Geologic Factors Related to Quality of Limestone Aggregates

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DETAILED petrographic studies of some Iowa limestone aggregates included the study of thin sections, insoluble residue analysis, determination of calcite-dolomite ratios, and identification of clay minerals by staining, differential thermal analysis, and X ray. Petrographic study of sound and distressed concrete was also included.

Insoluble residues range from about 1 percent to more than 10 percent, and we find no direct correlation between the amount and type of residues and the service record of the containing stone. The principal components of the residues are clays, pyrite, silt, and sand. The pyrite may be fresh or altered to limonite, the cherts are nonopaline, and the silt and sand are almost entirely quartz. The clays are mainly illitic but contain mixed-layer components and some kaolinite. Evidence for the presence of montmorillonite is not conclusive.

Specific gravity and absorption tests show that the fresh stone from the Ferguson, and Fort Dodge quarries have higher specific gravity and lower absorption than weathered stone from LeGrand. Stone from LeGrand shows an average specific gravity of about 2.5 and an average absorption of 3.5%. The absorption is higher in the lower cherty beds with maximum values in excess of 5%. The rock at Ferguson has an average specific gravity of 2.65 and an average absorption of 1.5%, for those at Fort Dodge the corresponding figures are 2.7 and 0.8%.

Correlation of petrographic characteristics with service records fail to reveal any explanation for the poor service record of the rocks at LeGrand. The study of concrete cores taken from satisfactory and from distressed pavements indicates that fresh stone gives satisfactory service, whereas, weathered stone produces distress.

Although the absorption capacity shown by the rocks at LeGrand may not, in itself, indicate unsatisfactory stone it is concluded that the increased absorption and other effects of weathering permit reactions between cement and aggregate which produce distress.

● THE application of petrology in the selection of concrete aggregates is becoming increasingly important, especially in areas where igneous rocks or mixed rock types comprise the major sources. The importance of petrology in the selection of limestone aggregates was stressed by Laughlin (1928). However, after twenty five years it remained necessary for Mather (1952) to write: "The problems encountered in efforts to explain the behavior of limestones, dolomites, and related rocks as concrete aggregate lie on the frontiers between the ignorance of the geologists and the ignorance of the engineers." A survey of the literature at this time indicates that these frontiers of ignorance in respect to limestones have remained essentially unchanged since 1928.

The first detailed studies of Iowa limestones by geologists at Iowa State College were started in 1948. One of the early studies that by Dorheim (1950) and (1951) was related to the quality of the stone for aggregate. Studies by Lawson (1951) and (1953) were mainly petrologic although to some extent stratigraphic. A little over three years ago the present study, supported by the Research Board of the Iowa State Highway Commission, was undertaken. Although this paper is primarily concerned with the results of the present study it will include data and pertinent results of the others.

THE PROBLEM

Rocks generally classed as limestone are of wide occurrence in Iowa. Over about three fourths of the state the quantity of available limestone is adequate for all purposes. In these areas the only real restriction on supply results from quality specifications. In the remaining quarter of the state both total quantity and the quantity of stone suitable for aggregate are low.

The experience of the State Highway Commission has shown that most of the Iowa limestones which pass the usual engineering tests for soundness will give good service records in pavement. One notable exception is the Mississippian limestones quarried at a number of places in the vicinity of LeGrand in Marshall County. Because these quarries are located near the center of the state and the stone passes the usual tests, the stone was for many years used extensively in pavement. Favorable transportation facilities made it possible to use the aggregate over a wide area, including areas with widely diverse subgrade environments and soil conditions. The behavior of the pavement made with this stone is also independent of the types of cement and of fine aggregate used. The Highway Commission is convinced that the distress shown by pavements containing LeGrand stone is produced by some inherent property of the limestone. The present study was designed to discover, if possible, the geologic factors which might account for the observed distress.

The rather uniformly poor service record of the LeGrand stone is not without certain exceptions. A few short sections of pavement containing stone from certain quarries or from selected beds have satisfactory service records.

The beds at LeGrand are usually referred to the Chapin and Hampton Formations which are mainly if not wholly Kinderhoodian, lowermost Mississippian, in age. The total thickness of the beds is just over 100 feet at a new quarry site near the village of Ferguson, whereas the maximum thickness exposed in any quarry near LeGrand is just over 60 feet.

The beds are highly variable in structure, texture, and mineral composition. In general it is possible to recognize four major units which from bottom to top are designated as follows. The "Basal" oolite or Chapin Formation, 12 to 15 feet thick. The Hampton formation consisting of a section of dolomites, dolomitic limestones and limestones containing numerous lenses and nodules of chert, the Maynes Creek member, 30–40 feet thick; a section free of visible chert and consisting of limestones, dolomitic limestones and dolomites, the Eagle City member, 30–35 feet thick; and an upper oolite, exposed only at the Ferguson quarry where it is 12 feet thick. The upper oolite may belong to the Eagle City member but its stratigraphic position is not certain.

Stone of Mississippian age but younger than the beds at LeGrand is produced at a number of other places in central and north-central Iowa. In order to provide for comparison with stones having good service records and contrasting lithologies we selected, in addition to the quarries near LeGrand, two quarries near Alden, a mine at Fort Dodge and a quarry at Iowa Falls. Stone from Alden has been widely used in pavement with excellent service; the stone from the mine at Fort Dodge, although not used extensively, has a good service record, whereas the stone from Iowa Falls does not pass engineering specifications and has not been used in pavement. Plans to include a quarry at Gilmore City were abandoned because at the time the field work was done a large part of the section was under water.

