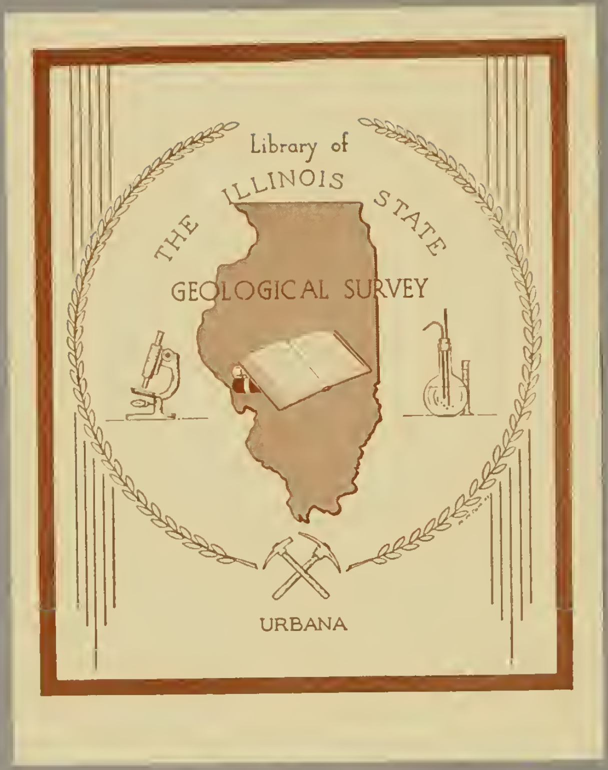

STATE OF ILLINOIS
DEPARTMENT OF REGISTRATION AND EDUCATION
A. M. SHELTON, *Director*

DIVISION OF THE
STATE GEOLOGICAL SURVEY
M. M. LEIGHTON, *Chief*

REPORT OF INVESTIGATIONS—NO. 12

LIMESTONE FOR SEWAGE FILTER BEDS

CAUSES OF DISINTEGRATION, DESIRABLE PROPERTIES, AND METHODS OF TESTING

BY

J. E. LAMAR

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INTRODUCTION

GENERAL STATEMENT

The matter of predetermining the suitability of a given limestone for use in sewage filter beds is one which is yearly coming to be of more interest to quarrymen and engineers of sanitation. This interest is linked with the growth of towns and cities, the consequent increase in the amount of sewage, and the endangering of public health by improper sewage disposal. As a result, the use of sprinkling and trickling filters has come to be of increasing interest. In a filter recently constructed for a town of 25,000 people, 650 carloads or about 13 trains of limestone were used. It is apparent, therefore, that the initial cost of such a quantity of stone is an important item to a municipality, and that an enduring stone is desirable not only because of initial cost but because of the cost of removing poor stone and replacing it with new material. The problem of sewage disposal during the time required for replacement of the filter stone is still another factor making this operation one to be assiduously avoided.

The study of limestones to determine their suitability as filter stone is new and still in the experimental stage. As yet, very few data are available which correlate laboratory tests and the actual life of the stone in the filter bed. The collection of such data should be the ultimate aim of research and investigation in this line. However, the processes operating to destroy the limestone and their action on the stone may be evaluated, and such tests as are at hand for determining the resistance of the stone to destructive agencies may be applied. Although the only real test of a filter stone is its behavior in the filter bed, the results of the laboratory tests give, at the present time, the most intelligent basis for judging the comparative merits of proposed filter stones.

The function of filter stone in a sewage filter is essentially that of a lodging place for bacteria which gather and grow upon the surface of the stone, and by their life processes effect a purification of the sewage.

ACKNOWLEDGMENTS

The author wishes to acknowledge with thanks the helpful criticisms and suggestions bearing on this paper, made by Dr. A. M. Buswell, Chief, Illinois State Water Survey, and Dr. M. M. Leighton, Chief, Illinois State Geological Survey.

CAUSES OF DISINTEGRATION OF FILTER STONE

The principal processes effecting the destruction of filter stone in sprinkling and trickling filters are mechanical disintegration and chemical disintegration. These two processes though they are doubtless greatly cooperative in their action, will be discussed separately, and their combined activity will be taken up in a subsequent statement. Although their destructive effect is slow,—not to be measured in single years—yet ultimately and in the aggregate these processes do produce a greater or lesser destruction of limestone filter media.

