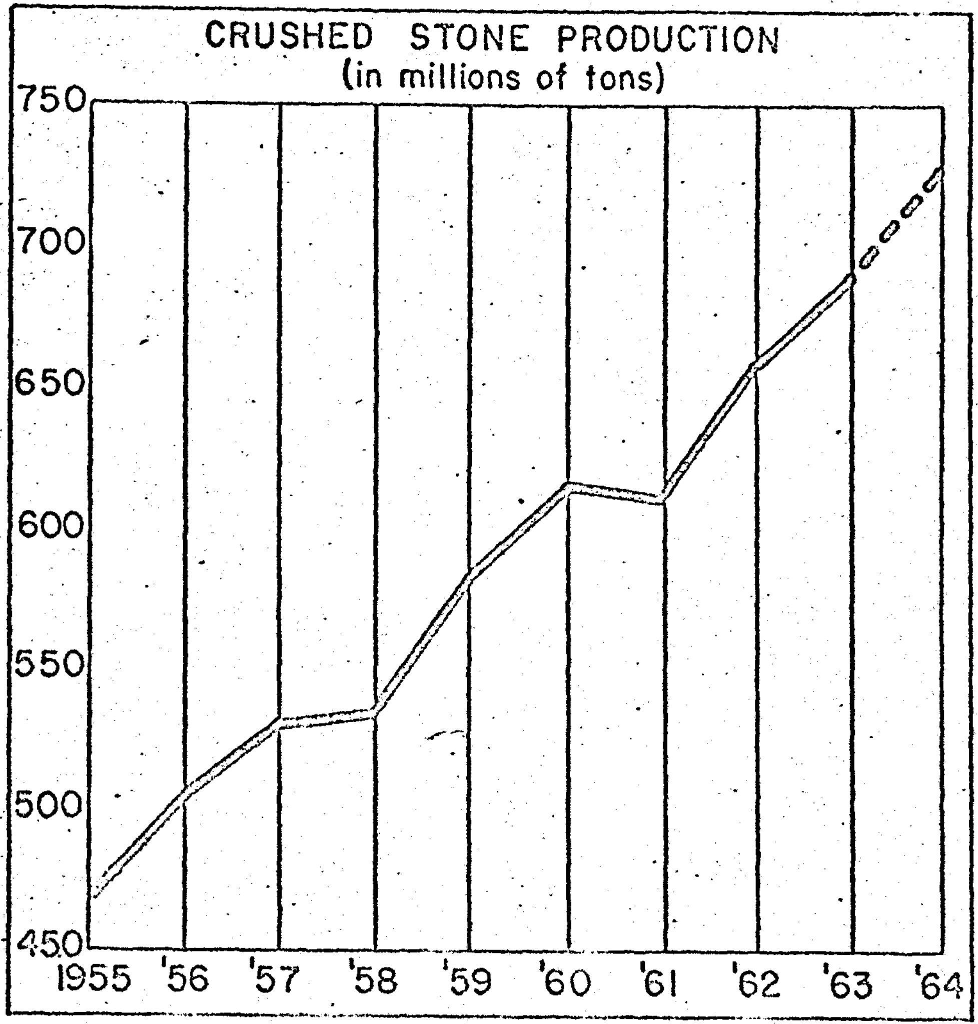
Previous to this surge of publications in 1960 and 1961, Bowles (1956) summarized many uses for limestone and dolomite, bringing up to date earlier publications of the U. S. Bureau of Mines by Bowles (1952) on the lime industry, Bowles and Jensen (1947) on the industrial uses for limestone and dolomite, Bowles and Jensen (1941) on limestone and dolomite in the chemical and processing industries, and Colby (1941) on the occurrence and uses of dolomite in the United States.

The U. S. Bureau of Mines annual publication, Minerals Yearbook, Volume I, (Metals and Minerals, except fuels) gives an excellent review of carbonate rocks and materials derived from them (e.g., calcium and calcium compounds, cement, lime, magnesium, magnesium compounds, manganese, sodium and sodium compounds, stone, and strontium) in which major uses are listed along with pertinent production and dollar statistics. This volume also includes data on production increases (or decreases) for given uses and makes note of the development of technological advances or new products which affect carbonate (and other) rock economics. The Bureau of Mines has a materials survey project under way and in 1963, Comstock treated magnesium and magnesium compounds in great detail and gave the principal uses for magesium compounds (derived in part from dolomite and magnesite) as listed below:

- Magnesium oxide
  - Refractory grades:
    - Basic refractories
  - Caustic-calcined:
    - Cement
    - Rayon
    - Fertilizer
    - Insulation
    - Magnesium metal
    - Rubber
    - Fluxes
    - Refractories
    - Chemical processing and manufacture
    - Uranium processing
    - Paper processing
  - U.S.P. and technical grades:
    - Rayon
    - Rubber (filler and catalyst)
    - Refractories
    - Medicines
    - Uranium processing
    - Fertilizer
    - Electrical insulation
    - Neoprene compounds and other chemicals
    - Cement
- Precipitated magnesium carbonate
  - Insulation
  - Rubber, pigments, and paint
  - Glass
  - Ink
  - Ceramics
  - Chemicals
  - Fertilizers
- Magnesium hydroxide
  - Sugar refining
  - Magnesium oxide
  - Pharmaceuticals
- Magnesium chloride
  - Magnesium metal
  - Cement
  - Ceramics
  - Textiles
  - Paper
  - Chemicals

Table 14 gives more than 100 uses for limestone, dolomite, marble, precipitated calcium carbonate, or products derived from them (e.g., lime). The table is constructed on a base of Lamar's (1961) paper and is supplemented by the sources already mentioned as well as trade magazines such as Rock Products or Rock Products (Mining and Processing) (name changed with the January, 1964 number). Several of the derivatives of the carbonate rocks (such as whiting or lime) have multiple uses; to give the reader an idea of the magnitude of applications a single derivative can have, the various uses in which and for which whiting is used are presented in Table 15. In some reviews of carbonate economics, the uses of carbonate minerals are neglected. Such data are readily available in most mineralogy and economic geology textbooks and other not so widely known reference works such as the Merck Index (1960) and Lange's (1956) Handbook of Chemistry. Table 16 summarizes some of the more important uses for natural or artificially prepared carbonate minerals.

The future looks good for the continued development of the major industries in which carbonate rocks are a primary raw product. Trends in the production of crushed stone, lime, and Portland cement (Figs. 1, 2, and 3 respectively) are all moving upwards. The effect of some technological advances have not been felt yet to any great degree in the United States. Development of the oxygen process for making steel is most encouraging to the carbonate rock and lime producer because in this process about twelve times more lime is used per day than in the conventional steel production processes. Although European and Japanese steel manufacturers produce large quantities of their steel by the oxygen process (Japan produces about 38 percent this way as compared to 10 percent in the United States) the major steel producers in the United States have been somewhat conservative and slow to convert to this speedy, more efficient technique. Because of domestic and foreign competition and lower prices, however, established companies such as U. S. Steel have been stimulated into constructing oxygen furnaces in an effort to maintain traditional markets and establish new ones.



CRUSHED STONE PRODUCTION
(in millions of tons)

Figure 1

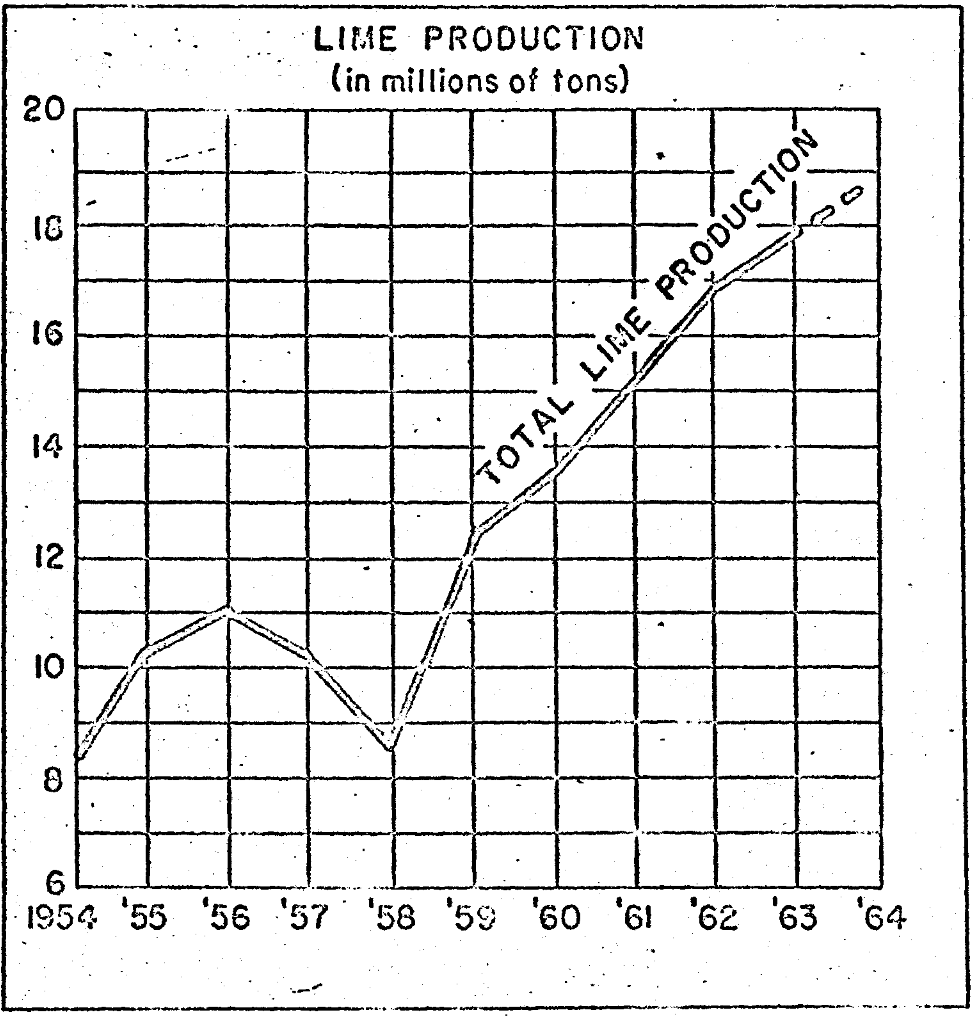
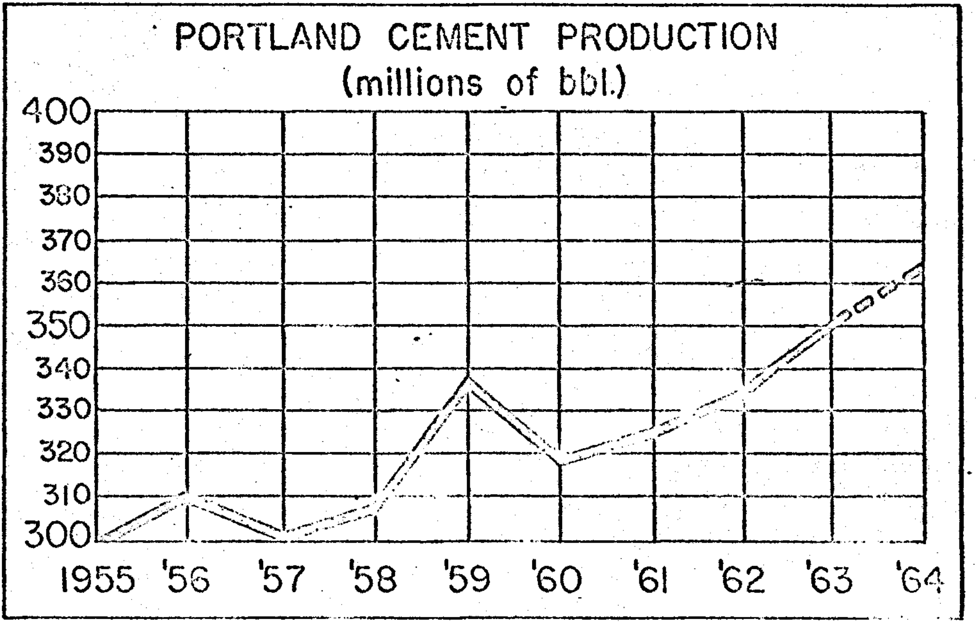

