Variations in Performance of Concrete with Carbonate Aggregates in Iowa

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Observation of concrete pavements over a period several years indicates that the majority of the carbonate aggregates used can be expected to perform satisfactorily for at least 20 to 25 years. Several aggregates from various geologic sources were used in concrete pavement that is more than 40 years old. Of more than 75 carbonate aggregate sources used, only a few have been associated with early deterioration of concrete.

Concrete deterioration associated with one geologic source of the coarse aggregate was recognized in Iowa in the early 1930's in pavement less than 10 years old. Since then, observations indicate that in some other cases of deterioration there appears to be a relation between the concrete durability and the geologic source of the coarse aggregate. Of the cases recognized, deterioration is first noticed in pavements ranging in age from 3 to 23 years. In these cases, deterioration progresses rapidly and is generally severe within five years after it is first observed.

The aggregates associated with deterioration are from rock formations ranging in age from Ordovician to Pennsylvanian. Rock types have a wide range of physical, chemical, and engineering properties similar to aggregates that have satisfactory performance. Of the aggregates associated with deterioration, current specifications and test limits have eliminated the carbonate rocks that have a high insoluble residue content, other than quartz sand and chert. There are still three known geologic sources capable of meeting current test limits. They are associated with concrete that has shown extensive deterioration on pavements ranging from 8 to 15 years old. These three are in different stratigraphic horizons with different lithologies, but have no distinctive properties that separate them from acceptable geologic sources. They are 95 percent or better total carbonate.

One of the basic research programs of the Iowa State Highway Commission for more than 20 years has been a study of the behavior of concrete made with aggregates from different sources. The program includes a study of the physical, chemical, and geologic properties of various coarse aggregates and of the properties of the concrete containing these aggregates. The purpose of this study is to relate these characteristics to the behavior of the concrete in service, and thus develop better methods for determining the probable performance of proposed materials.

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Several selected case histories are reported to illustrate the various aspects of the problem and the methods used to relate the characteristics of coarse aggregate to concrete durability.

A STUDY is being conducted by the Iowa State Highway Commission of the physical, chemical, and mineral properties of various coarse aggregates and of the properties of concrete containing these aggregates. It is the purpose of this study to relate these properties to the behavior of concrete in service and to develop better methods for determining the probable performance of proposed materials. The aggregate studies are a part of a continuous program of study on the performance of concrete that has been conducted for more than 30 years.

Continued observations of concrete indicate that the majority of the portland cement concrete pavements more than 30 years of age, containing carbonate aggregate, attain this age without any signs of serious deterioration. Some pavements are more than 40 years old and the concrete is still in excellent condition. Some other pavements have shown signs of deterioration (as defined in this paper) at ages ranging from 3 to 23 years. Deterioration that has become severe in pavements under 25 years of age has been associated with aggregate produced from ten different geologic sources. A geologic source of aggregate is defined as a particular stratigraphic horizon with known properties within a defined geographic area.

Study on five of these sources has shown that it is possible to establish a range in age at which the concrete containing aggregates from these sources will begin to show deterioration. These age ranges which generally span about five years seem to be consistent for a wide range of variables described herein.

It is recognized that the performance of concrete pavements with any one coarse aggregate may be affected by traffic as related to structural adequacy, site conditions and design features which change the amount of stress a pavement experiences. Although the variations in performances due to these factors are recognized, it is considered that within the broad general classifications of pavement performance defined in this report, the effects are within a range that allows a relationship between the geologic source of the coarse aggregate and pavement performance to be developed.

Deterioration was first associated with the geologic source of the coarse aggregate in the early 1930's. In this case the pavements were less than 5 years of age. Since that time extensive research has been conducted to develop tests on aggregate and concrete that will correlate with the performance of concrete pavements. Current specifications include tests developed under this program which eliminate seven of the recognized unsatisfactory aggregates. So far no diagnostic characteristics have been found to identify the remaining three aggregates with unsatisfactory service.

This paper presents a summary of the data that defines the current status of the carbonate aggregate problem in Iowa. It is only a partial summary of ten typical geologic sources representing more than 75 known carbonate aggregate sources and does not include any of the data available on more than 100 gravel sources that have been used.

The purpose of this presentation is (a) to show the accumulated evidence that associates the geologic source of the coarse aggregate with variations in concrete performance, and to show examples of concrete deterioration at successively greater ages; and (b) to describe the rock and concrete properties associated with satisfactory and unsatisfactory service.

RECORDS

Centralized records have been maintained on all portland cement concrete paving projects constructed under supervision of the Highway Commission. Records for all projects are available on construction data and sources of materials used. There are also records of crack or condition surveys that have been made for many projects.

Records are maintained for each source of material used in construction. All records, from initial prospecting to the present, are kept at one location in the files. For quarries, all test records are generally related to a geologic section for the quarry.

These records on aggregate and construction form a basis for establishing an informal classification for pavement service and categories for concrete aggregate service life.

During the past several years inspections have been made on pavement projects ranging from two to more than 40 years of age. Several selected sections of pavement for each of various geologic sources have been inspected at least once each year during the past five years. Current inspection reports generally include a description of the pavement surface and joint and crack condition. Patch counts are made and photographs are taken of the typical conditions of each section surveyed.

When deterioration is noted, other pavements containing aggregates from the same geologic source are examined and photographed. Inspections are conducted frequently on concrete showing signs of deterioration to determine the rate of deterioration. For each new geologic source one or two representative sections of pavement are selected to be checked at random intervals for pavement condition.

GUIDE FOR PAVEMENT CONDITION CLASSIFICATION

The current pavement condition classification is based on the comparative condition of all pavements inspected. Most of these have been in service for 35 years with some as long as 40 years or more. This classification is an attempt to develop a systematic method of categorizing concrete performance. Table 1 was developed from concrete condition survey reports.

CURRENT SPECIFICATIONS

Current specifications for concrete aggregate are contained in the Iowa Standard Specifications, Series of 1960. The physical test limits are as follows: Abrasion loss determined in accordance with AASHO T-96, grading A or B shall not exceed 50 for crushed stone that is consistently 90 percent or more calcium carbonate, and 45 for all other crushed stone. The percentage loss on 16 cycles freezing and thawing in water alcohol solution, method "A", shall not be greater than 6.0.

COARSE AGGREGATE CLASSIFICATION

More than 75 sources of rock have been used for coarse aggregate in concrete in Iowa. Most of these have been tested by current methods. On the basis of performance records and test results more than one-half of the aggregate sources can be placed in one or another of the four major categories in Table 2.

To date, ten geologic sources have been associated with deterioration. All but three are eliminated by current test limits and of these three only the Otis is still being used. This source is under study at this time.

To illustrate the problem and variations in service life, the case histories of ten typical geologic sources are described. Each case history includes a description of the geology of the source and the service record associated with the aggregate from each source. Five case histories are for satisfactory and five are for unsatisfactory aggregates. Data on construction and condition surveys for typical sections of pavement are given in Table 3. Chemical analyses and rock properties for each source are given in Tables 4 and 5.

SATISFACTORY SERVICE

Satisfactory service of more than 30 years is known for concrete containing carbonate aggregates from 15 geologic sources in several stratigraphic horizons with various lithologies. Five of these geologic sources have been used for concrete that shows no signs of deterioration after 40 years of service.

