NRC Publications Archive
Archives des publications du CNRC

Cell test method for study of alkali-carbonate rock reactivity

Gillott, J. E.

This publication could be one of several versions: author’s original, accepted manuscript or the publisher’s version. / La version de cette publication peut être l’une des suivantes : la version prépublication de l’auteur, la version acceptée du manuscrit ou la version de l’éditeur.

Publisher’s version / Version de l'éditeur:

Proceedings of the American Society for Testing and Materials, 63, pp. 1195-1206, 1964-06-01

NRC Publications Record / Notice d'Archives des publications de CNRC:
https://nrc-publications.canada.ca/eng/view/object/?id=b9c076ed-4057-4247-96cc-9ecda98b171
https://publications-cnrc.canada.ca/fra/voir/objet/?id=b9c076ed-4057-4247-96cc-9ecda98b1719

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L’accès à ce site Web et l’utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D’UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at
PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n’arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council
CANADA

DIVISION OF BUILDING RESEARCH

CELL TEST METHOD FOR STUDY OF ALKALI-CARBONATE ROCK REACTIVITY

BY

J. E. GILLOTT

REPRINTED FROM
PROCEEDINGS OF THE AMERICAN SOCIETY FOR TESTING AND MATERIALS
VOL. 63, 1963, P. 1195-1206

RESEARCH PAPER NO 220

OF THE

DIVISION OF BUILDING RESEARCH

OTTAWA

JUNE 1964

PRICE 25 CENTS

NRC 7685

This publication is being distributed by the Division of Building Research of the National Research Council. It should not be reproduced in whole or in part, without permission of the original publisher. The Division would be glad to be of assistance in obtaining such permission.

Publications of the Division of Building Research may be obtained by mailing the appropriate remittance, (a Bank, Express, or Post Office Money Order or a cheque made payable at par in Ottawa, to the Receiver General of Canada, credit National Research Council) to the National Research Council, Ottawa. Stamps are not acceptable.

A coupon system has been introduced to make payments for publications relatively simple. Coupons are available in denominations of 5, 25 and 50 cents, and may be obtained by making a remittance as indicated above. These coupons may be used for the purchase of all National Research Council publications including specifications of the Canadian Government Specifications Board.

Authorized Reprint from the Copyrighted *Proceedings* of the
AMERICAN SOCIETY FOR TESTING AND MATERIALS
Philadelphia, Pa.
Volume 63, 1963

ANALYZED

CELL TEST METHOD FOR STUDY OF ALKALI-CARBONATE ROCK REACTIVITY

BY J. E. GILLOTT[1]

SYNOPSIS

Argillaceous dolomitic limestone from Kingston, Ont., expands when placed in a strongly alkaline environment. Such expansion may disrupt concrete that contains aggregate made from this rock. A cell technique has been developed to test samples for reactivity. The apparatus is described and results are illustrated with reference to eight samples of concrete. Petrographic, mineralogical, and chemical analyses are given for the samples tested. The cell technique is discussed in relation to other test methods. It is possible to recognize potentially reactive carbonate rocks petrographically, but it is not possible to predict the amount of expansion a particular sample will produce. Linear measurements of concrete beams give reliable results, but the cell technique is more rapid. Dimensional change measurements of rock prisms soaked in alkali may give erroneous results if undetected microcracks develop. It is also difficult to allow for anisotropic properties of rocks, and many samples must be studied if the results are to be representative of a quarry. The cell technique eliminates these difficulties; powder is used and the expansive reaction may be smoothly followed to completion.

When argillaceous dolomitic limestone from Kingston, Ont., is used as aggregate it produces cracking and deterioration in concrete made with high-alkali cement. The concrete failure is caused by expansion of the rock in strong alkali. Similar behavior by aggregates has been reported from other localities (**1**,**2**).[2] Swenson (**3**) found that on the basis of test criteria developed for alkali-aggregate reaction up to the time of the initial investigation, the Kingston aggregate would not be considered deleteriously reactive. Concrete beams made with Kingston coarse aggregate cracked after several months' exposure to high humidity conditions and measurements showed that a systematic elongation occurred (**3**,**4**). Expansion was also measured on rock prisms soaked in alkali (**4**,**5**) and the method has been considered tentatively as a test method (**6**).

The concrete beam test, though reliable, is time consuming; measurements made on more than one rock prism soaked in alkali are needed if the information is to be representative, since great differences in reactivity are known within a single quarry. Directional properties in the rock such as bedding also influence results (**4**, Fig. 10). A test method has been developed in which powdered rock is used. The sample is readily made representative, variations due to directional properties are eliminated, and the fine particle size gives a rapid response. The apparatus is described and the behavior in this test of eight samples of

---

[1] Inorganic Materials Section, Division of Building Research, National Research Council, Ottawa, Ont.

[2] The boldface numbers in parentheses refer to the list of references appended to this paper.