Mechanical Disintegration

FREEZING AND THAWING

The most important process producing mechanical disintegration is freezing and thawing. The destructive effect of this process depends on the number of times it is repeated which in turn is related to the climate and to the operation of the filter bed. During the winter months filters may be operated continuously, or only during the daytime, to treat the more concentrated sewage, or, if the dilution is sufficient, the sewage may be by-passed entirely. In continuous operation in a moderate climate a certain amount of ice forms usually in wide circles around the nozzles of the sprinkler and at the surface of the filter bed. The temperature of the sewage and the biological action are usually sufficient to prevent frost from entering to any considerable depth.

Under severe conditions, such as a sudden cold wave accompanied by wind, the entire bed may become covered with ice. Under these conditions a given portion of the bed may freeze and thaw four or five times during the winter.

In filters in which only the strong day sewage is treated and the night sewage is by-passed, the exposed portion of the bed may freeze at night and thaw again when treated with the warm sewage so that freezing and thawing under certain weather conditions might occur daily, thus affecting the filter stone more severely.

Filters which are not operated during the winter months, should be shut down in time to avoid the earliest probable freezing temperature, so that they may drain completely and dry out.

Freezing and thawing disrupts a stone principally by reason of the fact that when water changes to ice it expands about 1/10 its volume. Therefore, if a stone is saturated with water, and the water freezes, the stone will be disrupted unless it has sufficient strength to overcome the force of the expansion accompanying the change of water to ice in the sub-surface pores. In the surface pores the expansion accompanying freezing is probably partly accommodated in the open direction of the pore, but not always sufficiently to eliminate disruptive stresses completely. Though a stone may withstand the forces occasioned during the freezing of water in its pores and in pits or pockets on its surface for a number of repetitions of the process, it eventually gives way and fractures or chips. Inasmuch as there is inherently less resistance to breakage in the surface portions of a stone, other things being equal, the common effect of freezing and thawing is a chipping or scaling off of the surface.

HEATING AND COOLING

Although not nearly so important as freezing and thawing, the expansion and contraction of the stone in a filter bed, as the result of heating by the sun's rays in the summer and subsequent cooling by dousing with sewage, is doubtless a contributory factor in the destruction of filter stone. The effect on the stone would probably be to cause it to chip or spall.

PHYSICAL FACTORS INFLUENCING THE RATE OF MECHANICAL DISINTEGRATION

POROSITY

The pores of a stone which can be penetrated by a liquid must have a connection with the surface of the rock and therefore the amount of water a stone can absorb is related to the volume of the connected pore space it possesses. This porosity is an important factor governing the effectiveness of freezing and thawing in destroying the stone. The distribution and size of the connected pores is also important in this regard. For example two stones may have the same porosity, the first with evenly distributed small pores, and the second with but a few large pores concentrated in a given zone; the second would fracture more quickly than the first, other things being equal, because of the concentration and localization of the stresses set up in the few larger pores of the stone by repeated freezing and thawing.

TEXTURE

Limestones in general may be grouped into three main classes according to their texture as apparent to the naked eye, namely, crystalline, non-crystalline or dense, and granular. There are some limestone formations which fall definitely into one of these three classes, but in general limestones have such a variety of texture that any two or even all of the above classes may be embodied in one formation. The terms are of value, however, in expressing the relative importance of the three textural divisions for purposes of discussion. There is a definite relation between the physical structure of filter stone and its resistance to disruption, for the strength of a crystalline limestone depends on the degree of interlocking of the crystals or, if the stone is granular, on the completeness of the bonding of the granular material. A stone which appears crystalline to the eye is likely to have well-interlocked grains. A stone which appears non-crystalline may or may not have well-interlocked crystals. All limestones when examined microscopically under sufficiently high magnification are seen to be composed, to a greater or lesser extent, of crystals of calcite; if the stone is a dolomite, the crystals are calcite and dolomite. Therefore, some limestones, non-crystalline to the eye, are simply so fine grained that the individual crystals are not megascopically recognizable. In many limestones appearing to the eye either crystalline or non-crystalline, though more frequently the latter, clay is present in varying amounts. This clay, in general, lessens the strength of the stone because it interrupts the interlocking of grains or coats them at the planes of contact. In some rocks the clay is segregated in zones or thin bands through the stone which often constitute planes of weakness. In the case of siliceous limestones, crystals of silica, either localized or evenly disseminated through the stone, will be found interlocking with or replacing the calcite crystals.