The rocks studied in the quarry at Iowa Falls are usually referred to as the Iowa Falls member of the Hampton Formation. This would mean that they would overlie the Eagle City member exposed in the quarries near LeGrand. The quarries at Alden are in beds designated as the Alden Formation and this is known to unconformably overlie the Iowa Falls member of the Hampton. The stratigraphic position of the beds in the mine at Fort Dodge is not certain. They are, however, known to be Mississippian and not greatly different in age from the others.

The selection of these sites enabled us to make some effort to observe the regional variation of the stratigraphic units involved and restricted the study to units of reasonably well known stratigraphic relations and of restricted range in geologic age.

SCOPE OF STUDY

Field Work

The field work comprised detailed description and sampling of the quarries selected for study and the examination of many additional quarries and natural exposures of the same beds throughout the region from LeGrand to Gilmore City.

For the selected quarries the field description included the identification of all observable changes in character; structure, texture, mineral composition, and fossil content. Samples were collected from each lithologic unit which could be differentiated from the beds above and below. In general this meant that samples were collected from each distinct bed observable in the quarry face and rarely were the samples more than five feet apart. One oriented sample was selected for thin sectioning and additional chips secured for use in obtaining insoluble residues.

Laboratory Analysis

The second and major phase of the study has been the laboratory analyses. This has included further megascopic description of the specimens, petrographic analysis of thin sections for data on texture and mineral composition, the determination of calcite-dolomite ratios, the differentiation of calcite types, and the analysis of insoluble residues. There was nothing unique in the megascopic or petrographic work except that all thin sections were cut normal to the bedding with known orientation with respect to top and bottom. The determination of calcite-dolomite ratios involved the development of a new technique using Versene under carefully controlled conditions. The details of this technique have been published by Weissmann and Diehl (1953). This method is more sensitive and convenient than the variation of the staining technique developed earlier by Lawson (1950). The analysis of the insoluble residues followed established procedures and included microscopic examination of the coarser material and the identification of the clay-minerals by the staining method supplemented by differential thermal analysis and X-Ray.

RESULTS

No attempt will be made to include the petrographic details here. Those who are interested may consult the unpublished theses by Weissmann (1953) and Schneider (1954), copies of which are on file at the Iowa State Highway Commission, and at the Library and the department of Geology at Iowa State College.

Those who are interested in the detailed lithology of the beds of the LeGrand area may consult the paper by Lawson (1951). This paper should be available to most readers who might be interested in such details. Similar analyses were made of rocks from other quarries near LeGrand as a part of this study but these did not produce any significant changes in the data.

Three sections in eastern Marshall County were selected for detailed study. These are the section near the village of Ferguson in the SW ¼ sec. 5, T. 82 N., R. 17 W. and two quarries near LeGrand. For the section at Ferguson we used a core obtained in 1951 during a program of prospecting for a quarry site. The quarry was opened shortly after the coring but the core was retained for our purposes because it represents a more complete section than any yet exposed in quarrying.

Two quarries in the vicinity of LeGrand were chosen in order to provide data on possible local variations. One of these, the Timber Creek quarry, SE ¼ sec. 8, T 83 N., R 17 W, was the source of aggregate mentioned above which has both good and poor service record. The section here correlates with a portion of the upper part of the section (Eagle City) at Ferguson. The second quarry is designated as the County Line Quarry located in NW ¼ sec. 29, T. 84 N., R 16 W. The section here consists of the upper parts of the cherty (Maynes Creek) beds and most of the overlying Eagle City member. These quarries, both abandoned at present, were chosen to provide a possible contrast between somewhat weathered beds and their corresponding units in the unweathered section at Ferguson. The Timber Creek quarry was of additional interest because of its erratic service record.

Petrography, LeGrand Area

The following is intended only as a summary of the petrographic data relating to the various sections studied. As the primary interest of this study is the rocks of the LeGrand area they will be discussed first followed by pertinent comparisons and contrasts of these rocks and those at the other localities.

Structure and Texture. The rocks in the LeGrand area show the usual structures characteristic of carbonate rocks. In general they are well bedded with a minimum of thin or platy bedding. Cross-bedding is to be observed especially in the crinoidal limestones and less commonly in other types. Beds of shale and continuous shale partings are absent although lenses of shale a few inches thick do occur locally. Stylolites are common and occur in all lithologic types. These are usually small and discontinuous and the associated clay seams are thin. The chert of the Maynes Creek member occurs in nodules and lenses so typical of Mississippian rocks. These are usually along bedding planes but may occur in the midst of a given bed. The chert is gray, some is banded. The contact of the chert is usually sharp but in some instances it is gradational.

The available textural terminology applied to carbonate rocks is not adequate to permit a meaningful description of these rocks. Textural relationships involve mainly the variety of genetic types of the mineral calcite and the associated dolomite in as much as the other minerals such as pyrite, quartz and others are minor accessories. Much effort was devoted to various attempts to devise a satisfactory terminology but without results worthy of publication at this time.

