Alkali-Reactive Carbonate Rocks in Indiana—A Pilot Regional Investigation

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A study of carbonate rocks exposed in Indiana indicated that by utilizing standard geologic field techniques coupled with specially developed simple, rapid laboratory tests, the distribution of the reactive rocks within the vertical sequence of beds and the geographic areas in which these reactive rocks were exposed could be rapidly delineated.

The reactive rocks are widely distributed in Indiana, with highly reactive material present in at least five of the formations exposed. Rock from at least one of these horizons is considered to have caused the disruption of field concrete. Fortunately, however, the reactive beds are normally thin, the general level of reactivity is low, and most of the highly reactive materials are of poor physical quality and consequently are not used frequently as concrete aggregate.

Studies on laboratory concretes show that many of the marginally reactive materials could be safely used as concrete aggregate if adequate precautions were taken.

•OBSERVED EFFECTS in concrete containing certain carbonate rocks as aggregate may involve at least two distinct types of chemical reactivity. One type, first reported by Swenson (1), involves disruptive expansion of the coarse aggregate particles; the other, described by Bisque and Lemish (2), is characterized by the development of siliceous reaction rims on the aggregate particles. The work of Bisque and Lemish (3, 4) on the rim-developing rocks, and that of Swenson and Gillott (5) and Hadley (6) on the expansive rocks, has shed additional light on the mechanisms of reactivity. Very little is known about the occurrence, relative abundance, and distribution of reactive rocks, information which is of immediate interest to the practicing engineer. As a first step in assembling such information, the Portland Cement Association Laboratories included in its research on reactive carbonate rocks a pilot field and laboratory investigation of the rocks exposed in a specific geographic area. Indiana was chosen for study because of its proximity, thick section of carbonate rocks exposed, and the presence of carbonate rocks with poor service records as concrete aggregates.

The investigation was designed to collect information on the occurrence and distribution of reactive rocks in the study area, and to develop and evaluate sampling and testing methods applicable to rocks exposed in other areas.

Preliminary laboratory work included the development of simple, rapid tests for both types of reactivity in rock samples. Therefore, the pilot study began with an integrated program of field sampling and laboratory testing to determine the geological and geographical distribution of both types of reactive rocks. Selected rocks of known reactivity were then collected in larger quantities and used as coarse aggregate in laboratory concrete tests to establish correlations between the preliminary laboratory test

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results and the properties of concretes containing these rocks. Additional testing of concretes made with the reactive rocks was performed to evaluate possible remedial measures.

Previous Studies

In 1945 Woods, Sweet and Shelburne (7) found that the expansion of concrete pavements in Indiana, which had led to map cracking and eventual blowups, could in many cases be correlated with the source of the coarse aggregate. In subsequent detailed investigations of rocks from these sources, Slate (8) found no evidence of alkali-silica reactivity, but Sweet (9) found that many of these rocks performed poorly in freezing and thawing tests of concretes. Patton (10) reported that many of the poorly performing aggregates were quite similar in lithology, and that rocks of this type were found primarily in limited zones of the Jeffersonville, St. Louis, and Kokomo formations. Patton felt that the poor service record of these rocks was probably due to poor durability under freezing and thawing conditions.

Types of Chemically Reactive Carbonate Rocks

Rim-Developing Rocks.—Bisque and Lemish (2) noted that certain carbonate rocks developed prominent reaction rims in concrete. These rims are composed in part of siliceous materials, first believed to have been derived from the cement paste. Subsequent studies (11) seem to indicate, however, that the rims are primarily the result of a redistribution of the siliceous components of the rock itself. The exact mechanism of rim formation is not yet clear nor has it been demonstrated that the development of rims per se indicates a deleterious chemical reaction.

Expanding Rocks.—The second type of reactive carbonate rocks expands rapidly both in concrete and in highly alkaline solutions. Hadley (6) found that the expansive rocks could be characterized on the basis of composition and texture. All were argillaceous dolomites or dolomitic limestones, and the most highly reactive of these rocks contained mixtures of calcite and dolomite and large amounts of clay. (Clay is used here as including all noncarbonate material in the rock having an equivalent spherical diameter of two microns or less. Clay contents were normally determined by subtracting from the total acid-insoluble residue the percentage of silt-sized and larger particles as estimated by petrographic techniques.) In addition, these rocks all shared a common texture, being composed of silt-sized dolomite rhombs "floating" in a matrix of clay and finely disseminated calcite. The expansion of these rocks accompanied the following chemical reaction between the alkali metal hydroxides and the mineral dolomite:

$$CaMg(CO_3)_2 + 2MOH \rightarrow M_2CO_3 + Mg(OH)_2 + CaCO_3$$

in which M = K, Na, or Li.

SAMPLING PROGRAM

Geologic Setting

The problems of locating reactive carbonate rocks in the field were much the same as would be encountered in the exploration for any mineral resource. Inasmuch as this phase of the study was essentially a geologic exploration, a summary of the pertinent features of the geology of Indiana has been included.

Structural Relationships.—Indiana lies in the central stable region of North America. In contrast to the highly contorted rocks found in those regions which have undergone periods of mountain building, deformation of rocks in the central stable region has been confined to mild warping and flexing. The resulting structural features are a series of broad domes and basins. The geologic map and cross-sections (Figs. 1, 2) show that Indiana lies between two of these basins. The rocks in northern Indiana dip gently northward into the Michigan basin, whereas in southern Indiana the dip is to the south-

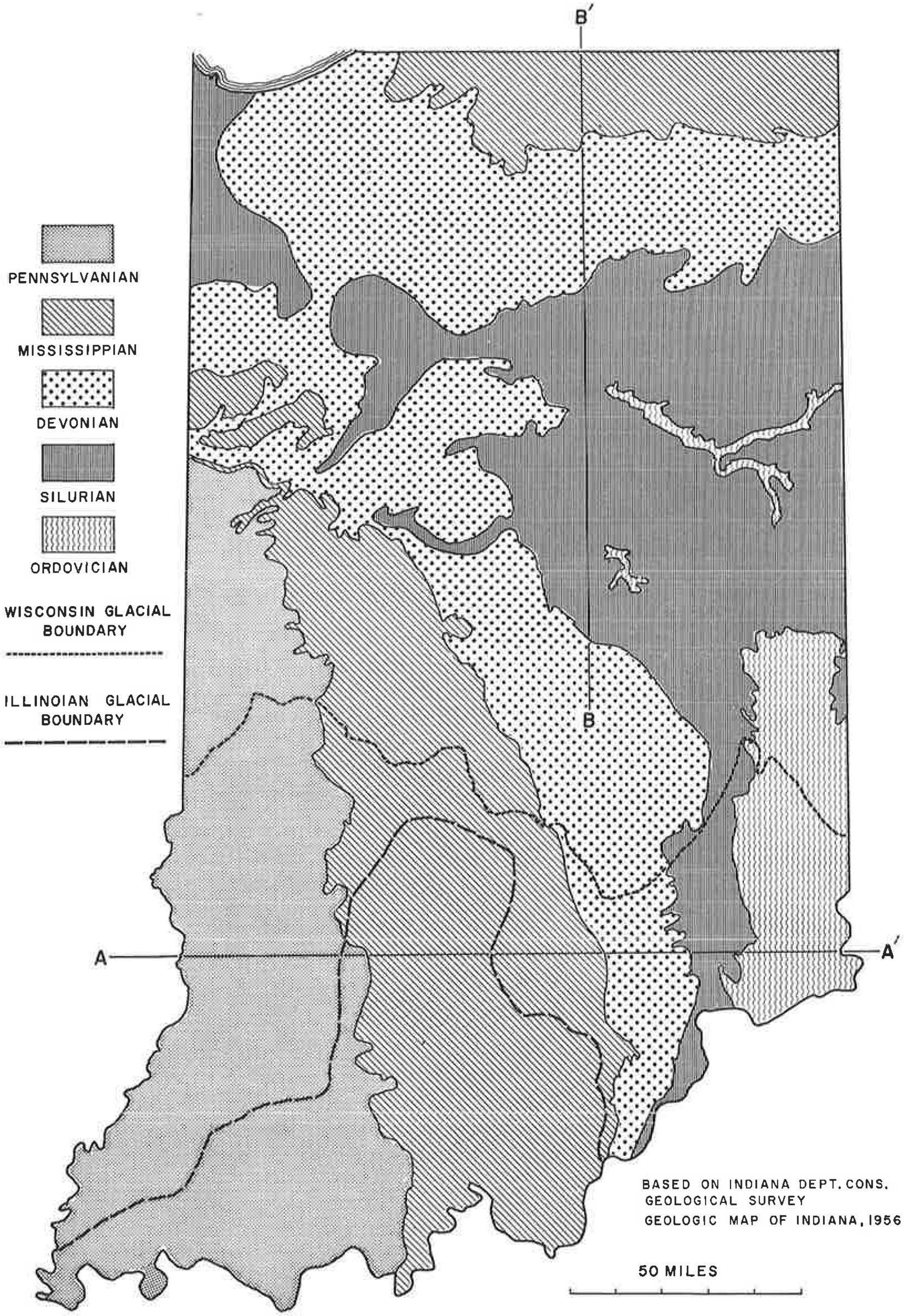


Figure 1. Generalized geologic map of Indiana.

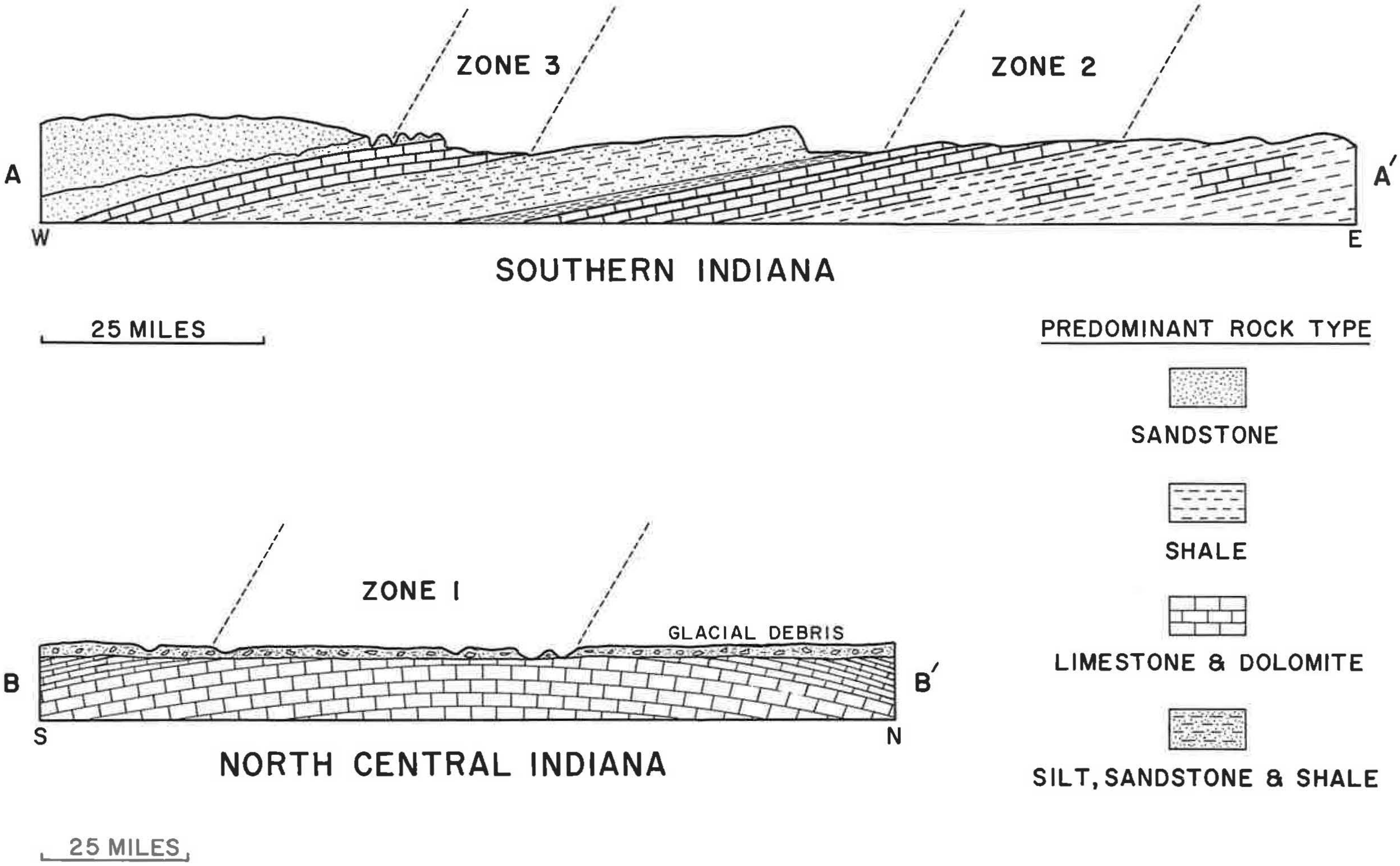


Figure 2. Diagrammatic cross-sections through southern and north-central Indiana showing major zones of limestone outcrop.