In granular limestones composed of fossils, fossil debris, oolite grains, or calcareous debris of any sort, the strength of the stone depends to a large degree on the completeness of the bond effected between the granular material and the matrix and on the strength of the bonding substance. In many limestones the bond is very good; in others a thin film of organic material surrounds many of the granules or fossils and consequently interrupts the continuity of the bond.

BEDDED OR LAMINATED STRUCTURE

Some limestones possess a distinct bedded or laminated structure which exerts an important influence on the ability of the stone to resist disintegration. The bedded structure is not the gross feature of bedding but rather minor, abrupt variations in the texture of the granular or detrital materials composing the stone within a larger bed. The laminated structure is not generally visible to the eye in fresh specimens, but is usually revealed during the accelerated soundness test by a flaking or splitting of the stone into thin sheets or laminae. Inasmuch as the contacts of texturally unlike sedimentary materials are often planes of weak, partly or wholly interrupted bond, a stone having a bedded or laminated structure should be thoroughly tested before it is accepted as filter stone.

Chemical Disintegration

SOLUTION

As long as a sprinkling filter is in operation, all of the stone in the filter bed is being repeatedly doused with the effluent from the settling tanks. In ordinary domestic sewage this effluent is largely water, but it contains carbonic acid and possibly a number of fatty acids. Although both are in very dilute solution they doubtless dissolve a relatively small but still appreciable portion of the filter limestone in a period of years. Furthermore, the bacteria growing on the stone produce carbon dioxide which forms carbonic acid. There is some question, however, as to whether the net effect of the coating of bacterial jelly is not more protective than injurious as regards solution of the filter stone.

Considering the effect of solution on limestones and dolomites, it is noteworthy that dolomites, though *more soluble* than limestones, are *less rapidly soluble*. The rate of solution is of importance because the movement of the water through the filter bed defeats any chance of saturation of the dissolving medium, thus nullifying the effect of differences in solubility, and facilitates the solution of the more rapidly soluble substance. The rate of solution of a stone, however, is influenced by an additional factor, namely, the area of surface exposed to the solvent. The larger the area the greater the potential rate of solution. In general, dolomite, as a result of the manner of its formation, is more porous than limestone, and consequently exposes a greater surface to the solvent than limestone. This tends to and may practically equalize in the net result the difference between the two rocks in rates of solution.

If a piece of limestone or dolomite with a plane surface is immersed in hydrochloric acid for a brief time, it will be found that certain parts of the stone have dissolved more rapidly than others (figs. 1-5, pp. 18-21). In some stones, the fossils, fossil debris, vein fillings, and the like dissolve the more rapidly and in others, the matrix. In still others the effect of the solution is about equal over the area exposed. If the stone is very pure, solution will leave a surface nearly similar to the original one; if, however, the stone is an argillaceous or siliceous limestone or dolomite, a protective residual coat will remain. If the residual coating is firm and hard, it is an asset in hindering further solution. The effect of selective solution on any given portion of the stone is to increase the surface porosity. As a result additional surface is made available to the action of the solvent, and the opportunities for mechanical disintegration are increased. The matter of selective solution is thought to be the crux of the potential destructive effects of solution on filter stone. A stone of even texture and uniform solubility would apparently be desirable to offset the effects of solution.

OXIDATION

Because of the frequent wettings and complete or partial dryings to which filter stone is subjected, the process of oxidation is greatly facilitated. Substances which oxidize are, therefore, to be consistently avoided. Probably the worst offenders in this class are pyrite and marcasite, both sulphides of iron. These oxidize to limonite, the hydrated oxide of iron, which occupies more volume than either of the sulphides. As a consequence, oxidation of either of the sulphides to limonite is accompanied by forces tending to disrupt or weaken a stone if they cannot be accommodated by free outward expansion as in surface pores.

