

EXPANSION OF REACTIVE CARBONATE ROCKS UNDER RESTRAINT

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It is suggested that the degree of expansion of alkali-reactive carbonate rocks is not only a function of the volume of dolomite contained in the rock but also of the texture of the material as reflected by its deformation characteristics under sustained loading. Theoretical equations are presented that can be used for calculating the expansion of a two-phase system composed of certain volumes of expanding elastic particles enclosed and restrained within an elastic matrix. A comparison of calculated expansions with the expansions of concrete measured experimentally indicates that the theoretical relationship gives a good approximation of the expansion of a two-phase system such as concrete. The solution is then applied to the analogous carbonate rock case, which is considered as a two-phase system composed of dolomite particles enclosed within a calcite-clay matrix. Carbonate rock samples, which were chosen with regard to their expansive reactivity in alkaline solution, were analyzed physically, chemically, and petrographically. The experimental data thus obtained, supported by the theoretical analysis, indicate that the degree of expansion of a reactive carbonate rock depends on a complex interplay of its structural texture and compositional properties. The deformation characteristics of a carbonate rock under sustained loading tend to reflect its structural rigidity, which in turn is a significant property when the effects of either textural or external restraints to expansion are considered. Thus a reactive carbonate rock with low textural restraint could be highly expansive when unrestrained, but when restrained in a mass of concrete it would be more compressible and less expansive.

•FROM the results of various tests, Hadley (1) postulated a dedolomitization reaction (the replacement of dolomite by calcite and brucite) between dolomite and alkali metal hydroxides as the basic reaction mechanism leading to the expansion of certain carbonate rocks. This reaction mechanism theory has been generally supported by the findings of others (2, 3, 4, 5). While several hypotheses have been proposed to explain the mechanism of expansion (6, 7, 8, 9, 30), all are based on expansion originating from the dolomite crystals following an initial dedolomitization reaction. As research has progressed, however, the classification of potentially expansive carbonate rocks has broadened considerably. The results of earlier studies by Hadley and others indicated that the majority of the expansive rocks could be classified as fine-grained, argillaceous, and dolomitic (1, 3, 10, 11). The rock texture was found to be that of small dolomite crystals dispersed in a matrix of microcrystalline calcite and clay material. The carbonate portion of the rock generally contained 40 to 60 percent dolomite, and insoluble residues consisting mostly of clays and other impurities constituted a 10 to 20 percent portion of the material. Other authors (12, 13) have reported on some expansive rocks that did not fit these criteria, and in some additional studies Hadley (14) found that carbonate rocks containing from 80 to 100 percent dolomite could be highly expansive when reacted in alkaline solutions. Hadley further suggested that clay content

was an important factor, since interstitial clays could weaken the carbonate skeleton and make a rock more susceptible to expansive pressures. In addition, Dolar-Mantuani (15) has reported on some carbonate rocks that did not expand until immersed in a sodium hydroxide solution for at least 30 weeks, whereas the more typically expansive rocks show significant expansions after only a few days of exposure. Thus, one might conclude from a review of the prior research that the potential for carbonate rock expansion and the rate of expansion will depend on a complex interplay of the rock's composition, the size and volume of its various components, and the structural rigidity of the total material.

CARBONATE ROCK STRUCTURE

In addition to the work mentioned previously, Hadley (1) conducted tests on a comparatively large 0.3-in. (7.6-mm) gauge length dolomite crystal and observed an expansion of 0.15 percent after 100 days' immersion in a sodium hydroxide solution. While the degree of expansion was small when compared to that of many reactive rocks, the dolomite crystal was considerably larger than the order of 30-micron size found in most expansive rocks. In view of other experimental evidence showing that the rate of dolomite reaction increases with decreasing particle size (1), the size difference between the experimental crystal and those found in expansive rocks would appear to be significant. Thus, the migration of alkalis into the structure of a large dolomite crystal would probably require considerably more time than that required to penetrate an equivalent volume of dispersed microscopic dolomite rhombs. Accordingly, one might expect the more porous clay media of the readily expansive rocks to provide access channels to the small dolomite rhombs. Expansion might then proceed at a high rate when the total material has a weak structure and contains a sufficient volume of dispersed microscopic dolomite particles. On the other hand, rocks with high carbonate contents would tend to have strong interlocking of the carbonate crystals, and hence the alkalis could not readily penetrate the structure, which would, in turn, tend to be strong and rigid.

The approximate volume of carbonate particles at which the interlocking of the crystalline structure of a rock might be expected is indicated from the work of Hsu (16), who determined that, in the close-packed state, a face-centered cubic lattice of spherical particles would occupy 74.2 percent of the total cubic volume. Although carbonate particles are not normally spherically shaped, this relationship does suggest a volume in which crystal interlocking might be expected. Furthermore, from a mechanics viewpoint, one would expect rocks with interlocking of the carbonate constituents to be comparatively rigid and have higher moduli of elasticity than rocks with little interlocking of the carbonates. It would follow that rocks with higher moduli of elasticity would have more textural restraint due to a more rigid structure and thus less tendency to expand.