LIME PRODUCTION
(in millions of tons)
20
18
16
14
12
10
8
6
1954
'55
'56
'57
'58
'59
'60
'61
'62
'63
'64
TOTAL LIME PRODUCTION

Figure 2


PORTLAND CEMENT PRODUCTION
(millions of bbl.)
400
390
380
370
360
350
340
330
320
310
300
1955
'56
'57
'58
'59
'60
'61
'62
'63
'64

In other fields, research is leading to new uses for the carbonates. The Texas Crushed Stone Company of Austin, Texas, is experimenting with crushed limestone base in livestock areas on farms in an effort to prevent livestock bogging (Kennerly, 1963). This company is also interested in other applications on farms and may experiment with limestone floors in poultry houses; with crushed limestone as a base for self-feeding hay to cattle from stacks in pastures; and its potentially most important use as a base for the hundreds of beef cattle feeding lots currently appearing in many of our beef producing states. Hedin (1963), head of the Chemical Department of the Swedish Cement and Concrete Institute, Stockholm, Sweden, believes that lime consumption can be increased if the lime is manufactured for specific uses by selecting starting carbonate rock of known chemical composition and crystal size, and then controlling the burning process. Falke (1963) described a new method for recovering manganese from manganiferous limestones and slimes, and found that 50 - 75 percent of the total manganese in manganiferous limestones can be recovered as manganese carbonate containing 45 percent manganese. Considering that only about three percent of the manganese used in the United States is of domestic origin and that our suppliers could be cut off in time of national emergency, this advance is extremely important.

Although one may review Tables 14, 15, and 16, trends in production, and technological advances or product development, and fully appreciate the importance of carbonate rocks to the development and advancement of our civilization, limestones and dolomites serve other purposes in which they are not actually "used" but for which they are esteemed or have actual economic meaning. For example, caverns and unique speleothem formations that have formed in them (Fig. 4) serve as a constant source of education and wonder to those visiting them. In the United States, thousands of visitors each year take guided tours through the Carlsbad Caverns, New Mexico, and the many caves of the Mammoth Cave

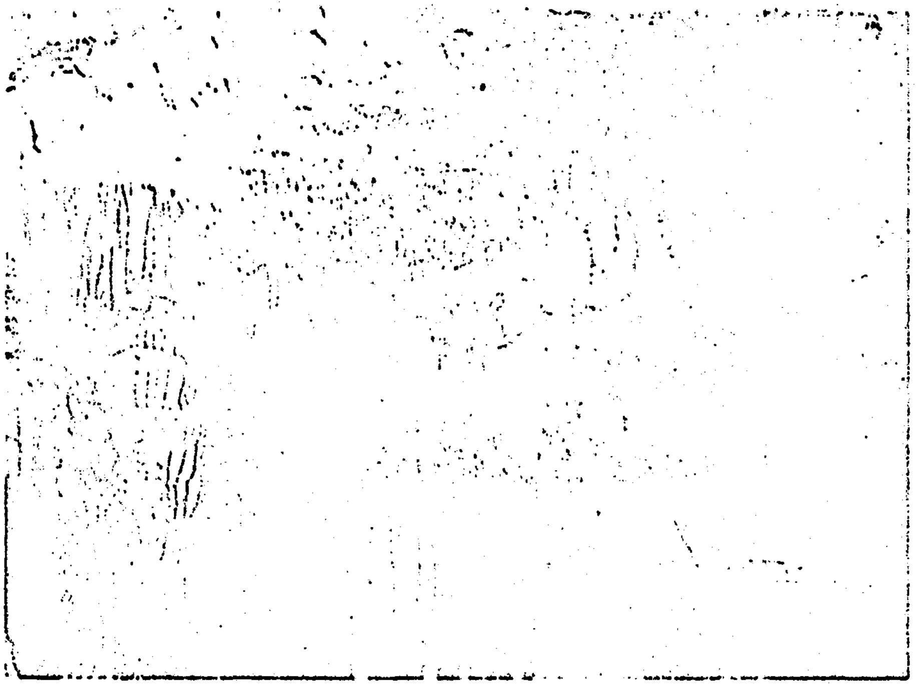


Fig. 4. Speleothem formations in the Great Onyx Cave, Mammoth Cave National Park, Kentucky.

National Park, Kentucky. The actual dollar value represented by payment for these tours is difficult to assess, but it no doubt exceeds that derived from many of the products given in the tables of uses (Tables 14, 15, and 16). Similar exhibitions of natural beauty are found in the coral reefs of the Pacific and off the east coast of the Florida Keys and the Bahamas, and the number of people who visit these features each year represents a good portion of the tourist trade. Unfortunately, in areas where conservation is not practiced or dictated by law, these non-replaceable features (stalactites, stalagmites, or flowstone) or coral specimens are sold at local souvenir stands for ornamental purposes.

In several areas where underground quarries have been worked out or where caves are present, the land owner can make substantial profit by renting the empty space for storage. Because of the constant and low temperature and humidity of these underground facilities, they are ideal for raising mushrooms, and for the storage of records, frozen foods, medicinals, bonded whiskey, military equipment, and other products. The U. S. government has set up specifications for these underground areas, which if they are followed, can lead to the eventual rental of the storage facilities to the government at favorable fees. Stearn (1963) has summarized these as follows for mined-out limestone caves (or quarries) to be used as storage areas of high security and unrivalled material preservation: the minimum size should be at least 200,000 square feet and there should be a geometrical pillar arrangement spaced at least 30 feet apart and a minimum ceiling height of 14 feet; only drift-type entryways are allowed and the exists and entrances must be serviced by paved roadways; proximity to a railroad spur is desirable; there must be at least 50 feet of overburden; a four hour fire rating is necessary for the installed doors and reinforced concrete walls separating the different areas and there should be a complete automatic sprinkler system throughout the facility;

proper equipment for temperature maintenance (between 55°F and 70°F) and for relative humidity maintenance (30 to 50 percent) must be installed. It is most probable that in the future, such rigidly constructed underground areas will house power plants or nuclear reactors.

The magnitude of the importance of carbonate rock to man can be further emphasized by the previously cited fact that more than one-half of the known petroleum and natural gas reserves are in carbonates as are a great percentage of our past and existing metalliferous reserves. Also, that precious commodity water comes from limestone aquifers in many parts of the United States and porous and permeable carbonate rock units have been developed for storage of natural gas and liquified petroleum products. On adding to this the secrets of the earth's history that have been, are being, and will be revealed by detailed, systematic studies of the carbonate rocks and their fossils and other than carbonate mineral content, one may see that "use" although considered mainly from an economic aspect, can be extended to include academic studies which can and many times do lead to economic development and successful exploitation.

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Table 1. Carbonate rocks sold or used by producers in the United States, by uses. Figures given are in thousands of short tons and thousands of dollars. Data for 1961 and 1962 were compiled from the U. S. Bureau of Mines Minerals Yearbook for 1962, Volume I. Data for 1963 were compiled from the Minerals Yearbook for 1963, Volume I.