HYDRATION

It is possible that some limestones contain clay minerals along bedding planes, or less probably in a disseminated state, which absorb water as a result of the constant wetting to which they are subjected, with an accompanying increase in volume. This increase would have the same general effect as that resulting from the change of pyrite into limonite.

Cooperative Effect of Mechanical and Chemical Disintegration

As previously stated, it is very difficult to divorce and identify singly the effects of mechanical and chemical disintegration, respectively, on a filter stone. Mechanical disintegration increases the surface area available for the agents of chemical disintegration. Chemical disintegration, in turn, if it is selective, results in an increase of porosity and favors further mechanical disintegration. Without doubt the upper foot of the filter bed is the zone of maximum effect of combined mechanical and chemical disintegration. It seems likely, also, that the basal two or three feet of a filter bed are the most favorable for chemical disintegration not excepting the process of oxidation.

PROPERTIES DESIRABLE IN FILTER STONE

From the foregoing discussion of the agencies causing the destruction of filter stone, the following properties seem desirable in filter stone:

(1) The stone should have a minimum volume of pore space connected with the surface.

(2) The pores of the stone should be small and evenly distributed.

(3) The stone should consist of well-interlocked crystals or if it is granular, the grains should be firmly bonded by a strong cement.

(4) The stone should be of uniform solubility.

(5) The stone should be free from minerals which oxidize or hydrate. Pyrite and marcasite especially are to be avoided.

(6) The stone should have a sufficiently rough surface to furnish anchorage for the bacteria which are to grow upon it.

(7) The stone should be comparatively pure chemically. Stones with high clay contents are generally to be avoided. A high siliceous content is probably not harmful if the silica occurs in fine crystals evenly disseminated.

(8) The stone as delivered to the filtering plant should be free from dirt or fine rock particles which might collect in and clog the basal portion of the filter bed.

TESTING OF LIMESTONE AND DOLOMITE FILTER STONE

Certain tests may be made on limestones and dolomites which individually indicate the relative value of specific properties of a stone. It is impossible, however, exactly to duplicate conditions in nature and at the same time accelerate in a laboratory the combined effects of mechanical and chemical disintegration. Therefore, the results of any set of tests are indicative rather than absolute. Nevertheless, as such they serve a purpose. The following series of tests, though doubtless not in their ultimate form, appear to give valuable data concerning filter stones and will serve, as well, as a basis for devising improved tests.

Tests for Hardness, Toughness and Wear

It is natural in developing a new set of tests for a certain material, to turn to known tests and attempt to adapt them to the work at hand. In an endeavor to find adequate tests for filter stone, engineers have turned to the tests made on limestone highway aggregates, and accordingly have employed the toughness test, the Dorry hardness test, the Deval abrasion test and the accelerated soundness test. Considering the first three tests as a whole, they indicate the resistance of rock to repeated impact and to wear and abrasion. Inasmuch as it does not seem probable that impact, wear, or abrasion plays any important part in the destruction of filter stone, it would appear that these tests might be dispensed with. However, since the results of the hardness, toughness and wear tests and the percentage of water absorbed are in most cases the only data available from the numerous tests of various stones for aggregate, these data may give clues as to range and character of the regional variations in a given limestone formation. For example, Table 1 gives data on the variation in the physical properties of the Niagaran dolomite in the three principal areas in which it is quarried in Illinois. From the table it appears that the stone from district No. 1 is likely to be more variable than the stone from districts Nos. 2 and 3 and consequently stone from that district should be more carefully and frequently sampled than stone from the other two districts.

Regarding the physical tests shown in Table 1, only the water absorption, discussed later, is individually significant. Although it may be said that rocks satisfactorily passing the above mentioned tests from the standpoint of highway material will probably pass the accelerated soundness test, there are known to be exceptions which make it highly desirable that the soundness test itself be applied. This test, if applied, practically eliminates the need of hardness, toughness and wear tests for filter stone.