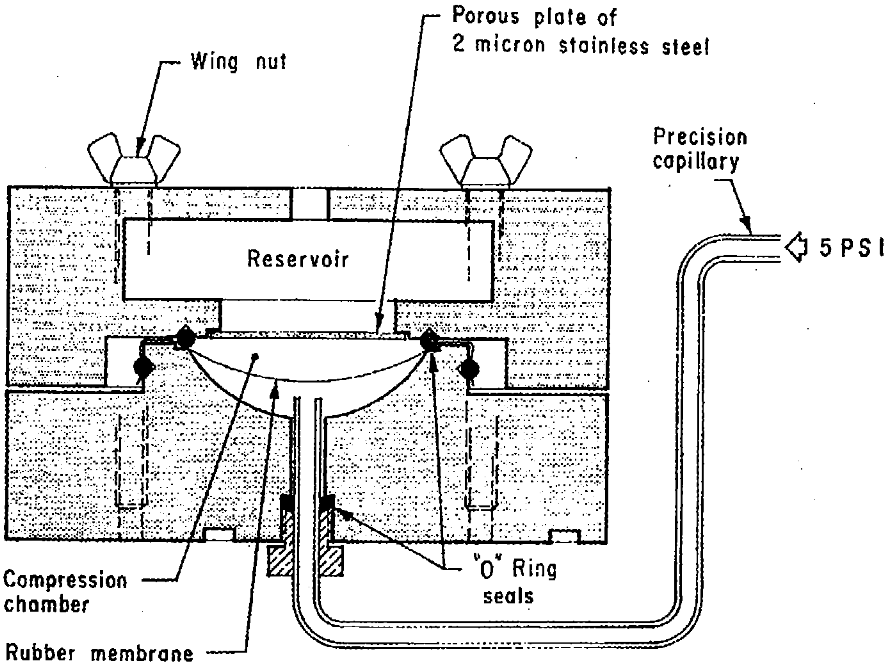

FIG. 1.—Cell for Testing Reactive Aggregate.

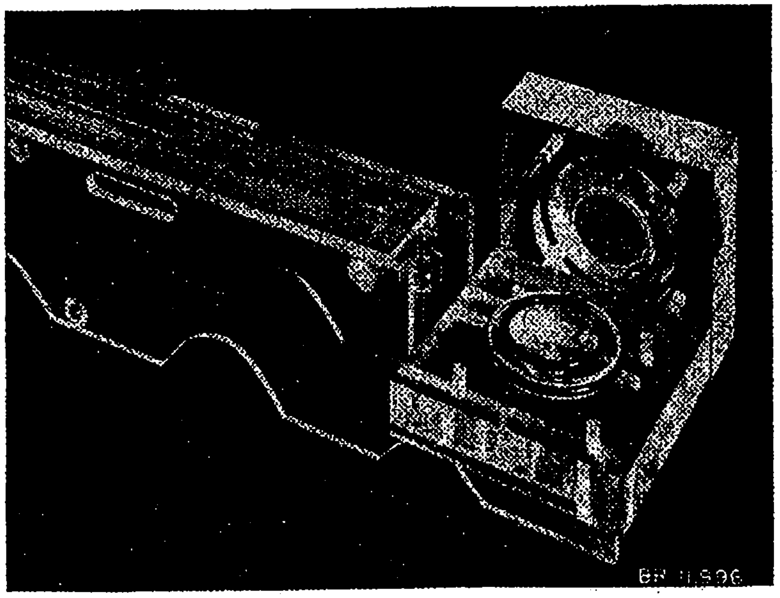

FIG. 2.—Two Halves of a Cell, Capillary Tube, and Metric Scale Used to Measure Volume Change in Powdered Aggregate.

known performance in concrete is discussed.

EXPERIMENTAL PROCEDURE

The apparatus is an adaptation of that used by Warkentin et al (7) in work on clays (Figs. 1 and 2). A powdered sample was mixed with a little water and placed on the rubber membrane in the compression chamber and sealed with O-rings. It had access to water or alkali via a porous plate of stainless steel of 2-μ pore diameter. The chamber below the rubber membrane was filled with water leading to the precision (1-mm bore) capillary tube so that volume changes in the compression chamber were registered by the meniscus. Phenolphthalein solution was added to this water so that any leakage of alkali through the rubber membrane would have been apparent. The sample was confined under a constant air pressure of 5 psi, and the whole apparatus was immersed in a water bath to maintain a constant temperature of 22 C.

TABLE 1.—DOLOMITE-CALCITE COMPOSITION AND REACTIVITY OF CARBONATE ROCKS.

Sample	Partial Analyses, per cent				Calculated				Total	Reactivity
	Acid-Insoluble	Fe	Ca	Mg	Dolomite,[a] per cent	Calcite, per cent	Calcite: Dolomite			
							Weight	*M*		
Kingston composite.	5.69	0.46	28.34	6.38	48.42	44.50	0.92	1.69	99.07	Reactive
Virginia B.........	14.97[b]	0.70	24.68	5.85	44.36	37.53	0.85	1.56	99.31	Reactive
Georgia...........	5.31	0.34	30.85	4.94	37.44	56.70	1.51	2.79	99.45	Reactive
Indiana B.........	14.08	0.43	26.64	5.21	39.55	45.06	1.14	2.09	99.12	Reactive
Indiana A.........	6.18	0.28	33.27	2.99	22.66	70.76	3.12	5.77	99.60	Slightly reactive
Ohio.............	6.67	1.88	25.66	7.84	59.43	31.81	0.53	0.99	99.79	Slightly reactive
Virginia A.........	1.87	0.11	34.33	3.47	26.3	71.45	2.72	5.00	99.62	Unreactive
Alabama..........	0.57	0.13	33.59	4.58	34.72	65.03	1.87	3.45	100.32	Unreactive

[a] Calculated from magnesium and calcium assumed present only as carbonate.