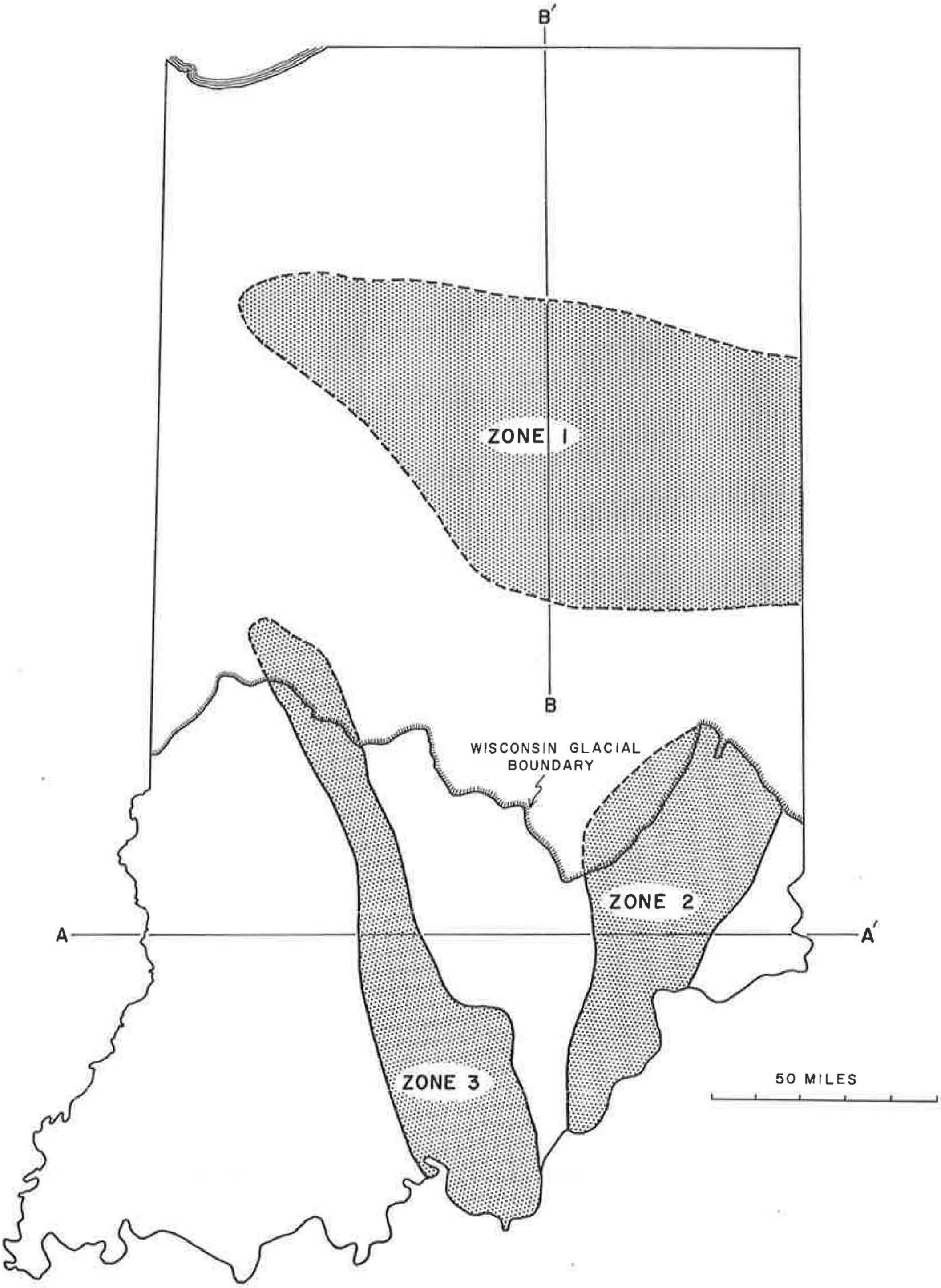


Figure 3. There are three major zones of limestone outcrop in Indiana.

west and into the Illinois basin. In north-central Indiana the strata pass through a transitional zone in which the rocks are essentially flat lying.

Glacial Deposits.—At least three times in the geologic history of Indiana much of the state was covered by the ice of the great continental glaciers. At the time of maximum advance the ice covered almost 85 percent of the state. Each time the ice retreated it left extensive deposits of glacial till.

These glacial deposits influence the location of crushed stone plants because quarrying is possible only in those glaciated areas where till is extremely thin or where erosion by the major streams or their tributaries has exposed the previously buried bedrock. The two principal till sheets exposed in Indiana are described in the following:

Illinoian Till.—More than half of southern Indiana is overlain by Illinoian till. The deposits are relatively thin, ranging up to only about 30 feet. Because this material

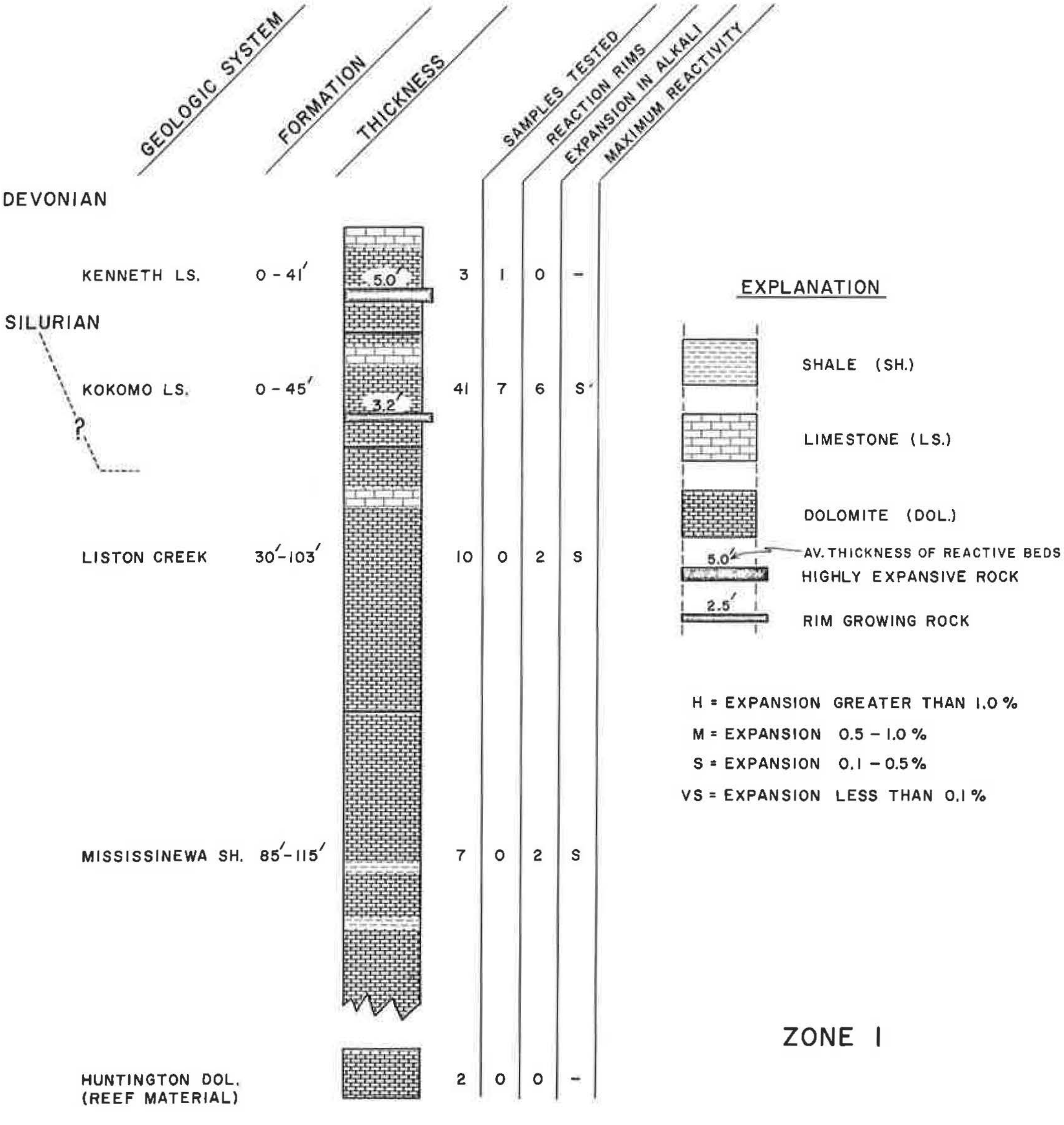
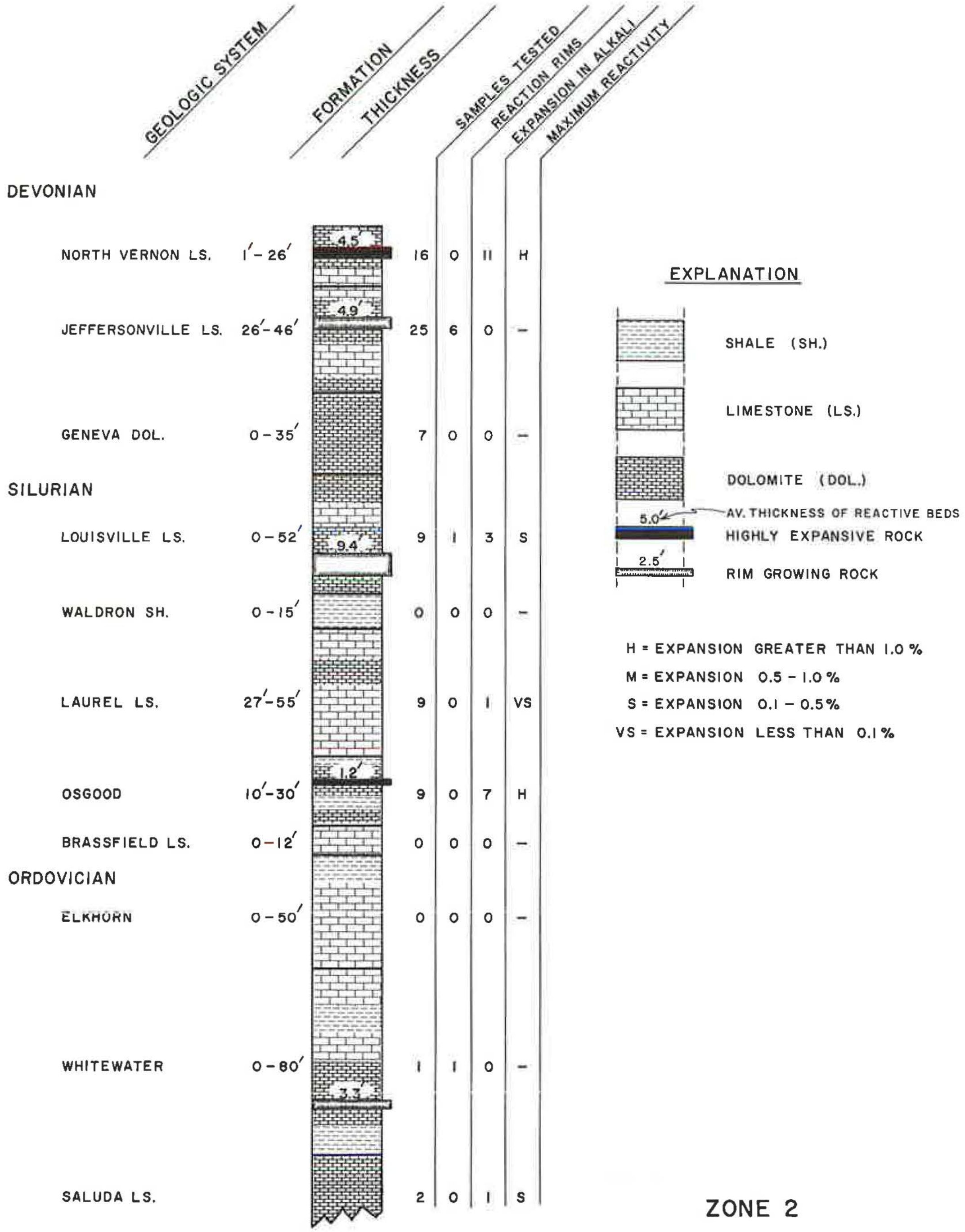


Figure 4. Columnar section showing distribution of reactive beds.



