Laboratory Evaluation of the Alkali Carbonate Reaction

JACK CROTEAU, JOHN QUINN, AND KIRAN SHELAT

New Jersey's carbonate rock study was undertaken to develop a procedure to evaluate local sources for potential alkali carbonate reaction. Laboratory tests were performed on rock samples obtained from eight local sources with unknown reactive characteristics and three control samples with well-known reactive characteristics. The screening criteria described in the paper identified the known reactive sources, and also indicated that some local sources are potentially reactive at higher alkali levels. It is recommended that use of carbonate aggregate be conditioned on demonstrated nonreactivity under the described battery of tests. As a precautionary measure, low-alkali cement (alkali levels less than 0.7 percent) should be used with carbonate rock aggregate to mitigate the effect of any failure to detect aggregate reactivity.

A laboratory investigation of the alkali-carbonate reaction undertaken to develop a screening and acceptance procedure for carbonate rock proposed for use in New Jersey Department of Transportation (NJDOT) concrete mixes is described.

New Jersey's current specifications prohibit the use of carbonate rock as an aggregate for concrete surface courses, culverts, and bridges. This restriction is based on two factors. The first of these is the potential for skid resistance problems. That is, because of the well-known tendency for carbonate rock to polish under the action of traffic, it is deemed generally unsuitable for riding surfaces. The second concern regarding carbonate aggregates is the potential development of destructive expansive stresses resulting from the so-called "alkali-aggregate reaction" (AAR).

The potential of carbonate rock for creating skid resistance problems is well documented. On the other hand, the potential for distress resulting from the alkali-aggregate reaction, although recognized as a widespread problem nationally, has until recently been based primarily on anecdotal observations in New Jersey. Perhaps the most frequently cited New Jersey example of alkali-carbonate rock distress—the Magnolia Street Bridge on Routes 1 and 9—concerns a structure constructed in the mid-1930s.

The blanket prohibition of carbonate rock as a concrete aggregate is a significant factor in an existing problem of aggregate supply in New Jersey's southern (coastal plain) areas. Absent this restriction, the potential sources of supply could increase significantly. About one-quarter of the aggregate sources presently supplying NJDOT projects are carbonate rock quarries.

This study was undertaken to evaluate the alkali-aggregate reactivity of carbonate rocks from quarries in the New Jersey-

Pennsylvania region to determine whether some carbonate aggregates could safely be used in Department of Transportation concrete mixes other than for riding surfaces.

The work basically consisted of a program of laboratory testing designed to determine the expansion characteristics of a representative sample of carbonate rock from eight nearby quarries. In order to provide a basis of comparison for these results, three carbonate rock samples known to be unacceptably reactive were subjected to similar tests.

NATURE OF THE ALKALI-AGGREGATE REACTION

Two reactions involving concrete aggregates and free alkali from cement have been identified, namely the alkali-silica reaction (ASR) and the alkali-carbonate reaction (ACR). These reactions involve susceptible siliceous and carbonate rocks, respectively. Collectively, these reactions are referred to as the alkali-aggregate reaction (AAR). As a result of either of these two reactions, the aggregate undergoes expansion that results in map cracking of the concrete. Water that accumulates in these cracks undergoes freezing and thawing cycles that in turn create spalling. The associated "growth" of the concrete can damage pavement joints and adjoining structures.

This reaction was first identified in the 1940s in California and in the 1950s in Virginia. A 1956 paper entitled *A Canadian Reactive Aggregate Undetected by ASTM Tests* generated significant interest among concrete mix designers, because it had been assumed that aggregates remained chemically inert during and after the hydration process. Today, AAR is of worldwide concern, with over 100 research papers having been presented in the United States and Canada.

Until recently, New Jersey pavements and structures had not displayed alkali-reactivity related damage. However, in 1988 approximately 12 lane-miles of distressed pavement on Route I-295 in Burlington County were identified (1) as undergoing the alkali-silica reaction. Figure 1 shows the typical pattern of map cracking associated with the alkali-aggregate reaction on the I-295 pavement. Figure 2 shows full-width cracks at the pavement joints resulting from the progressive "growth" of the pavement.