Limestone and dolomite (crushed and broken stone)

	1961		1962		1963	
	Quantity	Value	Quantity	Value	Quantity	Value
Concrete and roadstone------------	258,997	$338,798	276,878	$365,098	292,976	$380,893
Flux----------------------------	27,198	39,725	26,081	36,821	27,185	39,322
Agriculture----------------------	22,196	38,478	23,029	39,348	25,956	44,195
Railroad ballast------------------	4,260	5,376	5,065	6,578	4,923	6,410
Riprap---------------------------	9,138	10,440	10,016	12,253	10,690	13,229
Alkali manufacture----------------	2,560	2,878	2,840	3,188	2,955	3,282
Calcium carbide manufacture-------	764	785	(1)	(1)	(1)	(1)
Cement (Portland and natural)-----	79,779	85,883	83,318	92,886	86,842	92,646
Coal-mine dusting-----------------	372	1,527	400	1,667	539	2,268
Fill material--------------------	266	277	440	330	383	296
Filler (not whiting substitute):						
Asphalt---------------------	2,130	5,408	3.208	6,955	1,994	5,012
Fertilizer-------------------	438	1,080	448	1,132	457	1,133
Other-----------------------	219	873	351	1,567	419	1,921
Filtration-----------------------	148	221	79	141	62	117
Glass manufacture----------------	1,211	3,736	1,337	4,294	1,492	4,781
Lime and dead-burned dolomite-----	18,124	28,283	19,356	32,959	21,450	36,024
Limestone sand-------------------	1,693	2,596	1,706	3.103	1,759	3,234
Limestone whiting[2]----------------	802	9,242	838	9,639	785	9,298
Mineral Food---------------------	695	3,723	692	3,847	618	3,793
Paper manufacture----------------	400	1,129	271	821	358	1,099
Poultry grit---------------------	153	1,185	161	1,333	160	1,342

Refractory (dolomite)	235	465	322	563	769	1,297
Sugar refining	882	2,215	623	1,506	646	1,580
Other uses[3]	2,838	4,603	1,741	4,253	2,125	5,472
Uses unspecified	1,900	2,475	1,753	2,518	2,805	3,282
Subtotal	437,398	591,401	460,953	632,800	488,348	661,926
	Marble (crushed and broken stone)					
Terazzo	397	4,535	380	4,866	367	4,768
Other uses[4]	1,038	7,859	1,243	9,512	1,385	8,797
Subtotal	1,435	12,394	1,623	14,378	1,752	13,565
	Limestone (dimension stone)					
Building						
Rough: Construction	61	323	82	326	52	289
Rough: Architectural	223	3,455	197	3,000	196	3,091
Dressed: Sawed and Cut	330	12,066	318	12,476	347	13,498
Rubble	219	725	284	928	282	1,104
Curbing and Flagging	22	169	15	117	18	152
Subtotal	855	16,738	896	16,847	895	18,134
	Marble (dimension stone)					
Building[5]						
Rough: Architectural	37	1,168	34	1,330	28	1,334
Dressed: Sawed & Cut	106	14,670	95	14,269	80	12,574
Monumental: Rough & Finished	14	2,728	17	3,140	42	7,294
Subtotal	157	18,566	146	18,739	150	21,002

			Shell			
Concrete and road material-------------	11,499	18,256	12,792	18,611	11,821	17,277
Cement---------------------------------	4,406	4,881	5,117	5,531	5,278	5,847
Lime-----------------------------------	1,420	1,782	1,441	1,876	1,169	1,663
Poultry grit---------------------------	598	5,004	587	4,635	552	3,874
Mineral food---------------------------	3	14	4	22	(1)	(1)
Other uses[6]--------------------------	78	438	113	566	199	759
Subtotal	18,004	30,375	20,054	31,241	19,019	29,420
			Calcareous marl			
Agriculture----------------------------	223	168	226	156	260	178
Cement---------------------------------	876	819	956	855	904	811
Subtotal	1,099	987	1,182	1,011	1,164	989
Grand Total	458,948	670,461	485,042	715,016	511,328	745,036

[1] Included with "Other Uses."

[2] Includes stone for filler for abrasives, calcimine, calking compounds, ceramics, chewing gum, fabrics, floor coverings, insecticides, leather good, paint, paper, phonograph records, plastics, pottery, putty, roofing, rubber, wire coating, and unspecified uses. Excludes limestone whiting made by companies from purchased stone.

[3] Includes stone for acid neutralization, calcium carbide (1962), cast stone, chemicals (unspecified,) concrete products, disinfectant and animal sanitation, electrical products, magnesia, magnesite, magnesium, mineral wool, oil-well drilling, patching plaster, rice milling, road base, roofing granules, stucco, terrazzo, and water treatment.

[4] Stone for agriculture, asphalt filler, flux, poultry grit, roofing, stone sand, stucco, whiting and unspecified uses.

[5] 1961 $8,934,000 for exterior use
6,904,000 for interior use
1962 $9,575,000 for exterior use
6,024,000 for interior use
1963 $7,351,000 for exterior use
6,357,000 for interior use

[6] Agriculture, asphalt filler to whiting

Table 2. Cement production of selected countries which account for about 90 percent of the total world production. Compiled from the "Statistical Summary of the Mineral Industry (World Production, Exports and Imports) 1957-1962" prepared by the Mineral Resources Division, Overseas Geological Surveys (Great Britain), 1964.

Cement Production from Selected Countries - Figures given are in long tons.

	1961	1962
Argentina	2,856,900	2,857,000
Austria	3.035,450	3.008,830
Australia	2,813,000	2,887,000
Brazil	4,636,341	4,992,000
Belgium	4,678,792	4,817,296
Canada	5,541,025	6,059,133
China	9,800,000*	8,900,000*
Czechoslovakia	5,259,000	5,620,000
Denmark	2,879,140	2,937,900
Egypt	2,107,000	2,260,000
France	15,138,469	16,433,000
Germany (East)	5,192,000	5,346,000
Germany (Federal)	26,714,000	28,141,000
India	8,114,000	8,450,000
Italy	17,698,986	19,838,415
Japan	24,243,000	28,331,000
Korea (North)	2,226,000	2,338,000
Mexico	2,987,149	3,299,000
Pakistan	1,223,000	1,373,000
Poland	7,248,000	7,422,000
Roumania	3,255,538	3,434,129
South Africa	2,557,420	2,616,870
Spain	6,408,005	6,342,000
Sweden	2,964,000	3,006,000
Switzerland	3,544,292	3,667,018
Turkey	1,995,971	2,279,961
U.S.S.R.	50,194,000	56,394,000
United Kingdom	14,149,000	14,030,000
United States	56,841,100	59,074,300
Yugoslavia	2,299,000	2,478,000
World Total	331,000,000	353,000,000

*U.S. Bureau of Mines Estimate

Table 3. Physical properties of some economically important carbonate minerals. Compiled from Lange (1956), Dana-Hurlbut (1959), Kraus, Hunt, and Ramsdell (1959), and Deer, Howie, and Zussman (1962).

Mineral	Chemical formula (pure)	Hardness	Specific gravity	Color	Common impurities	Cleavage
Calcite	$CaCO_3$	3 on $(10\bar{1}1)$ 2½ on base	2.72	Colorless or white	Mn, Fe, Mg for Ca	$\{10\bar{1}1\}$ Perfect
Dolomite	$CaMg(CO_3)_2$	3½-4	2.85	Pink, white, or colorless	Fe, Mn, Co, Zn for Mg Pb for Ca	$\{10\bar{1}1\}$ Perfect
Magnesite	$MgCO_3$	3½-5	3.0-3.2	White, gray, yellow, or brown	Fe, Ca, Mn for Mg	$\{10\bar{1}1\}$ Perfect
Rhodochrosite	$MnCO_3$	3½-4	3.5-3.7	Rose-red, or light pink	Fe, Ca, Mg, Zn for Mn	$\{10\bar{1}1\}$ Perfect
Siderite	$FeCO_3$	3½-4	3.96	Brown	Mn, Mg, Ca for Fe	$\{10\bar{1}1\}$ Perfect
Smithsonite	$ZnCO_3$	4-4½	4.30-4.45	Brown or green	Fe, Mn, Ca, Mg, Cd, Cu, Co, Pb for Zn	$\{10\bar{1}1\}$ Perfect
Aragonite	$CaCO_3$	3½-4	2.95	Colorless, white, or pale yellow	Sr, Pb, Zn for Ca	$\{010\}$ and $\{110\}$ Imperfect
Witherite	$BaCO_3$	3½	4.3	Colorless, white, or gray	Sr, Ca for Ba	$\{010\}$ and $\{110\}$ Poor
Strontianite	$SrCO_3$	3½-4	3.7	White, gray, yellow, or green	Ca for Sr	$\{110\}$ Good
Cerussite	$PbCO_3$	3-3½	6.55	Colorless, white, or gray		$\{110\}$ and $\{021\}$ Good Fair

Malachite	$Cu_2CO_3(OH)_2$	$3\frac{1}{2}$-4	3.9-4.03	Bright green	{001} Perfect
Azurite	$Cu_3(OH)_2(CO_3)_2$	$3\frac{1}{2}$-4	3.77	Intense azure blue	{021} Imperfect

Table 4. Optical data on the economically important carbonate minerals. Compiled from Larsen and Berman (1934), Deer, Howie, and Zussman (1962), Winchell and Winchell (1951), and Moorehouse (1959).

Mineral	System	Optic sign	Indices of refraction	Birefringence	Optic axial plane	2V	Dispersion	Color in section
Calcite	Hexagonal	Uniaxial (-)	n_e=1.486-1.550 n_o=1.658-1.740	0.172-0.190	-	-	Very high	Colorless
Dolomite	Hexagonal	Uniaxial (-)	n_e=1.500-1.520 n_o=1.681-1.716	0.181-0.196	-	-	High	Colorless
Magnesite	Hexagonal	Uniaxial (-)	n_e=1.509-1.563 n_o=1.700-1.782	0.191-0.219	-	-	Very high	Colorless
Rhodochrosite	Hexagonal	Uniaxial (-)	n_e=1.597-1.605 n_o=1.817-1.826	0.220-0.221	-	-	High	Colorless to pink
Siderite	Hexagonal	Uniaxial (-)	n_e=1.575-1.633 n_o=1.782-1.875	0.207-0.242	-	-	High	Colorless to brown
Smithsonite	Hexagonal	Uniaxial (-)	n_e=1.621-1.625 n_o=1.849-1.850	0.228-0.225	-	-	High	Colorless
Aragonite	Orthorhombic	Biaxial (-)	n_x=1.530-1.531 n_y=1.680-1.682 n_z=1.685-1.686	0.155	Parallel to (100)	18-18½°	Low	Colorless
Witherite	Orthorhombic	Biaxial (-)	n_x=1.529 n_y=1.676 n_z=1.677	0.148	Parallel to (010)	16°	Very low	Colorless
Strontianite	Orthorhombic	Biaxial (-)	n_x=1.516-1.520 n_y=1.664-1.667 n_z=1.666-1.669	0.150-0.149	Parallel to (010)	7-10°	Low	Colorless
Cerussite	Orthorhombic	Biaxial (-)	n_x=1.803-1.804 n_y=2.074-2.076 n_z=2.076-2.078	0.273-0.274	Parallel to (010)	8-8½°	High	Colorless

Malachite	Monoclinic	Biaxial (-)	n_x=1.655 n_y=1.875 n_z=1.909	0.254	Parallel to (010)	43	High	Green
Azurite	Monoclinic	Biaxial (+)	n_x=1.730 n_y=1.758 n_z=1.838	0.108	Normal to (010)	68	Low	Blue

Table 5. Crystallographic data on some economically important carbonate minerals. Compiled from Deer, Howie, and Zussman (1962), Graf (1961), and the American Society for Testing and Materials Powder Diffraction File.