[b] Plus 1.75 per cent aluminum dioxide.

At the start of each experiment the sample had access to deionized or distilled water in the reservoir via the porous plate. When a slowed contraction was registered by the meniscus, indicating little further compaction of the powder under a pressure of 5 psi, the water was replaced by a 2 *M* solution of alkali.

In the initial experiments the solution was circulated continuously by a peristaltic pump. Similar results were obtained, however, when the solution was left static in a reservoir behind the porous plate, and a reservoir was incorporated in the design of the apparatus illustrated. Experiments showed that about 100 ml of alkali were required to exhaust the expansive capabilities of 30 g of rock. The expansive reaction normally went to completion in about two weeks, and the whole experiment took about one month.

DESCRIPTION OF SAMPLES

Rocks of different petrographic character, ranging in composition from almost pure dolomite to limestone, were obtained. Some of the samples were known to be reactive and were supplied by other workers. All were subjected to either the concrete beam test or the rock prism test. Those rocks that expanded in the tests were used in investigating the reliability of the cell technique as a test method. Certain of the samples produced no expansion in the rock prism test and concrete beam test but were still used in the cell test. Partial chemical analyses of the samples described here are given in Table 1, where the percentage composition is shown in terms of acid-insolubles, dolomite, and calcite. The carbonates were calculated from the experimentally derived values for magnesium and calcium on the assumption that these elements were present only as carbonates. The value shown for the calcite-to-dolomite ratio by weight and by moles was also calculated. These samples all fall within the composition fields of dolomitic limestone or calcitic dolomite (8), which includes the critical range of composition for alkali-carbonate rock reaction. Within this range, however, there seems to be no simple relationship between composition and reactivity. The very slightly reactive sample from Ohio, for example, is not much different in its percentage of acid-insoluble or carbonate composition from the highly reactive Kingston material. The calcite-to-dolomite ratio of the unreactive Alabama rock is not much different from the reactive Georgia sample, though there is a much lower content of acid-insoluble material. This is also true of the unreactive rock from Virginia and of other nonexpansive samples where the carbonate composition suggested potential reactivity.

Goldsmith and Graf (9) showed that dolomite may contain an excess of calcium carbonate above the theoretical 50 *M* per cent and that the lattice of such a dolomite is commonly disordered and the structure metastable. Such a dolomite is described as nonideal. Calcite sometimes shows variation in composition also, the most common being a replacement of calcium by magnesium. These changes of composition lead to such characteristic effects on the X-ray powder diffraction pattern as a line shift resulting from a change in lattice spacing. This may be determined by accurate measurement of X-ray powder patterns and is related to the composition of the dolomite or calcite expressed as *M* per cent magnesium carbonate in calcium carbonate. The composition of the dolomite and calcite in the rocks described in this paper was determined in this way from X-ray films taken with a Guinier quadruple focusing camera (Table 2). Results for the Kingston samples have been previously published (10). There is little sign of a correlation between composition and reactivity. Dolomite and calcite, which make up the unreactive Alabama rock, are both nearly ideal, whereas the unreactive Virginia A sample contains carbonates, which are very close in composition to the nonideal dolomite and slightly magnesian calcite of the reactive rocks.

TABLE 2.—COMPOSITION OF CARBONATES IN TERMS OF MOLAR PER CENT.

Sample	Dolomite[a]	Calcite[a]	Reactivity
Kingston:			
6 to 7 ft bed......	$Ca_{55.6}Mg_{44.4} \pm 0.72$	$Ca_{99.53}Mg_{0.47} \pm 0.21$	Reactive
10½ to 12 ft bed..	$Ca_{55.51}Mg_{44.49} \pm 0.77$	$Ca_{97.90}Mg_{2.10} \pm 0.71$	Reactive
20 to 21 ft bed....	$Ca_{55.14}Mg_{44.86} \pm 0.65$	$Ca_{96.17}Mg_{3.83} \pm 0.94$	Reactive
Virginia B..........	$Ca_{54.51}Mg_{45.49} \pm 0.49$	$Ca_{98.48}Mg_{1.52} \pm 0.44$	Reactive
Georgia............	$Ca_{55.08}Mg_{44.92} \pm 0.79$	$Ca_{98.12}Mg_{1.88} \pm 0.43$	Reactive
Indiana B..........	$Ca_{52.40}Mg_{47.60} \pm 0.68$	$Ca_{98.75}Mg_{1.25} \pm 0.46$	Reactive
Indiana A..........	$Ca_{51.65}Mg_{48.35} \pm 2.01$	$Ca_{98.10}Mg_{1.90} \pm 0.47$	Slightly reactive
Ohio	$Ca_{53.48}Mg_{46.52} \pm 1.22$	$Ca_{98.54}Mg_{1.46} \pm 0.73$	Slightly reactive
Virginia A..........	$Ca_{54.74}Mg_{45.26} \pm 0.68$	$Ca_{98.70}Mg_{1.30} \pm 0.24$	Unreactive
Alabama...........	$Ca_{50.92}Mg_{49.08} \pm 0.10$	$Ca_{99.34}Mg_{0.66} \pm 0.27$	Unreactive

[a] ± Tolerance gives the 95 per cent confidence interval for the mean value shown for either element expressed in mole per cent.