The principal concern, however, is potential problems associated with the alkali-carbonate reaction. ACR is described as a chemical reaction that takes place between free alkali from the cement and certain dolomitic limestones containing clay. As per ASTM C150, free alkali in cement is computed as percent of $Na_2O + 0.658K_2O$. This reaction is frequently

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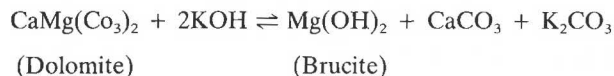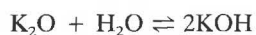
FIGURE 1 Typical map cracking caused by AAR, I-295, Burlington County, New Jersey.

FIGURE 2 Full-width map cracking, I-295, Burlington County, New Jersey.

referred to as "dedolomitization." The series of chemical reactions that occurs in this process is expressed as follows (2):

$$Na_2O + H_2O \rightleftharpoons 2NaOH$$

$$K_2O + H_2O \rightleftharpoons 2KOH$$

$$CaMg(CO_3)_2 + 2NAOH \rightleftharpoons Mg(OH)_2 + CaCO_3 + Na_2CO_3$$

$$CaMg(Co_3)_2 + 2KOH \rightleftharpoons Mg(OH)_2 + CaCO_3 + K_2CO_3$$

(Dolomite)   (Brucite)

As a result of the dedolomitization process, channels in the rock open, allowing water absorption on previously dry clay surfaces. The resultant swelling causes irreversible expansion of the rock, and subsequent cracking of the concrete. This process of progressive destruction takes from 3 to 15 years to produce detectable physical damage to the structure.

The destructive effects of the dedolomitization process can be further accelerated by two common highway maintenance practices. The first of these is the application of deicing salts, which increases the alkalinity of the concrete. The second is the use of cathodic protection systems. The latter systems, which are increasingly being used to prevent corrosion of bridge deck reinforcement, cause the entire reinforcing mat to serve as a negatively charged cathode. This negative charge attracts positively charged alkali ions to the rebars. These localized alkali concentrations can cause localized distress in a deck constructed with alkali-susceptible aggregates (3).

There are two basic ways to prevent AAR distress. First, avoid the use of susceptible aggregates. Second, reduce the free alkali content of the cement to a level below that required to initiate the reaction. (The latter approach is used in ASTM C150, which restricts the Na_2O equivalent alkali level to 0.6 percent.) Because the latter approach can be the most cost-effective under some conditions, both of the foregoing mitigation procedures were evaluated.

The alkali level of cement is primarily responsible for the alkali-aggregate reaction. The NJDOT's cement chemical analysis reports of the last 13 years (1976 to 1988) were reviewed to determine the average alkali levels of cement supplied during that period. As presented in Table 1, before the NJDOT's prohibition of the use of carbonate rock in 1983, only 3 out of 10 vendors consistently supplied high-alkali cement (alkali levels of 0.7 percent or higher). This number has increased dramatically in recent years. Currently, 7 out of 10 vendors consistently supply high-alkali cement. As shown in Figure 3, the weighted-average alkali level of cement supplied to the NJDOT has increased about 25 percent (from 0.57 to 0.73 percent) in recent years. This increase may be the result of environmental restrictions applied to the cement industry, which require recycling of high-alkali clinker and dust.