Mineral	Space group	Unit cell	Rhombohedral cell edge	Z # of formula units/unit cell	Cleavage	Twinning
Calcite	R$\bar{3}$c	a= 4.990 Å b– c=17.061	6.37 Å	2	$\{10\bar{1}1\}$ Perfect	$\{01\bar{1}2\}$ Very common $\{0001\}$ Common $\{10\bar{1}1\}$ Not common
Dolomite	R$\bar{3}$	a = 4.807 b– c=16.01	6.015	2	$\{10\bar{1}1\}$ Perfect	$\{0001\}$ Common $\{10\bar{1}1\}$ Common $\{11\bar{2}0\}$ Common $\{10\bar{1}1\}$ Rare $\{02\bar{2}1\}$ Glide twinning
Magnesite	R$\bar{3}$c	a= 4.633 b– c=15.016	5.675	2	$\{10\bar{1}1\}$ Perfect	$\{0001\}$ Translation gliding to [1011]
Rhodochrosite	R$\bar{3}$c	a= 4.777 b– c=15.66	5.91	2	$\{10\bar{1}1\}$ Perfect	$\{01\bar{1}2\}$ Rare (lamellar twins)
Siderite	R$\bar{3}$c	a= 4.69 b– c=15.30	5.77	2	$\{10\bar{1}1\}$ Perfect	$\{01\bar{1}2\}$ Rare (lamellar twins) $\{0001\}$ Rare
Smithsonite	R$\bar{3}$c	a= 4.653 b– c=15.028	4.432	2	$\{10\bar{1}1\}$ Perfect	
Aragonite	Pmcn	a = 4.95 b = 7.95 c = 5.73	–	4	$\{010\}$ Imperfect $\{110\}$ Poor	$\{110\}$ Common (lamellar and repeated)
Witherite	Pmcn	a = 5.26 b = 8.84 c = 6.56	–	4	$\{010\}$ Good $\{110\}$ Poor $\{012\}$ Poor	$\{110\}$ Always present, repeated

Strontianite	Pmcn	a = 5.13 b = 8.42 c = 6.09	*	4	{110} Good {021} Poor {010} Poor	{110}	Common (single, repeated, and lamellar)
Cerussite	Pmcn	a = 5.195 b = 8.436 c = 6.152	-	4	{110} Good {021} Fair	{110}	Common (repeated)
Malachite	$P2_1/A$	a = 9.502 b = 11.974 c = 3.240	-	4	{001} Perfect	{100}	Common
Azurite	$P2_1/C$	a = 5.008 b = 5.884 c = 10.336	6	2	{021} Imperfect		

Table 6. Some properties of limestone used in Kansas as building stone. Compiled from a 1964 Kansas Building Stone Association, Inc., pamphlet which serves as a guide for architects and engineers who needed rapid reference to the most important properties of Kansas building stone.

Name	Texture	Color	Absorption--%	Specific gravity	Weight lbs/ cu. ft.	Compressive strength		Temperature weak salt effect
						Normal to bed--psi	Parallel to bed--psi	
Onaga	Fine grain	Light buff	7.6	1.956	122	9629	9775	None
Chestnut Shell	Coquinoid	Chestnut	5.4	2.118	132	4806	5625	None
Neva	Dense, fine grain	White	3.1	2.440	152	22600	18800	No data
Cottonwood	Medium to fine grain	Gray	6.2	2.218	139	11292	11525	None
Silverdale	Medium to fine grain	Light buff	9.4	2.109	137	6189	8505	None
Benton	Fine grain	Buff	4.9	2.259	141	11589	10650	None
Kansas Cream	Fine grain	Creamy	9.0	1.674	105	4520	4710	None

Note: Compression tests (ASTM C170-50) determined by Clayton Crosier of Kansas University Civil Engineering Dept. Absorption and specific gravity (ASTM C97-47) and temperature -weak salt (C218-48T) tests by State Geological Survey of Kansas

Table 7. Selected physical constants of carbonate rocks. Compiled from Birch, Schairer, and Spicer (1942), Handbook of Physical Constants.

Subtable 7.-2-6. Porosity and bulk density, dry and saturated.

Lithology and age	Location	Porosity percent	Bulk density dry	Bulk density saturated w/ H_2O
Limestone	Buxton, Eng.	14.11	2.31	2.45
Limestone, Carboniferous		2.2- 9.4	2.34- 2.59	2.43- 2.61
Limestone, Silurian	Eng.	1.4- 6.3	2.53- 2.64	2.59- 2.65
Limestone	Dundee. Mich.	0.9	2.63	2.64
Caddo lime, Pennsylvanian	Ranger, Tex.	4.4	2.57	2.61
Greenhorn limestone Upper Cretaceous	Crook Co. CWyo. Co.	37.6	1.74	2.12
Limestone, sugary, quartz free		25.6	2.14	2.40
Oolitic limestone	Monk's Park, Eng	20.3	2.16	2.36
Chalk	Eng.	17.6-42.8	1.53- 2.22	1.96- 2.40
Dolomite	Mitcheldean, Eng.	8.6	2.54	2.63
Marble	Eng.	1.1	2.65	2.66
Marble, 34 samples	From 12 states	0.4- 2.1	2.66- 2.86	2.68- 2.86

Subtable 7.-3-4. Thermal expansion of rocks, temperature interval of 20-100 C.

Lithology	Number of Determinations	Average Linear Expansion Coefficient $\frac{1}{L}\frac{\Delta L}{\Delta T}$
Limestones	20	$8 \pm 4 \times 10^{-6}$
Marbles	9	$7 \pm 2 \times 10^{-6}$

Subtable 7.-4-13. Compressibility of rocks at low pressures. β= compressibility, in reciprocal bars, at the pressures given.

Lithology	Pressure kg/cm^2	$10^7\beta$ Enclosed	$10^7\beta$ Unenclosed
Dolomite	0	37.1	11.9
	120	25.4	11.9
	600	14.8	11.9
Marble (Vt.)	0	180.0	13.9
	120	33.1	13.8
	600	15.0	12.6
Limestone (Penn.) (carbonaceous)	0	29.2	24.7
	120	27.5	24.5
	600	23.5	24.1

Subtable 7.-4-14. Compressibility or rocks at high pressures. Room temperature unless otherwise indicated. β = compressibility, in reciprocal bars, at pressure P.

Lithology and location	P in bars	$10^7\beta$
Marble, Colorado (enclosed)	7000	13.8
Limestone, Solenhofen, Bavaria (unenclosed, linear method)	6000	13.6 (30°C)
	6000	14.2 (75°C)
	5000	12.9 (6°C)
	5000	14.2 (100°C)
	5000	16.3 (270°C)
	5000	17.1 (476°C)

Subtable 7.-5-4. Elastic constants of rocks at ordinary pressure and temperature. E = Young's modulus; G = Modulus of rigidity; σ = Poisson's ratio (dimensionless). Values of G or σ in parentheses have been derived from the measurements by the use of the connecting equations for isotropic materials.

Lithology and location	E dynes/cm^2	G dynes/cm^2	σ	Stress or stress range kg/cm^2
Limestone				
Knoxville, Tenn.	6.21	(2.48)	.251	70-600
Montreal, Canada	6.35	(2.50)	.252	70-600
Solenhofen, Bavaria	5.77	2.31	(.25)	
Dolomite				
Pennsylvania - 1	7.10	3.23		
Pennsylvania - 2	9.30	3.62		
Marble				
Dinant, Belgium	7.24	(2.98)	.278	70-600
Rutland, Vt.	5.24	(2.07)	.263	70-600

Subtable Q.-5-5. Effect of stress on Young's modulus of rocks, by the method of flexural vibrations of loaded bars.
E_o = Young's modulus at zero stress.
E_s = Young's modulus at a stress not quite great enough to cause failure (between 500 kg/cm^2 and 1000 kg/cm^2.
⊥ and ∥ refer to the orientation of the axis of the bar with respect to the bedding plane.

Lithology and location		Density gm/cm^3	E_o dynes/cm^2	E_s dynes/cm^2
Limestone, Bedford, Ind.	⊥	2.23	2.86×10^{11}	2.97×10^{11}
	∥	2.35	3.48×10^{11}	4.07×10^{11}
Marble, Danby, Vt.	∥	2.70	6.01×10^{11}	6.99×10^{11}
	∥	2.70	6.48×10^{11}	7.24×10^{11}
	⊥	2.70	4.36×10^{11}	6.94×10^{11}
	⊥	2.70	3.66×10^{11}	5.81×10^{11}
Marble, Cockeysville, Md.		2.86	7.50×10^{11}	8.84×10^{11}

Subtable Q.-5-8. Elastic parameters of certain rocks at 4000 kg/cm^2 and 30 C. Values computed from the measured G and by the use of equations for isotropic materials. The rocks were enclosed.
E = Young's modulus; G = Modulus of rigidity;
Volume compressibility; σ = Poisson's ratio (dimensionless)
V_p = velocity of propagation of compressional waves in an infinite medium
V_s = velocity of propagation of distortional waves in an infinite medium

Lithology and location	E dynes/cm^2	G dynes/cm^2	cm^2/dyne	σ	V_p km/sec	V_s km/sec
Limestone, Solenhofen, Bavaria	6.3	2.47	21.4	.276	5.54	3.08
Marble, Vermont	8.7	3.33	13.9	.299	6.51	3.49

Subtable Q.-5-9. Rigidity and velocity of shear waves as a function of pressure. All measurements made at 30°C. These results were obtained by a dynamical method, with enclosed specimens.
G = Modulus of rigidity, in units of 10^{11} dynes/cm^2
V_s = Velocity of shear or distortional waves, in km/sec
P = Hydrostatic pressure, in kg/cm^2

Lithology and location		G			V_s	
	P 1	500	4000	1	500	4000
Limestone,						
Solenhofen, Bavaria	1.96	2.20	2.47	2.75	2.91	3.08
Pennsylvania	2.67	2.88	3.00	3.15	3.27	3.34
Dolomite						
Pennsylvania	3.49	4.20		3.5	3.87	
Marble						
Proctor, Vt.	1.57	3.18	3.33	2.4	3.42	3.49

Subtable q.-9-1. Standard crushing strengths of rocks.