Those interested in this problem will find it discussed at some length in the theses cited above. The possible significance of texture with respect to aggregate quality will be discussed below.

Calcite-dolomite Ratios. The essential minerals of the carbonate rocks are calcite ($CaCO_3$) and dolomite ($CaMg\ (CO_3)_2$). The formulas should not be taken too literally as calcite may contain appreciable magnesium which proxies for the calcium in the structure and dolomite commonly contains ferrous iron which proxies for the magnesium. The rock names applied to the carbonate rocks seem to be both inadequate and confusing. In common practice all carbonate rocks are referred to as limestones but geologists prefer to divide them into two groups, limestone refers to those carbonate rocks in which the mineral calcite comprises more than 50 percent of the carbonate fraction, whereas the rock name dolomite refers to those in which the mineral dolomite predominates. The terminology suggested by Pettijohn (1949) p. 313 is commonly accepted. Table 1 is modified after Pettijohn.

TABLE 1
CARBONATE ROCK TERMINOLOGY

Type	% Calcite	% Dolomite
Limestone	95–100	0–5
Magnesian limestone	90–95	5–10
Dolomitic limestone	50–90	10–50
Calcitic dolomite	10–50	50–90
Dolomite	0–10	90–100

Because it is difficult if not impossible to determine the calcite-dolomite ratio with a precision of five percent we do not recognize the magnesian limestone category but combine it with limestones thus having a four-fold division.

The basal oolite (Chapin) consists essentially of pure calcite. The cherty section (Maynes Creek) consists, in order of abundance of calcitic dolomites, dolomitic limestones, dolomites, and limestones. About half of the beds assigned to the Eagle City member are limestones, the remainder consists of dolomite, calcitic dolomite, and highly dolomitic limestones.

The paper by Lawson (1951) figure 1 page 390, illustrates this relationship as well as one attempt to classify the types of calcite. The calcite-dolomite ratios determined by Lawson have not been significantly modified by more recent work.

Insoluble Residues. The total content of acid insolubles varies from less than one percent to more than 12 percent. The average of 73 determinations representing all lithologic types in the 91 feet of section cored at Ferguson is 2.73 percent. Nine samples contain less than 1.0 percent insoluble material whereas nine contain more than 5.0 and of these, four contain more than 10.0 percent.

There is a very good correlation of the amount of insoluble material with the calcite-dolomite ratio of the sample. Maximum insoluble content is invariably associated with high dolomite content whereas minimum values are found in rocks composed essentially of calcite. However, some of the beds high in dolomite content have only about the average content of insoluble residues.

The average insoluble content for 13 samples representing 22 feet of strata at Timber Creek is 2.65 percent. As only one sample contains less than 1.0 percent and only one exceeds 4.0 percent the average indicates that the total insolubles are uniformly distributed. Eighteen samples representing 37 feet of section at the County Line quarry show an average insoluble content of 1.91 percent. Nine samples are below 1.0 percent, three are above 4.0 percent and the maximum is 4.86 percent.

In both of these the correlation of high residues with higher dolomite content is apparent. The lower residue values at the County Line quarry are due to the abundance of limestone in that section.

After preparation, the insoluble residues which exceeded 2.0 percent of the sample were separated into two fractions by wet sieving. The finer fraction, <74 microns, was found by microscopic examination to be mainly clay, although silt, if any is included, and has been designated the clay-silt residue. The major components of the coarser fraction, >74 microns were determined microscopically. Table 2 gives the relative abundance of the two fractions in the residues from the the three localities in the LeGrand area. This illustrates the predominance of the clay-silt fraction in all residues which comprised more than 2.0 percent of the original sample.

TABLE 2
PERCENT SIZE FRACTIONS OF RESIDUES

Sample No.	Sand	Clay-Silt	Sample No.	Sand	Clay-Silt
F29.0[a]	32.5	67.5	F83.4	0.0	100.0
F30.7	36.2	63.8	F90.3	2.6	97.4
F35.3	4.9	95.1	F93.5	0.0	100.0
F35.5	4.4	95.6	F96.0	0.0	100.0
F36.2	3.0	97.0	F96.8	2.8	97.2
F36.9	1.3	98.7	F99.7	0.0	100.0
F39.0	1.5	98.5	F100.8	0.0	100.0
F40.3	12.9	97.1	F102.5	0.0	100.0
F43.8	8.8	91.2	F105.8	0.2	99.8
F45.0	25.9	74.1	LC-10[b]	23.4	76.6
F46.7	3.6	96.4	LC-12	15.1	84.9
F47.5	2.7	97.3	LC-14	2.4	97.6
F48.4	3.3	96.7	LC-14[a]	1.1	98.9
F50.0	27.9	72.1	LC-15	2.7	97.3
F50.4	42.6	57.4	LC-16	3.7	96.3
F50.9	34.3	65.7	LT-3[c]	3.2	96.8
F51.5	13.8	86.2	LT-4	2.4	97.6
F52.8	11.0	89.0	LT-5	22.6	77.4
F53.5	2.5	97.5	LT-7	14.6	85.4
F54.3	7.3	92.7	LT-8	1.2	98.8
F72.4	6.8	93.2	LT-13	1.5	98.5
F73.3	1.0	99.0	LT-9	6.8	93.2
F78.7	1.2	98.8	LT-10	6.0	94.0
F79.7	11.8	88.2	LT-12	7.1	92.9
F81.7	0.7	99.3			

[a] F = Runner Quarry, Ferguson, Iowa.
[b] LC = County Line Quarry, LeGrand, Iowa.
[c] LT = Timber Creek Quarry, LeGrand, Iowa.