TABLE 1   AVERAGE ALKALI LEVELS OF CEMENT SUPPLIED TO NJDOT, 1976 TO 1988

VENDOR	Carbonate Rock Allowed								Carbonate Rock Prohibited				
	'76	'77	'78	'79	'80	'81	'82	'83	'84	'85	'86	'87	'88
A	1.0*	0.9*	---	1.0*	1.0*	1.0*	0.9*	0.9*	0.9*	0.9*	0.9*	0.9*	0.9*
B	0.5	0.5	0.6	0.1	0.1	0.1	0.7	0.7	0.5	---	0.6	0.7	0.7
C	0.4	0.3	0.3	0.3	0.4	---	0.3	---	---	---	---	---	---
D	---	---	---	---	---	---	---	---	---	0.8*	0.8*	0.7	---
E	---	---	---	---	---	---	---	---	---	1.0*	---	---	---
F	1.2*	---	---	1.0*	0.9*	0.9*	1.0*	1.0*	0.9*	0.8*	1.0*	0.9*	0.8*
G	0.7	0.9*	---	---	---	---	---	---	---	---	---	---	---
H	---	---	---	---	---	---	---	---	---	0.6	---	---	---
I	---	---	---	---	---	---	---	---	---	1.0*	---	---	---
J	0.7	0.5	0.6	0.7	0.7	0.7	0.8*	0.7	0.6	0.6	0.7	0.7	0.6
K	---	---	---	---	---	---	---	---	0.7	---	---	---	---
L	---	---	---	---	---	---	---	0.8*	0.8*	0.9*	0.9*	---	---
M	---	---	0.5	---	0.7	0.3	0.4	0.3	0.2	0.2	0.2	0.2	0.2
N	0.6	0.7	0.5	0.6	0.6	0.6	0.6	0.8*	0.8*	0.8*	0.8*	0.8*	0.7
O	0.1	0.1	0.1	0.1	0.1	0.1	0.1	---	---	---	---	---	---
P	0.8*	0.8*	0.8*	0.9*	0.9*	0.9*	1.0*	0.9*	---	---	0.9*	1.0*	0.9*
Q	0.2	0.1	0.2	0.2	0.1	0.2	0.2	1.0*	1.0*	0.9*	0.9*	0.9*	---

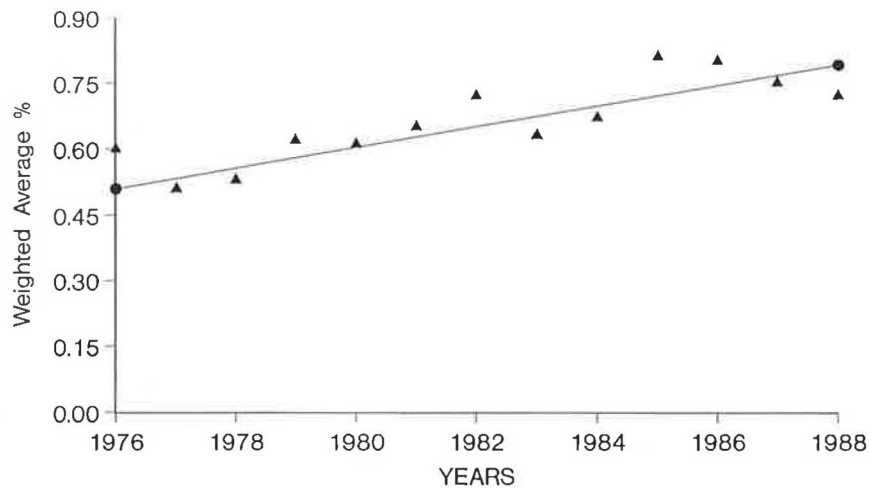*   Average Alkali Level exceeds 0.70 %

FIGURE 3   Cement alkali levels.

TEST METHODOLOGY

Sampling

More than 35 of the 150 NJDOT-approved aggregate sources are carbonate rock quarries. Of these, a representative group of eight was selected for tests on the basis of their geographic location and geologic type. The sampled quarries included the following local carbonate rock aggregate producers:

Name	Location
Eastern Industries	West Cocalico, Pa.
Keystone Portland Cement Co.	Bath, Pa.
A. G. Kurtz Co.	Denver, Pa.
New Enterprise Stone and Lime Co.	New Enteprise, Pa.
Huss Construction Co.	Andreas, Pa.
New Hope Crushed Stone Co.	New Hope, Pa.
Beaver Run Co.	Lafayette, N.J.
Carpentersville Sand and Gravel Co.	Carpentersville, N.J.

In order to provide a benchmark for gauging the sensitivity of the laboratory test procedures and the relative reactivity of the local carbonate aggregates, samples from three known reactive aggregate sources were also included in the testing program. These quarries were located in Kingston, Canada; Harrisonburg, Virginia; and Centerville, Tennessee.

Testing Procedure

Overview

The literature indicates that no single test can be relied on to consistently predict the reactive tendencies of carbonate rock. Rather, a battery of tests is required to determine potential reactivity.

The most commonly used combination of tests (the one adopted for use in this study) involves a petrographic examination (ASTM C295) and expansion tests performed on samples of the rock (ASTM C586) and concrete containing the carbonate aggregate (ASTM C1105). These procedures are outlined in the following subsections.

Petrographic Examination

The petrographic examination entails the use of an optical microscope to distinguish between nonreactive and potentially reactive carbonate rocks on the basis of their composition, texture, and grain size.