GEOLOGIC SYSTEM	FORMATION	THICKNESS	SAMPLES TESTED	REACTION RIMS	EXPANSION IN ALKALI	MAXIMUM REACTIVITY
DEVONIAN	NORTH VERNON LS.	1′ – 26′	16	0	11	H
	JEFFERSONVILLE LS.	26′ – 46′	25	6	0	–
	GENEVA DOL.	0 – 35′	7	0	0	–
SILURIAN	LOUISVILLE LS.	0 – 52′	9	1	3	S
	WALDRON SH.	0 – 15′	0	0	0	–
	LAUREL LS.	27′ – 55′	9	0	1	VS
	OSGOOD	10′ – 30′	9	0	7	H
	BRASSFIELD LS.	0 – 12′	0	0	0	–
ORDOVICIAN	ELKHORN	0 – 50′	0	0	0	–
	WHITEWATER	0 – 80′	1	1	0	–
	SALUDA LS.		2	0	1	S

Figure 5. Columnar section showing distribution of reactive beds.

C 227, could be used for a determination of the level of rock prism expansion below which the Indiana aggregates could be safely used with a given cement.

Strength Development in Concretes Made with the Rim-Developing Rocks

In studies of concretes made with a rim-developing Iowa carbonate coarse aggregate, Bisque and Lemish (4) found that under certain storage conditions the rate of strength development was adversely affected. Therefore, a series of tests was made to determine whether the rim-developing Indiana rocks would also affect the rate of strength gain.

Description of Concrete Mixes.—All mixes were maintained at a water-cement ratio of 0.40 and a slump of 1 to 2 in. The cement factor ranged from 6.3 to 6.7 sacks per cubic yard. Maximum aggregate size was ¾ in. and sand constituted 36 percent of the absolute volume of aggregate.

Materials.—The cement used was Cement 14 of the "Long-Time Study of Cement Performance in Concrete" (12). This cement, which is of high alkali content (0.06 percent Na_2O and 1.30 percent K_2O), is regularly used in tests of the alkali reactivity of aggregates at these laboratories. The fine aggregate was the Elgin, Illinois, sand described earlier; the coarse aggregate was either a rim-developing carbonate rock from a laminated zone of the Jeffersonville, Indiana, limestone or an inert gravel from Elgin, Illinois. The chemical analysis, specific gravity, and fineness of the cement, together with the grading, specific gravity, and absorption of the aggregates are given in Table 7.

Specimen Preparation.—Specimens were 3- by 6-in. cylinders cast in accordance with ASTM C 192-59.

Curing.—After casting, specimens were stored immediately under wet burlap covered with a polyethylene sheet. After 20 to 24 hr the specimens were removed from the molds and stored either at 100 F over water, at 73 F and 100 percent RH, or in a wetting and drying cycle of 2 days in water at 73 F followed by 5 days in air at 100 F and 24 percent RH.

Testing.—Cylinders were tested in compression at 7, 28, 90, and 180 days and at 1 yr.

TABLE 7

CHARACTERISTICS OF MATERIALS USED IN LABORATORY CONCRETE TESTS OF RIM-DEVELOPING COARSE AGGREGATE

Cement (LTS 14)			Coarse Aggregates			Gradation (% ret.)		
Determination	Result		Type	Bulk Sp. Gr.	Absorp.[a] (% by wt.)	¾ In.	⅜ In.	No. 4
	Value	Unit						
SiO_2	22.1	%	Elgin, Ill., gravel	2.65	2.00	35	65	100
Al_2O_3	4.7	%	Jeffersonville crushed rock	2.49	6.31	35	65	100
Fe_2O_3	3.0	%						
CaO	62.9	%						
MgO	2.4	%						
SO_3	1.7	%						
Na_2O	0.06	%						
K_2O	1.30	%						
Tot. alk., as Na_2O	0.92	%						
Mn_2O_3	0.13	%						
Loss on ignition	0.9	%						
Insol. residue	0.31	%						
Sp. surface:								
Wagner	3434	sq cm/gm						
Blaine	1880	sq cm/gm						
Passing No. 325 sieve	97.7	%						
Sp. gr.	3.183	-						

[a] 24 hr.

TABLE 8

ADVERSE EFFECT OF RIM-DEVELOPING ROCKS ON STRENGTH DEVELOPMENT RATE IN CONCRETE[a]

Test Age (days)	Compressive Strength (psi)					
	Stored 100 F Over Water		Stored 73 F, 100% RH		Storage Cycle 2 Days in H_2O at 73 F 5 Days in Air, 100 F, 24% RH	
	Jeffersonville	Elgin	Jeffersonville	Elgin	Jeffersonville	Elgin
7	6380	5760	5800	5700	5920	5220
28	6320	7190	7280	7060	7890	7750
90	6040	8790	6950	8350	7870	8300
180	6270	9750	6630	8320	7770	9220
360	6810	10070	5840	8700	9360	9740

[a] 3- by 6-in. cylinders made with Elgin, Ill., gravel and rim-developing Jeffersonville limestone from Indiana (both 3/4-in. max. size); cement content 6.3 to 6.7 sk/cu yd; w/c ratio 4 1/2 gal/sk; slump 1 to 2 in.; cured 1 day in molds at 73 F, 100% RH, then to designated storage.

Test Results.—Test results are given in Table 8. Under all storage conditions the over-all strength and the rate of strength development in the Jeffersonville concretes were affected.

The specimens subjected to the wetting and drying cycle showed normal strength development for the first month, but failed to show any gain in strength between 28 days and 6 mo. Between 6 mo and 1 yr, the specimens began once more to gain in strength, becoming comparable to the Elgin concretes at 1 yr.

The specimens stored in cans over water at 100 F were more severely affected and did not gain significantly in strength between 7 days and 1 yr. The specimens stored in the moist room at 73 F were the most severely affected and showed a slow but steady decline in compressive strength from 28 days to 1 yr. At the end of the test period, the Jeffersonville concretes moist cured at 73 F had developed only two-thirds the strength of the comparable Elgin specimens. Testing will be continued to determine whether long-term strength loss occurs and if it is sufficient to affect the performance of field concrete.

DISCUSSION

Evaluation of Sampling and Testing Techniques

In any study of this type, one of the most difficult problems is that of obtaining representative samples. In this respect, the geologically oriented approach taken in this investigation proved valuable. By sampling a relatively small number of key sections, it was possible to determine the general character of the rocks in each of the formations exposed in the area. All of the stratigraphic horizons found to bear reactive rocks were identified in the initial sampling that encompassed only 22 sites. Supplementary sampling delineated the horizontal extent of the reactive beds and investigated possible lateral variations in rock characteristics.

The test program, involving the great number of samples necessary for adequate coverage of the thickness of rock involved, would not have been feasible without the special test methods which were developed. These simple tests, which require only a small amount of rock and permit the concurrent testing of large numbers of samples, proved to be ideally suited for a large-scale reconnaissance of this type. They do, however, necessitate certain precautions. Because the prism size is small in comparison to the body of rock itself, great care must be taken in sampling to insure that the samples are actually representative of the bed being tested. Although the same is true to some extent of concrete and mortar bar tests, it is possible in these cases to

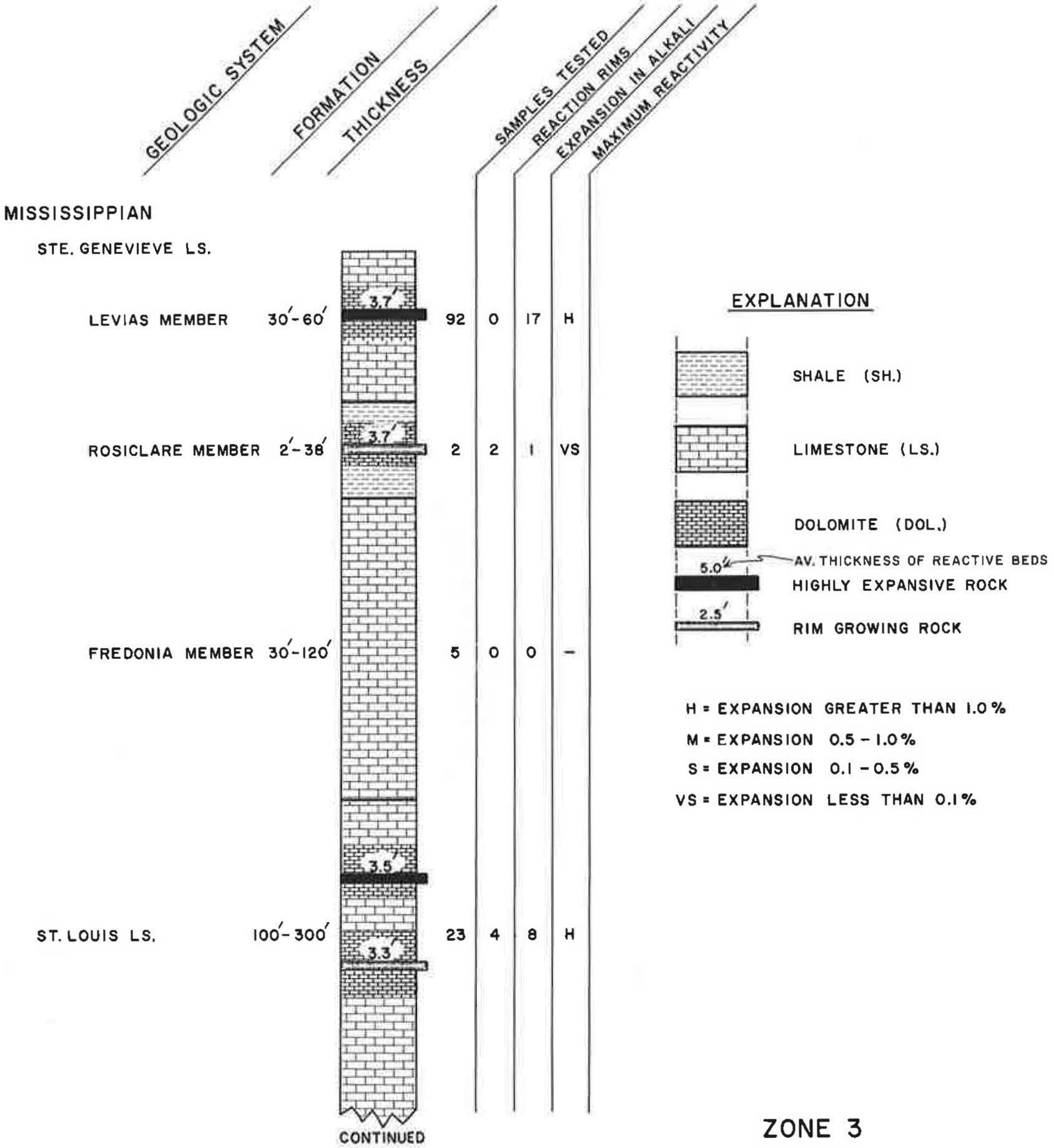


Figure 6. Columnar section showing distribution of reactive beds.

