Applied Geology of Industrial Limestone and Dolomite

BULLETIN 46
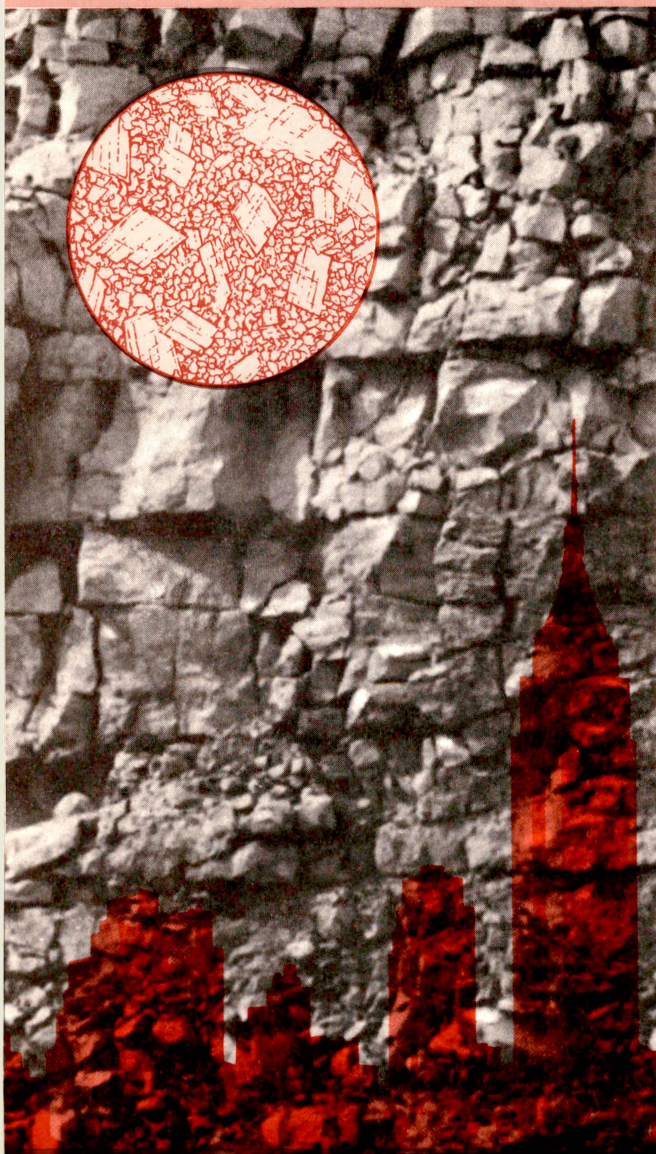
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Applied Geology of Industrial Limestone and Dolomite

By LAWRENCE F. ROONEY *and* DONALD D. CARR

DEPARTMENT OF NATURAL RESOURCES
GEOLOGICAL SURVEY BULLETIN 46

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Applied Geology of Industrial Limestone and Dolomite

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Introduction

The title of this report as first proposed was "What a Consulting Geologist Should Know About Industrial Limestone" because this effort was born of a request from the Indiana-Kentucky Geological Society, Inc., for a refresher course in the economic geology of limestone. The present title was adopted, however, because the completed report is understandable to anyone with some formal or informal geologic training and an interest in the applied geology of industrial limestones. Many of Indiana's mineral producers have developed a keen understanding of the geology associated with the particular deposit that they work, but because of a lack of training, they do not know how geology can be used in a broader sense to explore and exploit limestone deposits. We believe that this report will help answer some of the questions frequently asked by both the consulting geologist and the mineral producer.

Consulting geologists and mineral producers certainly need to know something about industrial limestone. The total tonnage of carbonate rocks mined or consumed in the United States in 1968 was about 603 million tons and the total value about 857 million dollars (U.S. Bureau of Mines, Minerals Yearbook, 1968). To meet the need for this basic building block of our society, the deposits now being sought must be larger, purer, and more strategically situated than ever before. Once a new quarry meant the investment of a few tens of thousands of dollars. Now it is likely to mean a million or more. The producer cannot afford to make this investment in an inadequate deposit. He needs the help of a geologist, and he needs to be able to evaluate geologic information properly.

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Table 1. Classification of limestone and dolomite by mineralogic and chemical composition

	Mineral		Chemical analyses[1]		
	Calcite (pct)	Dolomite (pct)	$CaCO_3$ (pct)	$MgCO_3$ (pct)	$\dfrac{CaCO_3}{MgCO_3}$
Limestone - - - - - - -	90-100	0- 10	100-95.5	0- 4.5	>21.2
Dolomitic limestone -	50- 90	10- 50	95.5-77.5	4.5-22.5	21.2-3.4
Calcitic dolomite - - -	10- 50	50- 90	77.5-58.5	22.5-41.5	3.4-1.4
Dolomite - - - - - - -	0- 10	90-100	58.5-55.0	41.5-45.7	< 1.4

[1]The $CaCO_3$ and $MgCO_3$ limits apply only if the carbonate is relatively pure. If impurities are significant, the $CaCO_3/MgCO_3$ ratio should be used.

To reach as broad an audience as possible, we have used a minimum of technical terms. According to custom, industrial limestone or limestone is here synonomous with limestone and dolomite unless the context indicates otherwise.

The chemical composition of limestone is important in many uses, and limestone and dolomite are often described in terms of their carbonate content (table 1). These terms are arbitrary and depend partly on the context, both in terms of use and availability of high-grade limestone. As used in this report, high-calcium limestone is limestone composed of more than 95 percent $CaCO_3$. Ultra-high calcium limestone is more than 97 percent $CaCO_3$, high-purity carbonate rock is more than 95 percent combined $CaCO_3$ and $MgCO_3$, and high-purity dolomite is more than 42 percent $MgCO_3$. (Theoretically, pure dolomite would contain 45.7 percent $MgCO_3$.)

Published Information on Industrial Limestone

Some reports that come close to performing the same function this manual is intended to perform have been published, and one of our goals is to bring these reports to the attention of persons interested in the geology of industrial limestone.

More than 30 years ago, J. E. Lamar and H. B. Willman (1938), of the Illinois Geological Survey, wrote a report on the uses of limestone and dolomite. Lamar compiled a second report, which was

published in 1961 and reprinted with addenda in 1965, on the same subject. He recently compiled a handbook for quarry operators (1967) that contained much information of interest to the general public.

These publications point up the fact that the publications of the state geological surveys or their equivalents are the best references for information on the common industrial minerals in states that have strong geological surveys. Most state publications are oriented toward areal geology, commodities, or the two combined rather than toward uses or methods. Some state publications purportedly on commodities, such as the California Division of Mines and Geology Bulletin 176 (Wright, 1957), contain valuable information on uses.

The U.S. Bureau of Mines and the U.S. Geological Survey also publish information on limestone and dolomite. We have found especially useful the Bureau's minerals yearbooks, which contain production statistics, and those circulars and reports of investigation that contain cost analyses of limestone production. Rather than list all the Bureau's relevant publications specifically, we refer the reader to the Bureau's list of journal articles and publications (Hardison and Weaver, 1960; Stratton, 1960; Sylvester, 1966, 1970) included in our bibliography.

Trade publications, such as Rock Products, Pit and Quarry, and Industrial Minerals, are the best sources of information on specific mineral producers, plants, and trends in the industry. These journals also contain much information on mining technology but little information on geology.

Single volumes have been written on different segments of the limestone and dolomite industries, such as the dimension stone and lime industries. The most important of these known to us are listed in the bibliography. Summary reviews of the economic geology of limestone and dolomite are included also in texts on economic geology and related publications, such as "Industrial Minerals and Rocks" (third edition, 1960) published by the American Institute of Mining, Metallurgical, and Petroleum Engineers (AIME). Some of these publications, such as Bates' "Geology of the Industrial Minerals and Rocks" (1969), contain large bibliographies.

The Forum on Geology of Industrial Minerals (FGIM) was organized in 1965 to direct attention to the geology of industrial minerals and to bring industrial mineral geologists together. The Forum is not a professional society but is hosted by organizations, such as state surveys and universities, and meets in a different city each year. The theme of the first meeting was limestone and set the tone for later meetings. Although an attempt has been made to broaden the subject matter to other common industrial minerals, all the programs have included papers on limestone, which has formed the backbone of the Forum at least through 1971. Almost all papers given at the Forum meetings are published by the host organization as the Proceedings.

The Forum meets each spring, generally for 2 days, and is attended mostly by industrial and government geologists and to a lesser degree by academic geologists. The Forum is probably the best place to meet within a few days the greatest number of geologists and other persons interested in the economic geology of limestone and other common industrial minerals.

The Society of Mining Engineers, a constituent society of the AIME, has an Industrial Minerals Division that is composed of engineers, geologists, metallurgists, economists, and virtually all professional people interested in the exploration, mining, beneficiation, and marketing of industrial minerals. The Division is responsible for part of the program at the Society's annual meetings held each fall and winter. The AIME meetings are longer and cover a broader range of industrial minerals than the Forum meetings and are attended by a large number of engineers and managers, as well as by geologists.

The calendar in Geotimes should be consulted for information about dates, places, and themes of future FGIM and AIME meetings.

Production Methods

OPEN-PIT MINING

Most limestone is mined by open-pit methods, and most limestone

producers will choose that method even where underground mining might be equally or slightly more economical. Open-pit mining is less costly than underground mining if the overburden can be removed cheaply. We do not know the practical limit in thickness of overburden that can be removed. One large aggregate producer in Indiana has adopted a rule of thumb that overburden can be removed economically if the rock to overburden ratio is greater than three to one. In Indiana, that rule assumes that the overburden is unconsolidated material, such as till or residual clay. Where the overburden is extremely thick, however, this rule apparently does not apply. In some parts of Indiana the market could support a large quarry, but rock is not quarried even though the quarryable section is 300 feet thick and the drift thickness is about 100 feet. Where the drift is so thick, the length of a boom on a dragline, disposal of overburden and water, and sloping of drift walls become limiting factors. On the other hand, in areas where thick limestone is not part of the stratigraphic succession, such as southwestern Indiana, overburden equaling or even exceeding the thickness of the limestone is removed. At Marquette Cement Manufacturing Co.'s quarry near Superior, Ohio, as much as 90 feet of overburden, part of it bedrock, was removed to quarry an average 6 feet of limestone. The plant was closed in 1965 (Bates, 1966, p. 27).

At the present time, the Allegheny Minerals Corp. is mining 16 to 18 feet of limestone under 60 feet of overburden in two quarries in Pennsylvania (Herod, 1969). Moreover, the overburden consists of 10 to 15 feet of clay and soil underlain by 12 feet of highly abrasive sandstone, 10 to 12 feet of soft shale, and 25 feet of hard shale. The hard shale and sandstone are blasted at the same time and the entire overburden stripped. In some areas the limestone is also immediately overlain by 2 feet of "ironstone" that must be blasted separately and stripped. Even then, some clay must be removed from solution channels in the limestone. Although the limestone is sold as portland cement raw material, bituminous concrete aggregates, road base, and aglime, it is clear that its market location and isolation from other sources of low-magnesium limestone must be the major factors in making the operation economical.
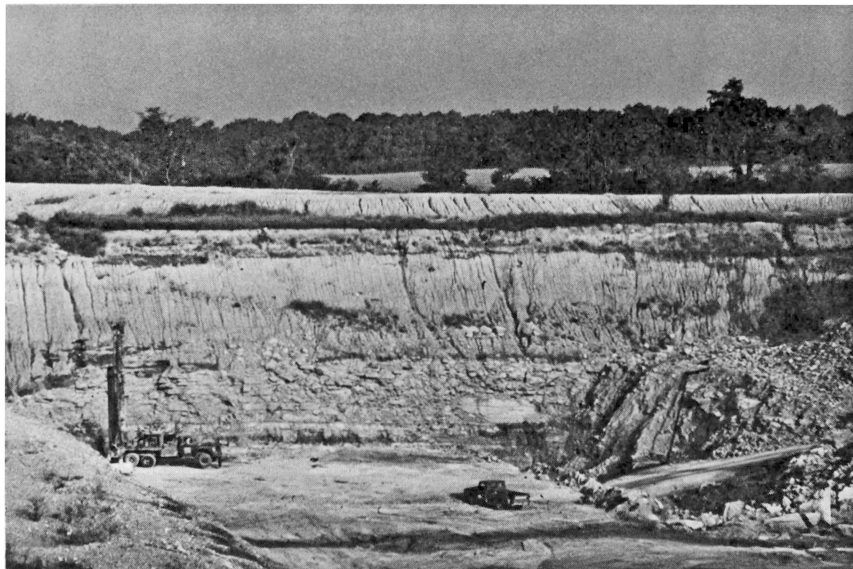
Figure 1. Thick overburden in a crushed stone quarry in Allen County, Ind.