Using the optical microscope, the common features of expansive carbonate rocks can be identified as follows:

- Dolomitic with appreciable quantities of calcite,
- Presence of clay,
- Extremely fine-grained matrix, and
- Characteristic texture consisting of small isolated dolomite rhombs disseminated in a matrix of clay and finely divided calcite.

The petrographic examination is quick, but only identifies rock constituents that have the potential for reactivity. Additional testing is required to determine whether a given rock will, in fact, react in the presence of alkalies.

Rock Cylinder Test

Two to four ⅜-in. diameter, 1⅜-in.-long cores were drilled perpendicular to the bedding from each of the representative ledge rock samples at random locations. The ends of each rock cylinder core were ground to obtain smooth orthogonal faces.

The samples were initially conditioned by placing them in polypropylene bottles filled with distilled water for 30 h. The samples were dried, and the initial core length was measured with a micrometer and recorded. (All measurements taken at subsequent test ages were made using the same micrometer. The average of two or three readings taken independently by separate technicians was recorded as the final reading for each sample at each test age.)

For the remaining test period, the samples were stored at room temperature in NaOH solution. Length measurements were made after 1, 2, 3, 4, 8, 12, 16, 26, 39, and 52 weeks of conditioning.

At each test age, length change to the nearest 0.01 percent was calculated as

$$\text{Length change (percent)} = \frac{L_1 - L_0}{L_0} \times 100$$

where

$$L_1 = \text{length at test age, and}$$

$$L_0 = \text{initial length.}$$

The average length change reported at a given test age was the average of two or three readings.
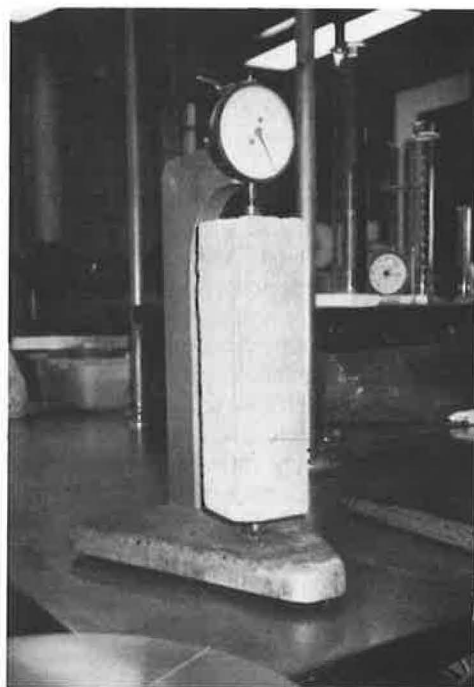
Concrete Bar Test

General   Each of the eight local aggregates and two of the three known reactive aggregates were used in separate batches of concrete made using a high-alkali cement (1.25 percent). In order to test the effect of lower alkali levels, two of the known reactive aggregates and one local source (Keystone) were also used in batches made with 0.74 percent alkali cement (see Table 2). Six concrete bars were cast from each batch. These bars were stored in the 100 percent humidity room. Length change measurements were made using the length comparator shown in Figure 4 at 1, 4, 12, 26, 39, and 52 weeks.

Mix Design   The concrete mix was designed using ACI 211.1–74, *Standard Practice for Selecting Proportions for Normal, Heavy Weight, and Mass Concrete.* Approximately 200 lb of ledge rock from each source were crushed and graded to comply with AASHTO No. 57 size. Physical properties such as dry rodded weight, specific gravity, and percent absorption were determined for each batch. Table 2 presents mix proportions, and Table 3 presents details of physical properties.

A chemical analysis of the cement from Independent Cement Corporation, Catskill, N.Y., indicated that its total Na_2O equivalent alkali content (ASTM C150) was 0.74 percent. In

TABLE 2 MIX DESIGN DETAILS (PER CUBIC FOOT)