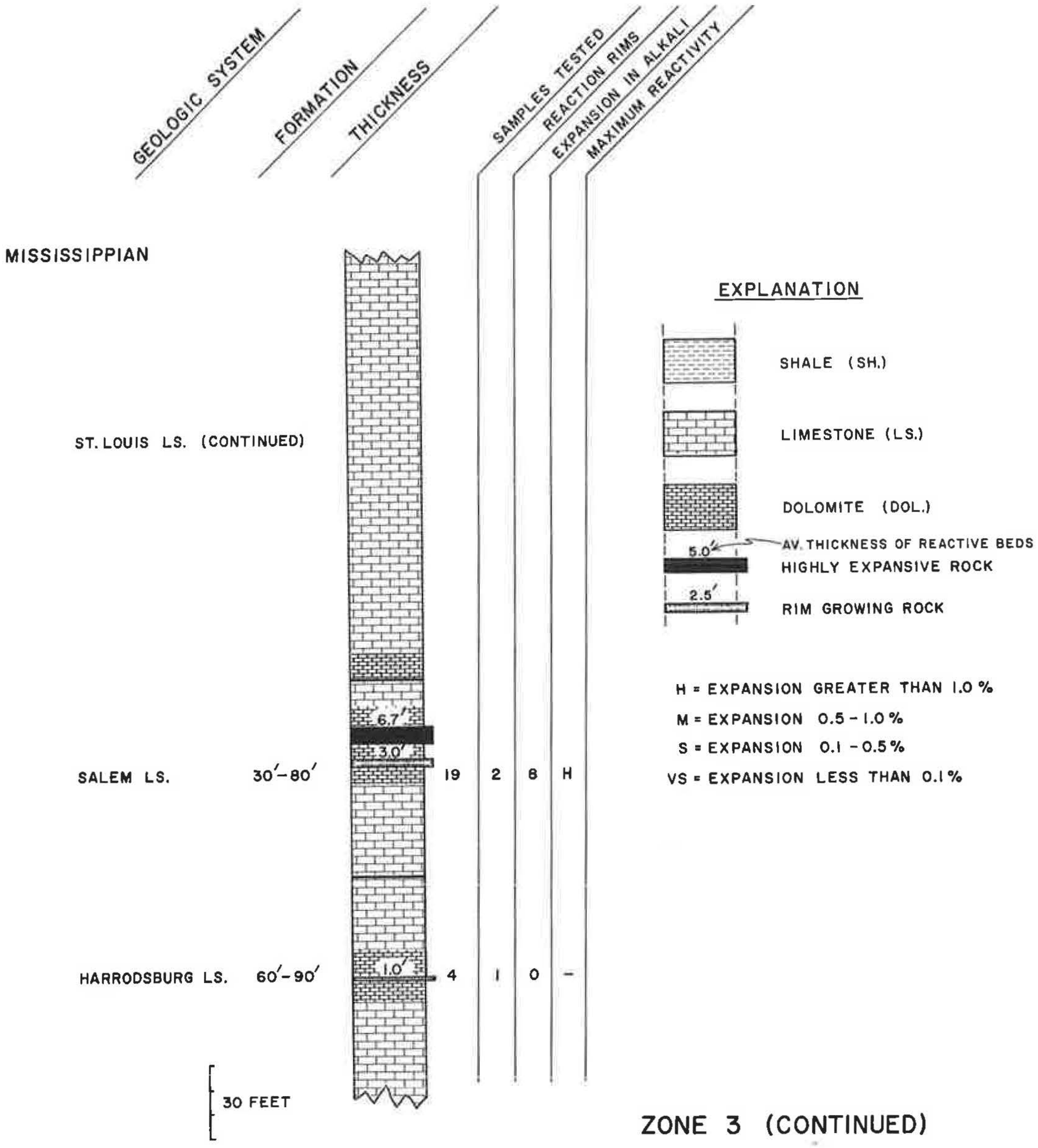


Figure 7. Columnar section showing distribution of reactive beds.

has been exposed to erosion for an extended period, there are many localities where bedrock is exposed or only thinly covered.

Wisconsin Till.—The Wisconsin till is the most recent and is a much thicker deposit than the Illinoian. The combined thickness of Wisconsin and earlier tills reaches as much as 550 feet. Exposures of bedrock are extremely rare in the portions of the state covered by the Wisconsin till.

The areas covered by the Illinoian and Wisconsin glaciers are shown on the geologic map (Fig. 1).

Distribution of Carbonate Rocks.—As is shown in the geologic cross-sections (Fig. 2), there are three major zones in the vertical sequence of rocks that outcrop in Indiana in which limestones and dolomites form the principal rock types. The production of carbonate aggregates is almost entirely confined to the rocks in these zones. Each of these zones contains one of the stratigraphic horizons cited by Patton (10) as holding rock which performed poorly in concrete. The approximate geographic areas in which rocks of each zone are quarried are shown in Figure 3.

Sample Collection

During the summer of 1959, 22 localities were sampled which included rocks from almost all of the strata exposed in each zone. Sampling was done on a bed-by-bed basis with additional samples taken from any bed which showed appreciable lateral variation within the limits of the outcrop. To avoid misinterpretation of this study as an evaluation of specific aggregate sources, sampling was largely confined to road-cuts, abandoned quarries, and natural exposures.

Although the initial sampling gave a good coverage of the vertical sequence of rocks, it was realized that a good deal of lateral variation probably existed in many of the formations sampled. Numerous additional exposures between the principal sections were therefore examined and sampled wherever significant variations in the nature of the rock were recognized. As a further check, the author obtained permission to study the fine collection of thin sections of carbonate rocks on file at the Industrial Minerals Section of the State Geological Survey in Bloomington. Because previous laboratory studies had shown that the reactive carbonate rocks all fell within a fairly narrow range of mineral compositions and textures, it was possible to differentiate quickly potentially reactive rocks from those which were obviously nonreactive. About 200 were selected as representative of the potentially reactive rocks in each formation, and the Geological Survey generously donated small samples of each for testing.

On the generalized columnar sections of the vertical sequences of rock exposed in each zone (Figs. 4-7) are shown the number of samples from each formation tested for chemical reactivity.

TESTING PROGRAM

Laboratory Tests for Reactivity

Inasmuch as the type of investigation envisioned called for the concurrent testing of a large number of samples, it was apparent that the testing of concrete specimens like those used by Swenson (1) and by Bisque and Lemish (2) in their early work would be cumbersome. Not only would there be an almost prohibitive number of specimens to be cast and stored but the large amounts of rock necessary would greatly complicate the sampling program. It was recognized that a need existed for the development of simple and rapid tests which could be carried out using relatively small quantities of rock. The results of these tests could later be confirmed by testing concretes made using representative reactive materials.

Test for Development of Reaction Rims.—The following test was designed to determine whether a rock would develop silicified rims in concrete:

Procedure.—Cubes ½ in. on a side were cut from each rock with a diamond saw. The cubes were then cast into 1- by 1- by 11¼-in. mortar bars made with graded Ottawa sand and a cement containing 0.06 percent Na_2O and 1.3 percent K_2O. Each bar con-

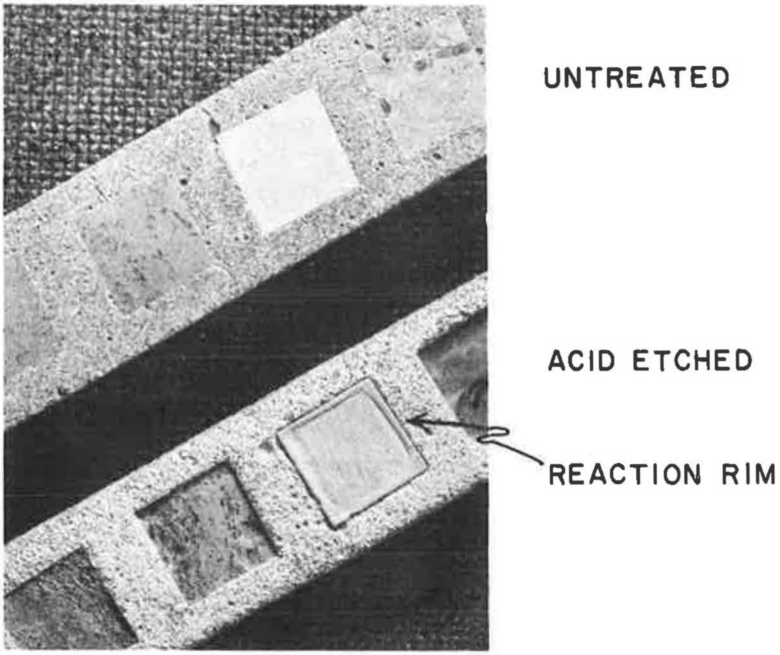


Figure 8. Rock cubes embedded in mortar bars. Development of reaction rims shown by acid etching of bars.

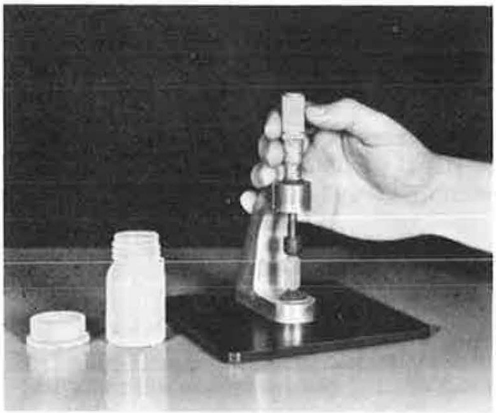


Figure 9. Simple test for measuring rock samples for expansion in alkali solution.

tained 12 aggregate cubes. The bars were stored over water in sealed containers at 100 F for 8 wk. They were then cut in half longitudinally with a diamond saw and one-half of the bar was etched with dilute HCl. The presence of reaction rims on the aggregate cubes was established by visual examination of the etched bars. Part of a typical test specimen is shown in Figure 8. In general, the rock is etched considerably below the level of the mortar. However, in the paste bordering reactive rock cubes there is a carbonated zone which etches to as great or greater depth as the interior of the rock. The rim itself is extremely resistant and remains at about its original level.

Test for Expansion.—Because the cause of distress in concrete containing these rocks had been found to be expansion of the coarse aggregate when exposed to cement alkalies, it was decided to test the aggregates themselves for expansion in alkaline solutions.

Procedure.—Small prisms were cut from each rock and exposed to a 1M NaOH solution. The presence and magnitude of expansion were determined by periodically measuring the prisms with a small comparator shown in Figure 9. This test was described in a previous publication (6).

Determinations were also made of the carbonate and clay mineralogy, insoluble residue content, and textural relationships for each rock in the test series as part of the research program on alkali-reactive carbonate rocks.

Test Results

Expansive Rocks.—Sixteen of the geologic formations exposed in Indiana were found to contain rock which expanded in 1 M NaOH solution. These formations and the ranges of expansions shown by the reactive samples tested are given in Table 1. Reactive rocks of this type were found throughout the vertical sequence of rocks and in each of the three zones of carbonate outcrop.

TABLE 1

FORMATIONS CONTAINING EXPANDING ROCKS

Formation	Expansion[a] (%)
Golconda	0.06
Kokomo	0.05 0.23 0.07 0.06 0.25 0.13
Laurel	0.11
Liston Creek	0.08 0.14
Louisville	0.05 0.13 0.27
Menard	0.25
Minshall	0.12
Mississinewa	0.14 0.22
Osgood	0.49 0.15 0.32 1.81 1.20 0.10 0.05
Providence	0.16
Rockford	0.09 0.06
Salem	0.05 0.24 1.46 0.07 0.24 0.03 0.04 0.06
Saluda	0.25
North Vernon (Beechwood member)	0.28
North Vernon (Silver Creek member)	2.00 0.56 0.20 0.45 0.74 4.88 0.18
North Vernon (Speed member)	0.05 4.05 2.22
Ste. Genevieve (Levias member)	0.17 0.13 0.11 3.06 0.07
Ste. Genevieve (Rosiclare member)	0.10
St. Louis	0.56 2.09 0.07 2.54 1.08 0.05 0.56 0.32

[a] In 1M NaOH solution during 30 weeks.

An appreciable number of the samples tested was found to be expansive in alkali. Table 1 shows that more than three-fourths of the reactive samples expanded less than 0.5 percent. The more highly reactive rocks were confined to limited portions of five formations: the Osgood, Salem, North Vernon, Ste. Genevieve, and St. Louis, the last being one of the three formations cited by Patton (10) as containing rocks with poor service records.

The expansive rocks were generally of poor physical quality, probably because of their high clay content. Figure 10 shows that greater than 80 percent of the rocks which expanded more than 0.5 percent contained more than 10 percent clay, and 7 of 17 contained more than 20 percent. Figure 10 also indicates that there is a minimum clay content necessary for reactivity (shown by the dashed line), and that this content increases as the carbonate fraction becomes more dolomitic. From a practical standpoint this is quite significant. Figure 11 shows that most of the expansive rocks in Indiana have high dolomite contents. Because these highly dolomitic reactive rocks were all found to have extremely high clay contents, there is a high probability that they would fail physical acceptance tests and be rejected as concrete aggregate.

Rim-Developing Rocks.—Nine formations contained rocks that developed reaction rims in concrete (Table 2). The pattern of distribution was much the same as that of the expansive rocks. It is interesting to note that each of the three formations listed by Patton was found to contain rim-developing rocks, with the St. Louis containing expansive rocks as well.