In Indiana about 40 or 50 feet is the maximum thickness of glacial drift that is removed consistently in any limestone quarry (fig. 1). In some quarries where the thickness of the drift averages much less than 40 feet, more than 50 feet of drift has been removed in small areas. A few feet of rock overburden can be removed economically, especially if it is platy and weathered. Under exceptional circumstances—such as a small area of rock overburden, an exceptionally good market location, or a high-value product like dimension stone— a greater thickness of rock can be removed. To our knowledge, the thickest rock overburden that has been removed in a crushed stone quarry in Indiana is 40 feet of Hardinsburg (Mississippian) shale in the Mulzer Crushed Stone Co. quarry near Derby, Perry County.

Removal and disposal of overburden constitute an art in itself and one that the geologist is not called on to master. The geologist, however, should be aware of uses for overburden other than fill, although generally such potential uses remain just that—potential uses. Shale overburden, for example, might be manufactured into brick or light-weight aggregate, but it has been our experience that most limestone producers are not interested in looking closely into such possibilities.

Figure 2. Combined crushed stone and sand and gravel operation in Allen County, Ind.

Residual clay, till, sandstone, and siltstone are generally used as backfill, although cement plants do use residual clay and till as sources of alumina and silica.

Sand and gravel are another matter and must always be considered marketable products. They serve the same aggregate market as limestone, and part of their processing is similar to that of limestone. Many aggregate producers in fact mine both limestone and sand and gravel (fig. 2).

UNDERGROUND MINING

The most important fact about underground mining of limestone is that it is done. In fact, there were at least 119 underground limestone mines in the United States in 1965 (U.S. Bureau of Mines, written communication, 1966), almost double the number of mines active in 1926. In 1900, total production of limestone from all underground mines was 105,000 tons, or 0.37 percent of the total limestone production (Thoenen, 1926, p. 4-5). In 1924, production was 5.8 million tons, or 4.5 percent of the total production. In 1965, it was 34.7 million tons (U.S. Bureau of Mines, written communication, 1966), or about 6 percent of the total limestone production. Many of the mines are in the Midwest (fig. 3), but their concentration reflects the abundance of high-quality limestone in horizontal beds in that part of the country rather than a concentration of population. We believe that this pattern will change gradually as more mines are built to serve urban centers.

Most limestone mines consist of horizontal drifts into the sides of hills (generally called tunnel mines, fig. 4) or into the walls of open-pit mines, but some consist of vertical or inclined shafts. Few limestone mines are more than 1,000 feet deep, and most are only a few hundred feet deep. The deepest limestone mine known to us is the Pittsburgh Plate Glass Co.'s mine near Barberton, Ohio, in which the floor of the mined level is 2,252 feet below the surface.

Most limestone mines are of the room-and-pillar type and, like salt mines, are characterized by cathedrallike dimensions. The rooms in

Figure 3. Map showing locations of active underground limestone mines in the United States. Most of the information was supplied by the U.S. Bureau of Mines in 1965. The locations of additional mines in Pennsylvania, Kansas, and Kentucky were added in 1969. The figure beside a location symbol indicates the number of mines represented by that symbol.
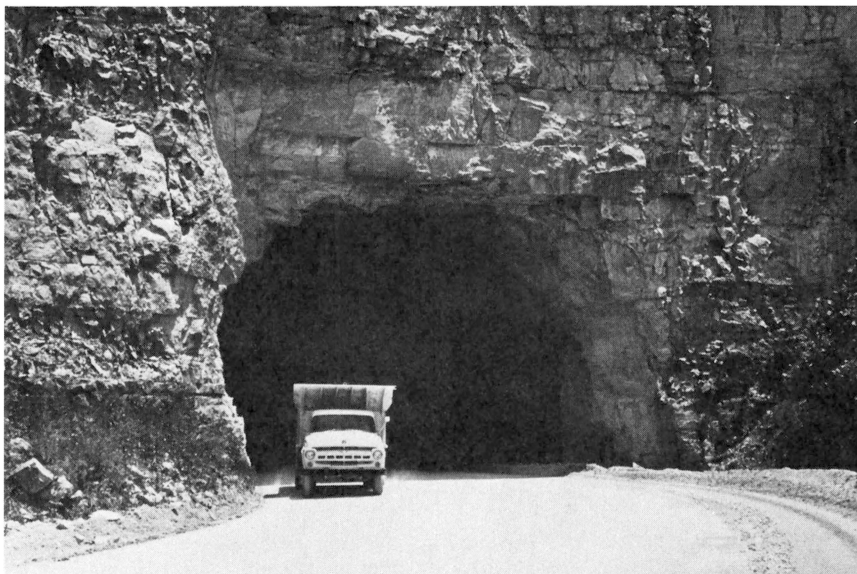
Figure 4. Tunnel limestone mine in Crawford County, Ind.

the Mississippi Lime Co.'s tunnel mines near Ste. Genevieve, Mo., are 90 feet high. The rooms in the Pittsburgh Plate Glass Co.'s mine near Barberton, Ohio, are 46 feet high. The inclined shaft that gives access to the Thomasville Stone and Lime Co.'s quarry near Thomasville, Pa., is so large that a transcontinental bus can be driven down it.

Underground mining is generally more expensive than open-pit mining, but no single cost ratio applies. It is misleading to compare the relative cost of underground mining of one deposit in one part of the country with open-pit mining of another deposit in another part of the country. Some open-pit mining might prove more expensive than some underground mining. Perhaps the best comparison is of costs of simultaneous underground and surface mining in the same formation at the same general location. We know of no published costs of this type, but one operator reported (oral communication, 1969) that stone mined by the room-and-pillar method, at about 400-foot depth, in a 40-foot face, and hauled out by truck via an inclined shaft cost $1.05 per ton to produce, 57 percent more than the $0.67 per ton for the same company to produce in its adjoining

quarry. Conversations with other mine superintendents have led us to believe that these costs were fairly representative.

Assuming then that limestone costs about 50 percent more to produce underground, why is it economical to do so, even in conjunction with open-pit operations? Some of the reasons are:

(1) Lack of surface deposits near the market. This is probably the most important reason. If no deposits of limestone suitable for a specific purpose are found at the surface, the additional cost of underground mining must be weighed against the cost of transporting stone into the area. For example, much of Indiana has no or inadequate deposits of limestone at the surface. Northern Indiana is covered by glacial materials. Bedrock in part of southwestern Indiana is shale and sandstone. Bedrock in southeastern Indiana is interbedded thin limestone and shale. Underground mining is not economical in southwestern Indiana, and probably not economical in southeastern Indiana, but it may become economical in northern Indiana and at certain other localities, such as Indianapolis or Lafayette.

In some places the lack of surface deposits may be caused by urbanization of the area near a quarry, and thus the operator is prevented from acquiring new land or even from expanding the open pit on land already owned.

(2) Unfavorable geologic structure. In some areas limestone may be found at the surface near markets, yet not be suitable for quarrying. Beds that dip steeply but are not vertical can be quarried, but the development of the quarry in two directions is limited to the thickness of the beds. In such places open-pit mines must become shaft mines so that the deposit can be worked downdip.

(3) Efficient utilization of reserves. Many tunnel mines are simply the extension of surface quarries into adjoining hills where the overburden is too thick to remove. Thus, when the rock that can be quarried has been exhausted, the plant need not be moved to a new location. In some places tunneling and quarrying are carried on side

by side to extend the life of the quarry or for the reasons given under 4 and 5 below.

(4) Selective mining. Underground mining permits the selective removal of particular beds without removal of, or contamination by, the overlying materials or clay seams. Room-and-pillar mining of low-dipping beds also permits some horizontal selection of materials. Many underground operations in the United States selectively mine premium-grade material for chemical flux stone, portland cement raw material, or other purposes. The mines near Barberton, Ohio, Carntown, Ky., and Riverside, Calif., are examples.

(5) All-weather mining and uniform production. Underground mining is not affected by rain, snow, wind, or even outside temperature. The operator of a shallow underground mine in Indiana reported that the temperature in the mine remained about 55°F summer and winter. The superintendent of a midwestern mine 350 feet deep reported a constant temperature of 59°F away from the air shafts. The superintendent of a mine 600 feet deep reported a temperature of 65°F. Deeper mines might be somewhat warmer, but few limestone mines are deep enough for the temperature to be above 70°F. The rock temperature in the Barberton mine, about 2,250 feet deep, is 85°F, but the air is cooled to 80° by forced air ventilation (Bergstrom, 1967, p. 82). A rule of thumb for increase in temperature with depth is 1°F for each 100 feet.

Some economies are thus possible through year-around operation. The workers have stable employment, stockpiles do not need to be large, rock does not freeze, and responses to unexpected demands of material are possible at any time. Some of the advantages of year-around operation, however, are lost in production of construction and agricultural materials because the maximum use of these materials is seasonal.

(6) Environmental problems. Underground mining is more inconspicuous than open-pit mining and consumes less land. Most dust and noise are confined below ground, neighbors are not endangered by thrown rocks, and the choice of mining site depends less on surface

Figure 5. Inland Underground Facilities, Kansas City, Kans. The extensive mined-
out areas of an active limestone tunnel mine (not shown here) are used for
frozen-food storage, warehousing, manufacturing sites, office space, and vital-
records storage.

topography and cultural features. If the roof is competent and suffi-
cient limestone is left as pillars, say 30 percent, collapse of the roof
causing subsidence at ground level should pose little threat. Under-
ground mining, therefore, is favored where the surface is expensive
or preempted, as near cities.

(7) Underground storage and waste disposal. Some operators have
reported that the space created by mining can prove more profitable
than the rock removed. Under some conditions the open space can
be used for waste disposal or storage of gas or liquids. Mines above
the water table with large rooms, solid roof, and level floor can be
used for warehouses, frozen-food storage facilities, office space, and
fallout shelters (fig. 5). One is even used for a marina (Vineyard,
1969, p. 102). Such facilities are less expensive than surface struc-
tures to build, and a constant temperature is easily maintained.
Limestone mines are generally large enough to permit truck traffic
and even railway spurs. Many underground installations have been
described in the trade journals.

Inasmuch as most limestone is mined by the open-pit method, we feel that the disadvantages of underground mining compared with open-pit mining are well known and need to be cited only briefly:

(1) A shaft mine requires a large initial investment before the first ton of rock is produced.

(2) The size of equipment is controlled by the dimensions of the entrance and rooms, and less rock can be shot down at one time. Thus it is not so adaptable to large-volume production.

(3) About 30 percent of the reserves are left in the ground.

(4) Equipment cannot be moved so easily in and out.

(5) Water is more likely to be a threat, and its removal more costly.

(6) Safety precautions must be greater. Roof fall is a major threat.

(7) Fresh air must be circulated through shaft mines.

(8) Some states regulate underground mines but not open-pit mines.

Only a few of the more than a hundred articles written on the underground mining of limestone are included in our bibliography. The U.S. Bureau of Mines report on the underground mining of limestone (Thoenen, 1926) is out of date and has never been revised, but it remains the best single reference that we are aware of on this specific subject. More recently R. L. Loofbourow (1966) has written on underground mining of industrial minerals in general.

Sampling

The goal in sampling is the accurate representation of the limestone deposit. It is one of the geologist's most important responsibilities and should never be delegated to untrained persons. In a large sampling program, thousands of dollars are likely to be spent in chemical and physical analyses. The analyses then become the basis for hundreds of thousands and sometimes millions of dollars of development work. Thus if great care is not taken in sampling, thousands and perhaps millions of dollars can be wasted.

Coring, rock bitting, and surface sampling are the most common sampling methods, and the choice among these depends on such

matters as the geology of the deposit, the proposed use of the material, and the availability of equipment.

CORING

Coring is generally the best method of exploring a new deposit. A single core may not always be more representative than a section sampled in a quarry or in a natural exposure, where some judgment may be used as to what is representative, but cores taken on a grid pattern certainly constitute a more representative and unbiased sample of a deposit than an equal number of surface sections. Coring avoids contamination by soil and weathered material and disproportionate sampling of different parts of a single unit, yet retains the surface material that may have worked its way down in solution cavities.

Initial drilling is generally widely spaced both to locate a potential deposit and to determine its potential size. Once an apparently large deposit is discovered it should be drilled in a more or less regular pattern. The core grid depends largely on the proposed use of the limestone, although other factors, such as the homogeneity of the deposit, geologic complexity, topography, and cost of drilling, are significant. If stone is to be used as cement raw material and the magnesium content of the rocks is believed to be marginal and unpredictable, no greater than 100-foot centers would be required. If the deposit is relatively homogeneous in one direction and not in another, a rectangular rather than a square grid might be used. If the stone is to be used as aggregate and has proved relatively uniform in other deposits, generally only a few cores need to be taken in several hundred acres. We recommend that for most deposits in which the chemical composition of the rocks is important, cores be spaced on 100-foot centers until a pattern of uniformity indicates that the spacing can be increased safely.