The typical structure of the more expansive carbonate rocks is quite similar to that of portland cement concrete. While concrete can be considered as a two-phase system consisting of aggregate particles dispersed in a cement-mortar matrix, the expansive-type rocks consist of dolomite rhombs dispersed in a matrix of clay, calcite, and miscellaneous impurities. Thus, the ultimate expansion of either system would depend on the volume of expansive particles present, their degree of reactivity, and the textural rigidity of each phase. Furthermore, if expansion is affected by the rigidity of a reactive rock's structural fabric, then the expansion of concrete containing the material could not be expected to be proportional to the expansion of rock samples reacted in alkaline solutions.

PURPOSE AND SCOPE

Reactive carbonate aggregates are usually detected in the laboratory by measuring the expansion of small rock specimens reacted in alkaline solutions by procedures similar to those in ASTM C 586 or by periodically measuring the expansion of concrete specimens containing the material. Accordingly, two types of restraint can be considered as countering the expansion of reactive carbonate rocks. These are the restraints that would be imposed by the texture (or structural fabric) of the rock and those

that would be imposed externally. In the latter case, the typical restraint would be that of the cement-mortar matrix surrounding the aggregate particles in concrete. The purpose of the study was to investigate the effects of each of these two types of restraint.

The scope of the work was limited to an investigation of the expansion and textural characteristics of some carbonate rock samples selected with regard to their magnitude of expansion when reacted in a 1N NaOH solution.

THEORETICAL CONSIDERATIONS

Although several expansion mechanisms have been proposed, as referenced earlier, each assumes expansion to be centered around the dolomite phase of the rock. Accordingly, a carbonate rock can be considered as a two-phase system composed of dolomite expanding within a surrounding matrix.

Elongation, or expansion, of a particular body of material can be defined in terms of stresses, moduli of elasticity, and geometrics. If a spherical body composed of a volume of one material surrounded by the matrix of another is assumed, the relationship between the expansion of the core volume and the expansion of the total volume can be developed from equations derived by Lamé (17) that define the stresses in the body. In addition, by using the relationships between stresses and strains and by taking Poisson's ratio as 0.2, which is a reasonable value for masonry and rock materials (18), an equation for the expansion of the body, ξ_b , was developed earlier (19) that takes the form

$$\xi_b = \frac{\xi_s}{\frac{1-g}{3g} \left(\frac{1.5E_m + 0.5}{E_s} \right) + \frac{1+2g}{3g}} \quad (1)$$

This relationship indicates that the unit linear expansion of the total body, ξ_b , varies directly as the unit linear expansion of the core material, ξ_s , and inversely as the fractional volume of the core, g , and the ratio of the modulus of elasticity of the matrix, E_m , to that of the core, E_s .

The restrained unit linear expansion of the core material, $\xi_{s(r)}$, has also been developed (19); it takes the form

$$\xi_{s(r)} = \xi_s - 1.5 \xi_b \frac{E_m}{E_s} \left(\frac{1-g}{3g} \right) \quad (2)$$

Experimental Versus Calculated Expansions

Newlon and Sherwood (20) have presented experimental data on the 1-year expansions of moist-cured concrete prisms made with an expansive aggregate (sample 1-8). These data show the effects on concrete expansion of cement alkali content and dilution of the expansive aggregate volume with a reference granite material. Since concrete can be considered as a two-phase system, these data offer a convenient means of comparing calculated and experimental expansions.

The relative volumes of aggregate and cement mortar in the hardened concrete prisms can be calculated from the original mix proportions by use of a relationship developed by Axon (18). Typical values for the modulus of elasticity of cement mortar range from 1 to 4 million psi and depend on the water-cement ratio and age (21). Because the elasticity of the mortar phase would vary with time, it would appear reasonable to assume an average effective E_m of 2.5×10^6 psi (17.25×10^6 kPa). Because of the long-term stresses induced in the materials by the expanding aggregate, considerable creep would also be involved. To account for this phenomenon the elastic modulus of cement mortar is normally reduced to approximately one-third of the actual value (22). A similar elasticity value (given in Table 3) must also be used for the aggregate sample 1-8. Accordingly, an effective E_m/E_s ratio of 0.48 was obtained that takes the time-dependent creep effect into account. Thus, for a given fractional volume of expansive aggregate, the unrestrained unit expansions of the aggregate, ξ_s , were calcu-

lated by use of Eq. 1. These values established the 1-year unit expansions of the aggregate reaction with a given cement alkali content. The concrete expansions, ξ_s , for each remaining value of the fractional volume of aggregate, g , were calculated and plotted against the experimental data (Figure 1). A very good correlation between the experimental and calculated expansions was obtained.

Equation 1 can be used to estimate concrete expansions that may result from reactive rock expansions measured by test methods such as ASTM C 586. It should be noted, however, that cracking can develop in concrete at expansions on the order of 0.05 percent (10, 11). Although minor isolated cracking should not have much effect on calculated estimates of expansion, the theory does not consider cracking in the matrix or in the expanding particles. In addition, the upper limit of g in Eqs. 1 and 2 would be on the order of 0.74 (for particles approaching spherical shapes, for example), because at this volume the matrix and particle relationship would reverse; i.e., the matrix would become enclosed in the surrounding aggregate material. Finally, effective E_m and E_g values cannot be determined from standardized tests and must be estimated either by applying approximate corrections to normal E values or by estimating the effective values by testing the materials under sustained loading.