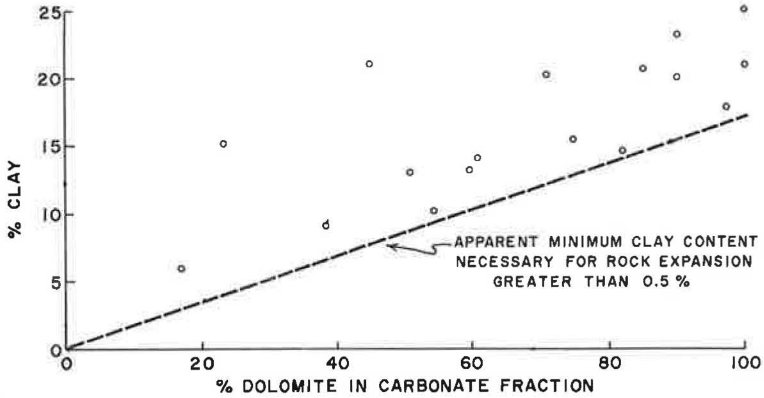


Figure 10. With increase in dolomite content, larger clay contents appear necessary for rock to show strongly expansive tendencies.

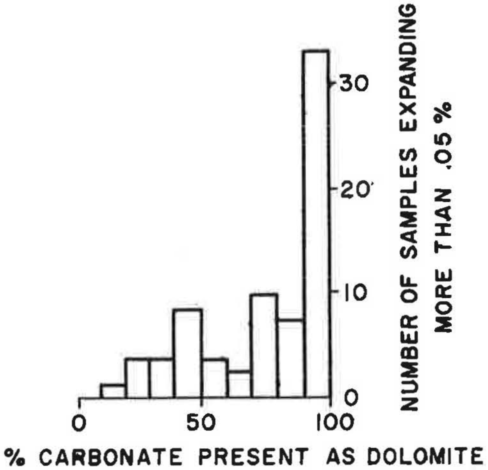


Figure 11. Most reactive rocks are highly dolomitic.

TABLE 2

FORMATIONS CONTAINING RIM-DEVELOPING ROCKS

Harrodsburg	Ste. Genevieve
Jeffersonville	(Rosiclare member)
Kenneth	Salem
Kokomo	St. Louis
Louisville	Whitewater

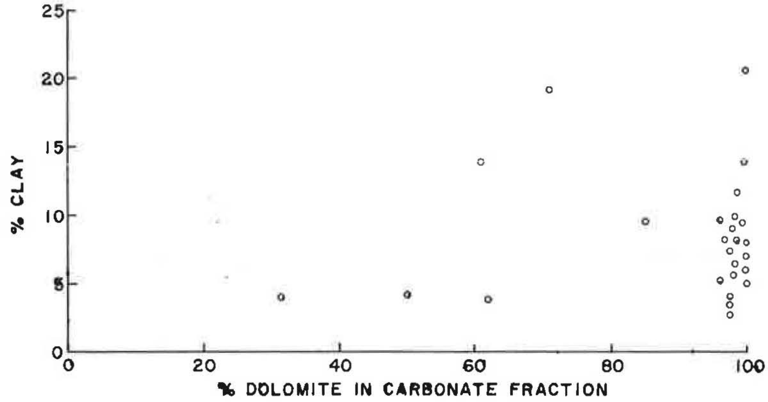


Figure 12. Rocks developing reaction rims tend to contain more dolomite and less clay than highly expansive rocks.

The rim-developing rocks were very similar to the expansive rocks in texture. The two types were often found interbedded and some expansive samples also developed weak reaction rims. The major difference between the two types of reactive rocks lies in their compositions. As is shown in Figure 12, the rim-developing rocks are generally highly dolomitic and contain appreciably less clay than expansive rocks of the same calcite-dolomite ratio. Almost all of the rim-developing rocks have clay contents that fall beneath the line in Figure 10 marking the minimum clay content necessary for expansion. The only rim-developing rocks that fall above this line also expanded and appear transitional between the two types. The rim-developing rocks as a class are physically superior to their expansive equivalents.

The test results for both the rim-developing and the expansive rocks are summarized on the columnar sections (Figs. 4-7).

INVESTIGATION OF STE. GENEVIEVE LIMESTONE

Of the five formations found to contain highly expansive rock, only one, the Ste. Genevieve limestone, is a significant source of concrete aggregate. Inasmuch as aggregate from this formation has an outstandingly good service record, the recognition of reactive beds in the Ste. Genevieve aroused considerable interest. Therefore, a detailed investigation of the rocks of this formation was conducted to determine whether the reactive material was potentially dangerous to the continued excellent service of this aggregate and to discover, if possible, the factors that had allowed the successful utilization of the reactive rock.

Field Studies

The Ste. Genevieve limestone is divided into three members: the Fredonia, the Rosiclare, and the Levias. As no reactive material had been found in the Fredonia member, and only one sample of quite low reactivity was found in the Rosiclare, this study was concentrated on the rocks of the Levias member.

In the summer of 1961, approximately 50 exposures of the Levias member were studied in the field. Twenty representative exposures were sampled on a bed-by-bed basis, yielding a total of 88 samples for laboratory study.

Laboratory Studies

Twenty-four of the samples, including rocks from 10 of the 20 sections sampled, contained dolomite. Tests for expansion in alkali showed 9 of the dolomitic samples to be reactive. These reactive rocks were found in 6 of the 20 exposures sampled. The gross mineral composition, thickness of the reactive beds, and expansions of the reactive samples are given in Table 3 and the areal distribution of the tested sections is shown in Figure 13.

Mode of Occurrence of Reactive Levias Rocks

Although the Levias shows rapid and extreme lateral variations, it is made up of a relatively small number of rock types. Relationships are confused, however, because in any given outcrop any of these rock types may be partially converted to dolomite and potentially reactive. The reactive rocks in the Levias, rather than occurring in a persistent bed or beds, are found in thin discontinuous deposits that cannot be traced laterally for any great distance and cannot be correlated between exposures.

Nature of Reactive Levias Rocks

The alkali-reactive rocks from the Levias are unusual because they contain much less clay than the reactive materials usually encountered. The rocks also differ from the other reactive Indiana carbonate rocks in that many are extremely compact and dense, probably as a consequence of the low clay content. Because the reactive Levias rocks are apparently physically sound, they probably would pass existing acceptance tests. The beds are thin and the reactive rocks are often interbedded with sound rock

TABLE 3

MINERALOGICAL COMPOSITION AND ALKALI REACTIVITY OF SPECIMENS FROM LEVIAS MEMBER OF STE. GENEVIEVE LIMESTONE

Sample	Thickness of Bed (ft)	Dolomite in Carbonate Fraction (%)	Insoluble Residue (%)	Expansion in 1 M NaOH (%)
61-2-2	6	23	4.5	0.10
61-2-4	12	17	4.7	0.04
61-2-6	4	51	14.1	0.36
61-6-2	3	58	6.5	0.25
61-9-3	7	78	6.3	0.05
61-10-2	1.5	34	6.2	0.11
61-14-1	3	36	4.6	0.09
61-16-6	2	39	8.7	0.09
61-16-7	4	10	8.7	0.05

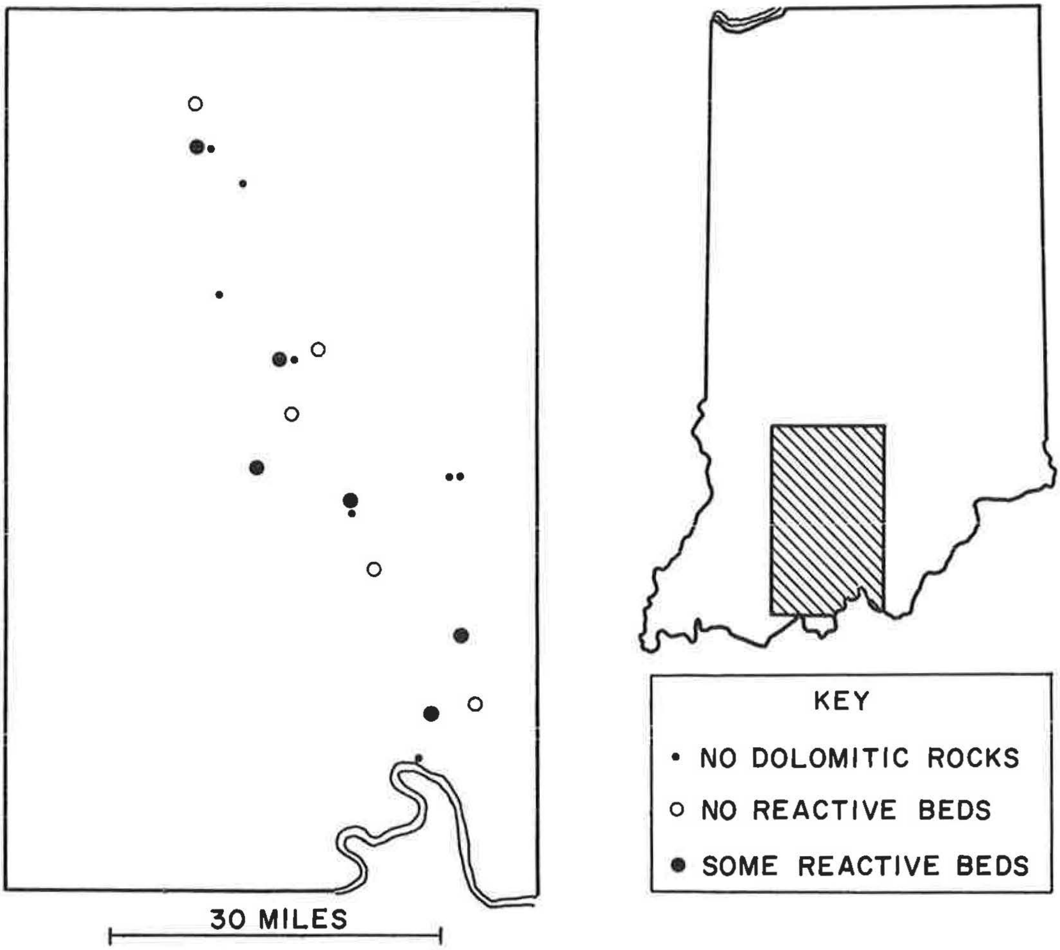


Figure 13. Thin reactive beds are randomly distributed throughout outcrop of Levias member of Ste. Genevieve limestone in Indiana.

material. It is likely, therefore, that the reactive material would pass undetected into concretes made with aggregate from quarries in the Levias.

Conclusions Regarding Investigation of Ste. Genevieve Limestone

Although one isolated sample of highly reactive rock was found in the initial sampling of the Levias, the general level of reactivity is relatively low. In addition, the reactive beds are thin and represent a very small proportion of the total Ste. Genevieve section. Probably this combination of generally low reactivity and dilution with sound rock permits the excellent performance of Ste. Genevieve aggregate in concrete. To check this hypothesis, three examples of expansive Levias rock were included in the aggregates used in the concrete tests described later. These tests indicated that even with a cement of high alkali content, the amount of dilution with sound aggregate that occurs in quarries now operating in the Ste. Genevieve is more than sufficient to reduce concrete expansion to an acceptable level. However, in some of the sections tested, a large proportion of the Levias rocks exposed were somewhat reactive. If a quarry opened in such a locality did not penetrate the nonexpansive rock of the underlying members to a sufficient depth to insure adequate dilution, some expansion might be produced if the material was used as concrete aggregate with a cement high in alkalies.

The excellent service record of the Ste. Genevieve reflects the fact that this potentially dangerous situation does not exist in any of the quarries now operating in the Ste. Genevieve.

CONCRETE AND MORTAR TESTS

Once the areal and stratigraphic distribution of the reactive rocks had been established, representative beds were selected for large-scale sampling. The rock was hand-quarried from the selected beds with every effort to secure rock like that initially sampled.

Tests of Expansion of Concretes Made with Expansive Rocks

Concrete tests were performed using six of the expansive rocks as coarse aggregate. The main purposes of these tests were: (a) to relate the expansion in alkali of the small rock prisms to that of laboratory concretes made with these rocks as coarse aggregate, and (b) to determine the degree of reactivity in the rock at which the laboratory concrete would be deleteriously affected.

The effects of variations in cement alkali content, air content, and of dilution with various proportions of essentially inert coarse aggregate were also investigated.

Description of Concrete Mixtures.—All mixtures were maintained at a nominal cement content of 6.0 sacks per cubic yard. The water content was adjusted to maintain a slump of 2 to 3 in. Sand constituted 38 percent of the absolute volume of aggregate and the maximum aggregate size was 1½ in.