Lithology	No. of Localities	Average Strength kg/cm^2	Range kg/cm^2
Limestone	216	960	60-3600
Marble	76	1020	310-2620

Subtable q.-9-6. Short time compressive strength of unjacketed materials with confining pressure of kerosene.
Strength $p_1 - p_2$ at failure, where p_1 axial compressive strength
p_2 lateral confining pressure

Lithology and location	Confining pressure, kg/cm^2	Strength, kg/cm^2
Limestone, Solenhofen, Bavaria	1	2560
	2000	2600
	4000	3260
	6000	4000
	8000	5970
	10000	>13000
Marble	1	810
	4000	860
	8000	1650
	10000	>5200
	11400	>11400

Subtable 7.-17-4. Thermal conductivity (at 1 atmosphere pressure).

Lithology and location	Temperature °C.	Conductivity K	
		$\frac{\text{Cal.}}{\text{Sec. cm. deg.}}$	$\frac{\text{Watts}}{\text{Cm. deg.}}$
Limestone			
Solenhofen, Bavaria	0	7.2×10^{-3}	30.1×10^{-3}
	100	5.5×10^{-3}	23.1×10^{-3}
	200	4.8×10^{-3}	20×10^{-3}
Pennsylvania, (carbonaceous)			
Parallel to bed	0	8.2×10^{-3}	34.5×10^{-3}
	100	7.0×10^{-3}	29.5×10^{-3}
	200	6.5×10^{-3}	27.4×10^{-3}
Perpendicular to bed	0	6.1×10^{-3}	25.5×10^{-3}
	100	5.4×10^{-3}	22.6×10^{-3}
Limestone, dolomitic			
Longford Mills, Ontario	130	3.9×10^{-3}	16×10^{-3}
	181	3.8×10^{-3}	16×10^{-3}
	268	3.7×10^{-3}	15×10^{-3}
	377	3.2×10^{-3}	13×10^{-3}
Queenston, Ontario	123	3.4×10^{-3}	14×10^{-3}
	177	3.4×10^{-3}	14×10^{-3}
	254	3.3×10^{-3}	14×10^{-3}
	332	3.2×10^{-3}	13×10^{-3}
Chalk		2.2×10^{-3}	9.2×10^{-3}
Dolomite	0	11.9×10^{-3}	449.8×10^{-3}
	100	9.3×10^{-3}	38.9×10^{-3}
	200	8.0×10^{-3}	33.3×10^{-3}
Marble (17 varieties)	30	$5.0\text{-}7.7 \times 10^{-3}$	$21\text{-}32 \times 10^{-3}$
Marble (black)			
St. Albert, Ontario	124	3.7×10^{-3}	16×10^{-3}
	210	3.6×10^{-3}	15×10^{-3}
	334	3.3×10^{-3}	14×10^{-3}

Subtable Q.-21-1. Electrical resistivity.

Lithology and location	Resistivity, ohm cm
Limestone	3×10^5
Limestone, Spain	10^4
Limestone, Missouri	$10^4 - 10^5$
Limestone, Kentucky	10^5
Marble	10^{10}
Marble, France	4×10^8
Marble, France	10^9
Marble, France	10^{10}

Subtable Q.-21-7. Dielectric constant.

Lithology	Dielectric constant, range
Chalk	8.0-9.0
Coral dolomite	8.0-9.0
Dolomite	7.3
Limestone	8.0-12.0
Marble	8.3
Marmorized limestone	15.2

Table 8. Some physical properties of selected carbonate rocks. Compiled from the following: 1, Windes (1949); 2, Windes (1950); 3, Blair (1955); 4, Blair (1956); 5, Trefethen (1959); 6, Woolf (1953); 7, Kessler and Sligh (1927); 8, Atchison, Duvall, and Petkof (1962); 9, Duvall and Atchison (1957).

Legend:

ASC = Apparent specific gravity
AP = Apparent porosity (percent)
CS = Compressive strength (lbs/in^2)x1000
TS = Tensile strength (lbs/in^2)x1000
MRup = Modulus of rupture (lbs/in^2)x1000
IT = Impact toughness (in/in^2)
AH = Abrasive hardness (rev x in^2 x 10^{-3})/lb

SH = Scleroscope hardness (scleroscope units)
YM = Young's modulus (lbs/in^2) x 10^6
MRig = Modulus of rigidity (lbs/in^2) x 10^6
PR = Poisson's ratio
SDC = Specific damping capacity (x10^{-2})
LBV = Longitudinal bar velocity (ft/sec)x1000

Rock Type	Location	ASG	AP	CS	TS	MRup	IT	AH	SH	YM	MRig	SDC	LBV	PR	REF.
Limestone (Fossiliferous)	Indiana	2.37	11	10.9		1.6	1.9	3	27	4.84	2.06	3	12.4		1
Limestone	Ohio	2.69	0.7	28.5		2.9	8.6	10	58	7.97	3.64	4	15.4		1
Limestone (coarse white)	Alabama	2.83	0.9	24.0			6.6	7	66	7.64	3.51	4	14.2		1
Limestone (kerogenaceous)	Colorado	2.25		16.6		0.4	3.7	10	56	1.8	1.0	22	7.8		1
Limestone	Utah	2.78	0.26	28.0		2.2	2.5	9.3	52	9.43	3.93	2	15.9	-0.12	2
Limestone	W. Virginia	2.68	6	23.0		1.9	2.5	9.6	61	9.56	3.96	3	16.4	0.21	2
Limestone	Ohio	2.6	2.7	8.0		13	1.5	2.6	33	4.2	2.0	4	11	0.06	2
Limestone	Illinois	2.68	0.8	22.3		2.6	3.0	7.4	52	9.87	3.84	3	16.5	0.28	3
Limestone (chalky-Smokey Hill-dry)	S. Dakota	1.71	26.0	2.4		0.3			13	0.65	0.37	10	5.7	0.13	3

ock Type	Location	ASG	AP	CS	TS	MRup	IT	AH	SH	YM	MRig	SDC	LBV	PR	REF.
imestone (chalky-Smokey Hill	S. Dakota	2.0		2.0		0.3			10	0.75	0.5		5.0		9
imestone (chalky-Fort Hays-dry)		1.81	8.3	3.7		0.6	1.2		16	0.98	0.57	13	6.3	-0.13	3
imestone (metamorphic)	California	2.80		15.3		0.6	3.2		42	4.51	2.15	7	10.9	0.05	3
imestone	Oklahoma	2.67	1.2	18.9		2.0	3.1	8	59	6.49	2.66	6	13.5	0.24	4
imestone (fossiliferous, oolitic)	Missouri	2.56		16.8	58	2.3	2.9		41	7.45				0.20	4
Dolomitic limestone	Ohio	2.5	6.4	13		17	2.1	3.7	30	6.1	2.6	7	14	0.19	2
Dolomitic limestone	Ohio	2.5	5.2	12		22	2.0	4.0	36	6.8	2.8	10	14	0.23	2
Dolomitic limestone	Ohio	2.8	1.3	26		28	4.0	7.2	55	9.6	4.1	4	16	0.16	2
Dolomitic limestone	Missouri	2.69	2.6	28.8		2.7	4.8	8.0	33	11.1	4.55	3	17.6	0.22	3
Dolomitic limestone, glauonitic	Missouri	2.67	3.6	21.2		1.5	4.2	7.2	48	5.61	3.05	>11	12.4	-0.07	3
Dolomite	Tennessee	2.84	0.7	46.7		3.8	5.9	14	74	12.3	5.1	2	17.9		1
Dolomite (gray)	Tennessee	2.76	2.3	52.0		3.8	7.1	13	69	11.3	4.6	3	17.4		1
Dolomite (siliceous)	Tennessee	2.77	1.2	35.6		2.5	4.6	11	66	10.9	4.62	2	17.0		1
Dolomite	Ohio	2.4	8.6	13		11	1.8	3.4	42	2.8	1.55	5	9.0	-0.09	2

Rock Type	Location	ASG	AP	CS	TS	MRup	IT	AH	SH	YM	MRig	SDC	LBV	PR	REF.
Dolomite	Ohio	2.6	3.4	23	—	19	2.7	7.3	56	6.7	3.2	5	14	0.05	2
Dolomite	Ohio	2.6	4.0	15		14	1.9	6.4	53	4.1	2.0	6	11	0.03	2
Dolomite	Ohio	2.6	3.0	19		14	2.3	7.8	58	6.9	2.9	3	14	0.18	2
Dolomite	Ohio	2.4	8.5	11		14	2.1	4.2	39	3.2	1.5	4	10	0.07	2
Marble	Maryland	2.87	0.6	30.8		2.8	2.7	8	56	7.15	3.78	4	13.7		1
Marble (white)	Nevada	3.2	2.3	34.5		2.4				11.9	5.02	4	16.6		1
Marble	New York	2.72	1.8	18.4		1.7	3.0	7	49	7.84	3.35	3	14.5		1
Limestone and Marble	Nevada	2.79	0.4	22.3		2.6	3.9	9	54	11.4	4.54	1	17.4		1
Marlstone (calcareous and dolomitic)	Colorado	2.31	4.9	21.9		1.8	4.3	6.7	56	3.61	1.61	14	10.5	0.11	2
Limestone		1.87-2.80	1.1-31.0	2.6-2.8	427-853	0.5-2	7ea	1-24		4.35-8.7	0.8-3.6				5
Marble		2.64-2.87	0.4-2.1	8-27	427-1280	0.6-4	6ea	8-42		7.25-10.15	1.3-6.5				5
Limestone		2.66					8	26							6
Dolomite		2.70					9	25							6
Marble		2.63					6	47							6
Limestone		2.34		2.5-28.4						3-6	1.2-3				7
Limestone		2.56		16.5	700					7.6			15		8
Marble (dolomitic)		2.80		22	950					12			18		8