SAMPLE	CEMENT Lbs.	AGGR. Lbs.	SAND Lbs.	WATER Lbs.	NaOH Added	ALKALI %
Eastern Indus.	24.22	65.39	44.70	12.60	0.16	1.25
Keystone Co.(1)	22.72	66.15	48.46	11.85	0.16	1.25
Keystone Co.(2)	22.72	66.15	48.46	11.85	0.00	0.74
Keystone Co.(3)	22.72	66.15	48.46	11.85	0.00	0.74
Keystone Co.(4)	22.72	66.15	48.46	11.85	0.13	1.00
A.G.Kurtz Co.	22.72	66.78	50.51	11.85	0.16	1.25
New Enterprise Co.	22.72	64.26	52.72	11.85	0.16	1.25
Huss Const. Co.	22.72	62.37	52.11	11.85	0.16	1.25
Beaver Run Co.	22.72	64.89	51.60	11.85	0.16	1.25
Carpentersville Co.	22.72	64.26	52.75	11.85	0.16	1.25
New Hope Co.	22.72	64.26	50.52	11.85	0.16	1.25
Harrisonburg Va.(1)	22.72	64.26	50.51	11.85	0.16	1.25
Harrisonburg Va.(2)	22.72	64.26	50.15	11.85	0.00	0.74
Kingston,Canada.(1)	22.72	61.74	54.16	11.85	0.16	1.25
Kingston,Canada.(2)	22.72	61.74	54.16	11.85	0.00	0.74
Centerville,Tenn.	***	No Concrete Bars Made			***	

Length comparator

-3 in. X 3 in. concrete bar sample

FIGURE 4 Length comparator with typical concrete bar sample.

TABLE 3 PHYSICAL PROPERTIES OF AGGREGATE SAMPLES

SAMPLE	BULK SP. GRAVITY	UNIT WT. (Lbs)	DRY RODDED WT. (Lbs)
Eastern Indus.	2.77	99.00	104.00
Keystone Co.	2.69	98.00	105.00
A.G.Kurtz Co.	2.80	97.00	106.00
New Enterprise Co.	2.79	96.00	102.00
Huss Constr. Co.	2.68	92.00	99.00
Beaver Run Co.	2.77	96.00	103.00
Carpentersville Co.	2.77	94.00	102.00
New Hope Co.	2.76	93.00	101.00
Harrisonburg,Va.	2.78	94.00	102.00
Kingston,Canada	2.74	91.00	98.00
Centerville,Tenn.	2.81	98.00	105.00

order to simulate severe in-service conditions (e.g., heavy application of deicing salts), the alkali level was raised to 1.25 percent by adding 0.16 lb of NaOH to the mixing water. Four batches were made with the alkali level at 0.74 percent (unchanged) to serve as a control.

Concrete Batching   A total of 16 1-ft³ batches of non-air-entrained concrete were made. From each batch, six 3 × 3 × 11 in. concrete bars were made for the length change test. These test bars were cast with stainless steel plugs at each end to act as reference points for length measurement using the length comparator equipment. The test bars were covered with plastic, cured at room temperature, and stripped on the following day. Each test bar was marked for identification and soaked in water for 30 min before initial length measurement.

Storage of Concrete Bar Samples   After the initial measurement, the bars were stored in water for 28 days at room temperature. On completion of this 28-day period, test bars were stored in a 100 percent humidity room at 73°F for the entire test period of 1 year.

RESULTS AND ANALYSIS

Petrographic Examination

The results of the ASTM C295 petrographic examination are presented in Table 4. As indicated in the table, none of the local carbonate rocks were judged to be potentially reactive. Only one of the known reactive aggregates, that from Virginia, displayed the characteristic constituents of an AAR-susceptible aggregate. The potential activity of the Tennessee and Kingston, Canada, aggregates could not be determined by the petrographic examination.

Rock Cylinder Test

Evaluation Criteria

ASTM C586 states that an aggregate that expands more than 0.10 percent has undergone a detrimental chemical reaction, and should be further tested in concrete.

Results

The results of the rock cylinder test are presented in Table 5. Examination of this tabulation indicates that none of the local carbonate aggregates exceeded the ASTM C586 criteria. Only 2 of the 11 samples expanded appreciably during the 1-year test period.

The results for the known expansive aggregates are shown in Figure 5. Examination of this plot indicates that the Canadian aggregate failed the rock cylinder test in convincing fashion. After 1 month in test, this aggregate exceeded the failure criterion by a factor of eight (0.8 versus 0.1 percent); after a year, it expanded nearly 2 percent. The sample from another known expansive source in Harrisonburg, Virginia, expanded steadily over the entire test period and exceeded the failure criterion after 2 months in test. The aggregate from the third known expansive source in Centerville, Tennessee, shrank rather than expanded. This unexpected behavior might have been the result of sampling from the nonreactive strata of the quarry. (Because of a shortage of material, this sample could not be tested in concrete.)