Materials.—Three Type I cements purchased in the Chicago area were used. The chemical analyses, specific gravity, and fineness of these cements are listed in Table 4.

The fine aggregate was a natural sand from Elgin, Illinois, and the coarse aggregates were selected reactive crushed stone from Indiana and an inert gravel from Elgin, Illinois. Grading, specific gravity, and absorption of these aggregates are given in Table 5.

Specimen Preparation.—Four 3- by 3- by 11¼-in. prisms were cast from each batch. Each reactive aggregate was tested at 0, 25, 50, and 75 percent dilution with inert Elgin gravel aggregate, and each of the dilutions was tested with each of the three cements.

Curing.—Immediately after casting, the specimens were stored under wet burlap covered with a polyethylene sheet. After 20-24 hr the prisms were removed from the molds, their lengths were measured, and two specimens from each batch were placed in sealed containers over water at 100 F. The remaining two specimens from each batch were stored at 73 F and 100 percent RH.

Testing.—Prisms were measured for length immediately after removal from the molds, weekly for a month, bi-weekly for two additional months, and monthly thereafter.

TABLE 4

CHEMICAL ANALYSES, SPECIFIC GRAVITY AND FINENESS OF CEMENTS USED IN LABORATORY CONCRETE TESTS OF EXPANSIVE COARSE AGGREGATES

Lot No.	Analytical Result (%)												Sp. Gr.	Fineness		
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	Tot. Alk., as Na_2O	Loss on Ign.	Insol. Residue	Mn_2O_3		Blaine	Wagner	-325 (%)
20070	22.10	4.36	2.86	62.75	3.10	2.36	0.14	1.14	0.89	0.93	0.03	0.10	3.18	3240	1800	92.0
20071	21.02	5.60	2.97	64.04	2.68	2.34	0.32	0.43	0.60	0.50	0.04	0.30	3.19	3140	1760	90.6
20072	20.54	5.59	2.28	63.50	3.23	2.48	0.13	0.16	0.24	1.43	0.20	0.74	3.18	3680	1850	91.6

TABLE 5

CHARACTERISTICS OF AGGREGATES USED IN LABORATORY CONCRETES

Aggregate	Grading (% retained)									Bulk Sp. Gr., S.S.D.	Absorp.[a] (% by wt.)
	1½ In.	¾ In.	⅜ In.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100		
Elgin, Ill., sand[b]	—	—	—	0	18	33	57	87	95	2.645	2.25
Elgin, Ill., gravel	0	50	75	100	—	—	—	—	—	2.651	2.00
Expansive coarse aggregates	0	50	75	100	—	—	—	—	—	—	—
Ste. Genevieve, 19999	—	—	—	—	—	—	—	—	—	2.655	1.95
Osgood, 20000	—	—	—	—	—	—	—	—	—	2.550	6.00
Ste. Genevieve, 20001	—	—	—	—	—	—	—	—	—	2.485	5.20
Ste. Genevieve, 20002	—	—	—	—	—	—	—	—	—	2.570	2.06
St. Louis, 20007	—	—	—	—	—	—	—	—	—	2.680	1.55
North Vernon, 20024	—	—	—	—	—	—	—	—	—	2.660	1.50

[a] 24 hr. [b] Fineness modulus 2.90.

Test Results.—Test results are summarized below and representative data are shown graphically in Figures 14-20. Complete test data are given in the Appendix.

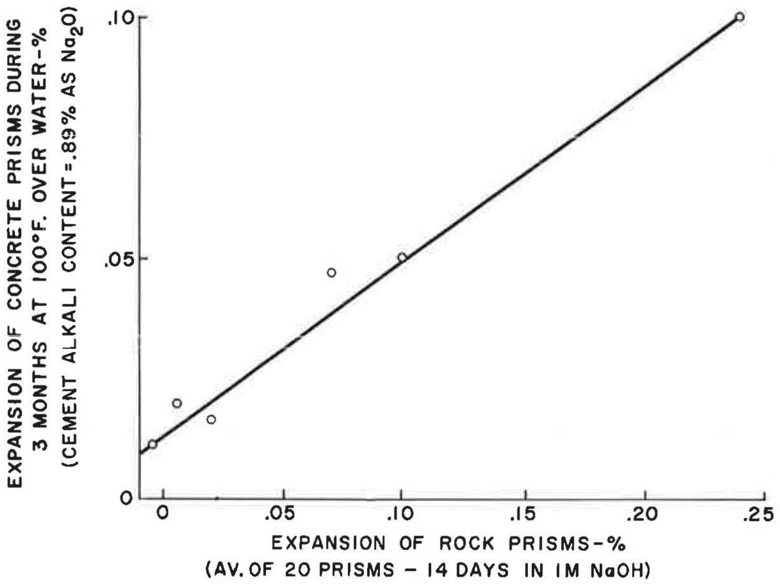


Figure 14. Correlation between expansion of rock prisms and concretes made with these rocks as aggregate.

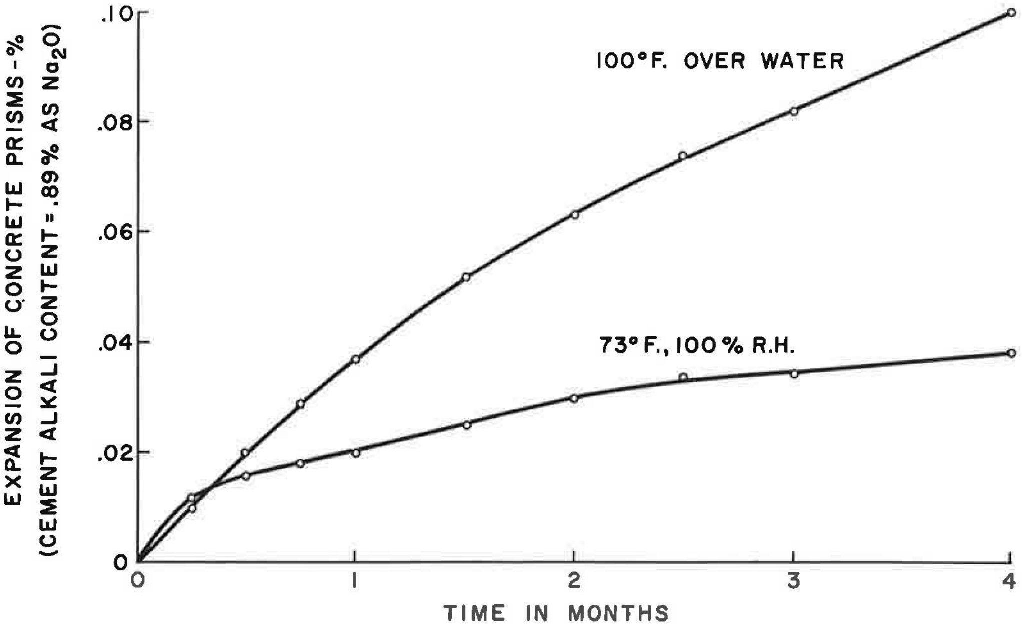


Figure 15. Rate of expansion of concrete was greatly accelerated by storage at higher temperature.

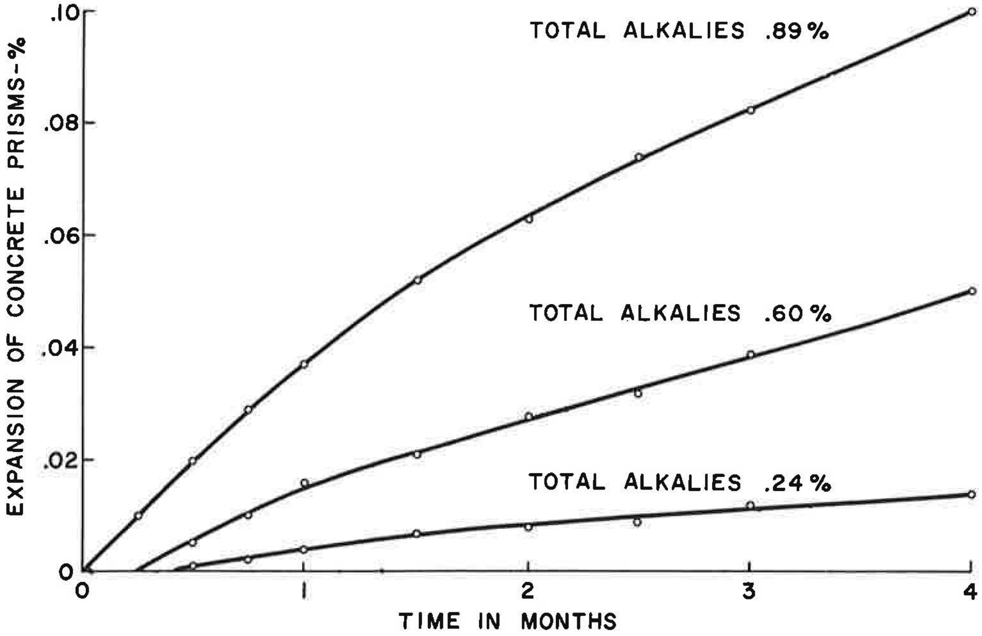


Figure 16. Rate of expansion of concrete is greatly influenced by alkali content of cement.

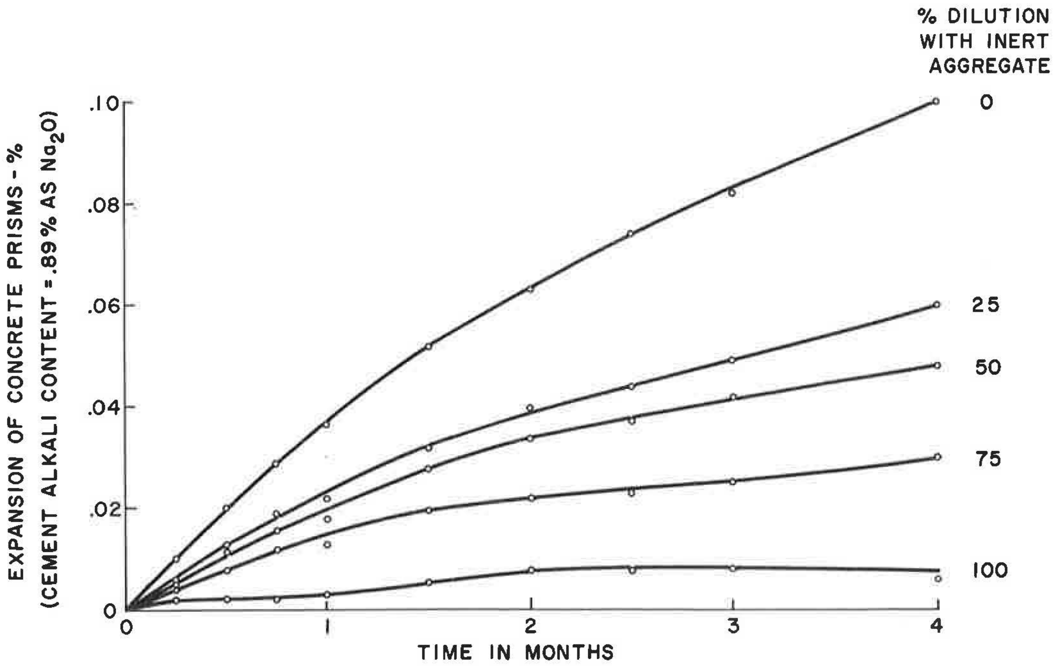


Figure 17. Dilution reduces concrete expansion by amount roughly proportional to amount of inert aggregate used.