Figure 1 shows the general condition of pavements ranging from 33 to 42 years old containing satisfactory aggregates. For pavements constructed before 1929 with no transverse joints, the transverse crack spacing varies from about 20 ft to more than 100 ft. The concrete is in excellent condition with no evidence of progressive deteri-

TABLE 1

DESCRIPTION OF PERFORMANCE FOR SATISFACTORY AND UNSATISFACTORY SERVICE

Classification	Age (yr)	Performance Description[1]
Satisfactory[2]	0-10	Absolutely no failures or signs of potential failure due to aggregate should be expected, except occasional pop-outs, spalls, development of expected transverse cracks and some diagonal corner cracks[1].
	10-20	Concrete should have essentially no progressive failure due to aggregate. Toward the 20-yr age there may be some "D" line cracking[1] showing around cracks and construction joints or there may be some discoloration that may be associated with future development of "D" line cracks. However, concrete should not show progressive scaling[1]. Many pavements have reached this age with as few as two or three patches per mile and no "D" line cracking.
	20 30	Sometime after 20 years some pavement patching would be anticipated. Amount of patching would be small at first and increase slightly each year. Cracks and joints are expected to begin to show progressive scaling toward 30 years of age.
Unsatisfactory	0-20	Concrete begins to show development of discoloration associated with "D" line cracks or map cracking[1], curb disintegration, severe spalling, and progressive scaling that results in pieces of concrete becoming dislodged under traffic on more than 5 percent of the joints and cracks and requires continuous and extensive patching. The number of full-width patches per mile increases rapidly with time. In severe cases, entire slab shows cracking and spalling. These various conditions are shown in Figures 2, 3, 5, 6, 7.
		There conditions may begin to occur at any age up to 20 years. In some pavements deterioration has begun occurring at 25 years of age and becomes severe at 30 years or more of age. Cracking and disintegration of concrete generally continues in old concrete adjacent to patches.

[1] Terms as defined in Appendix B., HRB Special Report 30, Pavement Condition Surveys (1957).
[2] Majority of pavements have far exceeded the satisfactory criteria; at age of 40 years some pavements show no deterioration.

TABLE 2

COARSE AGGREGATE CLASSIFICATION ACCORDING TO TEST RESULTS AND PERFORMANCE IN CONCRETE[1]

Performance	Class.	Description
Satisfactory	I.	Aggregates complying with current test limits, no signs of deterioration in concrete after: (a) 20 years of service, 20 sources; (b) 30 years of service, 10 sources (Dubuque Stone)[1]; and (c) 40 years of service, 5 sources (Alden, Davenport, Iowa City)[1].
	II.	Aggregates not complying with test limits: 30 years of service, 2 sources (Farmington)[1].
Unsatisfactory	III.	Aggregates complying or nearly complying with current test limits: deterioration begins on concrete less than 20 years of age, 3 sources (LeGrand, Decorah, Otis)[1].
	IV.	Aggregates that do not comply with specifications; deterioration begins in concrete at: (a) less than 20 years of age, 9 sources (Glory)[1]; and (b) less than 25 years of age (Fayette)[1].

[1] Some aggregates with less than 10 years service or where concrete condition is not known are not classified. Number of sources listed is for carbonate aggregates only. Sources used as examples are listed by name.

TABLE 3

PAVEMENT CONSTRUCTION AND CONDITION DATA, 1963[1]

Project Co.[2]	Project Cd.[3]	Year Built	Thickness (in.) Edge	Thickness (in.) Uniform	Joint Spacing Exp.	Joint Spacing Contr.	Cement	Sand	Coarse Aggregate	Miles	"D"Cr.	Prog.[4] Scale	Avg. No. Patches per Mile[5] 1958	Avg. No. Patches per Mile[5] 1963	Age (yr)	Concrete Condition
									(a) Satisfactory Performance							
42	22	1931	10	7	80'	None	2	2	Alden	9	No	No	—	1-3	32	Very good
85	5	1929	10	8	40'4"	None	1	1	Alden	6	No	No	—	2-10	34	Good
31	13	1932	10	7	60'	None	4	4	Dubuque	17	No	No	—	—	31	Very good
3	4	1931	10	7	80'	None	4	3	Dubuque	5	No	No	0	0-3	32	Excellent
28	1	1928	10	7	None	None	3	4	Dubuque	10	Yes	Some	2-3	5-10	35	Good, signs of deterioration
52	7	1927	10	7	None	None	5	6	Iowa City	12	No	No	0-1	0-3	36	Excellent for Coralville Ls.
52	2	1921	7	8	None	None	4	5	Iowa City	2	No	No	0-5	0-5	42	Very good to excellent
89	4	1930	10	7	None	None	5	8, 9	Davenport	5	No	No	0-1	0-2	33	Very good
89	1	1928	10	7	None	None	5	7	Davenport	7	No	No	0-2	0-2	35	Excellent
52	5	1927	10	7	None	None	1	6	Davenport	5	No	No	0-5	0-5	36	Very good, occasional blow-up
82	15	1923	8	8	None	None	9, 10	5	Davenport	3	No	No	—	1	40	Excellent
89	4	1930	10	7	None	None	5	8, 9	Farmington	5	No	No	0-1	0-2	33	Very good
									(b) Unsatisfactory Performance							
86	6	1930	10	7	None	None	8	18	Glory	4	Yes	Yes	—	75-100	33	200 + patches in 2 miles
Typical of many projects, sands, cements and designs									Glory[6]	100+	Yes	Yes	—	100-300	—	Very poor at 15 + years
28	15	1942	10	7½	120'	30'	5	10	Fayette[7]	8	Yes	Yes	0	0-1	21	3 patches in 8 miles
28	14	1940	9	6	120'	30'	1, 6	11	Fayette	15	Yes	Yes	0	7-20	23	70-90% of joints affected
28	11	1939	9	6	202'8"	25'4"	4	19	Fayette	3	Yes	Yes	0	15-30	24	Fair to poor at all joints & cracks
28	10	1936	10	7	60'	30'	3	12	Fayette	4	Yes	Yes	—	20-50	27	All joints & cracks deteriorating
85	11	1938	10	7½	90'	30'	2	13	LeGrand	6	Yes	Yes	—	70-90	25	Fair to poor, 535 patches
86	2	1927	10	7	None	None	3	14	LeGrand	1	Yes	Yes	—	35	36	95% of all joints & cracks affected
Typical of many projects, sands, cements and designs									LeGrand	100+	Yes	Yes	—	50-100	—	Very poor at 15 + years of age
96	18	1932	10	7	80'	None	5, 4	15	Decorah	7	Yes	Yes	75-100	100-175	31	Very poor, over 700 patches
Typical of many projects, sands, cements and designs									Decorah	45	Yes	Yes	10-30	25-100	—	Occasional good sections
57	54	1952	10	8½	None	20'	5	17	Otis	6	No	No	0	0	11	Very good, occasional spall
28	17	1948	8	7	As on	Plans	7	3	Otis	8	Yes	No	—	0-4	15	Good, 33 patches in 8 miles
64	22	1947	10	9	None	None	2, 4	16	Otis	6	Yes	Yes	Occas.	5-35	16	Fair
57	38	1946	10	8	120'	30'	5	17	Otis	5	Yes	Yes	Occas.	5-30	18	Fair
52	26	1941	10	7½	120'	30'	2	17	Otis	4	Yes	Yes	3-10	15-40	22	10-15% of all joints, as in Fig. 7b, right
52	23	1940	10	7½	120'	30'	1	17	Otis	4	Yes	Yes	3-5	10-15	23	Best pavement of Otis this age
53	11	1938	8	6	202'8"	25'4"	5	17	Otis	3	Yes	Yes	5-7	50-100	25	Very poor

[1]Only a few typical sections.
[2]County number.
[3]Pavement Index card number.
[4]On 10 percent or more all joints and cracks.
[5]Full width, concrete or bituminous.
[6]Based on reports on many projects.
[7]Typical projects—many others checked. 1938 pavement showed no cracks or patching in 1957.