The rocks were examined microscopically and some of the less familiar petrographic terms used are defined here:

1. *Intraclasts.*—Fragments of semiconsolidated sea-bed redeposited after local erosion.
2. *Micrite.*—Fine calcite ($CaCO_3$) in crystals of 1 to 4 μ in diameter.
3. *Intramicrite.*—A rock in which the dominant fragmental material consists of intraclasts in a matrix of micrite.

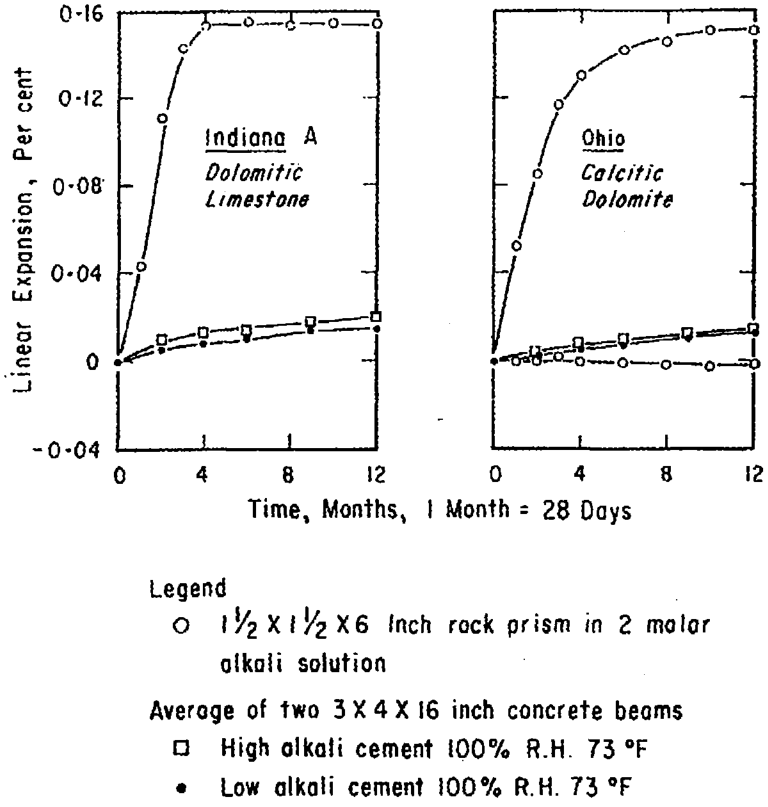

FIG. 3.—Expansion of Rock Prisms and Concrete Beams.

4. *Intrasparite.*—As No. 3, but matrix consists of clear calcite crystals generally larger than 10 μ.

More complete definitions are given in the literature (11,12).

Petrographic examination of the reactive Kingston rocks shows that they contain a high proportion of unrecrystallized fine lime mud or micrite (11,12). Bands occur of slightly disturbed calcareous ooze that contain a sprinkling of silt-size quartz. The dolomite euhedra attain a size of about 0.05 mm, but despite the extensive dolomitization, the fabric criteria of Bathurst (13) show that the matrix has not undergone grain growth or recrystallization. The rocks were deposited under generally quiet sedimentary conditions and have been dolomitized but not recrystallized (10). The petrography of the reactive rocks from Indiana, Georgia, and Virginia is quite similar to that of the Kingston rocks, although the dolomite euhedra reach a size of 0.2 mm in the Virginia B sample and 0.1 mm in the Georgia rock. Virginia B also differs from the Kingston samples in that skeletal material is present. The slightly reactive Indiana A sample contains beds of different microfacies. The rock prism, which expanded when placed in alkali (Fig. 3), is a dolomitized fossiliferous intramicrite, rather