TABLE 1.—*Variations in physical tests of Niagaran dolomite*

District	No. of samples	Water absorbed Lbs. per cu. ft.			French coefficient			Hardness			Toughness		
		Max.	Min.	Variation	Max.	Min.	Variation	Max.	Min.	Variation	Max.	Min.	Variation
No. 1	21	4.89	0.76	4.13	12.5	3.9	8.6	18.1	12.9	5.2	13	5	8
No. 2	24	4.98	1.39	3.59	10.8	5.6	4.2	15.3	9.0	6.3	10	4	6
No. 3	34	3.50	0.56	2.94	10.8	5.9	4.9	16.0	11.3	4.7	11	4	7

ACCELERATED SOUNDNESS TEST

The accelerated soundness test, also known as Brard's test or as the quick weathering or sodium sulphate test, consists of immersing a representative sample consisting of pieces of two-inch stone in a saturated solution of sodium sulphate for 20 hours and then drying it at a temperature of 100° C. for 4 hours. The process is repeated 5 times in testing highway aggregate, and the stone showing no disintegration is considered satisfactory aggregate. Stone which fails under this test is considered as doubtful until other tests prove or disprove its value.

The theory of this test is that the saturated sodium sulphate solution penetrates the pores of the stone during immersion. When the stone is dried, water is driven off and the sodium sulphate crystallizes and the growing crystals set up stresses within the stone. The process simulates in net effect, therefore, the action of the freezing of water in the pores of a stone. The crystallization of the sodium sulphate in the pores of the stone, however, appears to exert a greater destructive force than does the crystallization of water, and as a consequence the test is much more severe than normal freezing. Experiment has shown that sodium sulphate crystallizes in three different forms and consequently may not always give comparable results. Sodium chloride is therefore suggested as a substitute of similar action as it crystallizes in one form only.[1]

This test should be of great value in testing filter stone, inasmuch as it simulates natural mechanical disintegration and depends for its effects on essentially the same factors. The amount, distribution, and character of the porosity are involved, as are also matters of bond strength, and crystal interlocking. Since filter stone is subjected to more severe conditions of mechanical disintegration than is ordinary concrete aggregate, it should certainly be required to pass a minimum of five repetitions of the soundness test. The stone not passing this test should be regarded with suspicion.

The U. S. Bureau of Standards which has been making studies of weathering tests, states that the effect of one crystallization with sodium chloride is equivalent to about eight water freezings.[2] Sodium sulphate is at least equally severe in its action. There is, however, considerable variation of the ratio in different types of stone. The studies of the Bureau of Standards have been confined largely to limestones and sandstones and, to date, indicate a general average of about 1,000 freezings to produce disintegration, though some specimens have shown no disintegration after 2,000 freezings. These results suggest that with a correlative value of 1 to 8 for sodium chloride and water crystallizations, the ultimate strength of many

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[1] Kessler, D. W., Stone, vol. 46, No. 6, pp. 351-353, June, 1925.

[2] Idem.

limestones would not be reached with less than 100 repetitions of the soundness test. Possibly the best method of application of this test is to continue treatment of a representative sample of 50 or 100 pieces of stone till all show failure. As the respective fragments fail, they could be removed and the number of immersions and dryings recorded. When all pieces had failed, an average could be struck by multiplying the number of pieces failing by the number of immersions and dryings withstood without failure by each, totalling the product and dividing by the number of pieces used. This would give the number of immersions and dryings necessary to disrupt an average fragment of the entire sample. The stone having the highest average number would theoretically be the best. For example, hypothetically, of two samples failing as shown in Table 2, sample No. 2 would be the better stone.

TABLE 2.—*Hypothetical accelerated soundness tests*

Sample No. 1			Sample No. 2		
No. immersions and dryings	No. pieces failing	Product	No. immersions and dryings	No. pieces failing	Product
11	4	44	10	6	60
15	7	105	12	6	72
20	12	240	15	8	120
21	19	399	20	10	200
22	20	440	26	12	312
24	17	408	27	12	324
28	11	308	28	28	784
31	8	248	31	16	496
48	2	96	42	1	42
			44	1	44
	100	100)2,288		100	100)2,454
		Av. 22.88			Av. 24.54

It is highly desirable that, in conjunction with this accelerated soundness test, the resistance of the stone to weathering in the natural outcrop be also considered. It is generally possible to find outcrops of a given stone near a given quarry which have been exposed to the weather for many years. From these outcrops many points of interest may be gathered concerning how the stone is likely to weather. The loose material at the base of a cliff is likely to yield the most valuable data.