Concrete Bar Test

Evaluation Criteria

Unlike the petrographic and rock cylinder test procedures, there is no established criteria for evaluating the results of the concrete bar test. Rather, as presented in Table 6, a

TABLE 4   RESULTS OF PETROGRAPHIC EXAMINATION

SAMPLE	PETROGRAPHIC DESCRIPTION	REACTIVE ?
Eastern Indus.	Limestone. No distinct Dolomite. No visible clay concntration. Fine grained.	No
Keystone Co.	Limestone. Elongated "eyes" of carbonate. Scattered quartz silt.	No
A.G.Kurtz Co.	Limestone. Fine grained. Large Dolomite crystals. No clay.	No
New Enterprise Co.	Limestone. Fine grained. Dolomite in small,local patches. Some quartz silt.	No
Huss Constr. Co.	Limestone. Fine grained. No Dolomite.	No
New Hope Stone Co.	Limestone. Fine grained. Significant quartz silt. No Dolomite.	No
Beaver Run Co.	Dolomite present. No clay concentration visible.	No
Carpentersville Co.	Dolomite present. No clay concentration visible.	No
Harrisonburg, Va.	Fine grained. Brittle. Clay present in significant amount.	Yes
Kingston, Canada.	Calcareous Argillite, fine grained. Significant amount of clay.	Undetermined
Centerville, Tenn.	Large amount of clay,quartz silt.	Undetermined

TABLE 5   ROCK CYLINDER TEST RESULTS (WITH LENGTH CHANGES EXPRESSED IN PERCENTAGES)

SAMPLE	TEST AGE				REACTIVE ?
	1 MO.	3 MO.	6 MO.	1 YR.	
Eastern Indus.	-0.05	-0.05	-0.05	-0.17	No
A.G.Kurtz Co.	0.00	0.00	-0.01	-0.04	No
Kingston,Canada	0.81*	1.56*	1.78*	1.86*	Yes
Carpentersville, NJ	-0.02	0.01	0.00	-0.01	No
Keystone Co.	0.03	0.00	0.02	0.03	No
New Enterprise Co.	-0.06	-0.06	-0.01	-0.04	No
Harrisonburg, Va.	0.05	0.19*	0.29*	0.52*	Yes
New Hope Co.	0.03	0.01	0.00	0.02	No
Beaver Run Co.	-0.08	-0.09	-0.04	-0.03	No
Huss Constr. Co.	-0.13	-0.12	-0.15	-0.14	No
Centerville, Tenn.	-0.06	-0.04	-0.02	-0.01	No

*   Expansion exceeded the limit of 0.10 %
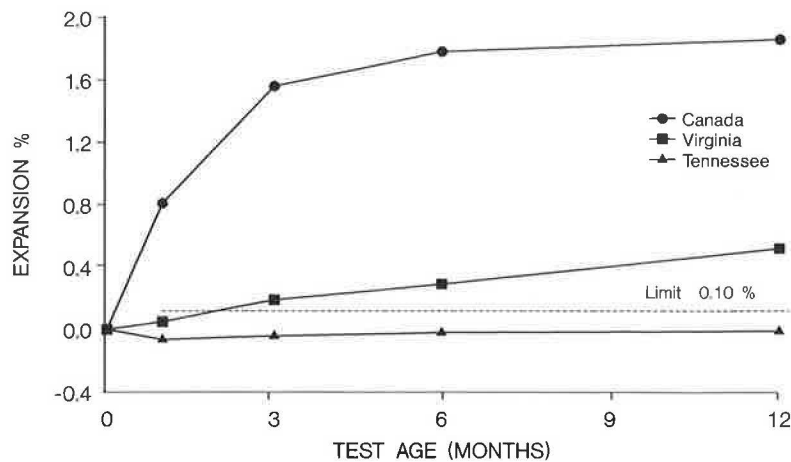
FIGURE 5   Rock cylinder test results for known reactive sources.