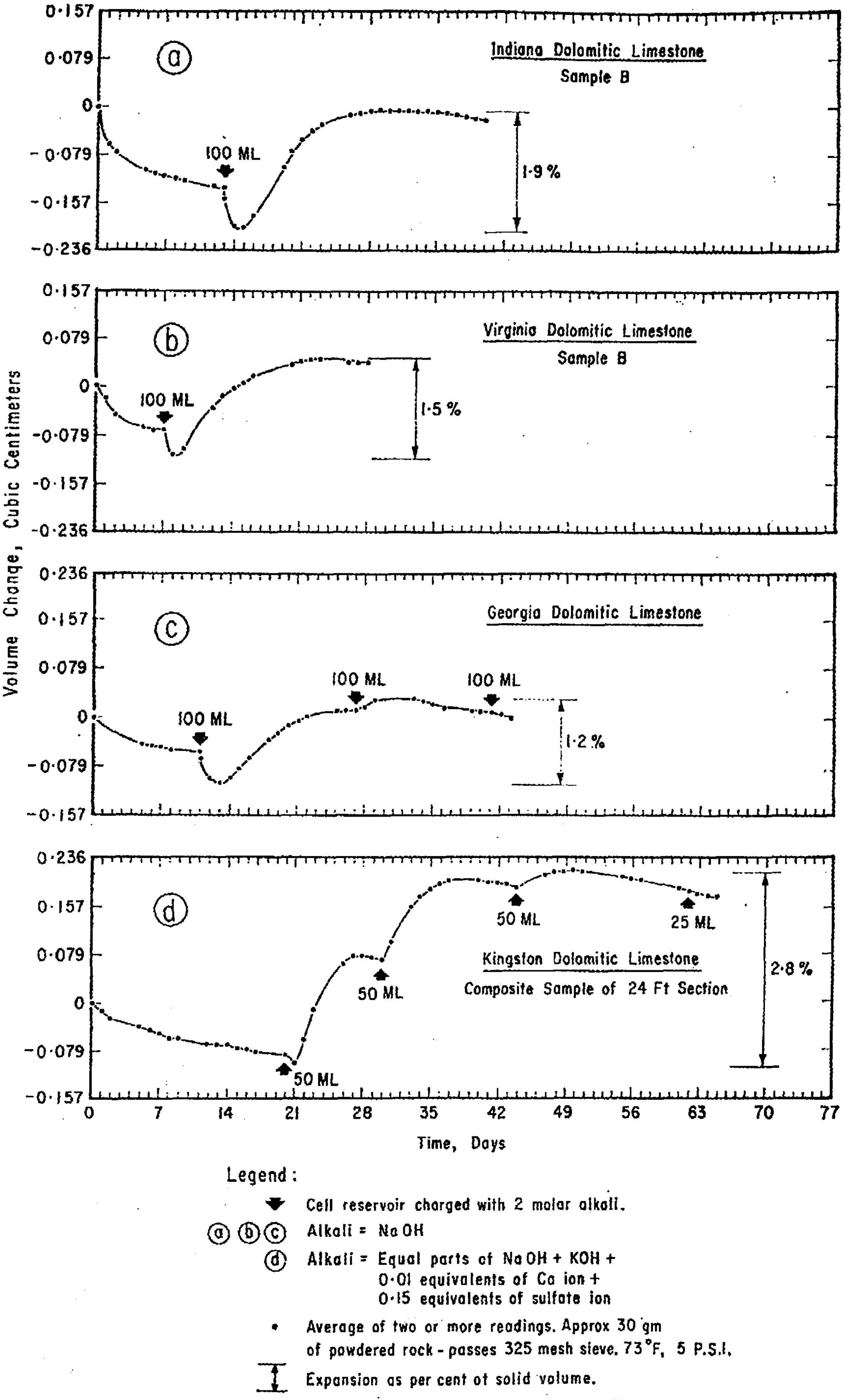

FIG. 4.—Expansion in 2 *M* Alkali of Reactive Carbonate Rocks in Cells.

similar to the Kingston rocks apart from the skeletal material. The remainder of these rocks contain more intrasparite and fossil fragments than the Kingston rocks. In addition to the biogenic material, some bands contain abundant oolites which are sometimes compacted. The conditions at the time of sedimentation of some, if not all, of these strata were probably different from those under which the reactive Kingston beds accumulated, since oolites are believed to indicate deposition in agitated water (14).

The rocks from Ohio and Alabama differ from the Kingston samples in that they are coarser grained, and crystals of both calcite and dolomite reach a size of about 0.2 mm or larger. Primary structures have been eliminated by recrystallization in places, but as this is of variable degree, intraclasts have elsewhere survived. These are now made up of 8 to 10-μ microspar and are surrounded by the coarser crystals of the matrix. A sample of Ohio rock that expanded in alkali (Fig. 3) shows less recrystallization than most of this material and retains a finely crystalline matrix. The unreactive Virginia A rock is an extensively dolomitized intrasparite, which is of coarser grain size than the Kingston material. The rock also has a cleaner appearance, due in part no doubt to the low acid-insoluble content.

EXPERIMENTAL RESULTS

The cell test was carried out first on a composite sample obtained from the top 24 ft of a quarry near Kingston and on a bed 6 to 7 ft from the surface. A sample of about 30 g of rock ground to pass a No. 325 sieve was used. As shown in Fig. 4(*d*), the composite rock from the quarry near Kingston expanded stepwise when 50-ml charges of 2 *M* alkali were supplied to the sample. The third addition, however, produced only slight further expansion, and the final addition none; the expansive capabilities of 30 g of rock were exhausted by the addition of a total of about 100 ml of 2 *M* alkali. In subsequent experiments a smooth expansion curve was obtained as 100 ml of 2 *M* alkali was used to replace distilled water in the cell reservoir as soon as equilibrium was attained.

The density of the powdered rock was determined by means of a pycnometer. As the weight of powder in the cell was known, the initial solid volume was obtained. The increase in volume was calculated from the experimental results obtained by use of the cell and hence the expansion as a percentage of the initial solid volume was calculated.

In the experiment in which the curve in Fig. 4(*d*) was plotted, the expansion in terms of the volume of solid amounted to about 2.8 per cent and the alkali was a solution of sodium, potassium and calcium hydroxide, and gypsum (4). In a later experiment in which pure sodium hydroxide was used, an expansion of nearly 8 per cent was registered. It is probable that this greater increase in volume was caused in part by the fact that the influence of the sodium hydroxide was more aggressive than that of the potassium hydroxide (4). Pure sodium hydroxide was used in the other cell tests described in this paper.