For most limestone exploration a BX core (1 inch in diameter) suffices, but if physical tests are required, a core of larger diameter must be used. The Indiana Geological Survey uses a drill rig that takes an NX core (2 1/8 inches in diameter) and has found that the

Table 2. Approximate density of limestone, dolomite, shale, and cement

Material	Weight lb (per cu ft)	Weight lb (per cu yd)	Weight tons (per acre-ft)
Limestone, broken or crushed - -	95	2,570	
〃 solid - - - - - - - - - -	[1]160	4,320	3,500
Dolomite, broken or crushed- - - -	105	2,840	
〃 solid - - - - - - - - - -	170	4,590	3,700
Shale, broken or crushed- - - - - -	100	2,700	
〃 solid- - - - - - - - - - - -	167	4,500	3,600
Portland cement - - - - - - - - -	100	2,700	
(1 bbl = 376 lb)			

[1]1 ft of 2 1/8-in. limestone core weighs about 3.7 lb.

size of the core is adequate for chemical analyses and limited physical testing. Even the NX core is too small, however, for some physical tests.

Each common physical test of rock used for aggregate requires about 5 kilograms (11 pounds) of rock. If tests for absorption, abrasion, and soundness are performed, more than 30 pounds of rock is required. (Some useful data concerning weight and volume of limestone are given in table 2.) If stone is to be tested for use as highway materials (ASTM D75-59 and AASHO T2-60), a minimum of 50 pounds of rock is required. The Indiana Highway Commission does not perform physical testing of cores and accepts only ledge samples. Testing agencies of some other states, however, will run physical tests on cores. For example, in prospecting for a quarry site near Skaneateles, N.Y., the General Crushed Stone Co. took a core 12 inches in diameter and had the stone tested for quality by the New York State Department of Public Works before opening the quarry (Moore, Matthews, and Dotter, 1968, p. 5).

A geologist or other trained, responsible person should be at the rig site when the core is removed from the core barrel to ensure that it is properly handled. In drilling by the Indiana Geological Survey, the core is placed in proper orientation on the pipe rack until the entire run is removed from the barrel. After the core is measured and the loss is recorded, the core is washed, arrows are drawn on each piece of core to indicate its orientation, and the pieces are placed in
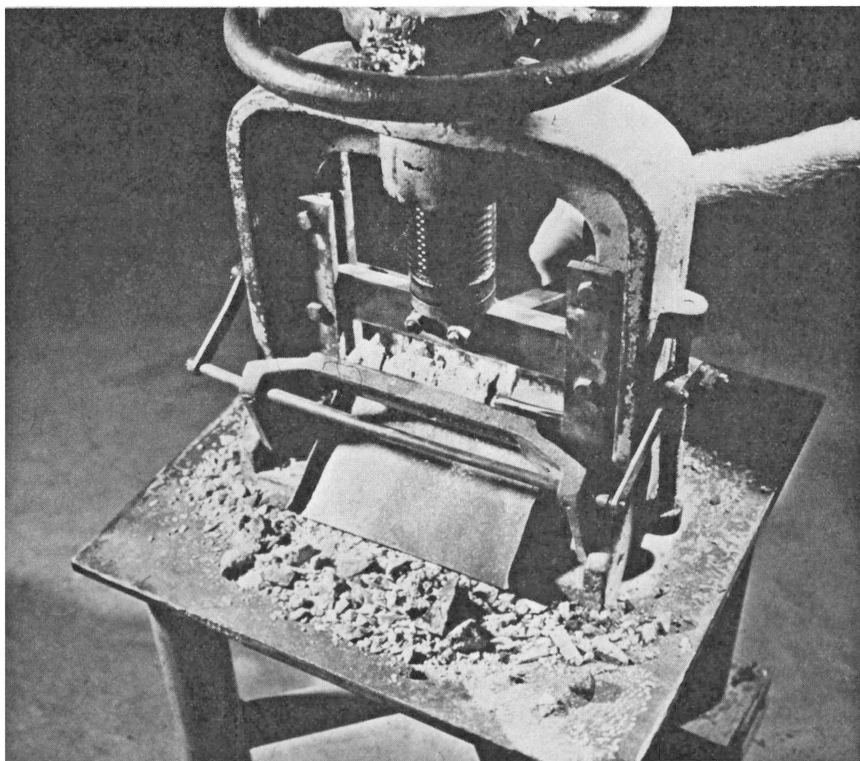
Figure 6. Machine used to split core.

core boxes. The top and the bottom of the core in each box are designated at the appropriate corners of each box and on its cover and the identification of the hole, run number, and drilling depth are written on each box.

In the laboratory, the core is split (fig. 6) after it has been checked to see that the broken ends of the segments match. The two split halves are reassembled into a complete core, and each piece of the split half that is to be saved is then numbered with indelible ink so that it can always be replaced in proper sequence in the core boxes. The core is then described unit by unit with reference to the piece numbers so that the description can always be checked precisely against the core. One split half is generally used to make chemical analyses. In some physical testing, the whole core rather than a split half is used.

When the core is sampled for chemical analysis, the entire split half of each unit is used and the corresponding piece numbers of each sample are recorded. The analysts, of course, make successive splits of the sample to obtain the few ounces that they use for chemical determinations.

ROCK BITTING

If used alone, drill cuttings are probably the least reliable samples in exploration, but if used to supplement cores or information obtained from nearby quarries or outcrops, they are a cheap, rapid method of acquiring much information. In fact, the percussion air drill is probably the fastest and least expensive (about 40 cents per foot) method for preliminary sampling.

Because of the large amount of drilling for oil and gas during the past few decades, cuttings of thousands of wells are on file in government and other sample libraries. Although not intentionally so, these cuttings constitute the largest exploration program for industrial minerals that has ever been undertaken. The persons most qualified to interpret them are geologists who have had some training and experience in exploring for gas and oil. Cuttings cannot be interpreted properly unless the interpreter understands drilling techniques, and the best interpretation requires considerable well-site experience.

SURFACE SAMPLING

Chip samples taken on a quarry face or on an outcrop can provide a good representation of the limestone deposit if the samples are carefully taken. The geologist should first inspect the quarry or outcrop face and divide the face into units of uniform lithology. Tops of units should be marked by some means, such as paint or flagging. If a thick homogeneous bed is present, the geologist should subdivide it arbitrarily, so that no sample is more than about 5 feet thick. He should then start at the base of the unit and take chips of uniform size as near as possible along a selected vertical line to the top of each unit. (He might start at the top and work down, but it is easier to

work up than down.) This method of sampling is sometimes called "channel sampling." Chip samples should be taken from unweathered surfaces or else the weathered rind must be chipped away. Samples should be washed to remove some contaminants, such as lichens or soil, from the samples, but care should be taken not to wash out thin interbedded shales.

Obtaining 10 to 20 pounds of sample from either core sampling or channel sampling is common, and this amount must be crushed, thoroughly mixed, and quartered several times to reduce the sample to the few ounces needed for chemical determination.

Testing

An experienced industrial minerals geologist can evaluate a limestone deposit largely just by looking at it, using a hand lens, hammer, and weak hydrochloric acid as his only tools. He can generally appraise whether a stone will make class A aggregate and cement raw material. He may not be able to determine whether it is of sufficient purity for some other uses, but he can eliminate much stone that is not of sufficient purity for those uses. Final evaluation of rocks suitable for aggregate requires physical testing. Rocks used for making lime or cement or other products that depend on chemical purity should be chemically analyzed.

A list of laboratories capable of making chemical and physical determinations of rocks can be found in "Directory of Testing Laboratories, Commercial-Institutional," which is available from the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.

PHYSICAL TESTING

Procedures for physical testing can be obtained from two main sources: the American Society for Testing and Materials (ASTM) and the American Association of State Highway Officials (AASHO). Both organizations describe explicit procedures, in cookbook fashion, for testing limestones. The Indiana State Highway Commission follows the procedures outlined by AASHO for aggregate, although the

Table 3. Physical tests of limestone and dolomite used for aggregate and dimension stone as specified by the American Society for Testing and Materials (ASTM), the American Association of State Highway Officials (AASHO), and the Indiana State Highway Department

Physical test	ASTM No.	AASHO No.	Indiana State Highway Specifications, 1969 (Section No.)
Aggregate:			
Abrasion:			
Deval machine- - - - - - - - -	D 289-63	T 3-35	
Los Angeles machine - - - - -	C 131-66	T 96-65	903.02
Amount of material finer than			
No. 200 sieve in aggregate - - -		T 11-60	903.02, 903.03
Determination of clay lumps in			
natural aggregates - - - - - - - -	C 142-64	T 112-64	903.02
Scratch hardness of coarse			
aggregate particles - - - - - - -	C 235-62	T 189-63	903.02, 903.03
Sieve analysis of fine and			
coarse aggregate - - - - - - - - -	C 136-67	T 27-60	903.02, 903.03
Soundness:			
Sodium sulfate - - - - - - - -	C 88-63	T 104-65	903.02, 903.03
Freeze and thaw - - - - - - -		T 103-62	903.02, 903.03
Specific gravity and absorption			
of coarse aggregate - - - - - - -	C 127-68	T 85-60	903.02
Specific gravity and absorption			
of fine aggregate - - - - - - - - -	C 128-68	T 84-60	
Dimension stone:			
Abrasion resistance of stone			
subjected to foot traffic - - - - -	C 241-51		
Compressive strength of natural			
building stones - - - - - - - - -	C 170-50		
Modulus of rupture - - - - - - -	C 99-52		

counterpart tests in ASTM are almost identical. The Indiana State Highway Commission issues from time to time a booklet of "Standard Specifications," which specifies the type of stone for different uses and the test requirements that must be met for stone to qualify as class A, B, or C aggregate. Tests for dimension stone follow procedures outlined by ASTM. Appropriate references should be consulted for procedure and equipment for specific tests (table 3).

AGGREGATE

ABRASION: This test measures the resistance of coarse aggregate to
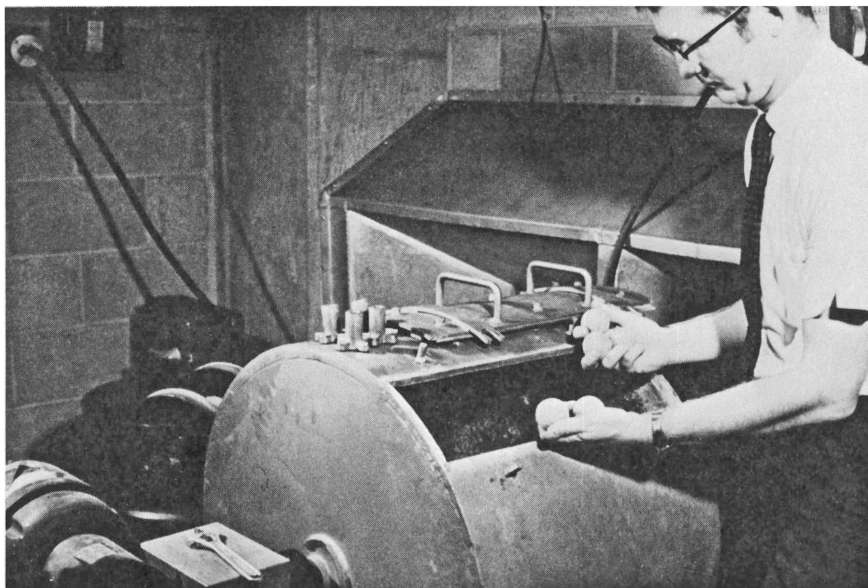
Figure 7. Los Angeles machine used to test resitance of aggregate to abrasion.

abrasion and requires the use of either the Los Angeles or the Deval machine. The Los Angeles machine looks something like a stubby oil drum turned on its side and suspended by a shaft at each end of the drum (fig. 7). The drum can be rotated at a precise speed for a specified number of revolutions. A steel shelf about 3½ inches wide runs the full length inside the drum. A specified number of steel balls about 1 7/8 inches in diameter are placed in the drum. As the drum turns, the steel balls are carried up on the shelf, roll off, and drop to the bottom of the drum. The noise that this machine makes has caused it to be dubbed the "Los Angeles rattler."

A sample of graded aggregate (that is, a composite sample consisting of several particle sizes) weighing about 5 kilograms is put into the drum along with the steel balls. The drum is rotated at a speed of about 33 rpm for 500 revolutions. The sample is then removed and sieved through a No. 12 sieve. The amount of material finer than the sieve is considered to be the amount lost due to abrasion and is expressed as a percentage of the original weight of the test sample.

A test using the Deval abrasion machine is somewhat similar. Although widely used in the late 1800's and early 1900's, it has now generally been replaced by the Los Angeles machine.