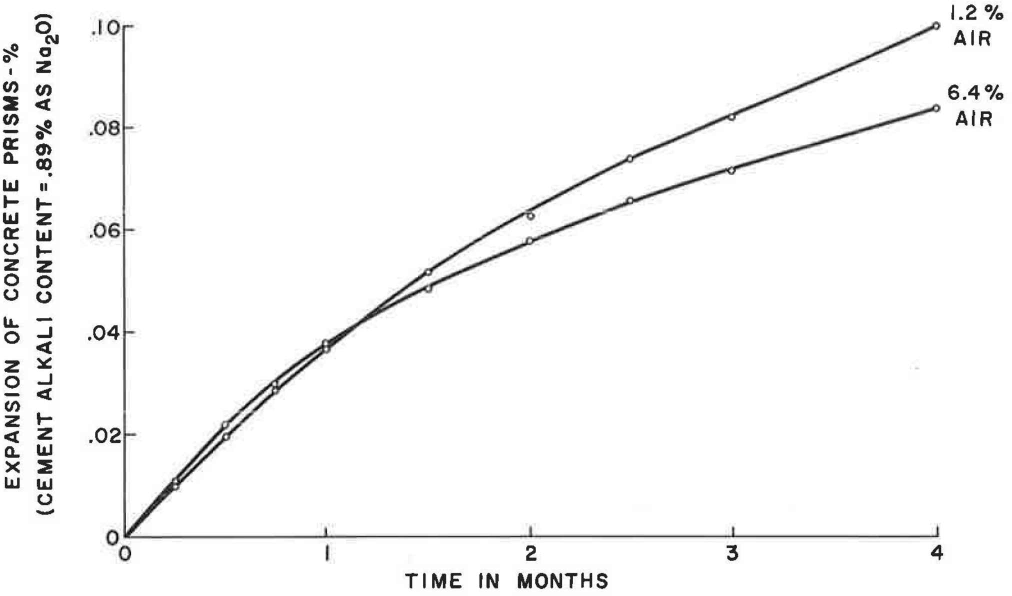


Figure 18. Air entrainment has no appreciable effect on expansion of concrete prisms.

1. Relation Between Expansion of Rock Prisms and Concretes Made Using These Rocks as Coarse Aggregate—The data from these tests indicate good correlation between the average expansion of a large number of rock prisms and expansions of concretes containing the rocks as aggregate. Figure 14 shows the 14-day average expansion of the rock prisms plotted against the expansion of the corresponding concretes after 3-mo storage.
2. Effect of Storage Conditions—Storage in cans over water at 100 F produced a more rapid expansion than storage in a moist room at 73 F and 100 percent RH, and the correlation between rock and concrete expansions was slightly better for specimens stored in cans (Fig. 15).
3. Effect of Cement Alkali Content—As Swenson and Gillott (5) found, the rate of expansion seems to be a direct function of cement alkali content (Fig. 16).
4. Effect of Dilution with Inert Coarse Aggregate—Dilution reduced expansion by an amount roughly proportional to the amount of inert aggregate used (Fig. 17).
5. Effect of Air Entrainment—The effect of air entrainment was studied in only one case. The air-entrained samples expanded at a slightly less rapid rate than their non-air-entrained counterparts (Fig. 18).

Mortar Bar Tests with Expansive Aggregates

Each of the six expansive aggregates was also tested by the Mortar Bar Expansion Test (ASTM C 227-61T) for potential alkali reactivity with the three cements used in the concrete tests.

Test Results.—Under a criterion that expansion greater than 0.05 percent at 3 mo indicates deleterious chemical reaction (ASTM C 33), the three most expansive aggregates failed the mortar bar test with the cement of 0.89 percent alkali content. On this basis the most highly reactive of the aggregates also caused deleterious expansion with the cement containing 0.60 percent total alkalies (Table 6).

Discussion.—These data differ from the findings of Swenson (1), who observed that although concrete prisms made with reactive Kingston, Ontario, aggregate expanded rapidly, mortar bars made with the same cement and aggregate showed only moderate expansions. Figure 19 shows that all mortar bars made with the reactive Indiana materials expanded more than the equivalent concrete prisms. The reason for this difference is not known and additional research is being conducted to study this question.

As is shown in Figure 20, the correlation between mortar bar expansion and the expansion of the rock prisms is good. This correlation indicates that the mortar bar test, ASTM

TABLE 6

EXPANSIVE ROCKS ALSO FOUND REACTIVE IN MORTAR BAR TESTS

Formation	Lot No.	Expansion, 3 Months (%)		
		Cement 20070[a]	Cement 20071[b]	Cement 20072[c]
Ste. Genevieve	19999	0.054	0.025	0.019
Osgood	20000	0.025	0.014	0.016
Ste. Genevieve	20001	0.035	0.019	0.018
Ste. Genevieve	20002	0.024	0.012	0.012
St. Louis	20007	0.101	0.053	0.026
North Vernon	20024	0.053	0.027	0.019
Elgin, Ill.	—	0.027	0.013	0.015

[a] Total alkali 0.89%.
[b] Total alkali 0.60%.
[c] Total alkali 0.24%.

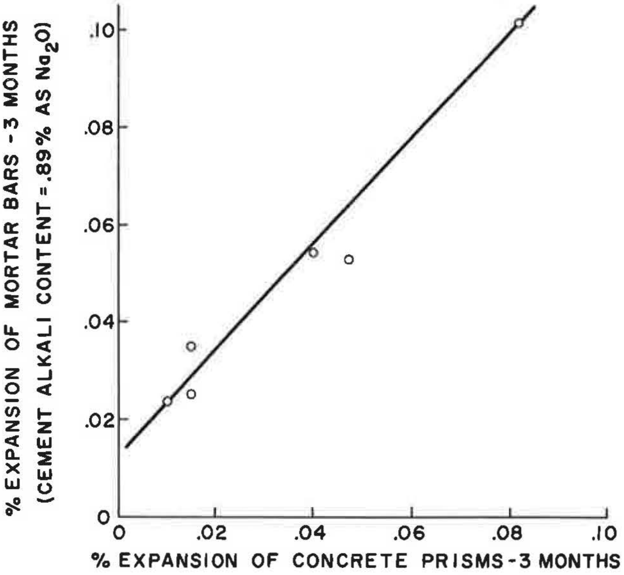


Figure 19. Expansive rocks produced slightly greater expansion in mortar bars than in corresponding concrete prisms.

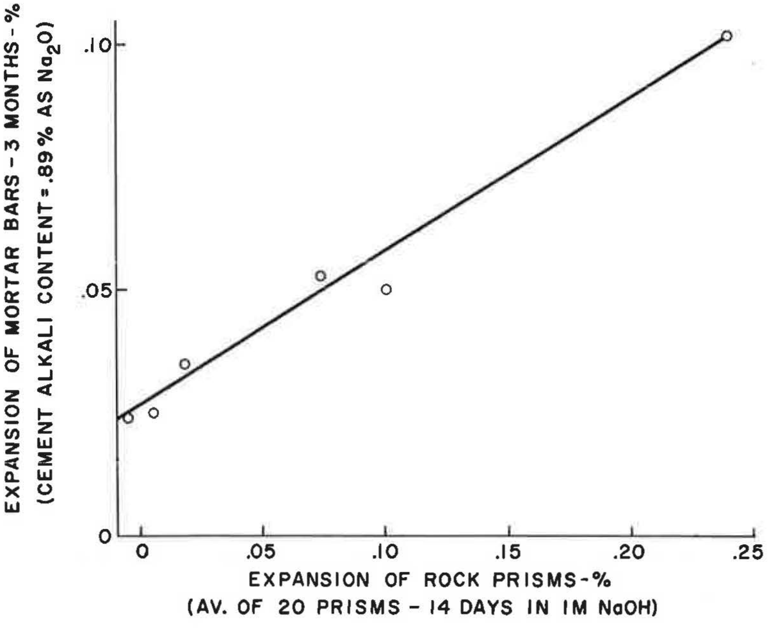


Figure 20. Expansion of rock prisms correlates well with that of corresponding mortar bars.

take much larger samples, and by using sample splitting techniques, achieve a more representative sampling.

If the necessity for careful sampling is recognized, however, these small-scale tests can be very useful tools. The correlation with concrete and mortar bar tests is quite good and a test for reactivity can be made in a fraction of the time that these tests would require.

Possible Utilization of Marginally Reactive Aggregate

The reactive rocks identified in Indiana showed expansions ranging from practically nothing to almost 5.0 percent. Although it is beyond the scope of this paper to attempt to define the lower limit of expansion that would produce deleterious results in field concrete, it appears obvious that many of the Indiana rocks are only marginally reactive. It seems prudent to investigate methods by which these marginal materials might safely be used in concrete.

The work of Swenson (1) showed that additions of pozzolanic materials or lithium salts, both somewhat effective in controlling the alkali-siliceous aggregate reaction, have no appreciable effect on the alkali-carbonate rock reaction. Similarly, although the expansion of affected concrete is dependent on the alkali content of the cement, measurable expansion might take place even with cements of low alkali content.

The remedial measure that seems to hold the most promise is that of dilution with inert aggregate materials. Unlike the alkali-siliceous aggregate reaction, in which there is a "pessimum" amount of reactive material, the expansion is decreased in the alkali-carbonate rock reaction by an amount roughly proportional to the percentage of dilution with inert material.

In most known occurrences, the reactive beds constitute only a small percentage of the rocks exposed, and the level of reactivity is for the most part low. In these cases, control would simply be a matter of making sure that adequate dilution and mixing took place in quarrying and crushing. In those rare instances where the percentage of reactive materials is high, the reactive rocks might still be safely utilized if dilution were coupled with the use of low alkali cement.

Correlation of Test Results with Field Service Records

The Expansive Rocks.—Although the reactive rocks are numerous in Indiana, there are few known cases of concrete damage in that area resulting from the expansion of alkali-reactive carbonate rocks. Due to their poor physical quality, most of the reactive materials in Indiana would probably never be used as concrete aggregate because aggregates of better physical quality are available. In those instances where the reactive rocks are physically sound, the level of reactivity is normally low, the reactive beds are thin, and the degree of dilution with inert aggregate occurring in the quarrying operation apparently is usually sufficient to reduce concrete expansions to within tolerable limits.

The Rim-Developing Rocks.—Attempts to correlate the test data on the rim-developing rocks with the available service records are complicated by several factors. The rim-developing rocks are often interbedded with closely related expansive rocks. In addition, many of these rocks were among those found by Sweet (9) to be highly susceptible to frost damage. However, because several of the rim-developing rocks do have extremely poor service records in concrete, future research plans call for intensified field and laboratory study of these rocks to determine whether their poor performance can be related to the processes that bring about the development of reaction rims.

SUMMARY

This study indicated that standard geologic field methods are well suited to large-scale surveys of the type described. The small-scale laboratory tests developed for this investigation provided a rapid indication of reactivity, and the results of these tests correlated well with those of conventional concrete and mortar bar tests.

Laboratory concrete studies, as well as field experience with the Ste. Genevieve limestone, indicate that many of the marginally reactive materials could be safely utilized as concrete aggregates through such measures as dilution with inert aggregate and the use of low alkali cement.

Although the reactive rocks were abundant in Indiana and have caused some damage to field concrete, such factors as exclusion of the reactive materials from concrete due to poor physical characteristics, generally thin deposits, and low over-all reactivity have combined to prevent the reactive rocks from becoming a major problem.

ACKNOWLEDGMENTS

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Appendix

EXPANSION OF LABORATORY CONCRETES[a]