MATERIALS, TESTS, AND PROCEDURES

Rocks Studied

A variety of carbonate rock samples that exhibited different magnitudes of expansion when reacted in a 1N NaOH solution were selected for study. The rock sample code numbers, the general source of the materials, and references to additional studies involving the material are given in Table 1.

Cylindrical specimens 0.45 in. (1.14 cm) in diameter and 1 in. (2.54 cm) and $1\frac{3}{8}$ in. (3.5 cm) long were drilled from the rock samples so that their axes were perpendicular to the sedimentation layers. The longer cylinders were tapered 45 deg on each end and used for unrestrained expansion measurements. The shorter cylinders were used for restrained expansion measurements and other physical tests. Material adjacent to that from which the cylinders were taken was used for chemical and petrographic analyses and for porosity determinations.

Composition and Texture

The major constituents of the rock samples were determined by the chemical method described by Bisque (25) and are given as percent by volume in Table 2. Although some petrographic data are given in Table 2, this information was used primarily to determine the relative textural characteristics of the rock samples.

The general texture of rocks 1-6, 1-8, 12-9B, 27-4, and K-B was similar to that of 12-9A shown in Figure 2, which clearly shows the similarity between the texture of some carbonate rocks and that of portland cement concrete in section. The major difference between the textures of this group of rocks was the relative amounts of the various constituents and the intergranular contact between the dolomite rhombs. In sample 1-6, for example, the dolomite rhombs were fewer and more widely dispersed in a matrix phase of calcite, quartz grains, and partially silicified or pyritized fossils. On the other hand, sample 12-9B contained a larger volume of dolomite with more contact between the individual grains than did 12-9A. Rock K-B was similar to the latter material except that in some areas the dolomite rhombs were not well sorted and were partially locked in by sparry calcite. In this respect rock 12-U was similar to K-B. The texture of sample 1-8 was similar to that shown in Figure 2 except that the dolomite was not as sharply defined and the matrix contained more clay-like material.

A photomicrograph of the most expansive sample, Mo, is shown in Figure 3. The matrix of this rock was the most porous of all the study materials, and it occupied smaller areas between the relatively high volume of discrete dolomite rhombs.

Sample B-A (Figure 4) had a very rigid structure composed almost entirely of dolomite, with some interstitial carbonate and quartz grains present. This rock was selected primarily for use as a reference because of its high dolomite content and be-

Figure 1. Comparison of computed expansions with the expansion of 4 x 4 x 11-in. concrete prisms containing variable volumes of expansive aggregate sample 1-8 (experimental data from 20).

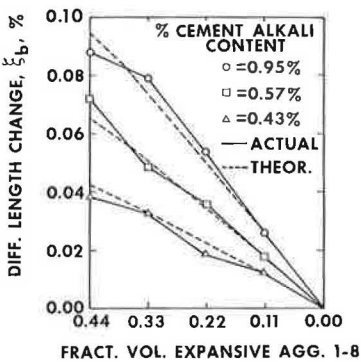


Table 1. Carbonate rocks selected for study.

Sample Designation	General Location of Source of Rock Samples	Additional References
1-6	Northwest Virginia	(10, 23)
1-8	Northwest Virginia	(2, 10, 20, 23)
12-9A	Southwest Virginia	(23)
12-9B	Southwest Virginia	(23)
12-U	Southwest Virginia	(23)
27-4	Central-western Virginia	(23)
B-A	Central-western Virginia	(23)
K-B	Kingston, Ontario, Canada	(24)
Mo ^a	Missouri	(12)

^aThis sample is the same as that designated as sample 8bb in Table 2 of Axon and Lind (12).

Table 2. Compositional and physical data of carbonate rock samples.

Sample Designation	Chemical Analyses ^a			Petrographic Analyses: Average Size of Dolomite Rhombs (microns)	Absorption (%)	Bulk Specific Gravity	Porosity (%)
	Volume Dolomite (%)	Volume Calcite (%)	Volume Insoluble Residue (%)				
1-6	15.8	68.7	14.9	40	0.20	2.76	0.552
1-8	32.4	36.7	29.7	41	0.451	2.78	1.254
12-9A	28.9	55.4	14.5	30	0.415	2.75	1.141
12-9B	44.6	39.3	14.8	34	0.480	2.74	1.315
12-U	27.8	61.9	9.9	40	0.133	2.72	0.362
27-4	19.4	67.9	12.1	35	0.215	2.74	0.589
B-A	94 ^b	— ^b	— ^b	90	0.064	2.84	0.182
K-B	44.3	46.3	8.7	40	0.262	2.79	0.731
Mo	58.6	23.5	12.3	34	2.11	2.67	5.634

^aVolume percentages were calculated from chemical analyses weight percentages by using the following specific gravities: dolomite, 2.85; calcite, 2.71; insoluble residue, 2.70 (26).

^bVolumes determined by petrographic analysis. Calcite, clays, and other impurities make up the remainder of the total volume.

Figure 2. General texture of sample 12-9A showing discrete dolomite rhombs dispersed in a fine-grained matrix of microcrystalline calcite and clay (100 X).