Abrasion testing by the Los Angeles machine helps predict how stone will perform under certain conditions, such as the breakdown of aggregate under rollers and wheel loads in traffic-bound and some low-quality bituminous road surfacing; the effect of aggregate on the strength of concrete in which the mix is rich enough so that the aggregate strength is an important factor; and the breakdown of aggregate during the mixing operation in concrete causing gradation changes in the aggregate (Sweet, 1948, p. 57-58).

AMOUNT OF FINE MATERIAL: This test is used to determine the amount of material finer than a No. 200 (74 micron) sieve in aggregates. A sample of graded aggregate, weighing a kilogram or more, is wet sieved. The results of the test are expressed as a percentage of the total material finer than the No. 200 sieve. Excessive fines are not desirable in concrete aggregate because they decrease mortar strength.

DETERMINATION OF CLAY LUMPS: Clay lumps are picked by hand from a sample of graded coarse aggregate that weighs 11 kilograms or more and are weighed. The results of the test are expressed as a percentage of clay lumps. Clay lumps and most other soft particles are not desirable as aggregate because they have low strength and because they tend to change in volume during wetting and drying or freezing and thawing.

SCRATCH HARDNESS: This test determines the amount of soft particles in coarse aggregates greater than 3/8 inch in diameter. The test is similar to the Mohs hardness test of minerals except that a brass rod 1/16 inch in diameter and of specified hardness is used to scratch test specimens of coarse aggregate particles. If the test specimen is scratched by the brass rod, the specimen is classified as "soft." The size of a test sample ranges from 200 grams to 12,000 grams according to the nominal maximum size of the particles. Test results are generally expressed as the percentage of soft particles greater than 3/8 inch in diameter.
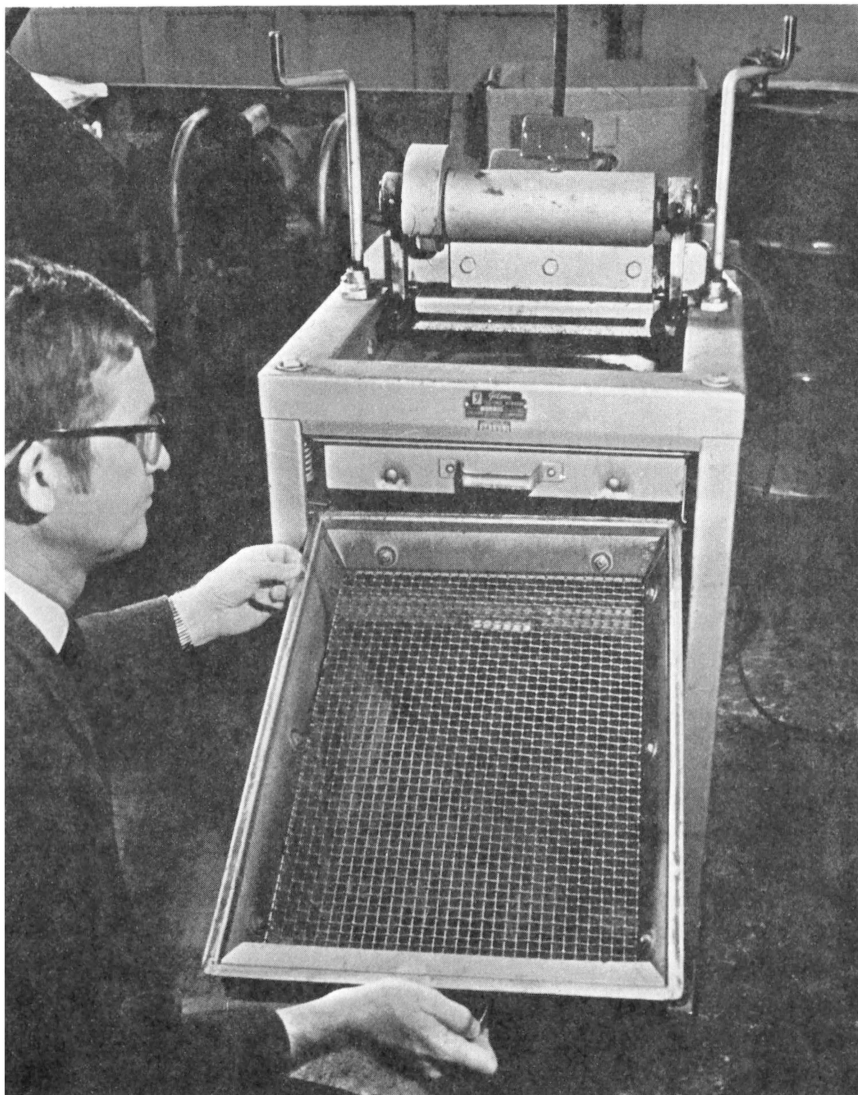
Figure 8. Machine used to sieve aggregate.

SIEVE ANALYSIS OF FINE AND COARSE AGGREGATE: This test determines the particle size distribution of fine and coarse crushed stone aggregate. The amount of fine aggregate necessary for a test is about 500 grams, and the amount of coarse aggregate ranges from 1 kilo-

Figure 9. Five different sizes of a clay-rich dolomite (Saluda Formation) after the fifth cycle in a sodium sulfate bath. Percentage loss for all samples was 33.9.

gram to 35 kilograms according to the nominal maximum size of the particles. The sample is sieved (fig. 8), and the results are generally reported as the percentage passing each sieve.

SOUNDNESS: This test determines the soundness of aggregate generally by use of sodium sulfate or magnesium sulfate solutions. A sample of graded aggregate that weighs 8.5 kilograms is totally immersed in a solution of sodium sulfate or magnesium sulfate for 16 to 18 hours, then is removed from solution, drained, and dried at a temperature of 105°C for about 4 hours. The sample is cooled and the cycle repeated for a prescribed number of cycles (fig. 9). (The Indiana Highway Commission prescribes five cycles.) After the final cycle, the sample is sieved to determine the amount of rock that has broken down as a result of expansion of salt crystals in the pores. The weight of loss of sample is expressed as a percentage of the total sample.

An alternate test for soundness is to subject the aggregate sample to 50 cycles of freezing and thawing. The results are expressed as

they are for the sodium sulfate test. The freeze-thaw soundness test is considered more diagnostic than the sodium sulfate soundness test but is used less because it takes much longer to run. In Indiana, samples that fail the State Highway Department's sodium sulfate test may be submitted to a freeze-thaw test. The performance in the freeze-thaw test takes precedence.

SPECIFIC GRAVITY AND ABSORPTION: The bulk specific gravity of aggregate particles is measured by weighing a sample of about 5 kilograms in air and water much like specific gravity is determined on a Jolly balance. The results are expressed as a ratio of the mass of the aggregate particle to the mass of an equal volume of water.

Probably the principal use of specific gravity data is to determine the amount of void space in concrete so that proper mixtures of aggregates can be designed; however, there also appears to be some relation between specific gravity and aggregate quality (Sweet, 1948, p. 63).

Absorption is a measure of the amount of water absorbed by the test sample after being immersed 24 hours. The results are expressed as the weight percentage of absorbed water.

Absorption is a measure of the apparent porosity of a rock. It is used mainly for design purposes in that it can be used to control the amount of water used in mixing concrete; however, there appears to be some correlation between the percentage of absorption and rock durability, particularly resistance to deterioration by freezing and thawing (Sweet, 1948, p. 64-66).

DIMENSION STONE

ABRASION RESISTANCE OF STONE: This test measures the abrasion resistance of dimension stone to foot traffic. Three test specimens about 2 inches square and 1 inch thick under 2-kilogram weights are rotated on a power-driven grinding lap (fig. 10) at a constant speed for a specified number of revolutions while an abrasive is applied. The abrasive resistance of the stone is expressed as its abrasive hardness, which is the reciprocal of the volume of the material abraded multiplied by 10.
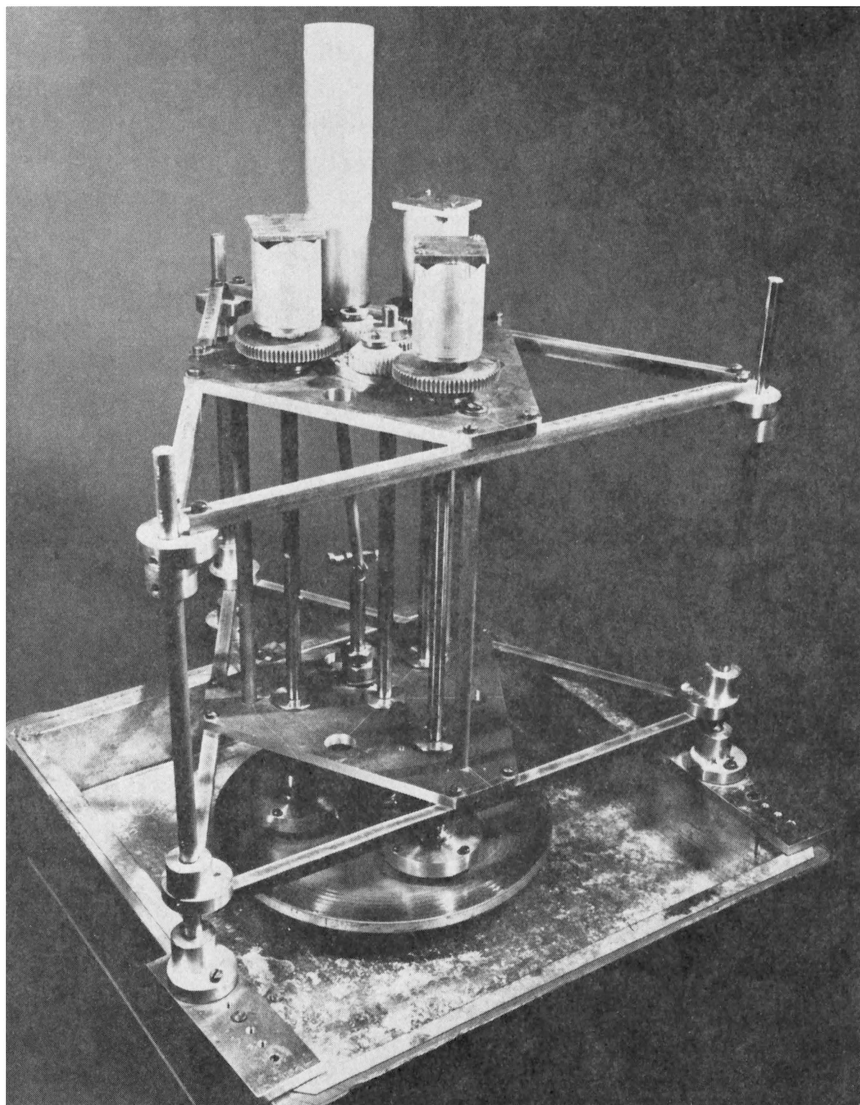
Figure 10. Machine used to test resistance of dimension stone to abrasion by foot traffic.
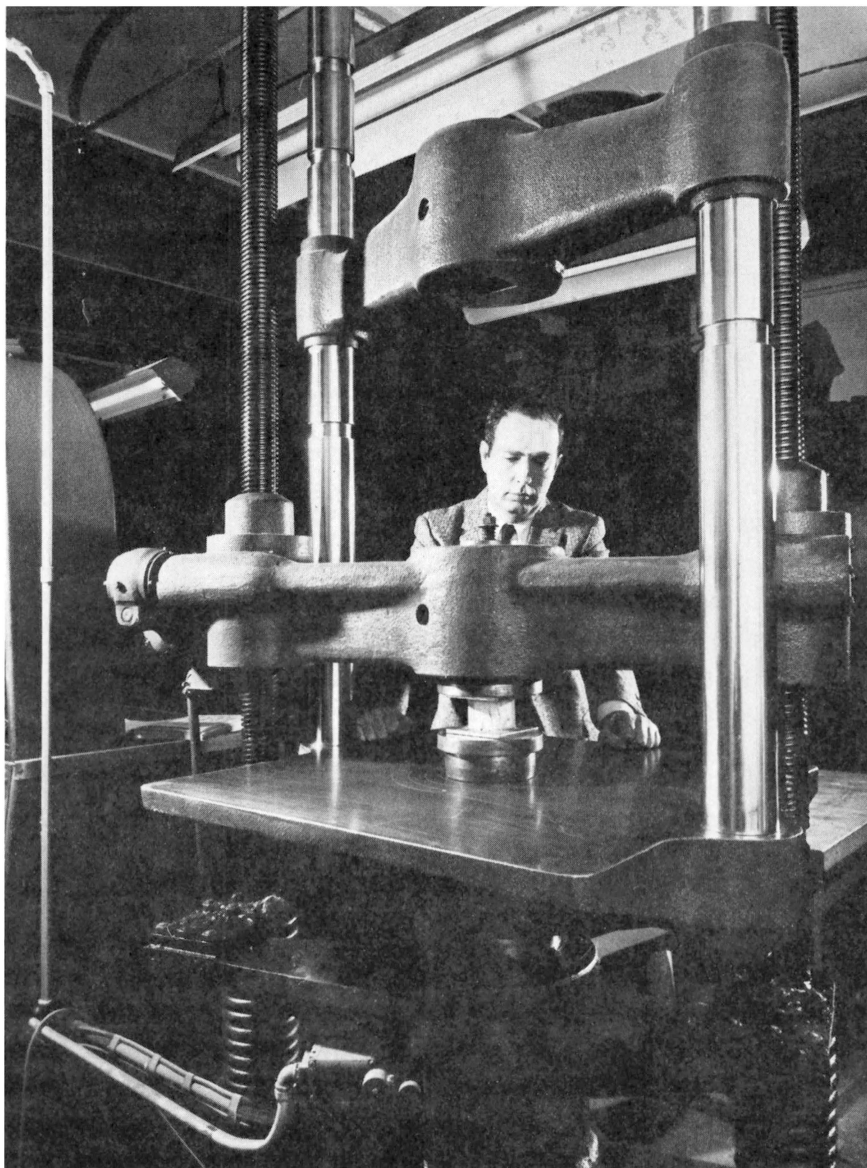
Figure 11. Machine used to test crushing strength (shown here), modulus of rupture, and other properties of dimension stone.