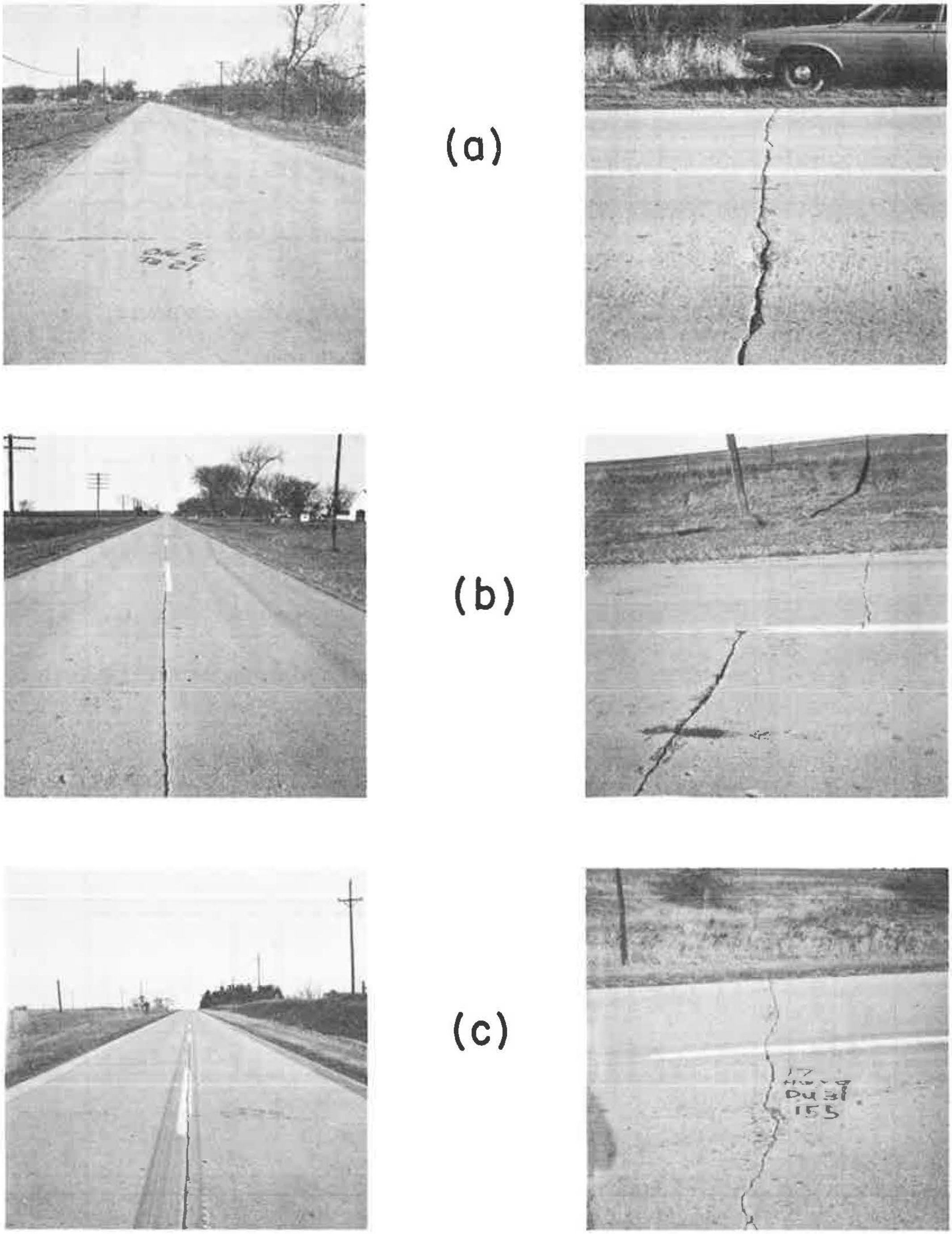


Figure 1. Concrete pavements with satisfactory service: (a) project 52-7, 42 years old, Iowa City stone; (b) project 52-5, 36 years old, Davenport stone; and (c) project 3-4, 32 years old, Dubuque stone.

oration. Some patching has been necessary where slabs are broken. The area of old concrete adjacent to patches 17 years old is in excellent condition.

Described in the following are five geologic sources with satisfactory service exceeding 30 years. Of these five, only the Farmington aggregate exceeds current limits of the water-alcohol freeze-thaw test.

Iowa City Stone (Devonian), Coralville Limestone Member, Cedar Valley Formation, Iowa City Area. —The rock is a medium to fine-grained limestone (classification of rock as used throughout this report is that of Pettijohn (6)) interbedded with biostromal (coral) layers, averaging 95 percent or better total carbonate. Currently the lower 26 ft of this unit is acceptable for use in concrete. The freezing and thawing test results are generally consistently within specifications, although the lithology is variable and becomes more dolomitic northwest along the outcrop belt.

Aggregate from this geologic source has been used in pavement with satisfactory results since 1921. Figure 1a shows a typical pavement constructed in 1921.

Davenport Stone (Devonian), Davenport Limestone Member, Wapsipinicon Formation, Davenport Area. —The Davenport member generally ranges from 20 to 30 ft thick and is essentially a uniform, very fine-grained, limestone averaging 95 percent or more total calcium carbonate. Figure 1b shows a typical section of 36-yr-old pavement containing this aggregate. This source has been used for aggregate since the early 1920's.

Dubuque Stone (Ordovician), Galena Formation, Dubuque Area. —The Galena formation in this area is a relatively uniform coarse-grained massive dolomite with a varying amount of white chert nodules scattered throughout the unit. The carbonate content of the chert-free rock is usually more than 95 percent. Working faces in this ledge vary from 40 to more than 100 ft in thickness. Concrete made with this aggregate has performed well for 35 years (Fig. 1c). Some pavements more than 35 years old are beginning to show signs of progressive deterioration but not at the same rate or to the same degree as that shown by pavements containing unsatisfactory aggregates.

Alden Stone (Mississippian), Gilmore City Formation, Alden Area. —The rock is coarsely crystalline, oolitic to crinoidal, limestone averaging 97 to 98 percent calcium carbonate. About 30 ft in the upper part of the formation have been worked at Alden. Aggregates have been produced from various horizons within the formation at Humboldt, Rutland, and Gilmore City. Some pavements up to 40 years old, containing this aggregate, have been checked, and generally the concrete is in excellent condition. Several sections more than 35 years old have only one or two patches in several miles of pavement.

Farmington Stone (Mississippian), St. Genevieve Formation, Farmington Area. — The 8- to 12-ft working face is very fine-grained limestone with thin shale partings and variable but generally thin, argillaceous limestone layers, with a variable carbonate content. Aggregate from this source exceeds present allowable loss limits on freezing and thawing in water-alcohol, but produces satisfactory concrete. Thirty-five-year-old concrete containing this stone is in excellent condition.

UNSATISFACTORY SERVICE

In this category the case histories of aggregates from five geologic sources (Glory, Fayette, Decorah, LeGrand, and Otis) are described. The Glory and Fayette sources do not meet current test requirements. Service records of these two are described to illustrate the similarities in the pattern of deterioration shown by concrete containing aggregates with different lithologies and physical properties.

For concrete containing aggregate from each of the five sources described, deterioration has been observed on at least one project where adjoining sections of pavement were constructed with concrete containing coarse aggregates from several satisfactory sources. For each section of pavement, site conditions are similar; sand, cement, and design were identical but the coarse aggregate was changed. In each project the deteriorated areas of pavement correlated with the suspect coarse aggregate. The other sections of pavement containing satisfactory aggregates remained in excellent condition. All observed concrete pavements more than 15 years of age, containing aggregates from any one of the five unsatisfactory sources, show deterioration.