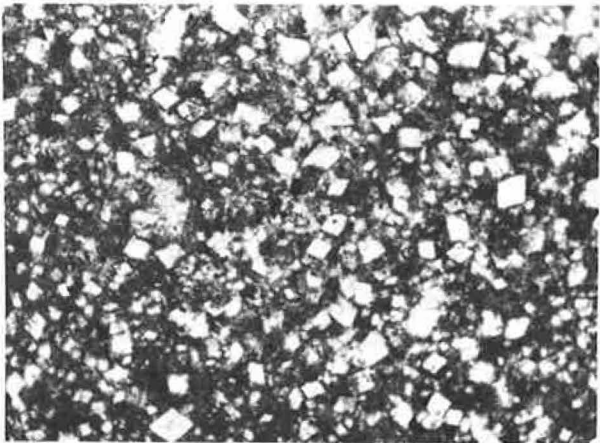


Figure 3. General texture of sample Mo showing a high dolomite content and porous matrix (100 X). Some of the clear areas are due partially to a loss of grains during preparation of the thin section.

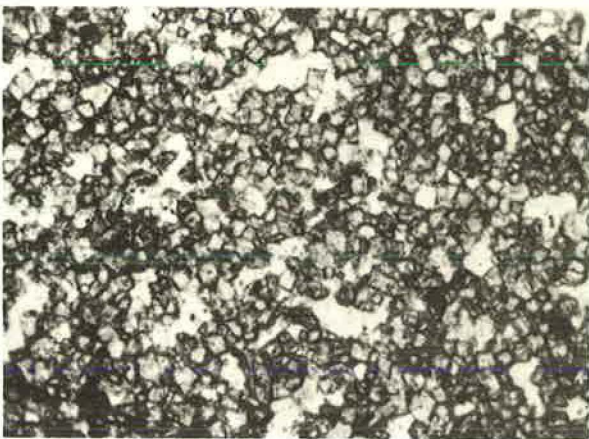


Figure 4. Texture of sample B-A showing a mosaic of equant dolomite grains forming a very homogeneous, virtually nonporous structure (100 X).

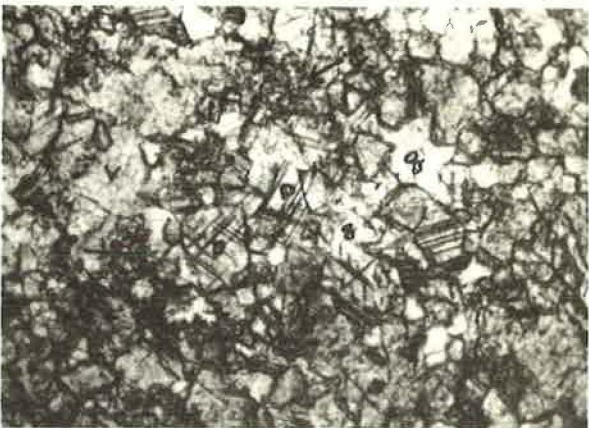


Table 3. Sustained modulus of elasticity of carbonate rock samples.

Sample Designation	Slope, E_s , Sustained Modulus, $\times 10^6$ (psi)	95% Confidence Range for Sustained Modulus, $\times 10^6$ (psi)		Sustained Modulus of Dolomite Phase E_d , $\times 10^6$ (psi) ^a	Sustained Modulus of "Matrix" Phase E_m , $\times 10^6$ (psi) ^b
1-6	2.62	2.54	2.71	2.68	2.61
1-8	1.73	1.64	1.82	2.68	1.48
12-9A	2.37	2.26	2.49	2.68	2.26
12-9B	1.91	1.80	2.02	2.68	1.56
12-U	2.26	2.18	2.34	2.68	2.14
27-4	2.17	2.11	2.23	2.68	2.07
B-A	2.68	2.51	2.86	2.68	2.68
K-B	2.15	2.07	2.24	2.68	1.86
Mo	1.13	0.94	1.32	2.68	0.62

^aThe value of sustained E_d for dolomite is assumed to be the same as the sustained E of sample B-A, which is virtually all dolomite.

^bThe values of sustained E_m were calculated by Eq. 3 using the data for the volume of dolomite, g , from Table 2.

cause it was not found to be expansive after soaking for 8 weeks in 1N NaOH. (The material did begin to expand, however, after approximately 40 weeks of continuous soaking in the NaOH solution.)

Physical and Mechanical Properties

The absorption and specific gravities of the rocks were determined by standard ASTM procedures (27) and are given in Table 2. Porosities were also determined by use of a mercury porosimeter and are given in Table 2.

The expansion of carbonate rocks against restraint involves time-dependent stresses, which in turn involve the effects of creep. Creep is normally taken into account by using a "modulus of deformation" or a "sustained modulus" value for E in calculations. In an effort to measure the materials' performance characteristics under sustained loads, stress-strain data on the rocks were obtained by applying deadweight loading to the 0.45×1 -in. (1.14×2.54 -cm) cylindrical specimens. By using a soil consolidation device, 40-kg loading increments were applied to the rock specimens. Strain readings were taken after each loading increment had been on the specimen for approximately 20 seconds. During this lapse of time some additional deformation occurs that is greater for the weaker structured rocks than for the stronger. Thus, in either case, lower than normal modulus values are obtained due to the higher strain measurements—and probably also due to the small specimen size. The order of magnitude of the values, however, is of little consequence since the study was concerned only with relative differences between the materials.