When distilled water was replaced by alkali, a sharp contraction was registered by the meniscus in the capillary tube, and expansion did not commence until two or three days after the alkali had been added to the system. The cause of this contraction is not definitely known, but further compaction of the powder may have resulted from the addition of alkali to the system, owing to a migration of water from between the particles of powder into the reservoir while alkali ions moved in the opposite direction via the porous plate. An alternative explanation is that while the sample was compacting

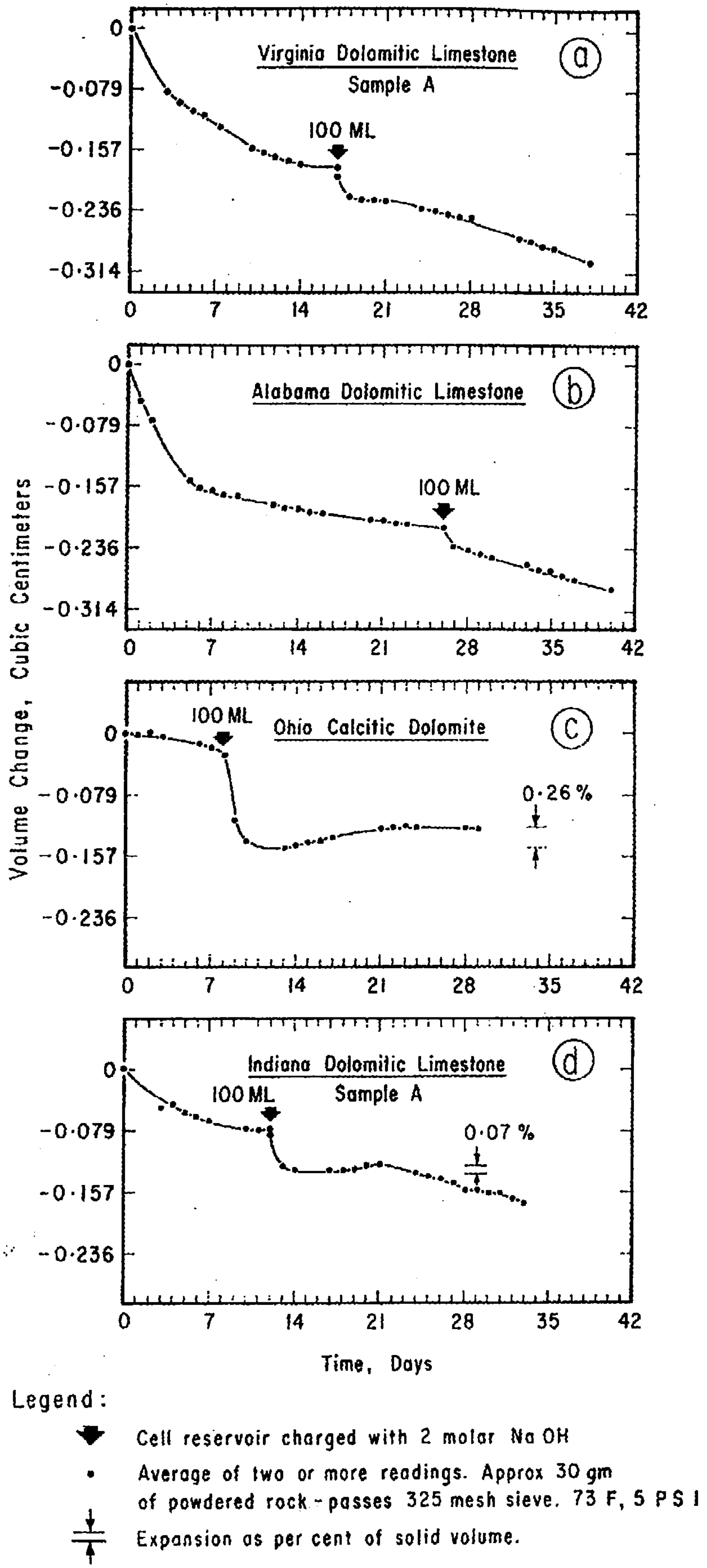

FIG. 5.—Behavior in 2 *M* Alkali of Slightly Reactive and Unreactive Carbonate Rocks in Cell.

in the presence of water in the cell reservoir a structure developed between the particles of powder, which ceased to be stable in the presence of alkali. This type of behavior is common in clay systems and is exploited commercially in ceramics where similar effects are induced by the addition of very dilute solutions of sodium carbonate. For the cell, it was found that the addition of 1 ml of 2 *M* sodium hydroxide to the distilled water in the reservoir resulted in a sharp contraction (registered by the meniscus in the capillary tube) similar to that following replacement of the water by 2 *M* alkali. Experience with nonexpansive samples showed that the rapid contraction normally lasted about two to three days, after which the curve assumed a slope approximately parallel to that of the curve prior to the addition of alkali (Figs. 5(*a*) and (*b*)). It seems probable that during the two days following the addition of alkali to reactive samples, this contraction prevented the registration of expansion by the meniscus in the capillary tube. If so, the delayed expansion does not imply a period of induction (the elapse of a time interval significant to the mechanism), before the expansion reaction commenced.