Identification of the Clay Minerals. Three methods were used in an effort to identify the clay minerals in the residues. All residues were examined by staining, using the technique described by Mielenz and King (1951). Later ten selected residues were subjected to differential thermal analysis but the presence of finely divided pyrite masked the clay mineral reactions in four of them. Of the other six (one from County Line, two from Timber Creek and three from Ferguson) five gave reactions indicating the presence of illite, the other indicated montmorillonite. Finally the clay minerals in a number of residues were identified by X-Ray. Seven residues, three from Ferguson and two each from Timber Creek and County Line were sent to Dr. Ralph Grim for analysis. His results are given in table 3. The number of X's indicate the relative abundance of the various clay minerals in the sample without regard for other minerals present. Sample F-43.8 showed a spacing of about 9.2A which Grim interprets as collapsed Montmorillonite but it did not expand with glycol. Sample LQ-2 is from the Wenke quarry near the village of Quarry and represents a bed in the cherty section.

TABLE 3
X-RAY DETERMINATIONS BY GRIM

Sample No.	Illite	Mixed-Layer	Montmorillonite	Kaolinite
F43.8[a]	X	XX	XXXX*	Tr.
F46.7	X	X		Tr.
F48.4	X	XX		Tr.
LC-14[b]	X	X		
LC-16	X	XX		
LT-13[c]	X	XX		
LT-10	X	XX		
LQ-2	XXX	X		X

[a] F = Runner Quarry, Ferguson, Iowa.
[b] LC = County Line Quarry, LeGrand, Iowa.
[c] LT = Timber Creek Quarry, LeGrand, Iowa.
* Identity uncertain.

In recent months it has been possible to make qualitative clay mineral identifications by X-Ray spectrometer methods at Iowa State College. Equipment in the Ames Laboratory of the Atomic Energy Commision has been made available to us at such times as it is not otherwise engaged. The clay minerals in five additional residues from Ferguson have been identified here. These data are presented in table 4.

Because we felt that significant clay minerals may have been altered or destroyed by the HCL treatment used to obtain the residues we tried two other procedures. The first variation was to digest the original sample in 6N acetic acid. Eight residues so obtained were examined by X-Ray, three of these are from Ferguson, three from County Line and two from Timber Creek. The results are given in table 5. Some of these duplicate the samples identified by Grim but this procedure failed to reveal any clay minerals not recognized previously.

An attempt was made to dissolve a number of original samples in Versene at a P.H. of 10 in order to produce a residue without acid treatment. All of the samples tried were high in dolomite and after several days the dolomite had not dissolved. It is hoped that this procedure may be made effective by further work.

About half of the residues identified by X-Ray were from rocks classed as calcitic dolomites, the other half are about equally divided between dolomitic limestones and relatively pure limestones.

The results of X-Ray identification agree quite well with those of Grim, Lamar, and Bradley (1937) and of Robbins and Keller (1952) with respect to rocks of similar petrography in Illinois and Missouri. The major difference is the identification of mixed-layer minerals as important components in the rocks considered here. It appears that illite, with varying proportions of mixed-layer components are the dominant clay minerals in Paleozoic carbonate rocks, especially those containing appreciable dolomite. Kaolinite is distinctly subordinate whereas true montmorillonites are rare or absent.

In the rocks of the LeGrand area the only observable occurrence of the clay minerals is that along stylolite seams. In many instances this is not sufficient to account for the abundance of clay found in the residue which means that much of the clay, and in many instances, most of it, occurs disseminated throughout the carbonates. Microscopic observation indicates that the dolomite is notably free of inclusions whereas the calcite commonly shows discoloration and cloudiness, especially along grain boundaries. We believe that this is due in part to the occurrence of clay minerals which are concentrated in the calcite.

TABLE 4
QUALITATIVE X-RAY DETERMINATIONS OF ADDITIONAL SAMPLES

Sample No.	Illite	Mixed-Layer	Kaolinite
F36.9	×		
F56.0	×	×	
F74.7	×	×	
F90.3	×	×	
F104.1	×	×	

[a] F = Runner Quarry, Ferguson, Iowa.
[b] LT = Timber Creek Quarry, LeGrand, Iowa.

TABLE 5
QUALITATIVE X-RAY DETERMINATIONS OF ACETIC ACID RESIDUES

Sample No.	Illite	Mixed-Layer	Kaolinite
F43.8[a]	×	×	
F48.4	×	×	×
F53.5	×		
LC-12[b]	×	×	
LC-14	×	×	×
LC-16	×	×	
LT-8[c]	×	×	
LT-10	×	×	

[a] F = Runner Quarry, Ferguson, Iowa.
[b] LC = County Line Quarry, LeGrand, Iowa.
[c] LT = Timber Creek Quarry, LeGrand, Iowa.