TABLE 6   SUGGESTED EVALUATION CRITERIA FOR CONCRETE BAR EXPANSION TEST

AUTHOR	% EXPANSION				
	3 mo.	6 mo.	1 yr.	3 yr.	5 yr.
Swenson & Gillot (HRB Record 45 pp 21-40 1964)	-----	0.02	-----	-----	-----
Smith (HRB Record 45 pp 126-133 1964)	0.02	-----	-----	-----	-----
Newlon (Va.HWY RES. Council 8 VHRC 71-R 41)	-----	-----	0.03	-----	0.05
Canadian Std. Assoc.	0.02	-----	-----	-----	-----
Walker (ASTM STP 1978 pp 772)	0.015	0.025	0.03	-----	-----
Ministry Of Trans. Canada	0.015	0.025	-----	-----	-----
ASTM Draft 10-81 (Com. C9)	0.015	0.025	0.03	-----	-----
NJDOT Research Suggestion	0.015	0.02	0.025	-----	-----

variety of threshold limits for expansion has been suggested by various agencies and authorities on the subject as being indicative of detrimental chemical reaction. The lowest of these test age suggested expansion limits are as follows: 0.015, 0.02, and 0.025 percent at 3, 6, and 12 months, respectively.

Results

The length changes presented in Table 7 represent the average measured on six samples. On the basis of the lowest threshold values, the known expansive source from Kingston (Canada) is identified as being an unacceptable concrete aggregate. It exceeded threshold values at all three test ages of 3 months,

6 months, and 1 year when concrete of 1.25 percent alkali level was used. Six additional concrete bars were made using the same Canadian source, but with a lower alkali level (0.74 percent). These bars also exceeded the threshold limits at all three test ages. These results indicate that this carbonate rock source is highly reactive. The second known expansive source from Harrisonburg, Virginia, expanded somewhat but never exceeded the threshold limit at any stage (see Figure 6). The third known expansive source from Centerville, Tennessee, could not be evaluated because of lack of material.

Two other sources, Eastern Industries (West Cocalico, Pennsylvania) and Keystone Portland Cement Co. (Bath, Pennsylvania), evidenced some expansion. The Eastern concrete bar sample exceeded the 3- and 6-month test age thresh-

TABLE 7 CONCRETE BAR TEST RESULTS (WITH LENGTH CHANGES
EXPRESSED IN PERCENTAGES)

SAMPLE	TEST AGE			ALKALI
	3 MO.	6 MO.	1 YR.	%
Eastern Indus.	0.018*	0.020*	0.020	1.25
A.G.Kurtz Co.	0.010	0.002	0.017	1.25
Kingston,Canada (1)	0.025*	0.024*	0.040*	1.25
Carpentersville Co.	0.005	−0.002	0.007	1.25
Keystone Co. (1)	0.080*	0.112*	0.170*	1.25
New Enterprise Co.	0.005	0.010	0.008	1.25
Harrisonburg, Va.(1)	0.010	0.015	0.010	1.25
New Hope Co.	0.010	0.012	0.004	1.25
Beaver Run Co.	0.000	−0.002	−0.010	1.25
Huss Constr. Co.	−0.017	0.002	0.000	1.25
Kingston, Canada (2)	0.018*	0.027*	0.037*	0.74
Harrisonburg,Va.(2)	0.000	0.010	−0.002	0.74
Keystone Co.(2)	−0.010	−0.010	−0.010	0.74
Keystone Co. (3)	0.003	−0.002	0.005	0.74
Keystone Co. (4)	0.001	−0.002	0.002	1.00
Keystone Co. (5)	0.015*	0.012	0.020	1.25

* Expansion equalled or exceeded allowable limit. Limits shown below:

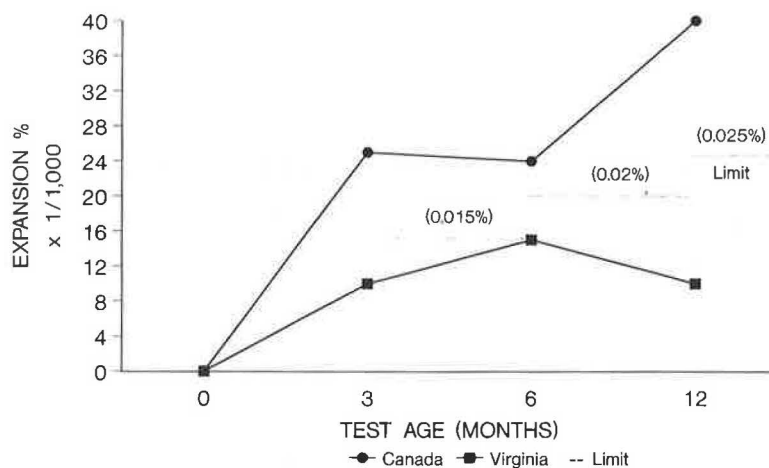|	
3 Months Test Age	0.015 %
6 Months Test Age	0.020 %
1 Year Test Age	0.025 %