From the stress-strain data taken on 15 specimens for each rock sample, the slope of the line of best fit through the data points was determined by the method of least squares. The slopes, which are the values of the sustained modulus, are given in Table 3.

Hansen (22) has reviewed the various theoretical and practical formulas that have been proposed for correlating the modulus of elasticity of a two-phase material to the modulus of elasticity of the component materials. For a two-phase material where the modulus of the embedded particles is greater than that of the surrounding matrix, i.e., $E_g > E_a$, it was concluded that the following relationship is sufficiently accurate for most practical purposes:

$$E = \frac{1}{\frac{1-g}{E_a} + \frac{g}{E_g}} \quad (3)$$

where E = modulus of elasticity of a two-phase material and g = fractional volume of the embedded particles. For two-phase materials such as concrete, E_g is normally greater than E_a ; if the carbonate rocks included in this study are defined as two-phase materials with an E_g of the embedded dolomite rhombohedrons equal to that of the reference sample B-A, then E_a can be calculated from Eq. 3. The sustained E_a were calculated from the sustained modulus values for E and E_g and are included in Table 3.

Unrestrained Expansion Measurements

For each rock sample, three of the conically tipped specimens described earlier were tested for expansion. With the exception of the specimen size and the intervals at which length change measurements were taken, the method of test and equipment conformed to the requirements of ASTM C 586-66T. The length change measurements were taken at weekly intervals for the first 8 weeks and at 4-week intervals thereafter for a total of 20 weeks.

Restrained Expansion Measurements

Samples 1-6, 1-8, 12-9A, 12-9B, K-B, and Mo were tested for expansion in a stainless steel restraining device (Figure 5). Electrical resistance strain gauges were mounted on the top side of each device to measure the amount of strain caused by the expanding rock specimen. By use of calibration curves developed for each device, the

strain readings could be converted to the restraining forces developed by the expanding specimens or to the amount of linear expansion against restraint. Two levels of restraint were used, and they were governed by the thickness of the upper beam, which was either $\frac{1}{4}$ or $\frac{1}{8}$ in. (0.635 or 0.318 cm) thick.

For each rock sample, four specimens were mounted in individual restraining devices and placed in a polyethylene container of 1N NaOH solution (19). Sufficient solution was added to cover the rock specimens, and the strain gauge lead wires were connected to multichannel switching units. Strain readings were taken weekly for a period of 90 days.

RESULTS

The average results of the unrestrained expansion tests are shown in Figure 6. The most expansive sample, Mo, expanded an average of 7.8 percent, followed by 12-9B at 6.25 percent, 12-9A at 2.23 percent, and 1-8 at 1.52 percent, after 20 weeks in the NaOH solution. Of the expansive rock group, sample 1-6 expanded the least at 0.31 percent, with samples K-B and 27-4 expanding slightly more. The expansion of sample 12-U was insignificant. Although this rock had a relatively high dolomite content, the petrographic analysis indicated that the dolomite occurred in localized clumps—possibly interlocked with sparry calcite to form a rigid structure. It is probable that this sample would expand considerably if soaked for a longer period of time.

In general, expansion of the rock samples during the 20-week period was related to the volume of dolomite in the rock. When consideration is given, however, to the expansions of samples K-B and B-A, it is apparent that factors other than dolomite content are involved. K-B, for example, had a dolomite content virtually equal to that of sample 12-9B but expanded only a fraction as much (0.36 percent in 20 weeks). Sample B-A had a 94 percent dolomite content but did not expand during the test period. In the latter case, the massive structural fabric, with great interlocking and coarseness of the mineral constituents, probably resists alkali penetration and expansion. Of the two lithologies studied in the case of K-B, neither contained the clearly defined discrete dolomite rhombs like those shown for 12-9A. In one K-B section studied petrographically much of the dolomite was partially locked in by sparry calcite.

Somewhat similar situations existed for samples 27-4 and 12-U except that these had isolated bands or pockets of material that contained the discrete dolomite rhomb type of texture.

The expansions of alkali-reactive carbonate rocks are thus not simply related to the volume of dolomite but rather to a complex interplay of other physical variables as well. Swenson and Gillott (9), for example, have shown that rocks having small dolomite rhombs with high specific surface tend to expand the greatest over a given period of time. Porosity, as shown in Figure 7, is generally higher in the most expansive rocks, and, as can be detected from Tables 2 and 3, the sustained modulus of elasticity generally decreases with an increase in porosity. A more pronounced decline in E_s than in E occurs with an increase in porosity, indicating, as would be expected, that the pores are concentrated in the matrix phase of the rocks. One would also expect that expansion would decrease with an increase in the rigidity of the rock matrix material, and this was found to be generally the case, as shown in Figure 8. Accordingly, two carbonate rocks with equivalent chemical compositions might be expected to have vastly different expansive characteristics if their structural fabrics differ to such an extent that their elastic properties are quite different.