Petrography, Alden Quarries

Two sections of the Alden limestone in the vicinity of Alden were studied in detail. These are the sections exposed in two quarries; one operated by Weaver Brothers, is located in the SW ¼ sec. 17, T. 89 N., R 21 W. which is just east of town; the other is operated by the Iowa Limestone Company and is located in the NE ¼, sec. 18, T. 89 N., R. 21 W which is in the north edge of the town.

The section exposed at the Weaver Brothers quarry had a total thickness of 41 feet at the time of the field study whereas the total section exposed at the other quarry was 48 feet. The beds at both quarries belong to the Alden Formation and consist of light-gray to white limestones. The dolomite content is uniformly low in all beds rarely exceeding 10 percent and in many beds it is not detectable by chemical techniques although scattered grains may be found in thin sections. The higher dolomite values obtained in this study occur in the lower half of the section at both quarries, the upper portion of the section being notably pure limestones.

The Alden rocks are also notably free of insoluble residues. The average of 10 samples representing the 41 feet at the Weaver quarry is 0.47 percent with only one sample above 1.0 percent; at the other quarry the average for 20 samples representing 48 feet is 0.54 percent and only three exceed 1.0 percent with a maximum value of 2.16. In each instance the higher values occur in the upper beds which contain one to three recognizable beds of shale from a few inches to as much as one foot in thickness.

In all samples containing significant amounts of insoluble residues the residue is almost exclusively in the clay-silt fraction. Staining tests on two samples from the Weaver quarry indicate kaolinite whereas one from the other quarry indicates montmorillonite, and another shows anauxite. These four samples have also been identified by means of X-Ray. Three samples from the Iowa Limestone Company quarry, including the ones showing montmorillonite and anauxite by staining, were examined by X-Ray. The results show that in all three samples kaolinite, illite and mixed-layer minerals are present. Quantitative estimates indicate that kaolinite is the most abundant with the others about equal but subordinate in amount.

The limestones at Alden provide a sharp contrast in lithology with those at Le Grand in every significant respect. They are pure limestones, free of chert and notably free of insoluble residues in contrast to the mixed carbonates, chert, and high insoluble content characteristic of the rocks of the LeGrand area. The prevailing clay mineral at Alden is kaolinite rather than the illite and mixed-layer types characteristic of the rocks at LeGrand.

Petrography, Fort Dodge

The section at Fort Dodge is that of the beds being produced by the Fort Dodge Limestone Company at a mine located in the SW ¼, Sec. 24, T. 89 N, R. 29 W. The section exposed in the mine face at the time of the field study measured just over 18 feet in thickness. Although these beds are known to be Mississippian in age their exact stratigraphic position is not known.

The lower half of the section consists of rocks which are notably pure limestones. The upper half becomes progressively more dolomitic upward, the lower portion being dolomitic limestones whereas the upper part is calcitic dolomite. The average insoluble residue of 13 samples representing 18 feet of section is 3.58 percent. The minimum content is 1.99 percent, three samples exceed 4.0 percent one of which shows a maximum of 8.19 percent. From this it is apparent that the insoluble content is rather uniform throughout the section. The seven samples from the lower half average 3.08 percent whereas the six samples from the upper, more dolomitic, half average 4.17 percent and one is the sample giving the maximum value. This indicates that the amount of insoluble residue in these beds correlates with the dolomite content although perhaps not as closely as in the case in the LeGrand area.

In all but two of the residues the clay-silt fraction exceeds 80.00 percent. The two exceptions are 59.33 and 42.76 percent respectively and these are in the upper, more dolomitic portion of the section. In these two the coarse fraction consists mainly of quartz sand with some chert.

Identification of the clay minerals by staining tests indicates montmorillonite in all samples. X-Ray determinations of the clay minerals in two samples were made by Grim. One from the lower limestones showed illite and mixed-layer minerals the latter three times as abundant as the former. The second sample from the upper dolomite beds showed the same minerals in the ratio of 2 illite to 3 mixed-layer.

Petrographically the rocks at Fort Dodge are quite similar to those of the LeGrand area. However, it should be recalled that these rocks have a satisfactory service record although they have been used less extensively. The length of service is also shorter but considered by the Highway Commission to be sufficient to indicate an aggregate quality distinctly superior to that of the stone from the LeGrand area.

Petrography—Iowa Falls Quarry

The section near Iowa Falls was described in an abandoned quarry located in the SE ¼, Sec. 18, T. 89 N., R. 20 W. The beds here represent the best exposed section of the

Iowa Falls member of the Hampton Formation and comprise a total thickness of 48 feet.

The rocks are interbedded limestones, calcitic dolomites, and dolomites the last two combined being somewhat more abundant. The limestones tend to be fine-grained to lithographic and white to light gray in color whereas the dolomites are dark gray where fresh and brown; where weathered, the texture is somewhat coarser than the limestones.

Detailed petrographic descriptions of these beds will be found in the thesis by Weissmann, (1953) mentioned above. That report includes the results of staining tests for the identification of the clay minerals. However, because this stone had not been used in pavement it was omitted from consideration during the latter phases of the study. No X-Ray identifications have been made at the present time but are to be included in work still in progress.