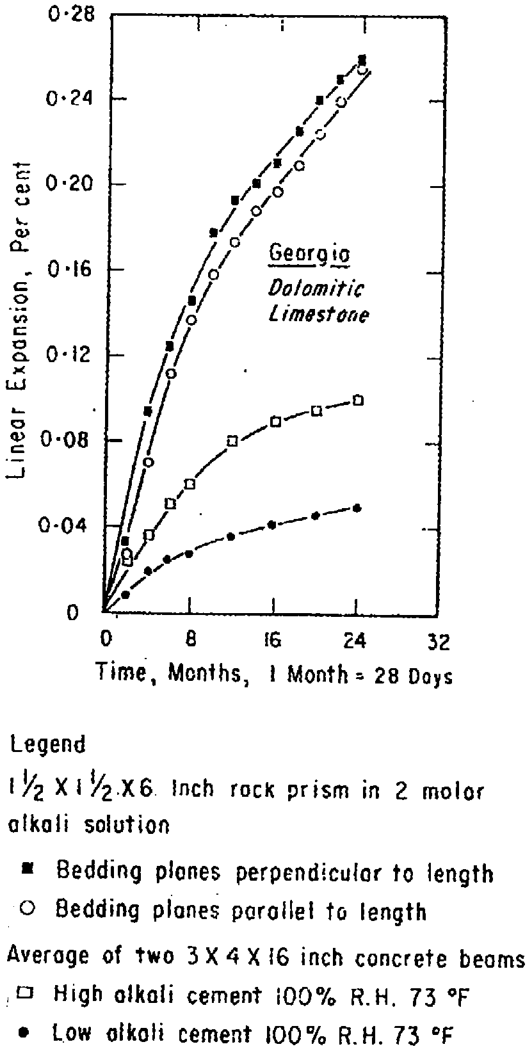

FIG. 6.—Expansion of Rock Prisms and Concrete Beams.

It was noticed also that after expansion had ceased the curve often had a greater downward slope than during the period of equilibrium prior to the addition of alkali. This may have resulted from an osmotic flow of water through the rubber membrane into the alkali, with a consequent contraction registered by the meniscus. Alkali was apparently unable to migrate in the opposite direction by this mechanism, since the water below the membrane remained neutral. The osmotic flow of water would, however, tend to counteract registration of expansion, which resulted in an apparently smaller volume increase than actually occurred. The curve obtained when using nonexpansive samples shows that the effect is of minor significance.

The profile registered during expansion is a fairly typical rate curve in which a high early expansion rate tapers off asymptotically with time, toward parallelism with the portion of the graph prior to the addition of alkali to the system (Fig. 4).

The linear expansion produced after two years by a reactive aggregate from Georgia when used in concrete beams made with high- and low-alkali cement and by rock prisms immersed in 2 *M* alkali is shown in Fig. 6. A split of 30 g of this rock, ground to pass a No. 325 sieve, produced an expansion of about 1.2 per cent in the cell test (Fig. (4(*c*)). A sample of reactive dolomitic limestone from Virginia and another sample from Indiana each gave a somewhat similar curve to the Georgia sample when used in a cell (Figs. 4(*a*) and (*b*)). Insufficient material was available from Virginia and Indiana for the concrete beam test, but the rock is known to cause expansion if used as aggregate[3] or in the rock prism test.[4]

Differences in response to the rock prism test have occurred in some cases. A sample from Ohio behaved in this manner: two prisms of the rock were immersed in alkali (Fig. 3), and while one produced a linear expansion of about 0.15 per cent at 10 months, the other showed none. Concrete beams made with high-alkali cement with this rock as aggregate showed only 0.02 per cent linear expansion after 2 yr exposure to high humidity conditions. A representative split of this rock, ground to pass a No. 325 sieve, produced only 0.26 per cent expansion in the cell test (Fig. 5(*c*)). Another example of this sort of behavior occurred with a sample from Indiana. Used as aggregate, this material caused a linear expansion of only 0.02 per cent in concrete beams, but a prism of the rock expanded 0.16 per cent in 4 months when immersed in alkali (Fig. 3). A representative sample of the material, when powdered, gave only 0.07 per cent increase of volume in the cell test (Fig. 5(*d*)). Hand specimens of Indiana rocks known to show differences of per cent linear expansion in the rock prism test showed fairly good agreement between the cell test and the rock prism test in that the rock producing the greatest expansion in the prism test showed the greatest volume increase in the cell test.

These and other results indicate that rock from different parts of the same quarry may show marked differences in behavior when placed in a strongly alkaline environment. It is therefore most important that the sample tested should be representative of the rock to be used as aggregate. This may be readily achieved for the cell test by quartering powdered rock or passing it through a splitter. Reliable sampling is much more difficult in any test method that relies on individual rock samples.

During these investigations over 50 carbonate rocks covering the composition range from limestone to dolomite were tested for expansivity by the concrete beam test and the rock prism test. Most samples produced no unusual expansion, even though some of them were similar in carbonate composition to the reactive rocks. A selection of unreactive samples was used in the cell test. None of those tested caused a volume increase, and typical profiles plotted during experiments with two of them are shown in Figs. 5(*a*) and (*b*).

CONCLUSION

By petrographic examination it is possible to recognize rocks similar to those from Kingston and elsewhere that expand deleteriously in alkali. A partial chemical analysis is also of some help since the calcite-to-dolomite ratio may be calculated and the acid-insoluble content determined. Since this falls between about 5 and 20 per cent in many of the reactive rocks it may well be significant to the mechanism. It is not possible, however, on the basis of these techniques, to predict the amount or degree of expansion that will be caused if rocks of this type are used as aggregate.