COMPRESSIVE STRENGTH: Measurement of compressive strength requires a mechanical press (fig. 11) capable of exerting compressive pressures at prescribed rates of speed. Generally three test specimens—in the form of cubes, square prisms, or cylinders, whose lateral dimension or diameter is not less than 2 inches and whose ratio of height to diameter is not less than 1:1—are required. Each test specimen is compressed in the machine until it fails. The pressure exerted at the point of failure is considered to be the compressive strength of the specimen. The compressive strengths of all specimens are averaged and reported in pounds per square inch.

MODULUS OF RUPTURE: Generally three test specimens about 4 by 8 by 2¼ inches in size are needed for this test. A specimen is placed lengthwise on the bed of a testing machine, such as a Baldwin Press, so that each end rests on a knife-blade support. A third knife-blade wedge is pressed down on the precise middle of the specimen until the specimen fails. The pressure exerted at the point of failure is considered to be the modulus of rupture of the specimen. The moduli of rupture of all specimens tested are averaged and reported in pounds per square inch.

CHEMICAL TESTING

The techniques for making chemical analyses are beyond the scope of this report and will not be described except to note that the Indiana Geological Survey uses a Jarrel-Ash Ja-70-15e 21-foot (W)-grating spectrograph for determining calcium, magnesium, silica, aluminum, iron, titanium, and manganese and gravimetric chemical analysis techniques for determining chemical CO_2, sulfur, and phosphorus. Details for making chemical analyses of limestones and dolomites can be found in Hillebrand and others (1953).

Chemical analyses are essential in determining whether a rock unit is suitable for many purposes. For some purposes the iron content must be low, for others the sulfur content, and so forth. Some of these are discussed under "Major Uses of Limestone and Specifications."

Table 4. Conversion factors useful in interpreting chemi-
cal analyses of limestones and dolomites

$Ca \times 1.40 = CaO$	$CaO \times 0.71 = Ca$
$CaCO_3 \times 0.56 = CaO$	$CaO \times 1.78 = CaCO_3$
$CaCO_3 \times 0.44 = CO_2$	$CO_2 \times 2.27 = CaCO_3$
$Mg \times 1.66 = MgO$	$MgO \times 0.60 = Mg$
$MgCO_3 \times 0.48 = MgO$	$MgO \times 2.09 = MgCO_3$
$MgCO_3 \times 2.19 = CaMg(CO_3)_2$	$CaMg(CO_3)_2 \times 0.54 = CaCO_3$
$P \times 2.29 = P_2O_5$	$P_2O_5 \times 0.44 = P$

Chemical analyses are also useful in estimating the value of a rock as aggregate. Chemical analyses are not made for this purpose, but many chemical analyses are made routinely on samples collected by state surveys and other government organizations. Thus a geologist or a mineral producer may wish to interpret a chemical analysis in terms of the probable soundness of the rock.

Rock that is almost pure (99 percent) dolomite is likely to be well-cemented reefal dolomite and can be predicted to make class A aggregate. Rock that is pure calcite, on the other hand, may be skeletal or oolitic limestone that is either well cemented or poorly cemented and might make excellent or only fair aggregate.

Aluminum is generally reported as aluminum oxide (Al_2O_3). The higher the Al_2O_3 content, the more argillaceous the sample is likely to be. Most of the silicon dioxide (SiO_2) is likely to be present as clay, silt, sand, or chert. The Al_2O_3 content can be multiplied by two to obtain an estimate of the SiO_2 tied up in clay. The way in which the remaining SiO_2 occurs in the rock can be determined only by reference to the sample description or by examining the sample itself.

Chemical analyses are generally reported as oxides. By use of the conversion factors presented in table 4, the oxides can be recast as elements or carbonates.

Major Uses of Limestone and Specifications

The uses of limestone depend largely on physical properties, chemical properties, or both. Physical properties are more important for aggregate or building stone. Chemical properties are more important if the stone undergoes changes from one form of matter to another, such as in the manufacture of cement or lime. Chemical and physical properties are often interrelated. For example, in whiteners the physical property of color is largely determined by the purity and chemical composition of the rock.

Virtually hundreds of uses for limestone exist, but for simplicity these can be grouped into eight major uses that include more than 95 percent of the total crushed limestone production (table 5). Only those major uses and dimension stone will be discussed here. For information about other limestone uses, see Lamar (1961) or Boynton (1966).

The references given in each section below are selective rather than exhaustive, but they will aid the reader in obtaining further information on a particular subject.

Specifications for limestones should be considered generally as guidelines. For some limestones, minimum and maximum percentages of certain constituents are based on real physical or chemical characteristics, but the precise figure may have been determined by custom, composition of the limestone being used, or "what the market will bear."

Published specifications may be based on a survey of manufacturers, but some are based on a survey of literature. For example, Bingham's (1916) recommended specifications for limestone used in manufacturing calcium carbide have been repeated often (table 6). These repeated specifications are based on physical and chemical reactions during both the manufacture and use of calcium carbide, but they have more latitude than the figures quoted from Bingham indicate or than Bingham himself suggested in his text. One should not interpret agreement in published specifications as corroboration so much as repetition of other published specifications.

Table 5. Crushed and broken limestone and dolomite sold or used by producers in Indiana and in the United States

[Data from U.S. Bureau of Mines Minerals Yearbook for 1968]

Uses	Indiana			Total United States		
	Tonnage (X 1,000)	Percentage of production	Average price per ton	Tonnage (X 1,000)	Percentage of production	Average price per ton
Aggregate (concrete and roadstone) -	19,261	74	$1.38	366,633	61	$1.38
Agriculture- - - - - - - - - - - - - - -	2,098	8	1.54	38,369	6	1.80
Cement- - - - - - - - - - - - - - - - -	2,771	11	0.94	97,773	16	1.07
Flux stone - - - - - - - - - - - - - - -	——	——	——	28,268	5	1.53
Lime and dead-burned dolomite - - -	——	——	——	30,528	5	1.81
Railroad ballast - - - - - - - - - - - -	440	2	1.33	5,721	1	1.29
Riprap and jetty stone - - - - - - - - -	937	4	2.35	12,934	2	1.30
Other uses (includes chemical uses, filtration, glass, mineral food, poultry grit, refractory, roofing granules, aggregates and chips, stone sand, terrazzo, and unspecified uses - - - - - - - - - - - - - - -	361	1	——	22,715	4	——
Total - - - - - - - - - - - - - - - -	25,868	100		602,941	100	

Table 6. Some published specifications of limestone used for manufacturing calcium carbide

$CaCO_3$	MgO	SiO_2	$Al_2O_3 + Fe_2O_3$	S	P	Reference
>97	<0.5	<1.2	<0.5	Tr[1]	<0.004	Bingham (1916)
>97	<0.5	<1.2	<0.5	Tr	<0.004	Mantell (1931)
>97	<0.5	<1.2	<0.5	Tr	[2]<0.004	Bowen (1957)
Very high	<0.5	<1.2	<0.5	Tr	<0.005	AIME (1960)
>97	<0.5	<1.2	<0.5	Tr	<0.004	McGregor (1963)
Very high	<0.5-2.0	<1.5-3.0	Low	Tr	<0.05	Searle (1935)
>97	<1.0-2.0	<1.0-3.0	<0.05-0.75	Tr	<0.004-0.01	Lamar (1961)

[1]Tr - Trace.

[2]The figure given in Bowen's publication is 1.2, a typographical error.

Specifications for a particular limestone may be based on the average composition of the limestone being used regardless of the fact that limestone of a different composition might be cheaper and better. The cost of manufacturing is generally greater than the cost of the raw material, and a change in raw material might prove a costly mistake. Inadequate or unreliable supply could also be costly, and therefore a manufacturer is likely to be loyal to a dependable supplier.

As an example of "what the market will bear," a steel manufacturer in the Midwest specified a maximum of 3 percent $MgCO_3$ and 0.04 percent sulfur in flux stone obtained from a contract supplier in Indiana. When the magnesium and sulfur content of the initial material proved to be much lower, the steel company revised its specifications to 1.5 percent $MgCO_3$ and 0.025 percent sulfur.

Some specifications are primarily economic rather than physical or chemical. For example, a low silica content in limestone and dolomite used for flux stone is desirable, but the cost is an equally important factor. Generally a silica content lower than 2 percent is desired, but if only stone of much higher silica content (say 8 percent) is available within an economical distance, it can be used. More high-silica stone than low-silica stone is required to flux the same amount of iron ore.

AGGREGATE

Material that is used to fill space in concrete or bituminous mixtures is called aggregate. Some aggregate, such as sand and gravel, is used almost as it is mined. Other aggregate, mainly rock, is crushed and sorted into various desired sizes. Limestone and dolomite are the principal rock types used for crushed stone aggregate, and they account for about 70 percent of the total production. Granite, basalt, and quartzite are some other rock types used for crushed stone, but they are important only where limestone and dolomite are absent.

Good aggregate should be durable, strong, and free of impurities, such as clay lumps and shale, porous chert, limonite concretions, organic matter, or other soft and nondurable particles. The aggregate should be relatively inert, so that it does not react with the binding material to cause distress and failure. Large amounts of crushed stone are also used for fill, for base courses for roads, and for road metal. Specifications for these uses are generally not as strict as they are for aggregate.

Specifications and testing for most aggregate are fixed by state and national government agencies. For example, the Indiana State Highway Commission (1969, p. 419) lists 17 size gradations for coarse aggregate. In 1967, the Illinois Highway Department listed 15 different specifications for coarse aggregate, the Kentucky Highway Department listed 13, and the Ohio Highway Department listed 18. Other government organizations, such as the U.S. Department of Commerce, U.S. Corps of Engineers, U.S. Bureau of Reclamation, and U.S. Department of Agriculture, have their own specifications. The individual agency should be consulted for current specifications because specifications are frequently modified, added, or deleted to conform to certain projects.

Testing of aggregate generally follows procedures outlined by the American Association of State Highway Officials (AASHO) or the

Table 7. Indiana State Highway Commission specifications for coarse crushed
aggregates
[From Indiana State Highway Commission, 1969, p. 416-417]

Class	Minimum specific gravity	Maximum deleterious materials (pct)	Maximum abrasion loss (pct)	Maximum soundness loss (pct)	Maximum absorption (pct)
A	2.45	5	40.0	12	3
B	2.45	6	45.0	16	–
C	2.45	10	50.0	20	–

American Society for Testing and Materials (ASTM). The Indiana State Highway Commission prescribes that sampling and testing of aggregate follow procedures outlined by AASHO.

The Indiana State Highway Commission collects ledge samples from every quarry supplying aggregate for state work. These samples are tested for physical properties and are classified (table 7). Class A stone, which is the highest quality, can be used for any purpose, but it is the only class of stone that can be used in portland cement concrete and in bituminous surface courses. Class B stone can be used for any purpose except portland cement concrete and bituminous surface courses, and class C stone can be used only for subbase and fill.

Limestone that makes good aggregate ideally should be tough and nonporous and contain few clay laminations. Skeletal and oolitic limestones make good aggregate if they are well cemented, but most poorly cemented limestones have high porosities and tend to abrade easily. Parts of the Salem Limestone (Mississippian) are good examples of poorly cemented skeletal limestone that have high abrasion-loss values. Micritic limestones, such as compose large parts of the Black River Limestone (Ordovician), make good aggregate if the clay content is low. Laminated limestone that contains clay along bedding planes makes poor aggregate. If not too numerous, clay seams less than, say, 1 inch thick may detract little from the value of otherwise sound limestone because the clay is likely to be pulverized in crushing and thus combined with the carbonate fines. Unless the clay content is large, the fines can still be sold as agricultural limestone. Thick

clay or shale beds, however, are likely to emerge from the crusher as large fragments and contaminate the aggregate. These beds must be stripped separately and removed from the quarry at considerable expense. The number of such beds that can be tolerated in most quarries is small.