Freezing Test

The freezing test, consisting of alternately freezing and thawing water-saturated specimens, is preferred by some for determining the weather resistance of a stone. It is a slower and more tedious process than the accelerated soundness test, and requires much more apparatus. It is somewhat doubtful if the greater accuracy claimed for this test compared with the accelerated soundness test warrants the extra time and equipment required in testing material like filter stone which is to be subjected to extremes of mechanical disintegration.

Water Absorption Test

This test is designed to measure the volume of connected pore space by determining the amount of water absorbed by a stone in 24 hours. A representative sample of about 1000 grams is dried at 100° C. to 110° C. to a constant weight, and its weight carefully determined. It is then immersed in water for 24 hours, removed, surface dried, and reweighed. The amount of water absorbed divided by the weight before absorption multiplied by 100 gives the percentage of absorption. This test is of great value as supplementary to the soundness test.

Microscopic Examination

It is often possible by microscopically studying thin sections of the typical phases of a limestone, to predict the general results of the soundness test and possibly eliminate a large amount of labor. Such examination reveals the size of the crystals and the condition of crystal interlock or, if the stone is granular, the character of the granules and the bond. Minute clay partings, grains of pyrite or other foreign minerals, and the distribution and size of the pores are also revealed. Hirschwald has proposed a classification[3] of limestones and dolomites, repeated by Howell[4] which divides these rocks into 24 different groups, into one of which almost every limestone may be placed. This classification may be used to standardize terms descriptive of texture, but the interpretation of the phenomena shown in a thin section depends chiefly on the skill of the examiner and his knowledge of applied sedimentary petrology.

Solution Tests

ETCHING

Under the discussion of chemical disintegration, the various effects produced by selective solution have been pointed out. In order to determine how a limestone or dolomite will dissolve, a number of representative pieces

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[3] Hirschwald, J., Handbuch der Bautechnischen Gesteinsprüfung, Berlin, 1912.

[4] Howell, J. V., Notes on the pre-Permian Paleozoics of the Wichita Mountain area: Am. Assoc. Pet. Geol. Bull., vol. 6, No. 5, pp. 412-425, 1922.

of stone should be ground so that each piece will have one flat surface. The pieces should be selected so that the flat surfaces constitute sections parallel to and at right angles to the bedding. These pieces should be set with the flat surfaces up and parallel to the bottom of a shallow dish, to prevent the production of irregularities by carbon dioxide currents, and then covered with a 10 per cent solution of hydrochloric acid. The etching action of the acid should be allowed to proceed until its effect is clearly apparent on the smoothed surface. The distribution and character of argillaceous and siliceous materials, partings, sand grains, and pyrite are usually revealed after etching (figs. 1-5, pp. 18-21). The stone showing the minimum of undesirable impurities and the minimum development of porosity, or, otherwise stated, the most even solution, is likely to be the more desirable, other things being equal.

RATE OF SOLUTION

The only truly satisfactory method for determining the rate of solution of filter stones is to subject a representative and carefully weighed sample to continual dousing with sewage water for a period of weeks and then to clean it thoroughly and weigh it. This process often takes too long to be of service where an immediate report is necessary. Comparisons may be made of limestones as a group, and similarly by dolomites, by cutting cubes of stone of the same size, weighing them, and immersing them in very dilute hydrochloric acid for a given time. The loss of weight gives a basis for calculating the amount which has dissolved. No tests have been developed for determining the relative rates of solution of limestone and dolomite in cold dilute hydrochloric acid, in which limestone is more rapidly soluble than dolomite.