Petrography of Sound and Distressed Pavement

Limited studies were made of concrete cores from a variety of pavements in which stone from the LeGrand area was used. These include cores from the two pavements, one satisfactorily sound the other distressed, in which stone from the Timber Creek Quarry was used. As these two pavements were laid at different times the precise source of the stone within the quarry may have been, and probably was, different. Unfortunately it is not possible to discover in what part of the quarry or from which beds the stone actually came in either instance. The pavement cores also included some from pavement in which the basal oolite (Chapin) was selectively produced as the coarse aggregate and others from distressed pavement in which the coarse aggregate used was the typical LeGrand stone produced at quarries exposing both the cherty beds (Maynes Creek) and at least the lower part of the Eagle City member. Again it was not possible to ascertain the precise source of the stone used in any specific pavement. However, we were informed that the visible chert was eliminated at the quarry. Examination of the cores indicates that this elimination must have been reasonably effective.

Any conclusions based on this limited study of the petrography of concrete would rest on feeble foundations. The authors have had no previous experience in such work and are therefore unqualified to either observe or interpret critically. Furthermore, as the cores examined in this study are mainly from distressed pavements we could only expect, as Mather (1952) says, to "know more about the pathology of concrete than about its normal structure and aspect."

One observation with respect to the cores seems to be worthy of record here. Of the two pavements containing stone from the Timber Creek quarry one contains aggregate fragments which are uniformly gray to dark-gray in color indicating that the stone was essentially unweathered when used. In the other pavement the aggregate fragments are buff, tan or brown in color indicating that the stone had undergone some weathering. In general the degree of weathering indicated is comparable to that shown by the average stone exposed in the quarries in the immediate vicinity of LeGrand. The pavement with the fresh-appearing aggregate is the one showing the more satisfactory service record.

The Highway Commission has promised to provide additional cores from both distressed and sound pavements. This will enable us to continue these studies and to make further analyses which we now think would be significant.

Summary of Petrographic Data

The rocks of the LeGrand area comprise a section attaining a maximum thickness of 100 feet or more and characterized by highly varied lithology. In content of calcite and dolomite, the essential carbonate minerals, these rocks show almost every possible variation. The basal oolite section is free of dolomite throughout the area. The uppermost oolite at Ferguson is similar to the basal oolite but does not occur at any other quarry in the area. The section between the two main oolites consists of interbedded dolomites, calcitic dolomites, dolomitic limestones and limestones. The fact that the various lithologies are so intimately associated makes it necessary for any aggregate produced to be of mixed composition.

The average insoluble residue content throughout the section is 2.73 percent. Beds with residues of 5.0 percent or higher occur throughout the mixed section between the two oolites. However, the greater number of beds with high insoluble content are in the upper, chert free part of the section.

The insoluble material falls almost wholly in the clay-silt size fraction. The clay minerals consist of illite and mixed-layer components of the latter being equal to or exceeding the former in abundance.

The only observable difference between the rocks at the several quarries within the area is the degree of weathering. At Ferguson the quarry is in a flat bottomed valley which means that the rock remains below the water table more or less permanently. The beds are mainly gray or dark colored, typical of unaltered limestones and dolomites. The other quarries in the area are at bluff-face locations. In most of them the rocks lie well above the adjacent valleys and are thus subjected to more intensive weathering. The rocks are typically buff to brown in color with gray or dark, fresh stone limited to local occurrence.

The rocks at Fort Dodge are comparable in their lithologic characteristics to those of the LeGrand area. This applies to all the major factors; carbonate ratios, insoluble residue content, and the nature of the clay-minerals. Because this stone is produced by underground mining it is unweathered and therefore typically light to dark-gray in color.

The rocks quarried near Alden are petrographically quite distinct from those of the other two areas. These are typically pure limestones, low in insoluble residue content, and the clay minerals are kaolinite and illite. Mixed-layer components, although present, are subordinate to illite and therefore comprise a minor portion of the total clay.

ENGINEERING TESTS

We have assumed that all of the rocks used as coarse aggregate in pavements have passed the usual engineering specifications. Therefore we have made no serious effort to compile the results of abrasion, freeze-thaw, sodium sulfate, or other such tests. However, in going over the records at the Highway Commission it was noted that in most instances the tests of rocks from all three areas gave satisfactory results.

Growth and Sonic Modulus Tests

Dorheim (1951) used samples from LeGrand and Alden in his study which included the preparation of concrete beams for growth and sonic modulus determinations. Both values were determined during a year of moist storage of the beams and during a series of 20 freeze-thaw cycles at the end of this time. Neither the Alden nor the LeGrand stone showed any marked growth or change in sonic modulus whereas stone with unsatisfactory service records from other quarries showed major changes in both regards. These tests correlate with the service records of all stones tested except those from LeGrand. In his petrographic studies Dorheim identified the clay in LeGrand residues as kaolinite by means of staining tests.

Although these growth and sonic modulus tests of beams seem to be an effective measure of secular soundness in some limestone aggregates, Dorheim concluded that the rocks from LeGrand are an exception.

Absorption

Laughlin (1928), Mather (1952) and others have indicated that the absorption capacity of a carbonate aggregate may be significant as an indication of its resistance to weathering. Mather states that an absorption of 1.5 to 2.0 percent may lower the durability of stone containing 5.0 percent montmorilloid clays whereas kaolinitic clays are less reactive.