Certain types of rocks have a history of poor performance as aggregates. Chert, which is undesirable anyway because of the accelerated wear it causes processing equipment, limits the usefulness of some cherty limestones because porous cherts are particularly susceptible to alkali reactions in concrete and can cause premature deterioration and failure. The Indiana State Highway Commission (1969, p. 416-417) specifies that cherts less than 2.45 bulk specific gravity are deleterious and limits the amount that can be present in aggregate used for different highway purposes. Many highly argillaceous limestones and dolomites are reactive and cause failure in concrete because of excessive expansion or contraction (Hadley, 1964, p. 197; Dunn and Hudec, 1966). The porosity of some limestone is such that it allows selective absorption of water, which results in poor durability under freezing and thawing conditions (Patton, 1954, p. 85).

Limestones from particular parts of the stratigraphic section are highly desirable for aggregate because of their exceptional physical properties and good service records. For example, of the Mississippian formations, the Ste. Genevieve and Paoli Limestones (Girkin and (or) Renault Formations) contain premium limestones and are extensively quarried in Indiana, Kentucky, and Illinois. Of the Silurian rock units in Indiana, the Huntington Lithofacies of the Wabash Formation, the Louisville Limestone, and the Laurel Member of the Salamonie Dolomite are composed largely of dolomite and limestone that have good service records. Of the Devonian formations, the Jeffersonville Limestone and the Geneva Dolomite have fair to good service records. Table 8 lists typical ranges of physical properties of some Indiana rocks used for crushed stone aggregate. These values can be compared with average physical property values of limestones throughout the United States that have been tested by the U.S. Bureau of Public Roads (table 9).

Table 8. Typical range of physical properties of some crushed stone aggregate from Indiana

[Data compiled from Indiana State Highway Commission records]

Unit	Number of samples	Number of locations	Specific gravity	Abrasion loss (pct)	Soundness loss (pct)	Absorption (pct)
Pennsylvanian rocks:						
West Franklin Ls. Mbr. (Shelburn Fm.)	1	1	2.69	24.5	17.6	0.8
Mississippian rocks:						
Glen Dean Ls.	13	2	2.46-2.69	24.7-32.4	4.3-27.2	0.5- 1.5
Golconda Ls.	4	1	2.56-2.65	28.8-35.7	10.7-17.6	0.8- 2.0
Beaver Bend Ls.	3	1	2.2 -2.4	31.7-37.9	8.8-27.8	5.3- 7.7
Paoli Ls.	5	3	2.60-2.67	27.9-31.9	2.5-24.5	0.6- 2.7
Ste. Genevieve Ls.	51	12	2.37-2.7	23.1-42.7	2.6-31.4	0.3- 3.7
St. Louis Ls.	20	5	1.91-2.70	19.7-67.7	3.8-32.2	0.3-13.6
Salem Ls.	14	4	2.29-2.70	21.8-44.6	5.3-39.9	1.8- 2.9
Harrodsburg Ls.	6	2	2.58-2.70	25.5-34.4	6.4-20.0	0.6- 1.4
Devonian rocks:						
North Vernon Ls.	15	9	2.5 -2.72	24.7-45.5	6.5-23.7	0.6- 6.4
Jeffersonville Ls.	32	11	2.2 -2.73	22.3-44.0	0.9-30.5	0.4- 7.7
Geneva Dol.	10	4	2.34-2.68	27.9-37.6	1.9-12.0	2.3- 5.0
Silurian rocks:						
Kokomo Ls. Mbr. (Salina Fm.)	1	1	2.61	25.3	2.1	1.7
Huntington Lithofacies (Wabash Fm.)	39	11	2.46-2.77	19.7-39.5	0.9-20.2	0.4- 2.8
Liston Creek Ls. Mbr. (Wabash Fm.)	11	3	2.48-2.78	23.2-28.8	2.7-48.0	1.1- 3.5
Louisville Ls.	25	10	2.43-2.78	22.9-37.1	3.5-34.4	0.7- 4.8
Salamonie Dol.	15	5	2.36-2.71	32.1-52.1	0.5-23.7	1.3- 3.9
Laurel Mbr. (Salamonie Dol.)	29	9	2.52-2.80	23.5-36.8	1.0-43.6	0.5- 2.7
Brassfield Ls.	2	1	2.62-2.76	28.3-35.6	6.2-11.2	0.7- 2.6

Table 9. Average values for physical properties of limestones in the United States
tested by the U.S. Bureau of Public Roads
[Data from Woolf, 1953, p. 8]

	Number of tests	Average value
Bulk specific gravity - - - - - - - - - -	1,695	2.66
Absorption (pct) - - - - - - - - - - - -	1,673	0.9
Los Angeles abrasion loss (pct) - - - -	350	26.

AGRICULTURAL LIMESTONE

Finely ground limestone and dolomite make up about 95 percent of
the liming materials used in the United States. Liming materials are
used principally to neutralize soil acidity, but they also help replenish
the calcium and magnesium content of leached soils, help condition
soil for easier tillage, and help provide the proper pH to soils, so that
other fertilizers can be assimilated more easily by plants. Agricultural
limestone production in Indiana has remained rather uniform for the
past few years and accounts for about 10 percent of the total crushed
stone production. Much of the agricultural limestone in Indiana is
not ground specifically for that purpose but is obtained from the
fines left over from crushing operations that produce aggregate.

Specifications for agricultural limestone are based on its ability
to correct soil acidity. The quality of agricultural limestone is con-
trolled by law in Kentucky, Ohio, and Michigan, but not in Indiana
or Illinois. Certain specifications, however, must be met in all states
for landowners to qualify for the federal cost-share program. Specifi-
cations for agricultural limestones that qualify for the federal pro-
gram vary slightly in different states, but in general an approved
agricultural limestone must have a minimum specified limestone
($CaCO_3$) and (or) dolomite ($CaCO_3 \cdot MgCO_3$) content and a particle
size sufficiently fine for the limestone to go easily into solution
in the soils. Minimum specifications for agricultural limestone that
qualify for the federal program in Indiana (U.S. Department of
Agriculture, 1968, p. 1) are:

(1) It must contain at least 80 percent calcium carbonate equiva-
lent, generally abbreviated as the CCE. (See below.)

Table 10. Computation of the calcium carbonate equivalent of a ledge consisting of four limestone units

Thickness of unit (ft)	Chemical analyses[1]	
	$CaCO_3$ (pct)	$MgCO_3$ (pct)
4.9 - - - - - - -	81.5	14.2
3.8 - - - - - - -	48.7	31.0
5.0 - - - - - - -	83.4	9.5
4.5 - - - - - - -	94.1	1.3
Total 18.2		

[1]The average values for the total thickness of rock are:

$CaCO_3$
4.9 X 81.5 = 399.4
3.8 X 48.7 = 185.1
5.0 X 83.4 = 417.0
4.5 X 94.1 = 423.5
Total 1,425.0

$MgCO_3$
4.9 X 14.2 =   69.6
3.8 X 31.0 = 117.8
5.0 X 9.5 = 47.5
4.5 X 1.3 =   5.9
Total   240.8

$$\text{Average } CaCO_3 \text{ content (pct) for 18.2 ft of rock} = \frac{1,425.0}{18.2} = 78.3$$

$$\text{Average } MgCO_3 \text{ content (pct) for 18.2 ft of rock} = \frac{240.8}{18.2} = 13.2$$

Assuming that 1 molecule of $MgCO_3$ is as effective as a neutralizer as 1 molecule of $CaCO_3$, then a given weight of $MgCO_3$ is 1.19 times as effective as a given weight of $CaCO_3$ (based on the molecular weights, which are 100.09 for $CaCO_3$ and 84.32 for $MgCO_3$). The calcium carbonate equivalent of this ledge of limestones is: CCE = percent $CaCO_3$ + (1.19 X percent $MgCO_3$) or CCE = 78.3 + (1.19 X 13.2) = 94.0.

(2) It must contain all the fine particles obtained in the grinding process and be ground fine enough for no less than 25 percent to pass through a U.S. Standard No. 60 sieve (0.25 mm) and 80 percent through a U.S. Standard No. 8 sieve (2.38 mm).

(3) Either the CCE or the percentage passing through a U.S. Standard No. 8 sieve or both must be greater than the minimum, so that the product of the two equals or exceeds 7200.

The cost that the federal government will share is different in different counties in Indiana, but in 1970 it ranged from $1.30 to $3.40 per ton. The difference in cost support is directly related to the average distance in a county to the nearest vendor of agricultural limestone. Thus, as compensation for transportation costs, counties far away from a producer of agricultural limestone receive larger amounts of assistance than do counties that have limestone production.

The neutralizing value of agricultural limestone is usually expressed in terms of calcium carbonate equivalent, with pure calcite ($CaCO_3$) having a value of 100. Pure dolomite ($CaCO_3 \cdot MgCO_3$) has a theoretical CCE of 108.6; that is, it is 8.6 percent more effective than pure limestone as a neutralizer. As an example, the average CCE of four limestone units is computed in table 10.
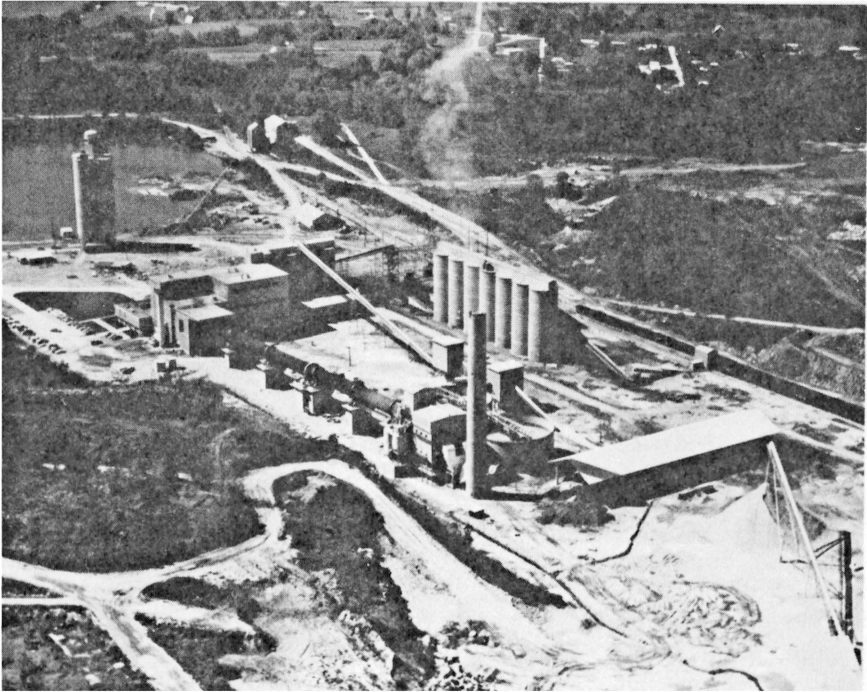
Figure 12. Lone Star Cement Co. plant near Greencastle, Ind.

CEMENT

Portland cement is a complex mixture of calcium-aluminum-iron silicates that hydrate to form a rocklike material. In addition to calcium carbonate, some limestone contains the proper proportion of aluminum, silicon, and iron oxides (not necessarily as oxides) to form a natural cement when calcined. Most portland cement is manufactured by heating a mixture composed dominantly of limestone and shale in a rotary kiln (fig. 12) until the CO_2 is driven off and the remaining materials combine into complex calcium-aluminum-

iron silicates. Because the proportions of calcium carbonate and other minerals in rocks are not constant, the limestone and shale mix may be supplemented by such things as aluminum dross, high-alumina clays, quartz sand, mill scale, and iron ore. Blast furnace slag may be used in place of both limestone and shale. Gypsum or anhydrite is added to retard the setting time of the finished product.

Limestone is the most critical raw material in determining the location of a cement plant, and most plants are built on or near a limestone deposit. That is not to say that attention is not paid to the location and composition of clay or shale deposits, but because clay and shale form a smaller part of the mix, are geologically more abundant, and are compositionally more likely to be acceptable, they do not determine the site of the plant.

Most limestone that contains less than 5 percent $MgCO_3$ (or less than 3 percent MgO if calculated as the oxide) is a suitable cement raw material. Occasionally limestone containing as much as 8 percent $MgCO_3$ (4 percent MgO) is acceptable if it is the limestone with the lowest magnesium content available. Thus a search for a suitable deposit of cement raw material is a search for a large deposit of low-magnesium limestone. The silica and alumina content of the limestone is of much less importance. Clay or other high-alumina material can be added to a pure limestone and high-calcium limestone can be added to an impure limestone to produce the proper mix. Other common but minor rock constituents, such as sodium, potassium, and sulfur, are rarely in such large amounts to be the major deterrent to cement production.