Table 9. Selected composite and individual chemical analyses of carbonate rocks.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Calc. $CaCO_3$			80.83	89.78	86.39	79.86	
Calc. $MgCO_3$			2.26	1.33	1.94	1.39	
CaO	42.61	41.32	45.44	50.40	48.49	43.01	42.92
MgO	7.90	2.19	1.68	1.09	1.29	1.03	0.42
CO_2	41.58	33.53					35.36
L.O.I.		(34.55)					
D.L.O.I. $\frac{105^\circ C}{550^\circ C}$			1.34	0.75	0.89	1.12	
D.L.O.I. $\frac{550^\circ C}{1000^\circ C}$			36.73	40.17	38.93	34.44	
SiO_2	5.19	14.11	8.47	4.67	7.08	14.45	1.36
Al_2O_3	0.81	4.16	1.91	0.81	1.22	2.32	0.18
Fe_2O_3	} 0.54	1.63	3.71	1.16	1.55	2.46	0.20
FeO							
Acid. Insol. Fe			0.14	0.29	0.13	0.14	
MnO	0.05	0.038					
MnO_2							
TiO_2	0.06	0.16	0.08	0.05	0.07	0.18	
K_2O	0.33	0.71	0.25	0.07	0.12	0.39	
Na_2O	0.05	0.39	0.07	0.02	0.04	0.10	
Li_2O	trace						
SO_3	0.05	0.04	0.03	0.10	0.04	0.03	trace
S	0.09	0.25	0.02	0.26	0.06	0.04	
FeS_2				0.49			
P_2O_5	0.04	0.15	0.09	0.03	0.05	0.08	
H_2O (-)	0.21(110C)						} 19.03
H_2O (+)	0.56(includes organic matter)						
Carbonaceous Material		0.61					
SrO		0.12					
F							
H_2							
V_2O_5							
TOTAL	100.09	99.40	99.96	99.87	99.96	99.79	99.47

	(8)	(9)	(10)	(11)	(12)	(13)	(14)
Calc. $CaCO_3$		70.10				55.41	
Calc. $MgCO_3$		3.96				43.00	
CaO	54.84		53.81	54.70	30.49		31.20
MgO	0.26		0.56	0.60	21.48		20.45
CO_2	43.26		42.69	41.70	47.25		47.87
L.O.I.				(43.00)	(47.52)		
D.L.O.I. $\frac{105^\circ C}{550^\circ C}$							
D.L.O.I. $\frac{550^\circ C}{1000^\circ C}$							
SiO_2	1.14	15.05	1.15	0.40	0.31		0.11
Al_2O_3	0.41	9.02	0.45	0.52	0.067	0.63	0.30
Fe_2O_3		1.27		0.08	0.084	0.70	0.19
FeO			0.26				
Acid. Insol. Fe							
MnO					0.006		
MnO_2							
TiO_2					0.005		
K_2O			0.07		0.03		
Na_2O				0.16	0.08		
Li_2O							
SO_3	0.09			0.05	0.035		
S				0.27	0.013		
FeS_2							
P_2O_5					0.003		
H_2O (-)			0.23				
H_2O (+)			0.69				
Carbonaceous Material				trace	0.08		
SrO					<0.01		
F							
H_2					0.008		
V_2O_5							
TOTAL	100.00	99.40	99.91	99.78	99.94	99.95	100.18

	(15)	(16)	(17)	(18)	(19)
Calc. $CaCO_3$					94.39
Calc. $MgCO_3$					0.61
CaO	53.54	29.9	51.09	42.75	53.03
MgO	1.02	9.9	0.93	1.46	0.29
CO_2		30.3		34.62	
L.O.I.				7.57	41.56
D.L.O.I. $\frac{105^\circ C}{550^\circ C}$					
D.L.O.I. $\frac{550^\circ C}{1000^\circ C}$	43.27	33.8	43.92		
SiO_2	1.57	17.7	0.10	9.07	4.43
Al_2O_3	0.40	2.5	0.14	0.85	0.54
Fe_2O_3	0.24	1.1	0.08	0.93	
FeO					
Acid. Insol. Fe					
MnO				0.18	
MnO_2	0.02				
TiO_2		0.1	0.04	0.05	
K_2O		0.9		0.16	
Na_2O		0.8		0.14	
Li_2O					
SO_3		1.0		0.69	
S	0.007				
FeS_2					
P_2O_5	0.007	2.6		0.09	
H_2O (-)	0.006(105C)	0.6		1.39	
H_2O (+)					
Carbonaceous Material		2.9			
SrO					
F		0.3			
H_2					
V_2O_5		0.1			
TOTAL	100.08	100.7	96.30	99.95	99.85

Explanation of Table 9.

(1) Composite analysis of 345 limestones (Clarke, 1924). Analyst H. N. Stokes

(2) Argillaceous limestone standard sample 1a, U. S. National Bureau of Standards, dried at 105°C (National Bureau of Standards, 1954).

(3) Composite analysis of 32 channel samples of the Toronto Limestone Member of the Oread Limestone Formation, Pennsylvanian age, Eastern Kansas, taken along the strike of the outcrop from the Nebraska border on the north to the Oklahoma border on the south. From a Bulletin of the State Geological Survey in preparation by W. N. Waugh, O. K. Galle, and W. E. Hill, Jr.
Used for riprap, rubble

(4) *Ibid.* for 32 channel samples of the Leavenworth Limestone Member

(5) *Ibid.* for 32 channel samples of the Plattsmouth Limestone Member
Used for aggregate, road metal, agricultural limestone

(6) *Ibid.* for 25 channel samples of the Kereford Limestone Member

Used for flagging

(7) Medway White Chalk, England (Johnstone and Johnstone, 1961).
Used for Portland Cement manufacture.

(8) North Wales Limestone, England (Johnstone and Johnstone, 1961).
Used for Portland Cement manufacture.

(9) Typical cement rock, Bethlehem, Pennsylvania (Eckel, 1913).

(10) Lithographic limestone, Solenhofen, Bavaria (Clarke, 1924).

(11) Spergen Formation (oolitic Salem Limestone), Mississippian age, Indiana (Loughlin, 1930, from U. S. Bureau of Standards Technical Paper 349, 1927).
Used for building stone. Analyst A. W. Epperson.

(12) Dolomite standard sample 88, U. S. National Bureau of Standards, dried at 105C (National Bureau of Standards, 1954).

(13) Ketona Dolomite, Cambrian age, Alabama (Ball and Beck, 1938)
Used for fluxstone and a source of magnesia.

(14) Niagara Dolomite, Silurian age, Illinois (Fisher, 1925).
Used as a refractory and for dead-burned dolomite.

(15) Composite analysis of 10 channel samples of the Baum Member of the Paluxy Formation, Lower Cretaceous age, Oklahoma (Wayland and Ham, 1955).
Analyst, T. E. Hamm and A. L. Burwell

(16) Composite of 15 analyses of the Meade Peak Member of the Phosphoria Formation, Permian age, Wyoming (Gulbrandsen, 1958, compiled from McKelvey et al, 1953).

(17) Composite of 8 analyses of the Marble Falls Formation, Pennsylvanian age, Texas (Barnes, 1952).

(18) Composite analysis of 9 marls from Minnesota lakes (Goldich _et_ _al_, 1959). *Total loss on ignition less CO_2 and H_2O (-).

(19) Limestone from Maquijata, Province of Santiago del Estreo, Argentina (Gamkosian, Jansson, and Umlandt, 1961; analyst Z. Murua).

Table 10. Melting and transformation temperatures (Compiled from Krauk, 1963, and Bulletin No. 118,(1949, of the National Research Council) and solubilities (Perry, Chilton, and Kirkpatrick, 1963) of some economically important carbonate minerals.

Mineral	Melting point	Dissociation temperature	Transition point	Solubility in 100
Calcite	1339°C (at 1038 bars CO_2 pressure)	898.6°C	970°C	0.0014 @25°C
Dolomite		At 500°C and 1 atm. CO_2 pressure, dolomite $\longrightarrow CaCO_3 + MgO + CO_2$ At 890°C, dolomite $\longrightarrow CaO + MgO + CO_2$		0.032 @18°C
Magnesite		404°C (at 1 atm. CO_2 pressure)		0.0106
Rhodochrosite		369°C (at 1 atm. CO_2 pressure)		0.0065 @25°C
Siderite		450°C (at 1 atm. CO_2 pressure)		
Smithsonite		300° - 400°C (at 1 atm. CO_2 pressure)		0.001 @15°C
Aragonite			To calcite at about 425°C and 1 atm. pressure	0.0012 @20°C
Witherite	1740°C (at 90 atm. CO_2 pressure)	1204°C (at 0.068 atm. CO_2 pressure) 1352°C (at 1 atm. CO_2 pressure)	806°C, 968°C	0.0022 @18°C
Strontianite	1497°C (at 60 atm. CO_2 pressure)	1091°C (at 0.152 atm. CO_2 pressure) 1289°C (at 1 atm. CO_2 pressure)	925°C	0.0011 @18°C
Cerussite		293°C (at 1 atm. CO_2 pressure)		0.00011 @20°C
Malachite		200°C		
Azurite		200°C		
Trona	195°C			

Table 11. Heats of formation, free energies of formation and heat capacities of some economically important carbonate minerals.