Studies of Residue

About 100 grams of stone as representative of the deposit as possible, crushed to pass a 10-mesh sieve and be retained on a 20-mesh sieve, is treated with hydrochloric acid until effervescence ceases. The residue is collected on a filter paper, washed free from acid, dried and weighed. The relative proportions of such materials as clay, silt or sand, are recorded as well as other items of interest concerning the presence of secondary silica, chert or flint and mineral grains. The presence of pyrite or marcasite is readily determined in this test. It is indicated in the chemical analysis as iron and sulphur, but such an analysis does not differentiate between iron present as the hydroxide and sulphur present in compounds other than iron sulphide.

Chemical Analysis

A chemical analysis showing the percentages of the following compounds in limestones and dolomites is important because it indicates the general composition of the rock for filter stone: calcium carbonate, magnesium carbonate, iron oxide, alumina, silica, and sulphur. These compounds are involved in a consideration of the resistance of a stone to disintegration. It is recommended that these tests be made in accordance with the procedure outlined by Hillebrand for the analysis of carbonate rocks.[5]

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[5] Hillebrand, W. F., The analysis of silicate and carbonate rocks: U. S. Geol. Survey Bull. 700, 1919.

Figures 1-5 show the effect on different types of limestones of etching for the same time period and with the same acid concentration.

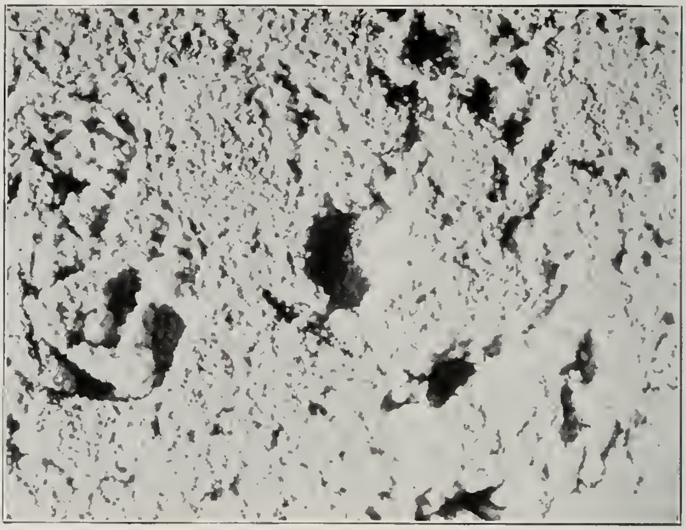

FIG. 1. Niagaran dolomite. Maximum surface relief about 1 mm. The etching has enlarged the surface pores and has left the specimen coated with fine dolomite crystals which may be easily brushed off. The effect of surface etching or solution of the calcium carbonate from dolomitic limestone is augmented by the consequent freeing of dolomite grains; hence the actual weight of dolomite disintegrated may in some cases be equal to or greater than the weight of limestone dissolved by simple solution under identical conditions. This specimen chipped slightly after 8 repetitions of the soundness test, but thereafter remained intact through the remainder of 20 repetitions. (Magnification six times.)

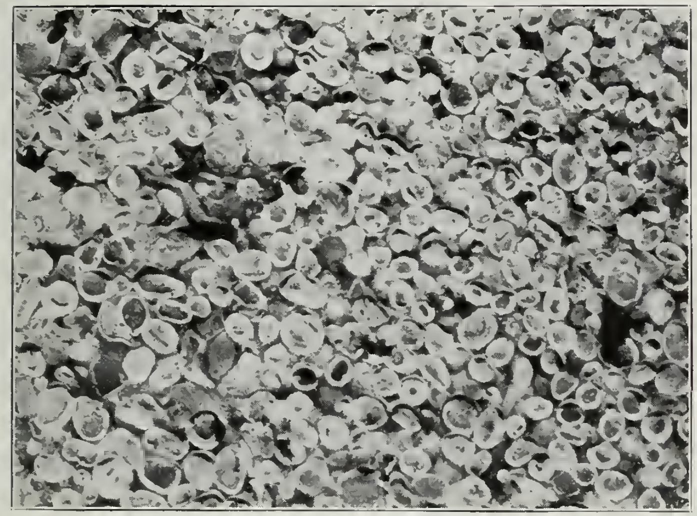

FIG. 2. Ste. Genevieve oolitic limestone. Surface relief about 0.2 mm. The etching has affected the stone very evenly but was slightly more pronounced on the white outer portions of the oolite grains. Near the center of the right margin of the illustration, a hexagonal quartz grain which is the center of an oolite grain projects above the general level of the surface and casts a pronounced shadow. That this specimen showed no disintegration after 20 repetitions of the soundness test indicates a good bonding of the granular material of the limestone. (Magnification six times.)