Given the basic constituents typical of reactive carbonate rocks, it becomes more apparent from the preceding relationships that other physical properties should also be indicative of the expansive nature of these rocks. In tests on a large number of different types of carbonate rocks, Nikolayev (28) found porosity to increase as compressive strength decreased. In still other studies on large numbers of carbonate rocks, Chel'tsov (29) found that compressive strength generally decreases with a decrease in specific gravity. Generally, expansion should increase with decreased compressive strength, and a decrease in compressive strength should be accompanied by a decrease in specific gravity. Since absorption is related to porosity, it is reasonable to expect

Figure 5. Typical device used for restraining expansive carbonate rock specimens.

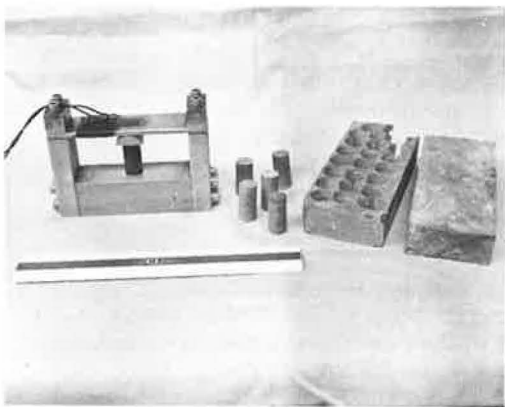


Figure 6. Average expansions of carbonate rock samples.

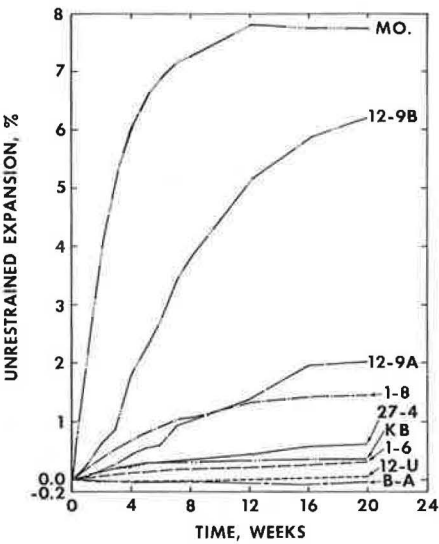


Figure 7. General increase of expansion as initial porosity increased.

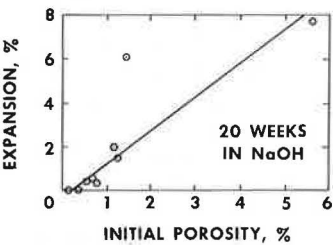


Figure 8. General decrease of expansion as sustained modulus of the rock "matrix" increased.

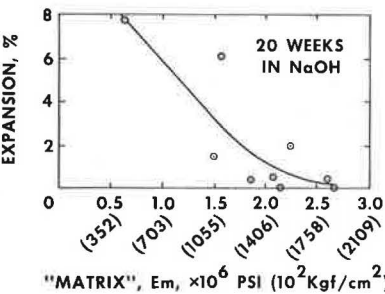


Table 4. Calculated expansions for dolomite phase of the expansive rocks.

Sample Designation	Ratio of Phase Moduli E_d/E_s	Expansion, ξ_d , Selected for Calculation Purposes (%)	Time Required to Expand 0.31% in 1N NaOH (days)	Fractional Volume of Dolomite, g	Ratio ξ_d/ξ_s	ξ_s	$\xi_s^{(b)}$, Eq. 2 (%)	Reduction in ξ_s Due to Restraint (%)
1-6	0.975	0.31	140	0.158	0.158	1.98	1.15	41.3
1-8	0.552	0.31	12	0.324	0.392	0.79	0.61	22.6
12-9A	0.843	0.31	23	0.289	0.308	1.01	0.69	31.9
12-9B	0.582	0.31	9	0.446	0.51	0.608	0.496	18.4
27-4	0.772	0.31	45	0.194	0.21	1.475	0.976	33.8
K-B	0.694	0.31	64	0.443	0.485	0.64	0.505	21.1
Mo	0.231	0.31	1.1	0.586	0.702	0.442	0.417	5.7

a highly expansive carbonate rock to generally have higher absorption, higher porosity, lower specific gravity, lower compressive strength, and a lower modulus of elasticity than less expansive rocks. A comparison of the samples based on data from Tables 2 and 3 indicates that, relative to the sample group, the most expansive rock sample, Mo, and the nonexpansive B-A both fit these criteria. The rock samples in between these two extremes generally follow suit, but uniform relationships cannot be expected since expansion depends basically on the volume and disposition of the dolomite present in the materials. In the final analysis, however, it is apparent that the sustained modulus of elasticity tends to reflect the net effect of the various physical properties of a rock.