General Pattern of Deterioration

The general pattern of deterioration, at whatever age it begins, is similar for aggregates meeting and for those failing to meet specifications. Significant variations are noted in the age at which deterioration is first observed, the rate at which it progresses, and the area of slab affected. Deterioration in all cases is progressive. The first noticeable sign is a general discoloration in the vicinity of the joints and cracks, and sometimes along the edges of the slab. The border of the discolored area is generally slightly concave toward the long axis of the crack or joint (Fig. 3c, left).

"D" line cracking, the next sign of deterioration, is a network of fine, parallel, hairline cracks which generally develop on both sides of a joint or fracture before progressive scaling is observed. These fine cracks parallel the joints, fractures or edges, usually curve across slab corners and are interconnected by random transverse cracks (Figs. 3c, right and 6b). Sometimes these cracks accumulate a small, light blue-gray, ridge-like deposit and are referred to as "blue-line" cracks. Within the cracked area, the surface layer of concrete from ⅛ to ¼ in. thick is loosened and is easily peeled from the slab. Discoloration generally continues to spread ahead of the "D" line cracking.

The deteriorated area is deepened by progressive scaling (Fig. 6d). The concrete in these areas is easily disintegrated by a light hammer blow. The matrix is generally chalky, and cavity walls may be coated with a white powder. This material has been identified by Lemish (1) to be predominantly calcium carbonate. During the early stages of deterioration, the central portion of the slab (Fig. 3) between cracks or joints shows no indication of distress. In extreme cases the entire slab may be affected (Fig. 2). In the final stage the concrete deteriorates to a condition resembling loosely compacted gravel. Any one pavement will generally show all degrees of deterioration. Variations in the severity of deterioration are greater in a horizontal direction away from joints and cracks than from top to bottom in the vicinity of joints or cracks.

On pavement with transverse joints, deterioration appears to start adjacent to the expansion joints, then the contraction joints and finally develop adjacent to the cracks. With time, progressively more area of the pavement is affected. In most instances there does not appear to be any obvious displacement of the pavement in the deteriorated areas.

The general pattern does not appear to be similar to that described and illustrated by Swenson and Gillott (2) in Canada or by Newlon and Sherwood (3) in Virginia. It appears to be similar to that described and illustrated by White and Peyton (4) in Kansas and Woods et al. (5) in Indiana.

Blow-ups or eruptions of the concrete similar to that illustrated in Figure 7c (left) have been observed on pavements containing both satisfactory and unsatisfactory aggregates. These eruptions may be caused by any number of factors and may or may not be related to the properties of the coarse aggregate. Once an area has been patched it is difficult to determine the reason for the failure.

Described in the following are the case histories for five unsatisfactory aggregate sources.

Glory Stone (Devonian), Rapid Member, Cedar Valley Formation, Waterloo to Davenport. —The Rapid member is a fine- to medium-grained, blue-gray, argillaceous, cherty, dolomitic limestone that may be massive or laminated, generally containing less than 90 percent carbonate.

The Rapid member occurs in many of the quarries where acceptable stone has been quarried separately from the overlying Coralville member and is the most widely studied geologic material in Iowa associated with concrete deterioration. Aggregate from the Rapid member consistently exceeds freeze-thaw test limits.

Deterioration of concrete containing aggregate from the Rapid member was first recognized in eastern Iowa early in 1930. This rock was not used again in that area. However, because the geologic correlation was not established for all the quarries in the outcrop belt, the rock was eliminated in some quarries and not in others. Deterioration was later associated with this same layer of rock for aggregate from the Glory quarry.

Between 1927 and 1934 aggregate from the Glory quarry was used in many paving projects in northeast Iowa. In nearly every case the pavement began to show signs of deterioration at ages ranging from 3 to 8 years. By 1950 nearly all the pavement made with Glory aggregate was in a critical state of deterioration. Figure 2 shows the appearance of typical sections of pavement containing aggregate produced from the Rapid member. Aggregate from this kind of rock is usually referred to as Glory type because of the association with the Glory quarry.

The 40-ft working face at the Glory quarry has up to 10 ft of the Coralville member overlying 30 ft of the Rapid member. The Coralville member is a fine-grained limestone containing 95 percent or more calcium carbonate. This quarry face is duplicated almost exactly at Pints quarry. Rock from Pints quarry has been used in these studies because no material has been produced from the Glory quarry for many years.

Test results on separate samples of aggregate from the Coralville or Rapid members are usually consistent. Rock from the Coralville member meets, but rock from the

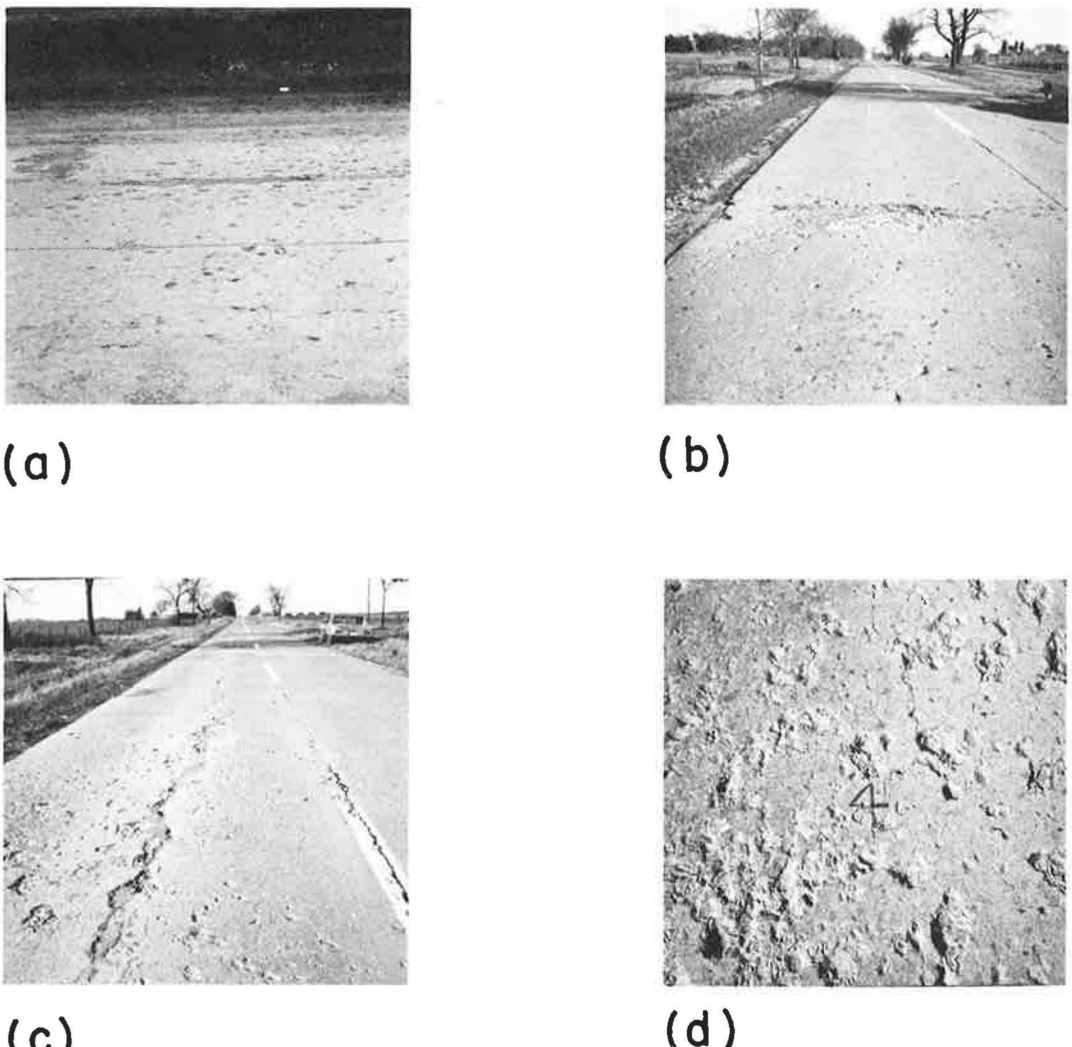


Figure 2. Typical condition of concrete containing aggregate from the Rapid member: (d) is close-up of area shown in (c).