	Heat of formation at 25°C, kcal./mole ΔH	Free energy of formation at 25°C, kcal./mole		Heat capacity at constant pressure (T=°K; 0°C=273.1°K) cal./deg. mol	Range of temp. °K	Uncertainty %
		(1) ΔF	(2) ΔF			
Calcite	-289.5	-270.8	-269.78	$19.68+0.01189T-307600/T^2$	273-1033	3
Dolomite	-558.8		-520.0	40.1	299-372	?
Magnesite	-261.7	-241.7	-246.0	16.9	290	?
Rhodochrosite	-211	-192.5	-195.4	$7.79+0.0421T+0.0000090T^2$	273-773	?
Siderite	-172.4	-154.8	-161.06	22.7	293-368	?
Smithsonite	-192.9	-173.5	-174.8			
Aragonite	-289.54	-270.57	-269.53			
Witherite	-284.2	-271.4	-272.2	α $17.26+0.0131T$	273-1083	5
				β 30.0	1083-1255	15
Strontianite	-290.9	-271.9	-271.9	21.8	281-371	?
Cerussite	-167.6	-150.0	-149.7	21.1	286-320	?
Malachite			-216.44			
Azurite			-373.73			

Note: Heats of formation, free energies of formation (1) and heat capacities, compiled from Liley, Touloukian, and Gambill (1963); free energies of formation (2) compiled from Garrels, Thompson, and Siever (1960).

Table 12. Magnetic susceptibilities of certain carbonate minerals. Unit of specific susceptibility $X = 1 \times 10^{-6}$ cgs electromagnetic units. Compiled from Powell and Miller (1963).

Mineral	Location	X
Calcite	Joplin, Missouri	12
Calcite	Not given	-0.384
Dolomite	Cumberland, England	156
Dolomite	Guanajuato, Mexico	73
Dolomite	Westchester County, New York	51
Dolomite	Berkshire County, Massachusetts	42
Dolomite	Not given	42
Dolomite	Not given	0.993
Magnesite	Regla, Cuba	83
Magnesite	Lancaster County, Texas	17
Siderite	Roxbury, Connecticut	499
Siderite	Allevand, France	492
Siderite	Not given	103.8
Siderite	Not given	103.7
Siderite	Kellogg, Idaho	91.5
Siderite	Saline County, Arkansas	90.8
Siderite	Rhine Province, Germany	87.3
Siderite	Saline County, Arkansas	85.8
Siderite	Saline County, Arkansas	84.2
Siderite	Los Angeles County, California	83.2
Siderite	Leadville, Colorado	81.5
Siderite	Cass County, Texas	77.2
Siderite	Pulaski County, Arkansas	75.4
Siderite	Clairborne Parish, Louisiana	72.5
Siderite	Pulaski County, Arkansas	72.1
Siderite	Rogers County, Oklahoma	66.6
Siderite	Bates County, Missouri	66.2
Siderite	Roxbury, Connecticut	66.1
Rhodochrosite	No value given	
Smithsonite	Mineral Point, Wisconsin	17
Smithsonite	Kelly, New Mexico	14
Aragonite	Not given	-0.408
Witherite	Cumberland, England	4
Strontianite	No value given	
Cerussite	New South Wales, Australia	65
Cerussite	New South Wales, Australia	23
Limestone	Not given	6

Table 13. Infrared absorption bands of some economically important carbonate minerals. Compiled from Huang and Kerr (1960) - (1) and Adler and Kerr (1963) - (2).

Mineral	Positions of absorption bands - wave length in microns (μ)								Ref.
Calcite	3.93	5.52	6.97			11.42		14.03	(1)
	3.92	5.50	6.97			11.40		14.02	
				7.02		11.40		14.02	(2)
				7.05		11.41		14.03	
Dolomite	3.95	5.50	6.90			11.35	13.70		(1)
			6.95			11.35	13.72		(2)
			6.97			11.35	13.71		
Magnesite		5.50	6.90			11.28	13.36		(1)
			6.86			11.28	13.35		(2)
			6.94			11.29	13.35		
Rhodochrosite	3.95	5.52	6.98			11.53	13.76		(1)
				7.07		11.54	13.75		(2)
				7.09		11.55	13.77		
Siderite	3.95	5.50		7.03		11.55	13.58		(1)
				7.06		11.53	13.54		(2)
				7.08		11.55	13.58		
Smithsonite	3.95	5.47	6.95			11.50	13.45		(1)
				7.04		11.48	13.42		(2)
				7.06		11.50	13.45		
Aragonite	3.95	5.55	6.70--7.00		9.22	11.42		14.03	(1)
						11.63		14.30	
	3.95	5.55	6.72		9.22	11.40		14.03	
						11.63		14.30	
	3.93	5.53	6.70--7.00		9.22	11.42		14.03	
						11.63		14.30	
			6.80			11.65		14.02	(2)
								14.31	
			6.79			11.64		14.04	
								14.31	
Witherite	4.00	5.65	6.92		9.40	11.63		14.43	(1)
			6.97			11.63		14.41	(2)
			6.99			11.62		14.41	

Strontianite	3.97	5.57	6.80		9.30		11.63				14.15 14.30	(1)
			6.88				11.65				14.16 14.31	(2)
			6.86				11.65				14.14 14.29	
Cerussite		5.75	6.95	7.13	9.48		11.90				14.77	(1)
				7.17 7.18			11.90 11.92				14.75 14.75	(2)
Malachite	2.85		6.62	7.00 7.17	9.10 9.52		11.45	12.17 12.90	13.33		14.05	(1)
Azurite	2.84	5.40	6.63 6.78	7.03	9.15	10.47	11.97	12.23	13.00	13.45		(1)
Trona	2.83	5.92	6.80		9.45 9.65		11.75				14.70	(1)

Table 14. Purposes for which limestone and dolomite (or lime derived from them) are used (with some general specifications). Constructed on a base of the report by Lamar (1961) and supplemented by Johnstone and Johnstone (1961), Bowles (1956), Bowles and Jensen (1947), Bowles (1952), Bowen (1957), Bowles and Jensen (1941), Colby (1941), and the U. S. Bureau of Mines Minerals Yearbook for 1962, Volume I.

USE	PHYSICAL REQUIREMENTS	CHEMICAL REQUIREMENTS
Abrasive (scouring and polishing preparations)	Finely pulverized; free of grit	
Acetic acid manufacture		High-calcium limestone
Acid neutralization	Size varies for each job and for equipment being used; particles 1-3mm. and 1-3in. in diameter have been used	$>95\%$ $CaCO_3$
A Aggregates and road stone	Resistant to abrasion; sound; size varies but coarse (0.187in.) to fine (0.187in.) is common	Free of deleterious substances such as chert, shale, or clay
Agricultural limestone and dolomite	Ground to specification for each job or according to state law	High calcium carbonate equivalent, at least 80%
Alcohol and phenol		High-calcium limestone, free of deleterious substances
Alkali	Stone 1 or 2 to 6in. in diamter	High-calcium limestone with $<1\%$ silica
Aluminum oxide (Bayer process)		$>97\%$ $CaCO_3$ and $<1\%$ silica
Aluminum production		High-calcium limestone, low in silica
Ammonia		
Asphalt filler	Size varies according to process; generally 80% should pass a 200-mesh sieve	
Athletic field marking	Light in color	

USE	PHYSICAL REQUIREMENTS	CHEMICAL REQUIREMENTS
Barnstone	Stone should pass an 8-mesh sieve	Reasonably high purity
Bleaching powder and liquid	Open-textured limestone or chalk preferred	High-calcium limestone with only traces of Mn, Fe, MgO, or clay
Brick glazing	Finely ground	
Brick making (silica refractory brick and sand-lime and slag brick)	Workable	Impure argillaceous limestone
Bulb growing (in planters)	In small chips and of an attractive color	
Calcium acetate		
Calcium carbide and calcium cyanamide	Limestone should not decrepitate during burning but should give a tough strong lump	>97% $CaCO_3$, <0.01% P, <2% MgO, maximum of 1-3% SiO_2, <0.05-0.75% Fe_2O_3+Al_2O_3, trace of S
Calcium carbonate (precipitated)		
Calcium hydride		
Calcium nitrate		High-calcium limestone
Carbolic acid and carbonic acid		
Carbon dioxide		High-purity limestone or dolomite which gives 30% CO_2
Ceramics		>97% total carbonates, <0.3% Fe_2O_3, <2% SiO_2, <0.1% SO_3
Chromate and bichromate		Dolomite
Citric acid		Free of deleterious substances
Coke and gas (gas purification and plant by-products		High-calcium limestone which gives >95% CaO

USE	PHYSICAL REQUIREMENTS	CHEMICAL REQUIREMENTS
Dimension stone	Good weathering resistance; free of deleterious substances	Minimum amount of iron or iron bearing minerals (pyrite and marcasite)
Cut stone, exterior use	Good waethering resistance; free from fractures or joints; pleasing aspect	Same as for general category dimension stone
Cut stone, interior use	Free from defects; pleasing appearance; resistant to abrasion if used for flooring or steps	Same as for general category dimension stone
Ashlar, rubble	Good weathering resistance; free from defects; one good face; resistant to abrasion if to be walked on	Same as for general category dimension stone
Veneering, flagging, and curbing	Good weathering resistance; one good face; resistant to abrasion if to be walked on	Same as for general category dimension stone
Monumental stone	Superior weathering resistance; free from defects; uniform, pleasing appearance	Same as for general category dimension stone
Disinfectants		Reasonably high purity
Dyes	Stone should all pass a 20-mesh sieve and 97% should pass a 100-mesh sieve	High-calcium limestone
Electrical products		
Epsom salts	Stone should pass a 60-mesh sieve	Dolomite with >99% calcium and magnesium carbonates combined
Explosives		Pure carbonate rock with as much magnesium as calcium
Fertilizer filler	Usually stone should pass an 8-mesh sieve but be retained on a 20-mesh sieve	Reasonably pure limestone or dolomite
Fill material (other than riprap)		
Filter stone	3½-2½ or 3½-1½ in. sizes are used; rough surface; should withstand 20 cycles of the $NaSO_4$ soundness test; minimum of fines	Minimum amount (if any) of pyrite, marcasite, and clay