Textural Restraint

The restraining effects of the texture of rock samples B-A and 12-U have been discussed in light of their structural properties and lack of expansion at 20 weeks in the 1N NaOH solution. If Eqs. 1 and 2 are applied to the remaining expansive samples, the effects of textural restraint on the expansion of the dolomite phase of these materials can be calculated. The use of these equations, in effect, considers textural restraint and the sustained moduli of elasticity of the materials to be synonymous. As a basis for comparison of the effects of textural restraint on the expansion of these rock samples, Table 4 has been prepared. The calculated values of ξ_e and $\xi_{e(r)}$ in the table are based on a ξ_b of 0.31 percent. This value was chosen because sample 1-6 expanded the least (0.31 percent) at the end of 20 weeks and it can be reasonably compared with identical expansion magnitudes of the other samples. The time required to attain a ξ_b of 0.31 percent ranged from 1.1 days for sample Mo to 140 days for sample 1-6. These two samples represent, respectively, the lowest and highest ratios of E_n/E_g . By comparing the samples in this manner the time factor can be eliminated. From the calculated values of ξ_e and $\xi_{e(r)}$, a percent reduction of ξ_e due to the restraint of the matrix phase of the materials was determined. If these reductions are plotted against the total sustained modulus of the rocks as in Figure 9, it can be seen that the greater the total sustained modulus of the materials is, the greater will be the reduction in the expansion of the dolomite phase. Consequently, the textural restraining effect on sample 1-6 is greater than 7 times that of sample Mo, and a corresponding effect occurs with regard to the remaining samples. Thus, a reduction in the expansion of the dolomite phase would result in a reduction in the volume change of the total material.

The results shown in Figure 9 are those calculated for the actual properties of the materials and consequently represent materials containing different volumes of expansive dolomite. For a better concept of the independent effects of textural restraint, a simulated curve is shown in Figure 10. This curve is based on the same ξ_b of 0.31 percent used previously, but it is assumed that all the rock samples contain an equal g of 0.35, while the ratios of E_n/E_g are those of the actual materials. For the particular conditions used in the calculation of this theoretical curve, it is apparent that the textural restraining effect on sample 1-6 is greater than 3 times that of sample Mo. The relationship given in Figure 10 might thus explain the relative difference in the magnitude of expansion exhibited by some carbonate rocks having nearly identical chemical compositions.

Restrained Rock Expansions

The effect of external restraint on the expansion of some selected test rocks is shown in Figure 11. The average results of three specimens subjected to the higher degree of restraint are represented by the solid curves, while one sample (1-8) subjected to the lower restraint is shown for relative comparison and is represented by the broken curve. Samples 12-9A and 12-9B expanded under restraint virtually the same as sample 1-8 and have been omitted from Figure 11 for clarity. Data for sample 27-4 were omitted due to malfunctioning of the strain gauges during testing.

If only the higher restraint specimens shown in Figure 11 are considered, it is apparent that the differences between the magnitudes of expansions of the various rock samples are not as great as those obtained for the unrestrained expansions shown earlier.

Figure 9. Effect of textural restraint on the expansion of the dolomite phase, ξ_g , of carbonate rock samples.

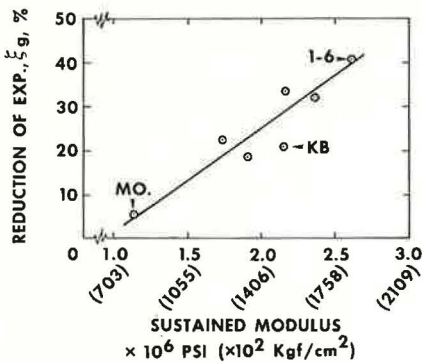


Figure 10. Theoretical curve showing the effect of textural restraint on simulated rocks having constant g and E_m/E_g equivalent to the actual rock samples.

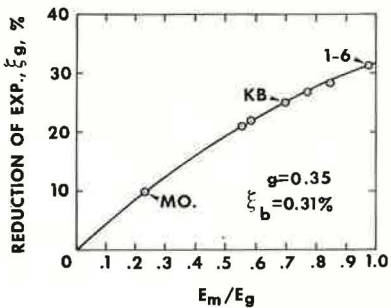


Figure 11. Restrained expansions of several carbonate rocks.

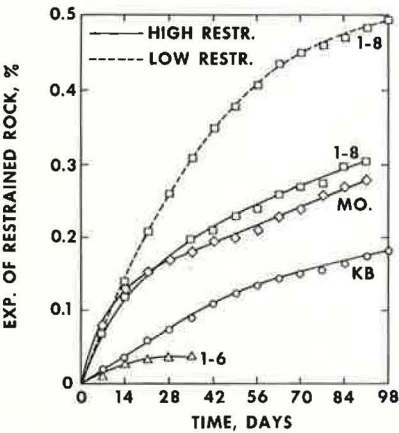
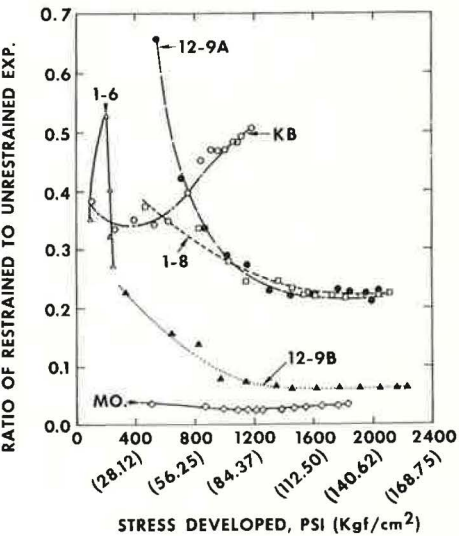


Figure 12. Stress developed by several carbonate rocks expanding against restraint.