Rapid member exceeds the freeze-thaw test limits. Test results on the crushed product are highly variable whenever stone from both members is present in the samples tested.

Glory type aggregate has been studied extensively by Lemish et al. (1, 7, 8, 9, 10). This was the rock in which Lemish (7) noted the presence of peripheral rims in the coarse aggregate particles taken from deteriorated concrete.

The Rapid also has an effect on the durability of concrete when mixed with aggregates that have shown 40 years of excellent service when used separately. Occasionally aggregate from the Iowa City quarries included variable amounts for the Rapid member wherever quarry operations extended deeper than the Coralville member. In one paving project variable amounts of aggregate from the Rapid member were included in the aggregate used in some randomly located areas of concrete, that is now 37 years old. Wherever the concrete shows deterioration, as in Figure 2b, it is almost always possible to find the characteristic blue-gray aggregate particles of Rapid member. For sections of pavement in excellent condition, few or no particles are found that are similar in lithology to the rock from the Rapid member. There appears to be a correlation between the amount of Rapid visible in the concrete and the extent of the deterioration. More work will be needed to verify this relationship.

Fayette Stone (Devonian), Solon Member, Cedar Valley Formation, Davenport and Spring Grove Members, Wapsipinicon Formation, Fayette Area.—Aggregate from the Fayette quarry was used from the late 1920's to the early 1940's. The upper part of the section in this quarry is assigned to the Solon member of the Cedar Valley formation, and the lower part to the Davenport and Spring Grove members of the Wapsipinicon formation. At this quarry the Solon member is an argillaceous, slightly dolomitic limestone similar in lithology to the rock of the Rapid member. The Davenport member at this quarry is of much poorer quality than at some other localities. The Spring Grove member is a laminated, high calcium carbonate limestone with a low percent of loss in the freeze-thaw test. The rock that was quarried at the time aggregates were produced for concrete was generally a mixture of varying amounts of Solon, Davenport, and Spring Grove members. Although the average quality of the rock as measured by the water-alcohol freeze-and-thaw test is slightly better than the material from the Glory quarry, it is still outside currently acceptable limits.

Pavement, made with Fayette stone, remains in excellent condition without any signs of deterioration for at least 20 years. Sometime between 20 and 25 years of age deterioration begins and progresses very rapidly. Figure 3 shows the general condition in 1963 of highways ranging in age from 23 to 27 years. Table 3 shows that most of the 23-yr-old pavement has only a few patches, whereas the number of patches increases very rapidly for progressively older pavements. Several of the projects in Table 3 have been under observation since 1957. In 1957 the concrete on project 28-11 was in excellent condition. Photographs of this project taken in 1958 are shown in Figure 4. In 1960 this pavement appeared similar to that in Figure 3c with several patches per mile. By the fall of 1963 deterioration had progressed in the original concrete adjacent to the older patches and the number of patches per mile has greatly increased.

Unsatisfactory Service but Meeting Test Limits

Although there is interest in the mechanics of the failure associated with the lithologies shown by the Rapid and Solon members, this rock is not a problem at this time. Rocks of this type, the argillaceous limestones and dolomitic limestones, are eliminated by the six percent maximum allowable loss in the current water-alcohol freeze-thaw test.

Presently the problem concerns three relatively pure carbonate aggregates, consisting of 95 percent or more total carbonate content, that meet all current test requirements, but give unsatisfactory service and have no known or currently measurable characteristics to differentiate them from the aggregates with good service records. Two of these sources, Decorah and LeGrand rocks, have been rejected on the basis of service record. Concrete containing aggregate from the Otis member is deteriorating very rapidly in pavements less than 20 years old.

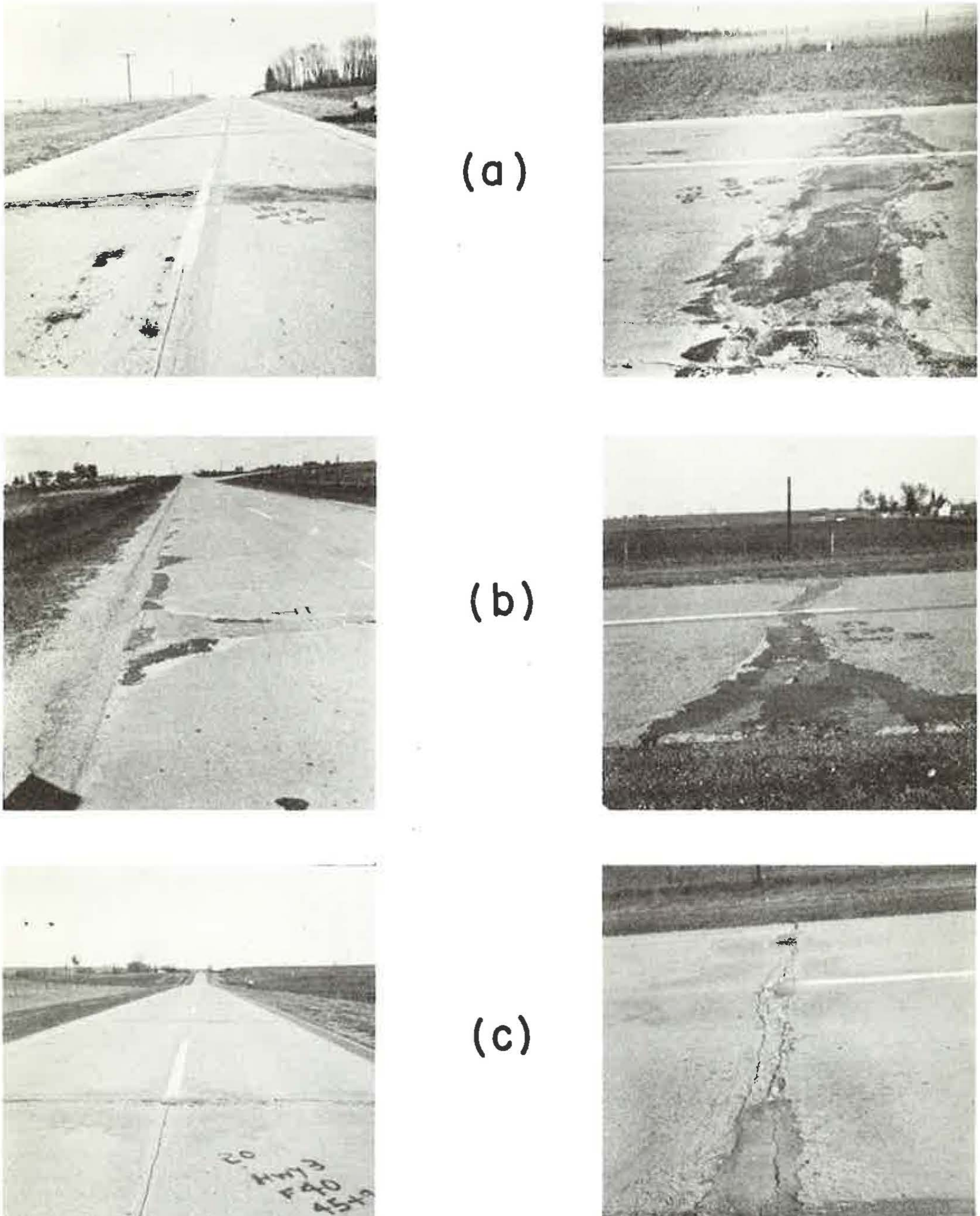


Figure 3. Typical condition of concretes of various ages containing Fayette stone: (a) project 28-10, 27 years old; (b) project 28-11, 24 years old; and (c) project 28-14, 23 years old.

