JOINT REPORT

CONCRETE DURABILITY STUDIES

Case Study # 3 — Severe Scaling of an Interstate Bridge Deck

and

POTENTIALLY REACTIVE CARBONATE AGGREGATES

Progress Report # 6 (Partial)

An Example of Bridge Deterioration Promoted by Alkali-Carbonate Reaction

by

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and
H. H. Newlon, Jr., Assistant State Highway Research Engineer

Virginia Highway Research Council
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PREFACE

1989

The project designated "Concrete Durability Studies" comprises case studies of unusual durability, either in kind or extent. These case studies are directed toward situations in which appearances suggest materials or construction rather than structural causes. Included in this project as Case Study #3 is an occurrence of severe scaling and pattern cracking in bridge decks of an interstate project: one deck showed severe scaling after only one winter's exposure.

Because the aggregate used in these decks was from a source known to contain potentially reactive carbonate rocks, the combination of scaling and chemical reaction was investigated as a likely dual cause.

Concurrently with this case study, an extensive study of potentially reactive carbonate aggregates was in progress. One aspect of that study was an evaluation of field manifestations of the alkali-carbonate reaction based upon field surveys of bridge decks in the region of the severely scaled deck. Thus this report, while primarily a case study of the Concrete Durability Study, is also considered to be a report of field performance for the project "Potentially Reactive Carbonate Rocks." The field survey for evidences of carbonate reactivity covers more decks than are treated in this report, so that this report serves as a partial Progress Report #6 for that project.

SUMMARY

Fifteen Interstate bridges in Virginia were constructed at the same time in the same locality with the same materials and engineering design except for differences in the lithologies of the coarse aggregate. In nine of the structures an argillaceous dolomitic limestone was used; in six a crystalline dolomite. Both aggregates meet abrasion and soundness specifications. The limestone has a rock prism expansion in alkaline solution of 1% at six months, the dolomite under the same conditions shows 0% expansion. Recent surveys of the 15 bridges, opened to traffic in July 1960, show 90% of the slabs of the six containing dolomite free of pattern cracking and scaling, but only 15% of the slabs of the nine limestone containing bridges free of these defects. The 15 structures have the same exposure and maintenance history and there are no differences in the air void system characteristics of the hardened concrete which could explain the differences in pattern cracking and scaling frequency.

Petrographic examination reveals that the argillaceous dolomitic limestone has the fabric of a prototypical alkali-reactive carbonate rock and the concrete containing this stone has abundant hairline cracks propagating through both the paste and the aggregate. The other stone is a mosaic of equigranular interlocked dolomite subhedra and the concrete containing it is virtually free of such features. Tests, using a nonreactive aggregate as a diluent and cement with varying percentages of alkalies, show increasing freeze-thaw distress with increasing alkalies or with increasing reactive aggregate at constant alkalies.

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BACKGROUND

Fifteen bridges of the interstate system in Virginia, which were opened to traffic on July 1, 1960, were constructed during the same nine-month period, on two separate but connecting projects, in the same geographic and climatic zone. The fifteen bridges were all built with the same engineering design and construction techniques. All have 8" thick decks on either 3 or 4 simple spans and all were placed with ready-mixed concrete screeded and finished by hand. Type II cement from the same commercial source was used in all of the concrete, and natural siliceous fine aggregate from the same geologic source was used. The structures are in the same highway residency and are maintained and deiced by the same personnel and equipment.

In short, everything about the concrete in the 15 bridges is the same, within the limits of construction practice, except for differences in the lithologies of the coarse aggregate used. The authors consider that the circumstances of the construction and location of the bridges were such that something closely akin to a controlled experiment (in which the only variable was coarse aggregate) was available by chance in the field. Nine of the bridge decks, designated the northern project, contain a dark, argillaceous, dolomitic limestone. And six, hereafter called the southern project, contain a pure crystalline dolomite.

Both coarse aggregates met conventional soundness requirements and the Virginia Department of Highways specifications of abrasion resistance (AASHO T 62) maximum loss at 500 revolutions — 35%, and $MgSO_4$ soundness (AASHO T 104) maximum loss at 5 cycles — 8%. The important characteristics of these aggregates and the main requirements for the concrete are shown in Tables I and II respectively.

1994

TABLE I

CHARACTERISTICS OF STONE

	Project 'N'	Project 'S'
(ASTM C 127) Bulk Specific Gravity	2.74	2.82
(ASTM C 127) Absorption, % at 24 hours,	0.32	0.50
Dolomite/ Total Carbonate, %	63	100
Insoluble Residue, %	28	6
(ASTM C 586) Prism Expansion, at 6 months, %	+0.95	-0.02
(ASTM C 88) Magnesium Sulfate Soundness Loss, % at 5 cycles	5.59	2.60
(ASTM C 131) L. A. Abrasion Loss, %	15.8	28.6

TABLE II

CONCRETE SPECIFICATIONS

Property	Requirement
Cement Content, min. sk/yd^3	6.25
Water/Cement, max. gal/sk	5.5
Slump, range, in.	0-5
Air Content, range, %	3-6
Maximum Aggregate Size, in.	1

The soundness loss of the northern stone is higher than that for the southern. Although both aggregates pass the tests required by the specifications, it might be argued that the sensitivity of the northern stone to freezing and thawing is greater than that of the southern stone and that the, still to be described, distress is due to that fact. The effects of sensitivity to freezing and thawing and alkali reactivity are discussed at the conclusion of the report.