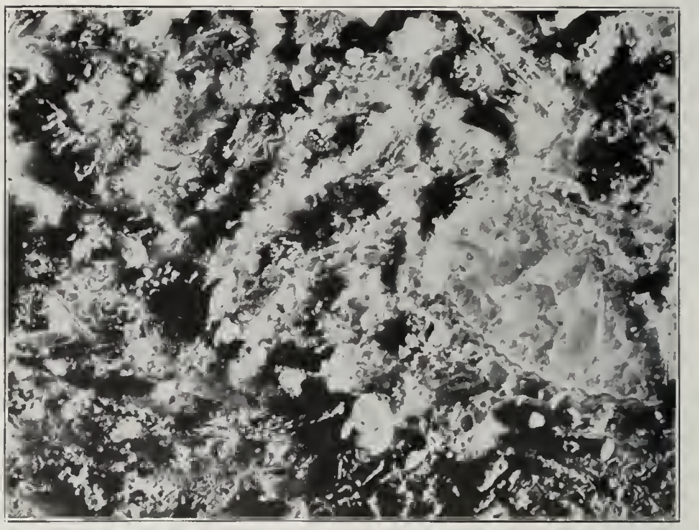

Fig. 3. Chester limestone. Maximum surface relief about 1 mm. This is a very pure limestone composed of fossil debris bonded by calcium carbonate. Etching has dissolved the calcium carbonate and left the fossil debris projecting from the general level of the surface. At the right of the picture is a brachiopod which has been filled with calcite. After 16 repetitions of the soundness test this specimen broke into three pieses along a large fossil. There was no breakage during the four subsequent repetitions of the test. The resistance of this specimen to the soundness test is evidence that in general it is well bonded. (Magnification six times.)

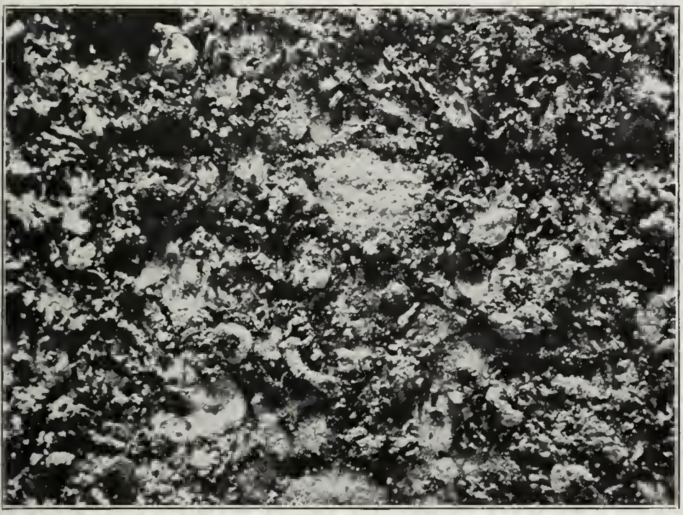

Fig. 4. Chester limestone. Maximum surface relief about 1 mm. Etching has removed the calcium carbonate cement and left the clayey, siliceous impurities of the stone as projections above the general surface. Disintegration of this specimen began after 4 repetitions of the soundness test, and complete failure resulted after 8 repetitions. The disintegration of the stone into a coarse sand showed that the bonding material was weak. (Magnification six times.)

Fig. 5. Pennsylvanian limestone. Maximum surface relief about 1½ mm. This is a siliceous limestone containing fossils composed of calcium carbonate. These were dissolved during the etching and gave rise to the linear depressions. After 6 repetitions of the soundness test this specimen began to chip and split along the surfaces of fossils. After 11 repetitions, disintegration of the entire specimen was complete. This sample shows the type of results which may be expected in limestone with a localized porosity. (Magnification six times.)