Concrete Characteristics						Expansion (%)											
						100 F Over Water						73 F, 100% RH					
Coarse Agg.	Dilution (%)	W/C (gal/sk)	Cement Factor (sk/cu yd)	Net Air (%)	Slump (in.)	7 Days	28 Days	3 Mo	6 Mo	12 Mo	18 Mo	7 Days	28 Days	3 Mo	6 Mo	12 Mo	18 Mo
(a) Cement 20070 (Total Alkalies, as Na_2O, 0.89%)																	
Elgin	0	4.7	5.9	1.2	1.7	0.002	0.003	0.008	0.008	0.009	0.010	0.008	0.007	0.011	0.008	0.009	0.008
19999	0	5.0	5.9	1.2	1.6	0.007	0.022	0.044	0.058	0.074	0.080	0.010	0.017	0.027	0.031	0.042	0.046
20000	0	5.4	5.9	1.2	2.2	0.000	0.004	0.015	0.022	0.028	0.033	0.012	0.013	0.019	0.022	0.025	0.028
20001	0	4.7	5.9	1.2	2.5	0.008	0.010	0.015	0.016	0.019	0.020	0.013	0.015	0.021	0.020	0.022	0.023
20002	0	5.1	6.1	1.2	2.4	0.004	0.006	0.010	0.011	0.012	0.012	0.006	0.008	0.012	0.012	0.010	0.012
20007	0	5.0	5.9	1.2	1.3	0.010	0.037	0.082	0.118	0.146	0.160	0.012	0.020	0.034	0.041	0.052	0.057
20024	0	5.2	5.9	1.2	1.3	0.010	0.024	0.042	0.051	0.056	0.060	0.011	0.016	0.026	0.032	0.038	0.041
19999	25	5.0	5.9	1.2	1.9	0.008	0.022	0.040	0.054	0.066	0.072	0.011	0.014	0.023	0.026	0.030	0.034
19999	50	5.0	5.9	1.2	2.1	0.008	0.018	0.029	0.038	0.041	0.046	0.010	0.014	0.022	0.024	0.027	0.031
19999	75	5.0	6.0	1.2	2.8	0.006	0.010	0.018	0.022	0.026	0.028	0.009	0.012	0.018	0.018	0.020	0.023
20000	25	5.4	5.8	1.2	2.7	0.001	0.004	0.012	0.016	0.020	0.024	0.008	0.008	0.014	0.014	0.017	0.020
20000	50	5.7	5.7	1.2	1.8	0.004	0.006	0.014	0.018	0.022	0.023	0.010	0.010	0.016	0.015	0.018	0.020
20000	75	5.1	5.9	1.2	2.5	0.002	0.005	0.010	0.010	0.012	0.014	0.008	0.008	0.014	0.014	0.015	0.016
20001	25	4.8	5.5	1.2	1.6	0.010	0.013	0.018	0.016	0.020	0.023	0.014	0.015	0.020	0.016	0.018	0.018
20001	50	5.1	5.9	1.2	2.8	0.008	0.010	0.015	0.016	0.019	0.020	0.012	0.010	0.016	0.015	0.015	0.016
20001	75	5.1	5.9	1.2	2.0	0.006	0.007	0.012	0.012	0.014	0.016	0.010	0.008	0.014	0.011	0.012	0.012
20002	25	5.0	6.1	1.2	1.8	0.006	0.006	0.011	0.010	0.010	0.011	0.005	0.004	0.010	0.006	0.007	0.008
20002	50	4.9	6.0	1.2	2.2	0.003	0.004	0.010	0.011	0.012	0.014	0.008	0.006	0.012	0.008	0.008	0.008
20002	75	4.8	6.0	1.2	2.1	0.005	0.007	0.012	0.013	0.014	0.015	0.008	0.006	0.012	0.008	0.010	0.009
20007	25	5.0	5.8	1.2	1.8	0.006	0.022	0.049	0.068	0.073	0.079	0.011	0.016	0.030	0.035	0.048	0.052
20007	50	5.0	5.9	1.2	2.3	0.006	0.018	0.042	0.055	0.064	0.070	0.012	0.014	0.026	0.026	0.032	0.033
20007	75	4.9	5.9	1.2	2.1	0.005	0.013	0.025	0.032	0.040	0.042	0.008	0.008	0.018	0.019	0.024	0.026
20024	25	5.1	5.9	1.2	1.7	0.006	0.016	0.030	0.035	0.040	0.041	0.010	0.012	0.022	0.026	0.032	0.035
20024	50	5.1	5.8	1.2	1.7	0.005	0.012	0.024	0.030	0.034	0.036	0.010	0.012	0.022	0.024	0.028	0.030
20024	75	4.9	5.9	1.2	1.7	0.004	0.014	0.019	0.020	0.022	0.024	0.010	0.013	0.020	0.018	0.020	0.022
20007	0	4.4	5.9	6.4	1.7	0.011	0.038	0.072	0.102	0.122	0.132	0.012	0.024	0.042	0.053	0.068	0.074
20007	25	4.3	5.9	6.0	1.2	0.008	0.023	0.044	0.063	0.073	0.080	0.010	0.018	0.031	0.040	0.052	0.056
20007	50	4.3	5.9	6.3	1.5	0.010	0.024	0.044	0.054	0.063	0.067	0.006	0.016	0.027	0.030	0.038	0.044
20007	75	4.3	5.9	5.9	1.2	0.009	0.015	0.026	0.033	0.038	0.040	0.010	0.014	0.022	0.022	0.026	0.028
(b) Cement 20071 (Total Alkalies, as Na_2O, 0.60%)																	
Elgin	0	4.6	6.0	1.2	1.8	-0.002	0.004	0.004	0.006	0.006	0.007	0.006	0.006	0.008	0.006	0.005	0.006
19999	0	5.1	6.0	1.2	1.7	-0.002	0.012	0.026	0.038	0.051	0.058	0.008	0.012	0.017	0.017	0.022	0.024
20000	0	5.2	5.9	1.2	1.1	-0.010	0.004	0.004	0.010	0.016	0.020	0.010	0.010	0.014	0.014	0.017	0.020
20001	0	4.6	6.0	1.2	1.6	0.000	0.007	0.009	0.010	0.012	0.012	0.008	0.010	0.012	0.012	0.012	0.012
20002	0	5.0	6.2	1.2	1.6	-0.002	0.001	0.003	-0.001	0.002	0.002	0.004	0.005	0.006	0.004	0.004	0.004
20007	0	4.8	6.0	1.2	1.1	0.000	0.016	0.039	0.063	0.082	0.090	0.008	0.010	0.018	0.020	0.028	0.032
20024	0	5.2	6.0	1.2	0.9	-0.002	0.010	0.024	0.033	0.041	0.048	0.005	0.008	0.014	0.018	0.022	0.024
19999	25	5.0	5.9	1.2	1.7	0.002	0.008	0.018	0.030	0.040	0.046	0.010	0.013	0.020	0.022	0.026	0.027
19999	50	5.0	5.9	1.2	2.3	-0.002	0.002	0.009	0.016	0.024	0.027	0.010	0.014	0.017	0.016	0.020	0.020
19999	75	4.9	6.0	1.2	2.3	-0.002	0.002	0.008	0.013	0.018	0.022	0.006	0.008	0.010	0.008	0.010	0.010
20000	25	5.2	6.0	1.2	1.0	-0.009	-0.006	0.001	0.005	0.012	0.017	0.018	0.016	0.021	0.019	0.022	0.024
20000	50	4.9	5.9	1.2	1.6	-0.003	0.001	0.005	0.008	0.014	0.015	0.008	0.006	0.010	0.009	0.012	0.013
20000	75	5.0	6.0	1.2	2.3	-0.004	-0.002	0.001	0.001	0.006	0.006	0.008	0.007	0.010	0.008	0.011	0.011
20001	25	4.7	5.6	1.2	1.0	0.001	0.004	0.006	0.005	0.008	0.009	0.008	0.009	0.013	0.012	0.014	0.014
20001	50	4.6	6.1	1.2	1.2	-0.002	-0.002	0.004	0.004	0.006	0.007	0.009	0.008	0.011	0.008	0.009	0.009
20001	75	4.6	6.0	1.2	2.2	-0.001	0.002	0.004	0.004	0.007	0.007	0.008	0.006	0.010	0.010	0.012	0.010
20002	25	5.1	6.1	1.2	2.5	-0.004	-0.004	0.002	0.003	0.004	0.004	0.010	0.008	0.012	0.007	0.008	0.008
20002	50	5.0	6.0	1.2	2.9	-0.004	-0.004	0.000	0.000	0.002	0.000	0.008	0.006	0.010	0.009	0.008	0.008
20002	75	4.9	6.0	1.2	2.2	-0.003	-0.002	0.002	0.001	0.003	0.004	0.006	0.006	0.008	0.006	0.006	0.007
20007	25	4.9	5.8	1.2	1.5	-0.002	0.004	0.002	0.040	0.052	0.060	0.008	0.010	0.018	0.016	0.021	0.022
20007	50	4.9	5.9	1.2	1.6	-0.002	0.004	0.014	0.022	0.031	0.034	0.006	0.006	0.013	0.014	0.018	0.014
20007	75	4.9	6.0	1.2	2.8	-0.001	0.002	0.008	0.011	0.018	0.019	0.006	0.004	0.010	0.004	0.008	0.008
20024	25	5.0	6.0	1.2	1.9	-0.002	0.006	0.016	0.020	0.028	0.032	0.010	0.010	0.018	0.015	0.017	0.020
20024	50	5.1	6.0	1.2	2.0	0.000	0.004	0.014	0.015	0.022	0.024	0.006	0.008	0.014	0.012	0.015	0.015
20024	75	5.0	5.9	1.2	1.8	-0.001	0.002	0.008	0.010	0.013	0.013	0.007	0.006	0.012	0.012	0.014	0.014
(c) Cement 20072 (Total Alkalies, as Na_2O, 0.24%)																	
Elgin	0	5.0	5.9	1.2	2.1	0.002	0.000	0.002	0.004	0.006	0.006	0.008	0.006	0.007	0.004	0.006	0.007
19999	0	5.2	5.9	1.2	1.6	0.000	0.003	0.008	0.009	0.016	0.022	0.006	0.006	0.010	0.008	0.010	0.012
20000	0	5.5	5.9	1.2	1.0	-0.005	-0.003	0.002	0.012	0.020	0.024	0.018	0.017	0.020	0.017	0.022	0.026
20001	0	4.7	5.9	1.2	2.3	0.004	0.006	0.010	0.012	0.014	0.016	0.007	0.007	0.008	0.006	0.006	0.008
20002	0	5.0	6.2	1.2	1.7	-0.002	0.002	0.005	0.005	0.005	0.005	0.004	0.006	0.006	0.002	0.004	0.004
20007	0	5.1	5.9	1.2	1.6	-0.002	0.004	0.012	0.020	0.025	0.030	0.009	0.010	0.014	0.017	0.022	0.026
20024	0	5.2	5.9	1.2	1.0	0.000	0.004	0.008	0.013	0.019	0.023	0.008	0.011	0.014	0.012	0.016	0.018
19999	25	5.1	5.9	1.2	2.8	0.000	0.004	0.011	0.013	0.019	0.024	0.004	0.006	0.007	0.006	0.008	0.010
19999	50	5.1	5.9	1.2	2.4	-0.001	0.000	0.005	0.008	0.015	0.018	0.009	0.011	0.013	0.010	0.014	0.015
19999	75	5.1	5.9	1.2	2.5	0.003	0.004	0.008	0.008	0.012	0.015	0.012	0.012	0.012	0.008	0.010	0.012
20000	25	5.4	5.9	1.2	2.2	-0.007	-0.006	0.000	0.007	0.014	0.020	0.014	0.018	0.020	0.020	0.024	0.026
20000	50	5.4	5.9	1.2	2.3	-0.002	-0.001	0.006	0.011	0.016	0.020	0.016	0.016	0.018	0.018	0.022	0.024
20000	75	5.4	5.9	1.2	2.4	0.000	0.000	0.004	0.006	0.010	0.012	0.010	0.012	0.014	0.013	0.016	0.017
20001	25	5.2	5.8	1.2	1.5	0.002	0.003	0.006	0.004	0.006	0.008	0.010	0.010	0.011	0.008	0.010	0.010
20001	50	5.0	5.9	1.2	2.2	0.003	0.004	0.006	0.006	0.010	0.012	0.006	0.008	0.009	0.006	0.008	0.008
20001	75	5.0	5.9	1.2	2.6	0.002	0.002	0.006	0.006	0.009	0.012	0.008	0.008	0.010	0.008	0.011	0.011
20002	25	5.3	6.0	1.2	1.9	-0.002	0.000	0.003	0.008	0.006	0.006	0.005	0.006	0.010	0.010	0.010	0.010
20002	50	5.1	6.0	1.2	1.9	-0.001	0.003	0.006	0.006	0.004	0.004	0.006	0.007	0.009	0.006	0.006	0.006
20002	75	5.0	5.9	1.2	2.7	-0.002	0.002	0.006	0.007	0.005	0.007	0.006	0.007	0.009	0.008	0.009	0.009
20007	25	5.0	5.9	1.2	2.3	-0.002	0.003	0.010	0.016	0.021	0.024	0.005	0.008	0.012	0.014	0.018	0.020
20007	50	5.0	5.9	1.2	1.6	-0.002	0.002	0.004	0.004	0.004	0.006	0.004	0.004	0.006	0.004	0.004	0.004
20007	75	5.0	5.9	1.2	2.0	-0.002	0.000	0.002	0.005	0.003	0.004	0.010	0.008	0.011	0.006	0.008	0.008
20024	25	5.1	5.8	1.2	1.0	-0.003	0.004	0.009	0.014	0.018	0.020	0.004	0.006	0.009	0.010	0.012	0.014
20024	50	5.1	5.8	1.2	2.0	-0.003	0.002	0.008	0.009	0.012	0.016	0.006	0.006	0.010	0.010	0.011	0.013
20024	75	5.0	5.9	1.2	2.9	-0.004	0.002	0.006	0.008	0.008	0.010	0.004	0.008	0.009	0.010	0.010	0.012

[a] Each value is average of two 3 × 3 × 11¼-in. concrete prisms.