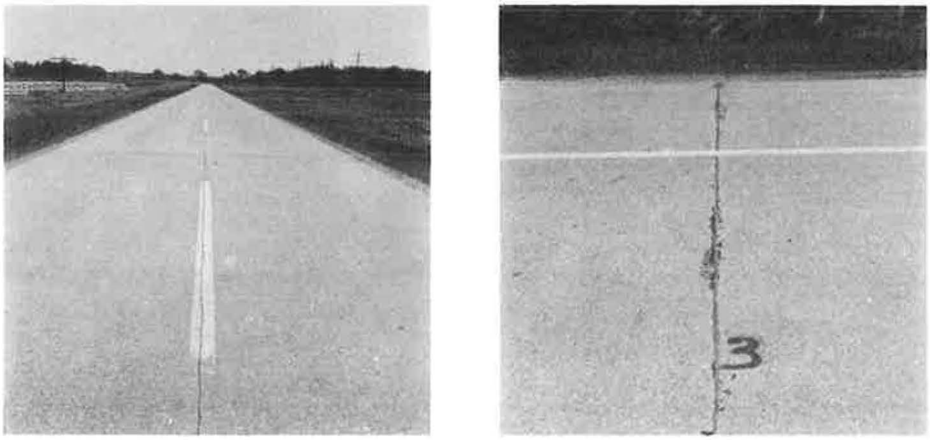


Figure 4. Project 28-11 in 1958, 20 years old. Compare with Figure 3b (left).

(a)

(b)

(c)

(d)

Figure 5. Typical condition of concrete containing LeGrand stone, project 85-11.

LeGrand Stone (Mississippian), Maynes Creek Member, Hampton Formation, LeGrand Area. —In general, the rock is a medium-grained, crinoidal, variably weathered, cherty, dolomitic limestone with induration ranging from hard and dense to soft, porous and friable. The total carbonate content of the chert-free rock averages about 95 percent.

The LeGrand aggregate was the first aggregate meeting test limits to be associated with early concrete deterioration. The rock was used extensively from the late 1920's to the late 1930's. Deterioration of the concrete did not appear as early as with Glory aggregate. Generally, deterioration was first noted when the pavements were about 10 years old and became severe when the concrete was between 15 and 20 years of age. The general pattern of deterioration (Fig. 5) is much the same as that seen on pavements containing Glory aggregate. Photographs (Fig. 5) were taken in 1963 of 25-yr-old pavement that has more than 500 patches in five miles.

Decorah Stone (Ordovician), Galena Formation, Decorah Area. —The rock is medium-grained limestone mottled with soft patches of dolomite, averaging about 95 percent total carbonate. Working faces in the quarries ranged from about 30 to more than 100 ft in height. In general, these faces are fairly uniform in lithology and comply with specifications test limits on a bed-by-bed basis.

The quarries in the Decorah area are in approximately the same stratigraphic horizon as those at Dubuque. Test results are very similar for aggregate from the Dubuque and Decorah sources. The most obvious difference is the lower MgO content of the Decorah rock although the total carbonate content is similar. Aggregate from the Decorah quarries was used in the late 1920's and early 1930's. In 1960 an investigation was made to determine the service record of the concrete made with this rock.

Pavements containing Decorah aggregate that were examined were from 28 to 30 years old. These were compared with pavements of similar age, in the Decorah area, that contained coarse aggregates with satisfactory service records. For several projects, Decorah aggregate and coarse aggregates from one or more other satisfactory sources were used separately for concrete in adjoining sections of pavement. Concrete containing Decorah aggregate was compared with that containing Dubuque crushed stone and Mason City crushed stone. In all projects the concrete with Decorah aggregate showed extensive deterioration. Typical sections of pavements containing Decorah aggregate are shown in Figure 6. The number of patches per mile varies from 30 to more than 150 for various projects under investigation. Concretes containing the other aggregates were in excellent condition. Compare patch counts for projects 3-4, and 96-18 in Table 3. These are adjoining projects on the same highway. The views in Figure 1c were taken on project 3-4, a few hundred feet west of the area shown in Figure 6.

Records of crack surveys made in 1944 of pavement containing Decorah aggregate indicated that deterioration was first noticed when the pavements were about 14 years old.

Otis Stone (Devonian), Otis Member, Wapsipinicon Formation, Cedar Rapids Area. —This geologic source is the most recent to be suspected of being directly related to early pavement deterioration.

The unit ranges from 20 to 25 ft in thickness and consists of alternating beds of fine and medium to coarse-grained rock that varies from dolomite limestone to calcitic dolomite and contains more than 96 percent total carbonate. Each ledge in the quarry face used for concrete meets the test requirements of the specifications.

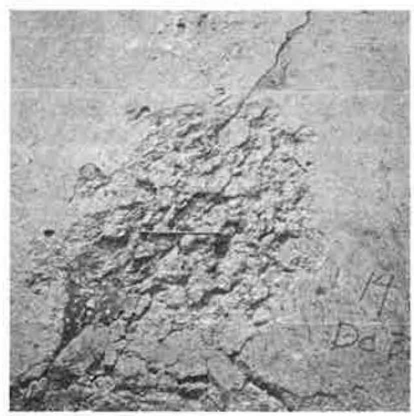
Deterioration was first noticed in 1958 on pavements ranging from 14 to 20 years of age. In 1957 and 1958 the condition of most Otis pavement was similar to that tabulated for project 28-17 (Table 3). Joints showed evidence of spalling near the quarter point and one to two joints per mile had been patched. Some discoloration was noted but no "D" cracks were seen. During the next few years periodic observations were made of many sections of Otis pavement ranging from 5 to 23 years of age. Deterioration of varying severity was noted in all pavements exceeding 14 years of age. In general, deterioration was more severe on pavements more than 16 years of age. Photographs taken in 1963 of several pavements containing this aggregate are shown in Fig-

ure 7. These pictures show the typical but variable pattern of increasing deterioration and patching with increasing age beyond 15 years. Some failures (Fig. 7c, left) were noticed where there appears to be displacement of the concrete.

(a)

(b)

(c)



(d)

Figure 6. Typical condition of concrete containing Decorah stone, project 96-18.