The unrestrained expansion of sample Mo, for example, was 4 to 5 times greater than the expansions of samples 12-9A and 1-8; but when restrained, sample Mo expanded slightly less than 12-9A and 1-8. Compared with sample K-B, Mo expanded 24 times as much when unrestrained but only $1\frac{1}{2}$ times as much when restrained. Samples 12-9A, 12-9B, 1-8, and Mo had substantially different expansive characteristics when unrestrained but had relatively the same expansive characteristics when restrained. This suggests that the rigidity of a carbonate rock and the volume of dolomite contained in the materials will have considerable influence on the degree to which it will expand under restraint. Hence, a carbonate rock with low textural restraint might be highly expansive in the unrestrained NaOH test, but when restrained in a mass of concrete (or mechanically as in this experiment) it would be more compressible and therefore less expansive. Optimum combinations of textural properties and dolomite content would thus result in the most detrimentally expansive rocks in concrete. Thus, sample K-B has considerable textural restraint acting to restrain free rock expansion, but this same rigidity combined with a high dolomite content is apparently sufficient to overcome moderate external restraint. Indications from the limited data available on sample 1-6 are that the external restraint combined with a high textural rigidity and low dolomite content (15.8 percent) are sufficient to limit restrained expansion to approximately 0.037 percent. If it is assumed that the 1-6 curve would have progressed with the same trend indicated in Figure 11, a restrained expansion of 0.037 percent would be about the maximum attained. This degree of expansion would be a marginal case if the rock were used as an aggregate in concrete.

Perhaps the most conspicuous indication from Figure 11, as compared with Figure 6, is that the magnitude of restrained expansion is not proportional to the magnitude of unrestrained expansion. This is clearly shown in Figure 12, where the ratio of restrained to unrestrained expansion is plotted against the stress developed by the expanding specimens. With the exception of 1-6, which was probably restrained from further expansion, the samples with the higher ratios (considering the right end points of the curves) are in inverse order as compared with their order of unrestrained expansion. While concrete distress in the form of cracking does not always correlate with expansion, these data suggest that some rocks that expand on the order of 0.3 percent to 1 percent might be just as detrimental to concrete as the more highly expansive ones. Sample K-B, for example, was capable of developing high stresses in comparison to the relatively low magnitude of unrestrained expansion developed. In fact, the trend of the curves in Figure 12 suggests that, if a higher degree of restraint had been used in the experiment, K-B might have developed stresses of magnitudes comparable to those of 1-8, 12-9A, Mo, and 12-9B.

For the particular degree of restraint used in this experiment, stresses on the order of 2,200 psi (15 200 kPa) were developed by some samples, as is indicated by the curve for sample 1-8 in Figure 12. Since the tensile strength of concrete is normally less than 1,000 psi (6900 kPa), there is little doubt that the expansive carbonate rocks can exert pressures of sufficient magnitude to cause fracture systems in concrete. Expansive rocks like that of sample 1-6, with low dolomite content and high textural restraint, however, might be exceptional cases.

SUMMARY AND CONCLUSIONS

The equations presented in this paper can be used to estimate the magnitude of carbonate rock expansion (obtained from tests similar to ASTM C 586-66T) that would be necessary to cause certain degrees of expansion in concrete specimens containing certain volumes of the rock as an aggregate. The amount of dilution of an expansive aggregate (with an inert material) that would be necessary to keep concrete expansions within certain limits can also be estimated.

An analogy between the physical structure of portland cement concrete containing expansive aggregate particles and dolomitic carbonate rocks containing expansive dolomite rhombohedrons was drawn by considering each as a two-phase system. A select group of carbonate rocks was investigated experimentally and by combining the experimental with theoretical data. The following conclusions were drawn:

1. The expansion of reactive carbonate rocks generally increases as the sustained modulus of elasticity decreases, and increased expansion is more pronounced when the modulus of the matrix phase of the rocks decreases.

2. The calculated reduction in the expansion of the dolomite phase of the rocks investigated increased with an increase in the sustained modulus of elasticity of the materials.

3. The textural restraining effect on the least expansive of the actual rock samples investigated was greater than 7 times that of the most expansive sample. However, if all the rock samples investigated had equal dolomite contents, but the same elastic properties as the actual materials, the textural restraining effect on the least expansive rock would still have been greater than 3 times that of the most expansive sample.

4. The magnitude of restrained carbonate rock expansion is not proportional to the magnitude of unrestrained expansion, but, analogous to the effects of textural restraint, the dolomite content and the sustained modulus of the material are related to the degree of expansion under restraint.

5. The experimental data suggest that certain combinations of textural properties and dolomite content would result in the most detrimentally expansive carbonate rocks in concrete. On the other hand, rocks having low dolomite content and high textural rigidity might be relatively innocuous.

6. For the particular degree of restraint used in the experiments described in this paper, stresses on the order of 2,200 psi were developed by the expansion of some of the rock samples. It is apparent that the use of higher restraint or longer duration of test would have resulted in higher forces being exerted by some of the rock specimens.

7. Since the tensile strength of concrete is normally less than 1,000 psi, forces of the magnitude measured in these experiments show that expansive carbonate aggregates can exert pressures of sufficient magnitude to ultimately cause fracture systems in concrete made with cements having high alkali content.

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