The data available on absorption capacities of the rocks at LeGrand, Alden and Fort Dodge are those in the files of the Highway Commission. These have been examined and will be summarized here. In general, records are available on the older quarries for the period since about 1925 and for the period of existence for newer quarries such as the one at Ferguson and the mine at Fort Dodge.

Most of these measurements are described as "surface dry" rather than "surface moist" absorption values.

Absorption values for stone from the older quarries at LeGrand are quite variable. The average for nine tests made in 1927 on stone representing the quarry section above the basal oolite is 2.48 if we use the minimum value for each bed where two or more tests were made. Only one test is below 1.0 percent whereas four of the nine are above 3.0 percent. The maximum value for any bed is 6.47 percent.

For all the tests examined for rocks from the older quarries values below 2.0 percent are uncommon and in most reports covering exposed sections values above 3.0 percent are more numerous than those below 2.0 percent.

The absorption capacity of the basal oolite appears to be about the same as that for the beds above.

Of 16 tests on stone from the new quarry at Ferguson only one is above 2.0 percent and three are below 1.0 percent. The average for all values is 1.43 which agrees well with three samples taken from cars or stockpiles, 1.25, 1.45 and 1.47 percent respectively.

For the Fort Dodge stone four samples representing various portions of the working face at two places in the mine give values of 0.8, 0.8, 1.6 and 0.6 respectively. Selected samples described as "soft portions" give values as high as 3.6 percent. The values described as "average for the mine face" or as "mine run," or for samples from stockpiles average about 1.4 percent.

Of more than forty values for samples of the stone from Alden, 10 are below 1.0 percent whereas only 8 are above 2.0 percent and the maximum value is 3.3 percent.

These data indicate that of the rocks studied those from the older quarries at LeGrand have average absorption capacities of about 2.5 percent. The rocks from Fort Dodge, although similar in lithology to those at LeGrand, show appreciably lower absorption. The rocks at Ferguson have low absorption capacities which suggests that the higher values observed for samples from the quarries at LeGrand are the result of weathering. The stone at Alden also shows low absorption values.

DISCUSSION

Two petrographic features of the rocks of the LeGrand area would appear to be possible causes of the poor service record. First, any aggregate produced from the beds above the basal oolite will consist of a variety of rock types ranging from limestones to dolomites. Because of the rather large difference in the linear coefficient of thermal expansion of the various rock types it might be expected that some physical distress would occur in the concrete. Secondly, the presence of a rather high content of insoluble residue rich in illite and mixed-layer clay minerals combined with absorption capacities in excess of 2.0 percent. This may permit reactions which result in swelling and thus cause distress in concrete containing these rocks.

Thermal Expansion

Callan (1952) and Mather (1952) have published results of experiments which show some correlation between the thermal expansion characteristics of the coarse aggregate and the durability of concrete. Callan did not report on the clay mineral content of the carbonate aggregates used. He did consider absorption and this too shows a correlation with durability. Only a summary of the results reported by Mather has been available to the writers. This indicates that a similar correlation between thermal characteristics of the aggregate and concrete durability was found. Mather, however, did consider the amount and nature of the clay minerals present and reports a convincing correlation between low durability and a content of montmorillonoid clay minerals in excess of four percent.

In the present study thermal properties of the rocks were not investigated as the known values for the various rock types were considered sufficient. Petrographically the rocks at Fort Dodge and those above the oolite of the LeGrand area are so similar that the variation of thermal properties in aggregate from both should be about the same. However, the service records indicate that the aggregate produced at Fort Dodge is superior to the other. It would appear that differential thermal expansion is not the major factor in producing distress in concrete pavements in which the LeGrand stone has been used.

Clay Minerals and Absorption

Although the petrology of carbonate rocks with respect to their suitability for aggregate seems to have been neglected during the period since 1928 the same can not be said of the study of the clay minerals. The study of these ubiquitous and varied substances has been very intensive in recent years. Although the details of their classification, occurrence, genesis, alteration, and behavior are by no means fully known even now, it is possible to reach a better understanding of their significance with respect to many problems.

We still have inadequate information on the nature and occurrence of clay minerals in carbonate rocks. Valuable data are to be found in papers by Grim, Lamar and Bradley,

(1937) and by Robbins and Keller (1952). However, these authors do not report other petrographic details of the rocks studied. Both studies indicate that illite is the most common clay minerals in limestones, especially those of Paleozoic age. Montmorillonoid clays and kaolinite are reported to be present in some rocks but rarely is either the dominant clay mineral.

To our knowledge there is no previous discussion of the occurrence of mixed-layer components among the clay minerals found in carbonate rocks. Laughlin (1928) identified the clay mineral found in some carbonate aggregates as beidellite which was then considered to be a distinct mineral and a member of the montmorillonite group. Grim, Lamar, and Bradley (1937) report "beidellite (?)" in four of the 35 rocks studied. At present it appears that much of the material previously identified as beidellite is really a mixture of illite and interlayered montmorillonite, see Grim (1953) pages 39–40. Grim shares the opinion of many clay mineral investigators that the term beidellite should be dropped as a mineral name.

An excellent summary of clay mineral classification and properties are to be found in two recent books, Brindley et al. (1951) and Grim (1953). Significant details of the chemical, structural and physical properties of the illite-montmorillonite type clay minerals have recently been discussed in papers by Foster (1951) and (1953), Weaver (1953), and Earley, Milne and McVeagh (1953).