Dolomitic limestone unsuitable for manufacturing portland cement can generally be distinguished in the field by etching it with dilute acid. When etched, the dolomite rhombs stand out in relief, and the percentage of them can be calculated.

In Indiana, middle Mississippian limestones (especially in the Paoli, Ste. Genevieve, Salem, and Harrodsburg Limestones) and Devonian limestones are suitable for manufacturing cement.

FLUX STONE

Limestone and dolomite are used today in sizable amounts as fluxing agents, especially in the steel industry, although lime rather than limestone is used in the basic-oxygen process that is replacing the open-hearth method for making steel. The specifications for open-hearth or blast-furnace flux stone may vary from a high-calcium limestone to a high-purity dolomite, but generally the total calcium and magnesium carbonate content must exceed 95 percent (Boynton, 1966, p. 80).

As indicated in the discussion of specifications, the amount of silica that can be tolerated in limestone and dolomite used in blast furnaces is determined largely by economics. The function of the calcium carbonate is to combine with the silicate, aluminum, and other impurities in the iron ore to form a slag. If the limestone contains these same impurities, part of the calcium carbonate is used up in combining with its own impurities. The cost of using a larger amount of low-grade flux stone must be weighed against the possible higher cost of using better grade limestone. If the ore is very pure, some silica in the flux stone is desired because a slag cover must be maintained. If the slag is to be used for manufacturing cement, low-magnesium limestone is required.

The manufacture of steel from pig iron and scrap in open-hearth furnaces requires high-calcium limestone of higher quality than the stone used in smelting iron ore. The magnesium content, as well as the phosphorus and sulfur content, should be low. Specifications for open-hearth flux stone from a major steel company are given in table 11.

Table 11. Physical and chemical specifications for open-hearth flux stone used by a major steel company

Grade size	Minimum $CaCO_3$ (pct)	Maximum $MgCO_3$ (pct)	Maximum SiO_2 (pct)	Maximum S (pct)
1 in. to 3 in. - -	96.0	3.0	1.5	0.25

Indiana has large deposits of limestone and dolomite suitable for blast and basic-oxygen furnace flux. The limestone deposits, however, are far from the present markets.
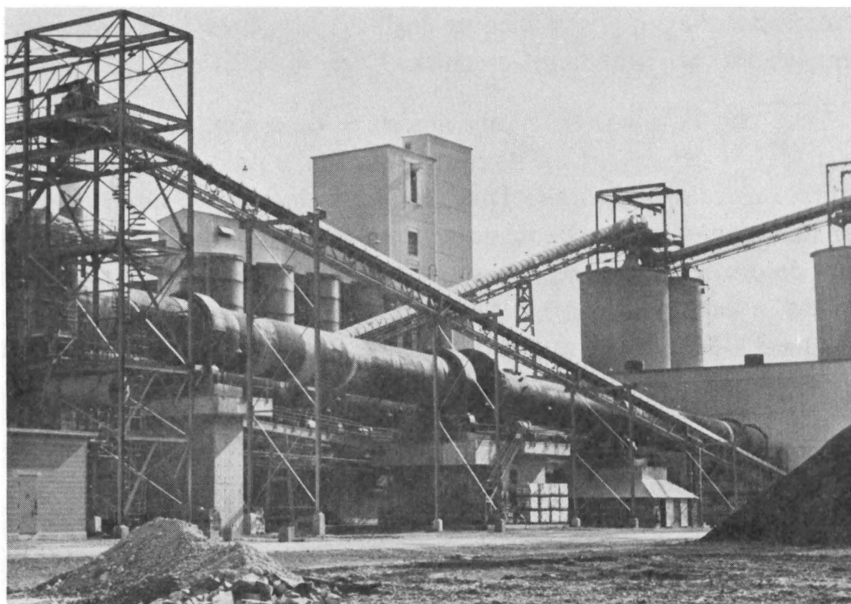
Figure 13. Rotary kilns at the Marblehead Lime Co. plant near Gary, Ind.

LIME

In terms of total consumption, lime is one of the world's most important chemicals because it is the most abundant low-cost alkali. The two major types are high-calcium lime and dolomitic lime. They are manufactured through the heating or calcination of limestone or dolomite in various horizontal or vertical kilns (fig. 13). Carbon dioxide is driven off, and calcium and magnesium oxides, a product called quicklime that reacts slowly with CO_2 to revert to a carbonate but quickly with water to form hydrated lime, are left. Quicklime must be protected from air and moisture to prevent "air slaking." Much quicklime, however, is deliberately hydrated because hydrated lime is much more stable.

Lime has more than a hundred uses in the construction, chemical,

and metallurgical industries and is used in turn to manufacture such products as calcium carbide, insecticides, and bleaches. A major new use is as a flux in the manufacture of steel by the basic-oxygen method. For many uses, high-calcium lime and dolomitic lime are interchangeable, but much more high-calcium lime than dolomitic lime is used (Boynton and Gutschick, 1960, p. 512).

Lime can be made from any limestone or dolomite, but its total reactivity is dependent on its purity, and for certain uses it must not contain certain impurities. Thus, to meet all or most specifications for its many uses, lime is manufactured from high-purity limestones and dolomites. Because limestone is almost 50 percent CO_2 by weight, noncarbonate impurities are almost doubled when limestone is calcined. Most stone used for lime averages about 98 percent total carbonates (Boynton and Gutschick, 1960, p. 498).

Physical characteristics of carbonate rock used for lime are also important, although less so than chemical characteristics. Dolomite of uniform grain size calcines better than dolomite of nonuniform grain size. Soft limestones may not be desired in the kiln feed because they may produce fines while moving through the kiln. Limestones that decrepitate on burning also may produce excess fines not desired in the final product.

Lime was produced commercially from Indiana deposits in the early 1800's and continued until 1953, when the last plant stopped operations. Indiana has large deposits of carbonate rock suitable for producing lime (Rooney, 1970), but Indiana's deposits are not well suited with respect to water transportation and markets. Ohio has become the foremost producer of lime because the location of its kilns close to Lake Erie allows cheap transportation to practically all important midwestern markets.

RAILROAD BALLAST

Ballast must serve many functions: to drain water from ties; to provide a firm, even bearing for ties and distribute pressure from ties to roadbed; to provide drainage so as to avoid frost heaving; to provide

Table 12. Physical specifications for railroad ballast
[From American Railway Engineering Association, 1964, p. 2-3]

	Maximum percentage
Deleterious substances:	
Soft and friable pieces -	5
Material finer than 200 sieve - - - - - - - - - - - - - - - - - -	1
Clay lumps -	0.5
Abrasion: Loss in the Los Angeles abrasion test - - - - - - - - - -	40
Soundness: Loss after five cycles of sodium sulfate soundness test -	10

tie anchorage by full cribs; to prevent plant growth; and to allow surfacing and raising of track without disturbing the roadbed (Smith, 1956, p. 2). Grading of aggregate for railroad ballast is similar to that for road construction, although the American Railroad Engineering Association (1964, p. 3) has specific requirements for grading and for the quality of the stone (table 12). In Indiana, the limestone aggregates that pass class A State Highway Commission requirements have been found suitable for railroad ballast.

RIPRAP

Riprap consists of large angular blocks of limestone that may range from about 1 cubic foot (160 pounds) to about 250 cubic feet (20 tons) in size. Riprap is used principally to protect bridges, piers, dams, and other construction from abrasion by water. Although specifications may vary considerably, stone for use as riprap must be durable. The Indiana State Highway Commission requires that riprap pass a soundness test consisting of five cycles of sodium sulfate bath or 50 cycles of freezing and thawing. Any stone losing more than 25 percent of its initial volume through a No. 12 sieve after the test is considered unsuitable.

Probably the largest single use of riprap in Indiana occurred during 1967 and 1968 in the building of the Burns Harbor facility on Lake Michigan. About a half-million tons of dimension limestone blocks, ranging from 3 to 20 tons in size, were retrieved from the waste piles in the Salem Limestone quarries near Bloomington and Oolitic, Ind.

Large quantities of riprap from the Ste. Genevieve Limestone have recently been used by the U.S. Corps of Engineers in constructing the new locks on the Ohio River.

OTHER USES

DIMENSION LIMESTONE

According to Bowles (1960, p. 321), "dimension stone is...stone sold in blocks or slabs of specified shapes and usually of specified sizes, contrasted with crushed, broken and pulverized stone...." In our age of metals, plastic, and glass, dimension stone is somewhat archaic and its relative share of the market has been decreasing for decades. The consulting geologist will probably not be called on for his advice concerning dimension stone deposits except as a witness in the evaluation of an estate or in a condemnation suit. Stone is both an excellent and an abundant building material, however, and will always be used. It may even one day regain part of the market that it has lost.

The varieties of dimension limestone are many, and each producing locality holds its stone to be unique. All dimension limestone can be divided roughly into two types: stone that is massive enough to be cut to specified dimension, and stone that is used largely as it is quarried from the ground, one dimension being fixed by a parting along a bedding plane. The stone produced from the Salem Limestone in Monroe and Lawrence Counties, Ind. (fig. 14), is of the first type. The stone produced from Devonian and Silurian rocks in southeastern Indiana (fig. 15) is of the second type.

The geologic considerations of overburden are the same as those of a crushed stone quarry except that the greater value of dimension stone allows more money to be spent uncovering a given thickness of dimension stone. For most deposits, however, this advantage does not mean a greater thickness of overburden can be removed, because part of the overburden is generally rock unsuitable for dimension stone and is more expensive to remove than unconsolidated materials.

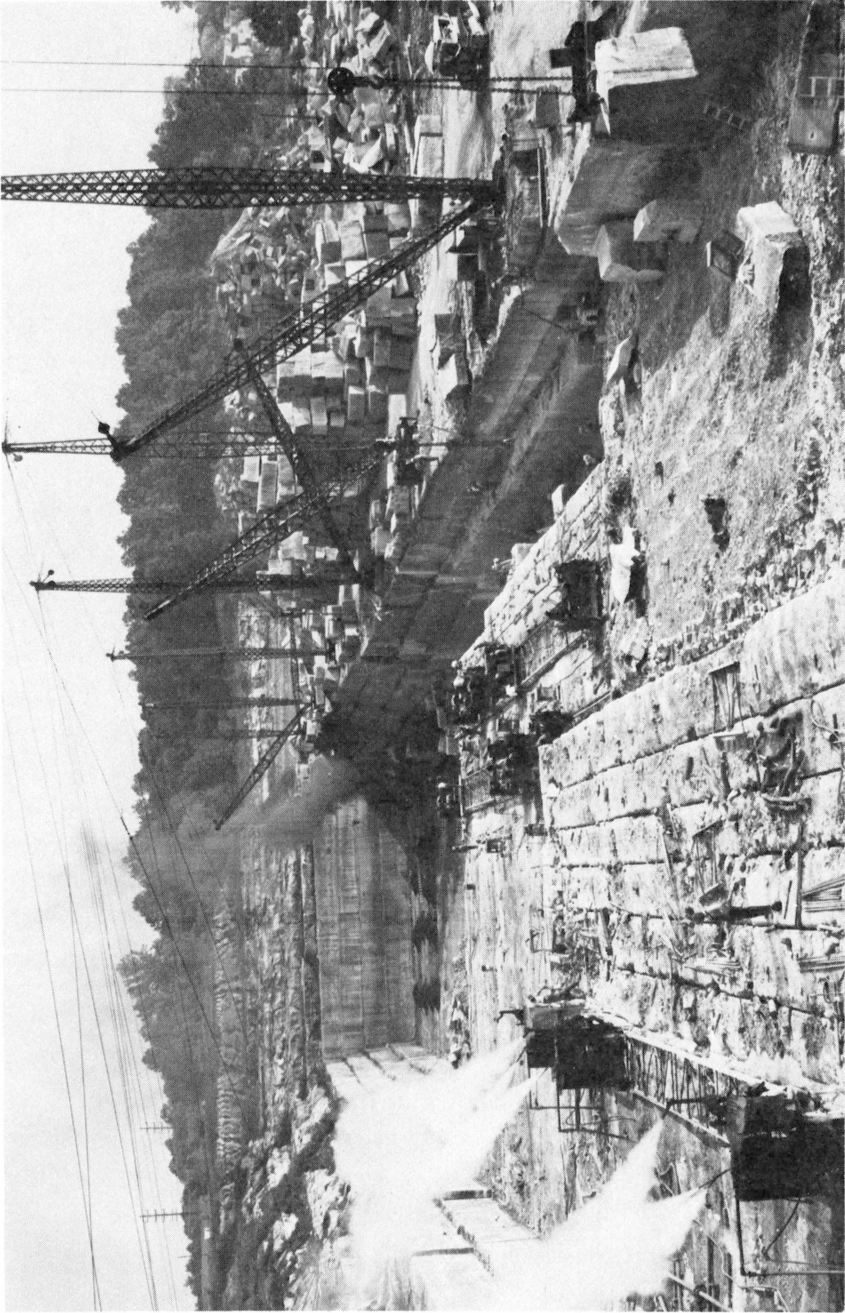Although the value of stone is partly determined by its color and

Figure 14. Dimension stone quarry in the Salem Limestone, Lawrence County, Ind.