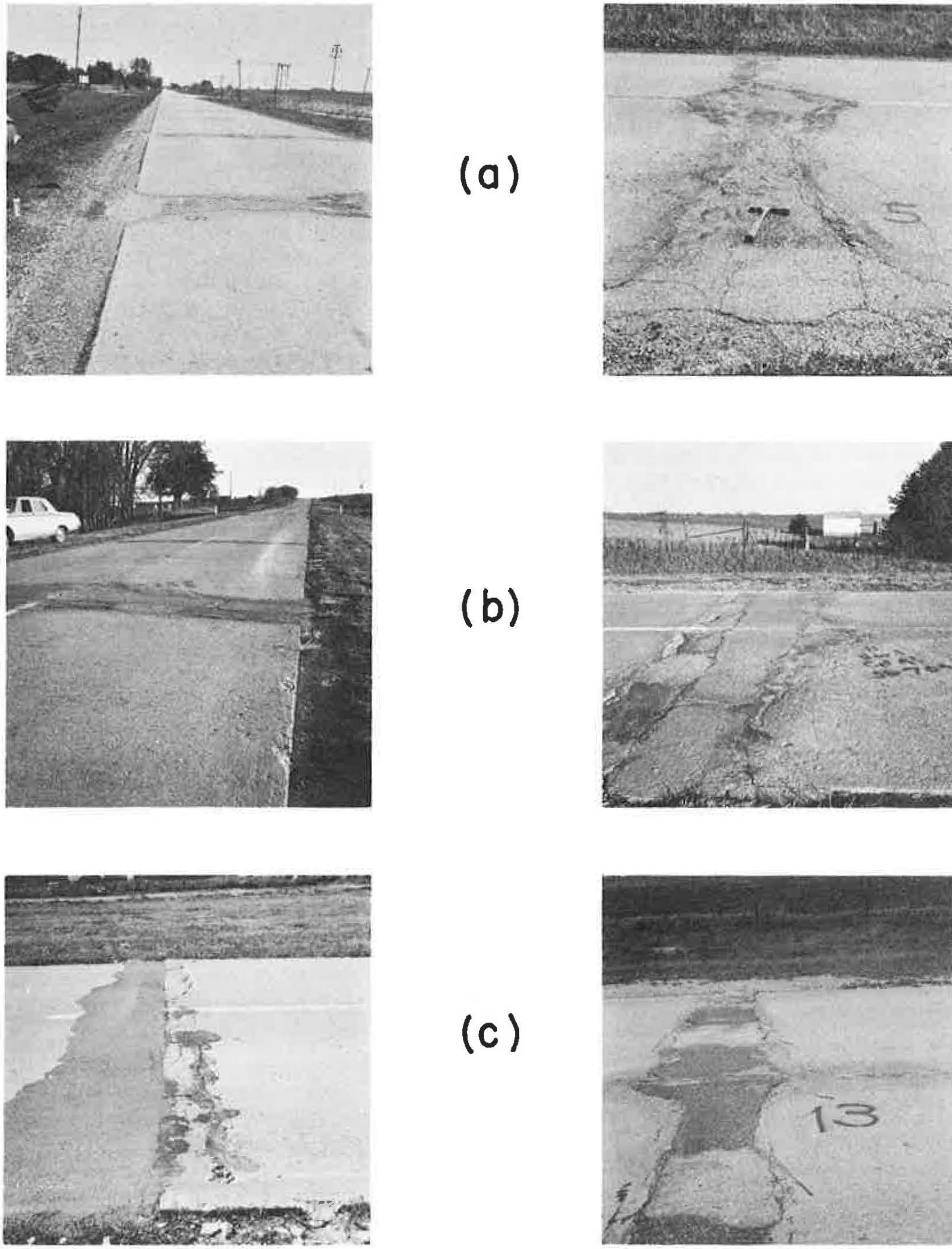


Figure 7. Typical condition of concrete of various ages containing Otis stone: (a) project 53-11, 25 years old; (b) project 52-25, 22 years old; and (c) project 57-38, 18 years old.

ROCK PROPERTIES STUDY

It is not within the scope of this paper to go into the details of testing procedure or to tabulate the numerous test results that have been obtained on a wide variety of rocks currently being studied, other than those given in Tables 4 and 5. Other test results can be found in publications referred to throughout the text. Current studies include routine tests, conducted by the Highway Commission, and special studies being made under separate research projects by Lemish, and Biggs, at the Geology Department, Iowa State University. Routine tests include the Los Angeles abrasion, freezing and thawing in water-alcohol solution, chemical analyses, and sometimes X-ray studies. Special studies of the carbonate rock at Iowa State University include calcite dolomite distribution, variations in carbonate mineral composition, physical property determinations, specific gravity, absorption, porosity, permeability, specific surface, pore size distribution, determination of insoluble residue, petrographic studies, and rock expansion studies.

Although all tests are conducted on a ledge-by-ledge basis for each quarry the data given in Table 4 are averages for the face worked concrete. Where ledges with significantly different properties are used, each ledge is tabulated separately.

Table 4 shows that unsatisfactory aggregates that exceed 6 percent loss on the freeze-thaw test, range from limestone to calcitic dolomite and contain more than five percent insoluble residue. The residue is generally silt and clay-size quartz and illitic clay. Rocks in this group have freezing-and-thawing losses as high as 60 percent. Lemish (7) initially demonstrated that the greater the insoluble residue content in excess of five percent, the higher the loss on the water-alcohol freezing-and-thawing test. Subsequent testing carried on at the laboratory of ISHC on hundreds of samples has verified this relationship. The relationship does not always hold true when the insoluble residue is chert or sand-sized quartz grains.

Table 5 shows that some of the Glory rock has properties similar to expanding rocks described as occurring elsewhere in the United States and Canada (2, 3, 12), that are associated with the alkali-carbonate rock reaction.

The LeGrand, Decorah and Otis rocks associated with deterioration have measurable properties that are similar to rocks with satisfactory service. They are usually within the allowable six percent freeze-thaw loss, average less than five percent insoluble residue, have little or no illitic clay, and show a variety of lithologies. One characteristic that all three have in common is an intermediate MgO content, ranging from about 5 to 15 percent. However, there is one other aggregate source (Ferguson) with a similar composition that appears to give satisfactory service. Studies by Lemish (11) indicate that these rocks either show no length change or shrink when soaked in alkali solution (Table 5).

Sodium sulfate soundness test results in Table 4 do not appear to have any correlation with service record or the Method "A" freezing-and-thawing test.

CONCRETE STUDIES

The same carbonate aggregates that are being studied for rock characteristics have been and are currently being studied in concrete specimens, in various test environments, and in the concrete pavement. Some phases of the study have been completed and found to be inconclusive by themselves when run on a concrete containing one or another of a wide variety of satisfactory and unsatisfactory aggregate. These tests may have more significance when analyzed in terms of rock characteristics.

Aggregates from more than 25 sources have been used in making 4- by 4- by 18-in. beams for long-time outside storage and for use in the automatic freezer, ASTM method C291-61T, and for special wetting, drying, heating and cooling tests. Cylinders have been made for 3-yr strength studies (Table 4). Special tests for alkali reactivity have been run on mortar bars according to ASTM method C227-52T. Gage plugs have been set in various pavements to study growth. To date, the characteristics measured by these tests have not shown any definite limits that are not present to the same degree in concrete containing one or another of the satisfactory aggregates.