It seems to be generally agreed that illite may alter to montmorillonite or to a mixed-layer complex under a variety of conditions, Weaver (1953). This change may be produced by weathering, (beidellite) Grim, Lamar and Bradley (1937) and has been produced artificially, White (1950). It also seems likely that this transformation may be expected to occur in an environment such as would exist in a concrete pavement containing dolomite or dolomitic limestone. There are no data on the time which might be required for such transformations to become significant in the durability of concrete aggregates but it can not be safely assumed that 10 or 15 years is inadequate.

In illites containing interlayered montmorillonite the latter component will have the property of swelling when water is available. The presence of such swelling clays in an aggregate may produce stresses in excess of the tensile strength of concrete. It was for this reason that Laughlin and other earlier writers concluded that an appreciable content of beidellite (illite plus mixed-layers) combined with a high absorption capacity would indicate an unsatisfactory stone.

Conclusions

The following conclusions seem to be justified by the data available at the present time.

(1) The mixed carbonate rocks of the LeGrand area and those at Fort Dodge have as their principal clay mineral an illite mixed-layer complex.

(2) The pure limestones of the Alden area are characterized by kaolinitic clays with subordinate illite.

(3) Where fresh, the LeGrand and Fort Dodge rocks have absorption capacities which average less than 2.0 percent. However, where they are weathered as they are in the older quarries of the LeGrand area the absorption capacity is notably higher.

(4) That the combination of the presence of swelling type clay mineral and absorption capacities in excess of 2.0 percent in so much of the older aggregate produced at LeGrand favors reactions which will produce stresses adequate to seriously affect the durability of the concrete.

This seems to disagree with the conclusions reached by Dorheim after growth and sonic modulus studies of concrete beams. However, it should be pointed out that the three aggregates which showed maximum growth and deterioration of the sonic modulus during 15 months of moist ageing followed by 20 cycles of freeze-thaw were the ones highest in clay content. The most seriously affected beams contained aggregate with 22.23 percent clay, the other two contained 14.78 percent and 6.75 percent respectively. In terms of growth during one year of curing the LeGrand aggregates had an average four times that of the good stones (including Alden), twice that of the "bad" stone containing 6.75 percent clay, equal to that of the stone containing 14.78 percent, but greatly exceeded (20 times) by the stone containing 22.23 percent clay. During the freeze-thaw experiment all aggregates showed the greatest effects during the first five cycles, beyond this the curves for the good stones show a marked flattening whereas those for the bad stones show much less flattening. The curves for LeGrand stone are intermediate, flattening less abruptly than the good stones, indicating a slow steady deterioration of the concrete.

(5) That mixed carbonate rocks containing swelling-type clay minerals but having absorption capacities of less than 2.0 percent will probably produce satisfactorily sound concrete. This would indicate that the fresh stone, otherwise similar to that at LeGrand, now being quarried at Ferguson should prove satisfactory as concrete aggregate.

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Secondary Minerals in Rock as a Cause of Pavement and Base Failure.

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Secondary or alteration minerals were found in large percentages in the rock used in base and pavement of several highway sections which failed under use. The most common of these are kaolin clays, chlorite, serpentine, calcite, and limonite. Their presence causes rock in the ¾- to 0-inch size to disintegrate or dissolve when subjected to water and traffic loads. Rock in larger sizes does not seem to be affected, probably because of the sharp decrease in surface area. Microscopic study and field data indicate 0 to 20 percent of secondary minerals in a fine aggregate will have little effect; 20 to 35 percent will produce some failures and borderline results; and 35 percent and above will almost certainly cause failures.

● THE application of the principles of soil mechanics has made possible a more intelligent design of pavement foundations. There are, however, other features that must be considered. Failures have occurred in spite of the best design and most careful control. These failures commonly affect a whole section of a highway rather than an area of a few square yards. Such failures are not new, and therefore, have been subject to examination and study by many engineers for a considerable period of time. These, and and the writer's, studies showed that the failures usually occurred within, or affected the whole of a single construction unit. They were consistently confined to the base and paving courses; only rarely was the subbase or subgrade affected.

These characteristics all point to the surfacing rock as the probable cause of trouble. In Oregon, these failures were concentrated in the northwestern quarter of the state. As a basis for study, twelve sections which had failed or caused trouble were selected on the advice of the Construction Engineer. All sections were on western Oregon highways.

The investigation began with the location and examination of the quarry which had supplied the rock for each section. In each case the quarry which supplied the base or surfacing aggregate showed the rock to be badly weathered or composed of altered submarine rock. In all cases the rock used was the black basalt typical of western Oregon. Without exception all deposits studied were intrusive bodies, such as dikes, or submarine lava occurring as flows interbedded with sediments. In hand samples the rock appeared sound but of poor quality.

Table 1 shows the results of the routine laboratory tests run on these twelve sources over the last 20 years. In all cases the rock was passed as acceptable although the quality was borderline in several instances.

Geologic study of the quarries and of hand samples showed the rock to be extensively altered. Thin sections were cut and examined under a petrographic microscope which revealed large percentages of unstable secondary minerals as alteration products. A research project was set up within the Geology Section of the Oregon State Highway Department to