FIGURE 6 Concrete bar test for known reactive aggregate sources.

old criteria but did not exceed the 0.025 percent threshold limit for test specimens 1 year old. The sample from Keystone (Bath, Pennsylvania) far exceeded the threshold values at all test ages. Because this particular sample did not fail either the petrographic or the rock cylinder test, it was decided to retest using the same source. Three different alkali level con-

crete mixes identified in Table 7 as Keystone 3, 4, and 5 were batched using new material (AASHTO No. 57 stone) from the same source. The three alkali levels selected were 0.74, 1.0, and 1.25 percent.

As shown in Figure 7, the average expansion of the Keystone aggregate bars made at the 0.74 and 1.0 percent alkali
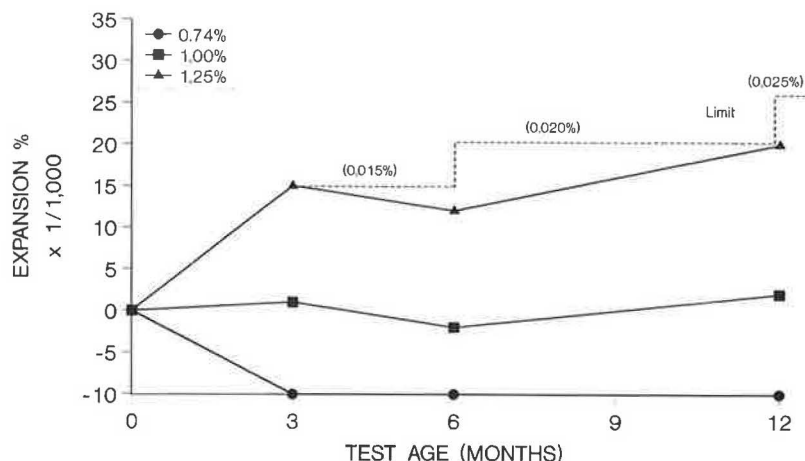
FIGURE 7 Concrete bar test for Keystone aggregate at various alkali levels.

levels was insignificant over the entire test period. The average expansion of the bars made at the 1.25 percent alkali level was significant, yet within allowable limits, indicating that the detrimental effects are indeed associated with the amount of alkali in the concrete mix.

The behavior of the Keystone aggregate may be akin to the experience noted with the Centerville, Tennessee, rock cylinder test. That is, the sampling procedure at the quarry apparently results in samples of varying rates of reactivity on the basis of the strata from which they are obtained.

CONCLUSIONS

The principal conclusions derived from this research study are as follows:

1. Application of the screening criteria will identify potentially reactive carbonate rock sources. The results suggest that the entire battery of tests—the petrographic examination and expansion tests on rock and concrete samples—should be performed. Passing any single test will not necessarily ensure that the aggregate is in fact nonreactive.

2. The careful selection of representative samples is critical, because the degree of reactivity may vary significantly within a given quarry.

3. The results of this study confirm that use of low-alkali cement is a viable means for reducing potential detrimental alkali-carbonate reactions. As a practical matter, selection of

a limiting value defining a suitably low alkali level should take into account both the relative reactivity of the local aggregates and the prevailing level of alkali in the cement being supplied. For New Jersey conditions, it appears that a cement alkali level of 0.7 percent or less would provide a reasonable safeguard against destructive carbonate reactions. This 0.7 percent level should be attainable by local cement suppliers.

4. A satisfactory specification for carbonate aggregate can be based on a demonstrated nonreactivity under the battery of tests outlined here, coupled with the use of a low-alkali (0.7 percent or less) cement. The latter provision will help mitigate the effects of any failure to detect aggregate reactivity. Such a specification has been developed and is under consideration in New Jersey.

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