TABLE 4

ROCK PROPERTIES AND CONCRETE TESTS

Source	Soundness Loss (%)		LA[2]	Sp. Gr.	Abs. (%)	Typical Chemical Analysis (%)						Insol. (%)	Conc. Compr. (psi)		
	$NaSO_4$	"A"				CaO	MgO	Loss	Fe_2O_3	Al_2O_3	SiO_2		28 Day	1 Yr	3 Yr
(a) Satisfactory Performance															
Alden	26.9	1.2	41	2.56	1.83	54	1	43	0.1	—	1.0	0.4	5,558	6,378	NC[3]
Dubuque	22.3	2.7	34	2.72	1.08	30	19	44	0.4	0.5	5.0	5.0	5,328	6,172	7,165
Iowa City[4,5]		2.3	32	2.64	1.03	49	4	43	0.1	2.0	0.7	2.0	4,815	5,978	7,043
Davenport[5,6]		1.6	32	2.68		52	2	44	—	—	1.0		5,275	6,125	6,285
Farmington	19.6	8.0	25	2.69	0.63	49	2	41	—	0.6	5.6	5.3	5,151	6,133	6,224
Ferguson	18.6	1.7	36	2.69	1.70	39	12	45	0.9	0.4	1.9	2.0	5,385	6,378	6,790
(b) Unsatisfactory Performance															
Decorah		1.2	35	2.74	0.70	41	11	44	0.3	0.7	2.4		5,160	6,584	NC[3]
Otis[5]	15.5	1.8	33	2.68	1.35	34	16	45	0.6	0.6	1.8	1.2	5,537	6,821	7,030
LeGrand[5]	25.9	3.8	36	2.65	0.95	45	7	43	0.3	0.5	3.3	3.4	5,572	6,748	NC[3]
Fayette															
Solon		20.4	30			51	0	41	0.6	3.3	3.3				
Davenport		41.0	48			50	0	40	0.7	3.2	4.6				
Sp. Grove		2.3	34			53	0	43	0.3	0.5	1.7				
Glory quarry[5]															
Coralville		1.8	30			56	0	41	0.1	0.2	0.4				
Rapid		30.0	34			30	15	40	0.7	2.0	11.1	14.0			
Pints[7]	31.1	16.0	32	2.58	3.65	28	15	39	2.0	1.1	13.1	17.0	5,682	5,911	
Iowa City[4,5]															
Rapid		60.0	43			28	15	39	2.0	1.1	13.3	13.0			

[1] 16 cycles freezing and thawing in water-alcohol.
[2] Los Angeles abrasion test.
[3] Not completed as of Jan. 1964.
[4] River Products quarry.
[5] Quarries studied by Lemish (11).
[6] Linwood quarry.
[7] Same horizons as Glory quarry.

Lemish (11) has undertaken a systematic study of cores from concrete pavements of various ages containing one or another of coarse aggregates from different sources to learn more about changes in the concrete system with time. Aggregate particles are being studied petrographically in concrete beams after testing and in cores from concrete pavements of various ages and conditions to determine, if possible, what changes are taking place and if these changes are different for different aggregates.

Compressive Strength of Pavements

Compressive strengths of cores taken taken in 1963 from 15 projects representing aggregates from six different geological sources are given in Table 6. All cores were taken from the sound portion of the pavement. No relation between condition and strength is apparent.

TABLE 5

EXPANSION DATA AND ANALYSES OF ROCK PRIOR TO ALKALI TREATMENT[1]

Quarry	Bed	Residue Wt. (%)	Ca, as $CaCO_3$ (% wt.)	Mg, as $MgCO_3$ (% wt.)	Si, as SiO_2 (% wt.)	Expansion[2] (%)
Dubuque	1	3.5	92.9	3.0	3.1	- 0.1
	3	15.5	45.0	38.8	12.9	- 0.2
	4	3.3	51.6	44.3	2.3	- 0.2
Ferguson	2	1.8	89.3	9.0	1.7	- 0.1
	4	7.1	52.6	38.6	5.2	- 0.1
	6	0.8	93.8	5.3	0.6	- 0.1
	7	11.2	50.6	36.1	7.5	0.1
	9	1.6	71.3	23.9	0.4	- 0.2
	10	2.7	63.0	33.2	2.1	- 0.1
	11	3.2	62.0	33.4	2.1	- 0.1
	12	1.9	95.1	2.2	1.7	- 0.1
	13	2.8	64.8	31.2	1.9	- 0.1
	14	1.4	78.8	18.3	1.1	- 0.1
	16	1.3	89.0	8.6	1.7	- 0.2
	17	1.4	78.3	19.1	1.7	- 0.2
	19	1.9	59.9	36.5	1.2	- 0.2
Glory	2	7.2	66.5	24.8	5.2	0.8
	3	10.1	65.2	23.4	6.8	1.2
	4	10.9	60.9	26.1	7.5	0.4
	5	12.1	61.9	23.9	8.6	1.1
	6	12.8	62.9	22.1	9.2	0.8
	8	9.1	68.4	20.7	6.9	0.2
	9	15.9	53.3	28.4	11.2	0.0
	10	16.1	50.3	31.5	11.7	0.1
LeGrand	8	2.7	57.4	37.7	1.9	0.0
	9	2.6	56.1	39.0	1.9	0.0
	10	1.6	70.3	26.3	1.5	0.0
	11	1.6	64.1	31.9	1.6	0.0
	12	2.0	62.0	34.1	1.7	0.0
	13	1.0	82.0	15.0	1.3	0.0
Linwood	3	0.4	97.0	1.9	0.6	- 0.1
	4	0.8	98.3	0.4	0.7	- 0.1
	6	0.7	97.1	1.6	0.3	- 0.1
	9	1.2	96.8	1.6	0.9	- 0.2

[1] Partial table: Lemish and Moore (11).
[2] 150 days in NaOH.

TABLE 6

COMPRESSIVE STRENGTHS OF CORES FROM CONCRETE PAVEMENTS

Project Co.	Project Cd.	Coarse Aggregate	Sand	Cement	Age (yr)	Avg.[1] (psi)
(a) Satisfactory Performance						
40	13	Alden	20	2	27	7,462
85[2]	5	Alden	1	1	34	7,805
31	26	Dubuque	4	5	6	8,137
31[2]	13	Dubuque	4	4	31	10,080
31		Dubuque	4	3	35	10,797
31	2	Dubuque	4	5	36	10,982
52[2]	2	Iowa City	5	4	42	6,940
52[2]	7	Iowa City	6	5	36	8,616
(b) Unsatisfactory Performance						
96	6	Decorah	21	5	35	9,761
57	64	Otis	17	5, 7, 4	2	7,136
57	60A	Otis	17	5	7	8,430
57	54	Otis	17	5	11	8,230
57[2]	38	Otis	17	5	17	9,698
52	26	Otis	17	2	22	10,000
53[2]	11	Otis	17	5	25	8,627

[1]Avg. 3 or 4 cores, generally less than 500-psi variation.
[2]Also in Table 3.

DISCUSSION

From service record studies, it is found that most of the concrete containing carbonate aggregates that meet current test limits can be expected to remain durable for 25 to 30 years. Deterioration of concrete with less than 20 years of service has been associated with the five sources in this report. For each of these sources an age span can be assigned at which the first signs of deterioration in the concrete are noticeable, even with variations in design, cement, sand, foundation conditions, and traffic. These are Glory, 3-5 years; Fayette, 20-23 years; LeGrand, 10-14 years; Decorah, 12-16 years; and Otis, 14-17 years. In all cases the pattern of deterioration is similar and progressive with disintegration throughout the entire pavement containing the unsatisfactory aggregates, when the concrete is about 25 to 30 years of age.

In general, the six percent loss limit on the water-alcohol test shows a good correlation between performance and test results for about 40 geologic sources. The Farmington aggregate is the exception, it averages eight percent loss but has a 35-year satisfactory service record. The other seven sources that exceed the six percent loss, like Glory and Fayette, have unsatisfactory service records. However, this freeze-thaw test and other test procedures that have been tried do not show any properties to separate the unsatisfactory LeGrand, Decorah, and Otis aggregates which meet test limits from aggregates with satisfactory service. This would indicate that there are other properties or combinations of properties not being measured that affect the durability of the concrete.

It is hoped that the research studies now in progress will show a measurable property or combination of properties that will establish a better correlation between test results and concrete durability.

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