Alkali-carbonate rock reactivity may, however, be detected by the measurement of length change of concrete beams held under controlled conditions of 100 per cent relative humidity and 73 F.

---

[3] H. Newlon, personal communication.

[4] D. W. Hadley, personal communication.

The advantages of this test method are that aggregate of the same size and composition may be used with the cement to be used in practice. Interaction between aggregate and cement occurs under conditions commonly encountered under natural exposure. The main disadvantage is that a conditioned room is required and it takes considerable time before definite conclusions can be drawn as to whether or not deleterious expansion will be caused by a particular aggregate.

Comparative linear dimensional change measurement of rock prisms soaked in alkali is another technique used to evaluate reactivity. By this means the rock may be shown to be the causative agent for the expansion found in concrete, but as a test method for aggregate it has several disadvantages. In particular many specimens must be studied to evaluate properly the reactivity of a representative sample of the rocks in a quarry. There is also an inherent danger of spurious results, since expansion is known to cause cracking, and microcracks may go undetected and cause errors in the evaluation of per cent linear expansion. In addition, the measurement of length change is less appropriate than volume change measurement to the understanding of behavior of concrete aggregate, because interaction with cement paste is three dimensional. Rocks also have strong directional properties such as bedding planes, joints, and cleavages, and results are likely to be strongly affected (4, Fig. 10) depending on the angle such planar structures make with the direction of linear measurement used to evaluate the dimensional change.

The cell test appears to provide a rapid and reliable means of estimating the reactivity in alkali of carbonate rocks. Since powder is used the sample is easily made representative of the rock to be used as aggregate. The small particle size of the powder ensures a rapid response to alkaline attack, and the increase of volume may be followed to completion with no danger of spurious results owing to cracking or anisotropy.

Acknowledgments:

Thanks are due to P. J. Lefebvre, who was responsible for most of the sample preparation and technical duties involved in assembling and reading the cells and whose substantial contribution to the work made this paper possible. Thanks are also due to B. P. Warkentin for help in the early phases of the work, to J. Harris for help with statistics, and to D. S. Russell, under whose supervision the chemical analyses were performed. Appreciation is also expressed to D. McGinnis, H. Newlon, D. Hadley, G. Peyton, J. L. Calver, H. D. Pallister, K. V. Hoover, and W. L. Dolch, who supplied samples.

REFERENCES

(1) U. S. Army Engineer Waterways Experiment Station, Corps of Engineers, "Alkali-Silica and Alkali-Carbonate Reactivity of a South Dakota Sand," *Miscellaneous Paper No. 6-530*, Sept., 1962, pp. 1–11.

(2) Howard H. Newlon Jr., and W. Cullen Sherwood, "An Occurrence of Alkali-Reactive Carbonate Rock in Virginia," *Bulletin 355*, Highway Research Board, 1962, pp. 27–44.

(3) E. G. Swenson, "A Canadian Reactive Aggregate Undetected by ASTM Tests," *ASTM Bulletin*, No 226, 1957, pp. 48–51.

(4) E. G. Swenson and J. E. Gillott, "Characteristics of Kingston Carbonate Rock Reaction," *Bulletin 275*, Highway Research Board, 1960, pp. 18–31.

(5) D. W. Hadley, "Alkali Reactivity of Carbonate Rocks—Expansion and Dedolomitisation," *Proceedings*, Highway Research Board, 40th Annual Meeting, 1961, pp. 280–282.

(6) A.C.I. Committee 201, p. 1805, *A.C.I. Journal*, Dec. 1962 (Discussion and closure to discussion contained in *A.C.I. Journal*, June 1963, pp. 2071–2080).

(7) B. P. Warkentin, C. H. Bolt, and R. D. Miller, "Swelling Pressure of Montmorillonite," *Proceedings*, Soil Science Soc. America, Vol. 21, No. 5, 1957, pp. 495–497.

(8) F. J. Pettijohn, *Sedimentary Rocks*, 2nd edition, Harper Bros., New York, N. Y., 1957, 718 pp.

(9) J. R. Goldsmith and D. L. Graf, "Structural and Compositional Variations in Some Natural Dolomites," *Journal of Geology*, Vol. 66, No. 6, 1958, pp. 678–693.

(10) J. E. Gillott, "Petrology of Dolomitic Limestone, Kingston, Ontario, Canada," *Bulletin*, Geological Soc. America, Vol. 74, No. 6, June 1963, pp. 759–778.

(11) R. L. Folk, "Practical Petrographic Classification of Limestones," *Bulletin*, Am. Assn. Petroleum Geologists, Vol. 43, No. 1, 1959, pp. 1–38.

(12) D. G. Murchison and R. G. C. Bathurst, "The Term Micrite in Coal and Limestone Petrography," *Fuel*, Vol. 41, No. 4, July, 1962, pp. 403–407.

(13) R. G. C. Bathurst, "Diagenetic Fabrics in Some British Dinantian Limestones," *Liverpool and Manchester Geological Journal*, Vol. 2, Pt. 1, 1958, pp. 11–36.

(14) C. O. Dunbar and J. Rodgers, *Principles of Stratigraphy*, John Wiley and Sons, New York, N. Y., 1957, pp. 1–356.