Figure 15. Dimension stone quarry in Silurian rocks, Shelby County, Ind.

texture, probably the most significant factor, especially as it concerns the geologist, is what might be called the workability of the stone. If it can be quarried in large cohesive blocks that can be fabricated, transported, and installed economically without breaking, it is probably potential building stone of the first type. Some stone may be riddled by solution cavities, shattered by fractures, mineralized, or otherwise imperfect and therefore unusable. The biggest problem, however, and the most difficult to evaluate, is splitting along bedding planes. Some clay layers that cause splitting are readily visible, but some "dry seams" are almost invisible. It takes a fine eye to detect them in a quarry wall and a finer eye to detect them in a core.

Any sound carbonate rock that has bedding planes more than 1 inch apart can be considered potential building stone of the second type. Ironically, imperfect stone of the first or massive type is not likely to make stone of the second type, because the bedding planes

are too far apart. Formerly, stone of the second type was split apart by hand. Now it is ripped up by a fork mounted on front of a bulldozer or tractor.

AIR-POLLUTION CONTROL

Although not a single piece of limestone has been sold for this purpose in Indiana, the future market may be considerable because of the need to control air pollution. One cause of wide-scale air pollution is the burning of bituminous coal with high sulfur content in large power plants.

Numerous methods have been proposed for removing SO_2 gas from flue gases; however, the methods of most interest to crushed stone producers depend on the chemical reaction of SO_2 and limestone or dolomite. In one system, finely pulverized limestone is injected into the boiler furnace, where it is calcined into burned lime (CaO). The burned lime then reacts with the SO_2 in the flue gas to form calcium sulfate, a solid that can be collected along with the fly ash. In another system, called wet scrubbing, stack gases are passed through a wet slurry of lime or limestone. This system has some important advantages over the dry limestone system, including better efficiency for removing sulfur oxides, less potential interference with boiler operation, and generally lower operating cost for large power plants.

Chemical and physical specifications for crushed stone that is to be used in removing SO_2 gases have not yet been established; however, full-scale tests are now being conducted to determine optimum specifications for this purpose. Theoretically, it appears that a high-calcium limestone is more desirable than dolomite or magnesium limestone, because CaO reacts more efficiently than MgO with SO_2 gases (Battelle Memorial Institute, 1966, p. 32). A low sulfur content of course would be essential. In pilot studies, it has been found that limestones with high micron-range porosity, such as is found in chalks and some oolitic limestones, are most effective in reacting with SO_2 gases (Potter, 1969, p. 6-7). The ability of limestones to react with SO_2 gases appears to increase as the volume of pores greater than 1 micron in diameter increases and as the mean

grain size of the limestone decreases (Harvey, 1970, p. 28). Also, finely ground limestones, such as those with an average particle size of 0.0198 inch (28-35 Tyler mesh size), are more effective than more coarsely ground limestones in reacting with SO_2 gases because of the greater surface area of the fine particles per unit of volume (Harrington, Borgwardt, and Potter, 1968, p. 157-158).

In 1970, one of the first full-scale tests of the limestone injection process was begun at the Shawnee Power Plant of the Tennessee Valley Authority. A high-calcium Ste. Genevieve oolitic limestone from Kentucky is being used in this study, but similar oolitic limestones are abundant in Indiana and should work equally well. Also, high-calcium limestones of the Salem containing high micron-range porosities are abundant in central Indiana and should be effective in reacting with SO_2 gases.

Major Cost Variables

TRANSPORTATION

If a number of independent characteristics are essential to the value of a product, it is difficult to say which characteristic is most important. For most purposes to which limestone is put, however, location with regard to market is probably the most important variable. Cost of mining, except for thickness of overburden (discussed above), and cost of exploration are much the same within any given region. Costs imposed by zoning restrictions are so arbitrary that it is not possible to generalize on them. Quality of stone is important; in fact, it is essential. Shaly calcareous siltstone will not be used as concrete aggregate or the major cement raw material no matter how close to the market it may be. But limestone is so plentiful and its transportation relatively so costly that an inferior stone locally available is likely to be used rather than a superior stone shipped in by rail or barge.

Of course use is an important factor in determining how far limestone can be shipped economically. Ground white limestone used as a filler, say in toothpaste, could probably be transported thousands of miles without adding appreciably to the cost of the finished

product. High-calcium limestone used as a flux in open-hearth steel furnaces can bear transport more than 100 miles if none is available near the steel mill. Cement and lime plants are constructed generally, but not necessarily, at the raw material site. Limestone is shipped via the Great Lakes from northern Michigan to Gary, Ind., to supplement slag used in the Universal-Atlas cement plant and as the raw material for manufacturing lime.

Aggregate cannot be transported long distances economically, except under most unusual circumstances. Aggregate is carried as ballast in some ships and thus might travel thousands of miles. Limestone quarried on the fringe of a market area without limestone might bear long transportation, especially by water or rail. Limestone quarried on a waterway can be transported past producing areas that are not on a waterway but that are much closer to the market. Most limestone used as aggregate, however, is transported short distances and by truck.

A recent study of transportation of aggregate in Indiana has been made by Robert R. French (1969), and his generalizations probably hold true for the rest of the United States. He found that once trucks had replaced rail freight and horse-drawn wagons, most aggregate was hauled in trucks owned by the producing companies, later in trucks owned by the drivers, and now in trucks owned by large contract haulers. Because these contract haulers are required in Indiana to file their rates with the Public Service Commission, State Office Building, Indianapolis, he was able to estimate trucking costs, although actual rates may depart from the published rates. French (1969, p. 350) found that one hauler charged "...approximately 5 cents per ton-mile for the first 6 miles, 3 cents per ton-mile for the next 18 miles, and 2½ cents per ton-mile thereafter." He (1969, p. 351) also found that a haul of about 30 miles in rural areas would about double the cost of crushed rock, which averaged $1.27 per ton in Indiana, and that a haul of only about 9 or 10 miles might be required to double the cost in urban areas.

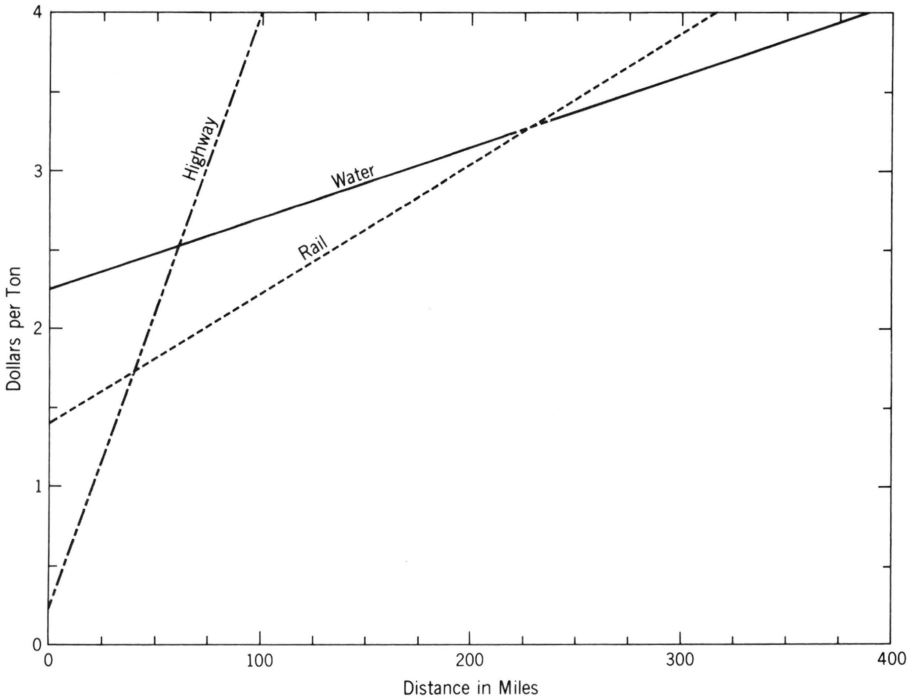Costs of transportation by rail are more difficult to predict.

Figure 16. Graph showing average tariffs for highway, rail, and water transport of mineral aggregates in Indiana. From French, 1969.

Because of the cost of loading and unloading, most stone shipped by rail is shipped long distances, and the railcars are likely to be switched from one line to another, a practice which results in additional costs. But if a quarry is on a railway line and stone is shipped directly to the market on that one line, the only additional cost is the rehandling at the market end. In addition, if a large amount of stone is shipped, say on a unit train, the cost can be low. If the stone is shipped in cars owned by the aggregate company, the cost may be even lower. French (1969, p. 352) found that the average charge for rail transport of aggregate in southern Indiana was 0.61 cents per ton-mile with a 99-cent-per-ton minimum, but in northern Indiana the charge was an average 0.92 cents per ton-mile with a $1.84-per-ton minimum.

Water transportation of limestone is by far the cheapest method, and limestone deposits near navigable waterways have much more value than other deposits. We have already cited the transportation

of limestone on the Great Lakes. Limestone also is transported on the Ohio River from Indiana as far as West Virginia. Loading and unloading barges and ships are expensive, but the cost per ton-mile is reduced by long hauls and large capacities. The rate for transporting aggregate on the Ohio River is reported to be about 0.4 cents per ton-mile. French (1969, p. 352) reported one rate of ".4 to .65 cents per ton-mile for minimum barge loads of 1,200 tons (plus 50-100 cents per ton for loading and 100-200 cents per ton for unloading)." A comparison of the costs of truck, rail, and water transportation is given in figure 16.

LAND

The cost of land can be an important variable but for many quarries is not. Because of their nature, new quarries are generally located on the fringe of populated areas. The typical quarry in the Midwest is on land purchased as farmland and, if possible, on the side of a hill having marginal agricultural value. Thus the cost per acre is not high. Assuming a deposit 100 feet thick, an acre of land would be underlain by about 350,000 tons of stone with a gross market value of about $450,000. The cost of producing that stone, exclusive of land cost, would probably be no more than $250,000 to $300,000. Even considering the fact that the quarrier must purchase large amounts of land on which he is paying taxes and obtaining no income, one can see that for most farmland a cost that probably is as much as a few hundred dollars per acre is not a major factor in the total cost of operating the plant.

In urban areas, however, where land may cost several thousand dollars per acre, the investment required is so high that small operators may not be able to afford it. At $5,000 per acre, for example, taxes and interest on an investment of 100 acres could amount to more than $50,000 per year. Even so, the cost of the land over the life of a large deposit is a small part of the total cost and is a subordinate consideration to the location of the land with regard to market and transportation routes.

ROYALTY

We have not made a systematic survey of the ownership of limestone quarries or mines, but we are confident that the mineral producers own most of the land being quarried, mostly by open-pit methods, and pay royalty as an exception rather than as a rule. Mineral producers in general are more likely to pay royalty on limestone mined underground where the surface can continue to be farmed or used for some other purpose.

Information on royalty amounts and terms is hard to come by. But this information is of such interest to the geologist, the mineral producer, and the landowner that we feel justified in listing the figures that have been given us, although we caution the reader that the figures are not necessarily representative. Royalty figures of 20 years ago, however, are likely to be valid today, because the average value of limestone has risen only slightly.

Stone of exceptional quality located close to market areas or on major waterways commands or should be able to command higher royalty than stone far from market or major transportation arteries. A geologist employed by a railway informed us that royalty on sand and gravel is as high as 25 cents per ton in the Washington, D.C., area. The royalty on limestone should be as high. In Indiana, however, most of the producers that we interviewed said that 5 cents per ton was typical, regardless of the location of the quarry with regard to markets. But, as stated above, so few producers in Indiana pay royalty that the concept probably has not been tested. One Indiana producer was paying 6 cents per ton for stone quarried in a relatively unpopulated area, and one Kentucky operator reported that his company was paying royalty of 3 to 6 cents per ton.

Danner (1966, p. 29), writing of limestone deposits in the State of Washington, listed a range of 3 to 20 cents per ton. Evans and Eilertsen (1957, p. 3) reported that limestone is mined underground near Sunbright, Va., on "a royalty basis of 3 cents per ton usable material accepted for plant consumption, which is exclusive of fines rejected by screening and waste rock sorted in the mine and discarded on the surface dump."

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