USE	PHYSICAL REQUIREMENTS	CHEMICAL REQUIREMENTS
Flux		
Blast furnace	Size varies from about ½-6in. depending on the user and the economics of the operation; minimum amount of decrepitation is necessary	Vary according to the user and economics of the operation
Open-hearth furnace	Size varies from about 4-11in. for the same reasons cited above	Vary with user; generally >98% $CaCO_3$, trace of P
Foods		
Fungicides and insecticides		High-calcium limestone, low in Fe_2O_3 and Al_2O_3; composition should be uniform
Glass	Stone should pass a 16 to 20-mesh sieve but should be retained on a 100 to 140-mesh sieve	>98% total carbonates, <0.05% iron oxide, low in S and P, minimal amount possible of C
Gelatin		Free of deleterious substances
Glue		Free of deleterious substances
Grease	98% should pass a 200-mesh sieve and 95% should pass a 325-mesh sieve	High-calcium limestone with < 1.5% MgO, <1% silica, <0.5% Fe_2O_3
Leather dressing (tanning)		High-calcium limestone, low in Fe or other metallic impurities; MgO and clay are injurious
Lime	Vary with production techniques; stone should be hard and should not decrepitate upon burning; fines are undesirable	>90% $CaCO_3$ (preferably 97-98%) and <5% $MgCO_3$, <3% other impurities for high-calcium lime >40% $MgCO_3$ and < 3% other impurities for high-magnesium lime
Lithographic limestone	Even texture; free of defects, grit or granular impurities	
Magnesia recovery from		

USE	PHYSICAL REQUIREMENTS	CHEMICAL REQUIREMENTS
Magnesium and magnesium compounds	Size stone used varies with individual operations	Dolomite of high purity
Magnesium chloride		42% $MgCO_3$, 55% $CaCO_3$, and $<$ 3% SiO_2+ R_2O_3
Masonry cement		
Membrane waterproofing	Stone should be sound; size varies with operation	
Mineral feeds for livestock	Stone should pass a 200-mesh sieve	$>$95% $CaCO_3$; low or not F
Mineral treatment processes (e.g. flotation)		High-purity limestone, low in Mg
Monocalcium phosphate		Pure, high-calcium limestone
Natural cement	Finely pulverized	Limestone or dolomite with 13 to 35% clayey material (of which SiO_2 is 10-22%) and 4-16% Al_2O_3+Fe_2O_3
Oil well drilling		
Ore concentration and refining (See mineral treatment processes		High-calcium limestone
Paints		
Paper	Stone $>$ 3in. in diameter	High-calcium limestone, low in Mg, $<$2% Al_2O_3+Fe_2O_3+Acid insoluble material; acid insoluble material should be light in color and should settle rapidly
Petrochemicals (glycol)		
Petroleum refining		
Pharmaceuticals		High purity limestone (artificially prepared usually)

USE	PHYSICAL REQUIREMENTS	CHEMICAL REQUIREMENTS
Portland cement	Hard impurities are undesirable	$>75\%$ $CaCO_3$, $<3\%$ MgO, $<0.5\%$ P_2O_5 For white portland cement, limestone should be low in Fe ($<0.01\%$ Fe_2O_3); low Mn is desirable
Poultry grit	Stone passes a 4-6-mesh sieve but is retained on a 10-mesh sieve	High-calcium limestone with $<0.1\%$ F
Pozzolana cements		
Railroad ballast	Various sizes of stone are used; should have good abrasion hardness and a minimum amount of deleterious substances	
Rayons		
Refractory dolomite and dolomite refractories		
Raw dolomite	Stone should pass a 3/4in. sieve; fines are removed; should not disintegrate when heated	$>20\%$ MgO, $<0.05\%$ S, $<2\%$ SiO_2
Calcined dolomite	Same as for raw dolomite	Same as for raw dolomite
Dead-burned dolomite	Size stone used varies but is usually $<\frac{1}{2}$in. in diameter	$>35\%$ $MgCO_3$, $<1\%$ SiO_2, $<1.5\%$ $Al_2O_3+Fe_2O_3$
Retarder		
Rice milling		
Riprap	Weather resistant; free from defects that cause spalling and splitting	
Rock dusting (mines)	100% should pass a 20-mesh sieve and 70% should pass a 200-mesh sieve; will not cake if wetted and dried	$<5\%$ combustible matter $<5\%$ free and combined silica
Rock or mineral wool	Size stone used varies with plant operation but 2-5in. is common	45-66% $CaCO_3$ or $CaCO_3+MgCO_3$
Roofing granules		

USE	PHYSICAL REQUIREMENTS	CHEMICAL REQUIREMENTS
Sewage and trade-waste treatment	See filter stone	High-calcium limestone
Silica brick manufacture		High-calcium limestone
Silicones		
Soap	Free of deleterious substances	High-calcium limestone
Soil stabilization (and structure stabilization)		High-calcium hydrated lime
Stone chips	Uniform, attractive color; hard, durable, and tough; low absorption; free from dust; ability to take a polish; size used varies	
Stucco		
Studio snow	Finely pulverized; light color	
Sugar refining (cane and beet)	Size varies with plant operation; stone should retain shape during burning	High purity, $>96-97\%$ $CaCO_3$, $<1\%$ SiO_2, $<1-4\%$ MgO, $<0.5\%$ iron oxide
Sulfuric acid purification		
Table salt		
Target sheets		
Terrazo	See stone chips	
Textiles		High-calcium limestone with $< 3\%$ MgO, $<2\%$ $Fe_2O_3+Al_2O_3$, $<2\%5\%$ SiO_2+ insoluble residues
Tobacco		
Varnish manufacture		High-calcium limestone, low in Mg and Fe
Whiting	Passes a 200-mesh sieve; no grit; specifications vary with user	Specifications vary with user
Wire drawing		
Wood pullers		
Wood distillation		

Table 15. Uses in which and for which whiting (manufactured and artificially prepared) is used (From Lamar, 1961; supplemented by Johnstone and Johnstone, 1961, Key, 1960, and Bowles and Jensen, 1947).

Acoustic tile
Antibiotics
Asbestos products filler
Asphalt
Calcimine and cold water paints
Caulking compounds
Ceramic glazes, enamels, and bodies
Chemical manufacture
Chewing gum
Cigarette papers
Coating on glazed paper
Confectionery
Cosmetics
Crayons
Disinfectants
Dolls
Dressing for white shoes
Dusting and polishing agents
Dusting unberned brick to prevent sticking to kiln
Dusting printing rollers
Dyes
Explosives
Fabric filler
Facing for molds and cores in brass casting
File manufacture
Fireworks
Flat wall paint and enamel undercoats
Flavoring extracts
Floor coverings
Food
Foundry compounds
Fungicides
Glue
Graphite filler
Grease
Gypsum plaster
Insecticides
Leather goods
Linoleum
Linseed oil putty
Locomotive works
Magazine and book papers
Making buff brick from red-burning clay
Manufacture of citric acid
Medicines (Pharmaceutical products)
Metal polish
Neutralizing in fermentation processes
Oil cloth
Oil paints
Paints
Paper
Parting compounds
Petroleum refining
Phonograph records
Picture frame moldings
Plastics
Pottery
Printing ink
Printing and engraving
Putty
Roofing cement
Rubber
Rubber goods (footwear, heels, hard rubber objects, white rubber stock, molded rubber goods, sponge rubber, hose, belts, and mats and electric cable insulation)
Sealing wax
Ship building
Shoe manufacturing
Shoe polishes
Soap
Structural iron making
Toiletries
Toothpaste (Dentifrices)
Welding electrode coatings
White ink
Whitewash
Window shades
Wire insulation

Table 16. Uses for which and in which carbonate minerals (natural and artificially prepared) are used. Compiled from Dana-Hurlbut (1959), Kraus, Hunt, and Ramsdell (1959), and the Merck Index (1960).

Mineral	Uses
Calcite	As limestone, see table 12, or whiting, see table 13; variety Iceland Spar used for the Nicol prism in polarizing microscopes to obtain plane polarized light; in tooth powders, white polishes, and whitewash (paint); in removing acidity from wines; as a gastric antacid and for mild diarrhea; ore of calcium.
Dolomite	As dolostone, see table 12; ore of metallic magnesium
Magnesite	Dead-burned (MgO with less than 1% CO_2) used in the manufacture of refractory brick linings, furnace hearths, and Sorel cement; source of magnesia used for the manufacture of many industrial chemicals; mixed with asbestos, serves as a fireproof and heat insulating covering for boilers and steam pipes; calcined magnesite used in flooring, tiling, wainscoting, and sanitary finishes; in tooth and face powders and in polishing compounds; as a filler for rubber; in the manufacture of mineral waters, pigments and paper; used to clarify liquids by filtration; as an antacid and laxative; ore of metallic magnesium.
Rhodochrosite	Ore of manganese; used in feeds and as a drier for varnishes; as the pigment "manganese white"; has been used in anemia.
Siderite	Ore of iron
Smithsonite	Ore of zinc; used polished as a gem or for ornamental purposes; used as a pigment and in the manufacture of porcelain and pottery; has been used topically as a mild antiseptic and astringent in inflammatory skin diseases.
Aragonite	No economically important use except as a gem (pearl)
Witherite	Ore of barium; used in the extraction of sugar from sugar beets; as a drilling mud, as an adulterant in white lead, and as a rat poison; in paints, enamels, marble substitutes, and in rubber; used in the ceramics, glass (especially optical glass), vacuum-tube, and paper industries; used for the preparation of many barium compounds.
Strontianite	Ore of strontium; used in pyrotechnics and military rockets; in the separation of sugar from molasses; as a lead replacement in certain enamels; in the manufacture of irridescent glass; used in the preparation of many strontium compounds.
Cerussite	Ore of lead; as a pigment in oil paints and water colors; used in certain cements and for making putty and lead carbonate paper.

Malachite	Ore of copper; as jewelry and for ornamental purposes such as vases and veneer for table tops.
Azurite	Ore of copper
Trona	Ore of sodium; used in the manufacture of glass, pulp and paper, and in the preparation of sodium compounds; used for water treatment and in the production of nonferrous metals, cleaners, soap, textiles, and dyes.