Rock prisms from the northern aggregate have an average expansion in alkaline solution of about 1% at six months while the southern aggregate has no expansion for the same length of time. The northern aggregate was from the source which contained the stone designated "1-8" in previous Virginia Highway Research Council reports of studies of alkali-carbonate reactivity ([1]). Pertinent to the subject of expansion of the rock in alkaline solution is the fact that plant analyses supplied by the cement producer for the period of construction indicate a total alkali content between .45 and .55% expressed as Na_2O equivalent. Additionally, data from random samplings, given in Figure 1, from various construction projects during this period show that 80% of the samples from the cement source were between .40 and .60% total alkalies. The remaining 20% were greater than .60% alkalies, although in general the cement would conventionally be referred to as "low alkali."

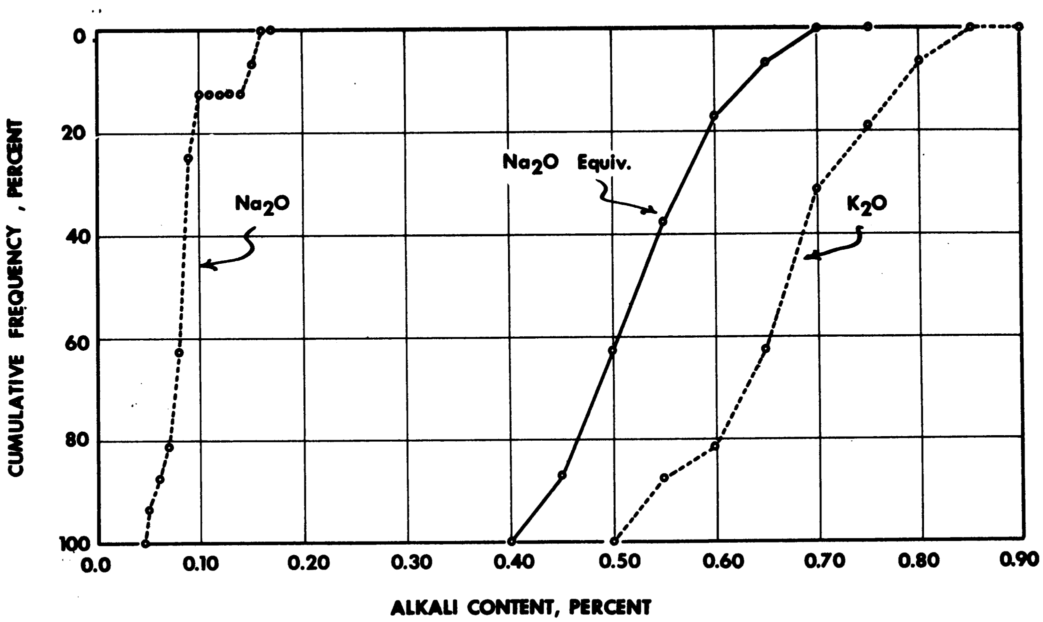

Figure 1. Alkali contents of cements used during the period of construction of bridges in both the northern and southern projects.

1998

Condition of Bridge Decks

Severe scaling on some of the bridges, which subsequently necessitated periodic repairs, was noted after the second winter; however, a detailed slab by slab survey of the decks was made in the summer of 1966 when the decks were about eight years old. The survey revealed two principal types of distress: (1) Scaling as shown in Figure 2, and (2) map or pattern cracking, shown in Figure 3, which in most cases is coincident with the scaling. The frequency of occurrence and the amount of area affected by this distress were vastly different for the northern and southern projects. Ninety percent of the decks on the southern project were free of pattern cracking, and of the 10% affected all had less than 25% of the area affected. Sixty-five percent of the decks in the southern project were free of scaling. Of the percent not free, 85% had less than 25% of the area affected. Figure 4 shows a typical view of the pavement condition in the southern area.

In contrast, in the northern area only 15% of the decks were free of pattern cracking, and of the 85% affected greater than two-thirds had more than 25% of the area affected. Only 12% of the area in the northern project was free of scaling; and of the scaled fraction, a little more than half had more than 25% of the area affected. A more complete representation of the percent of affected decks and the are of those decks affected is given in Table III.

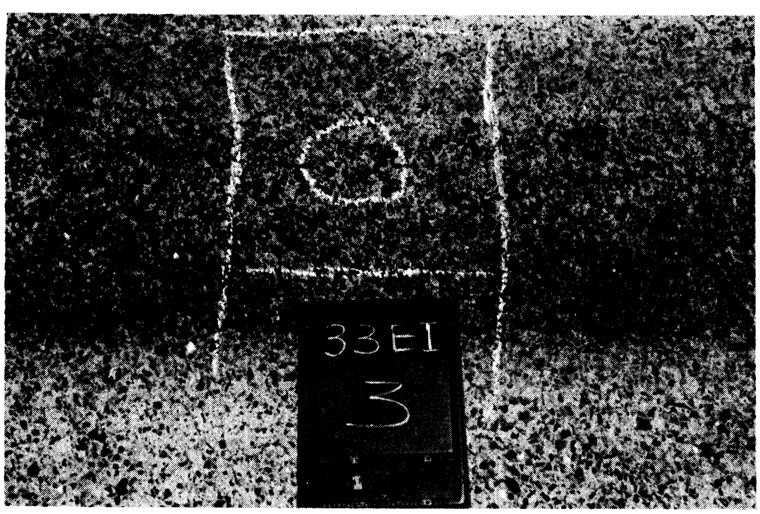

Figure 2. Typical view of severely scaled area in northern project.

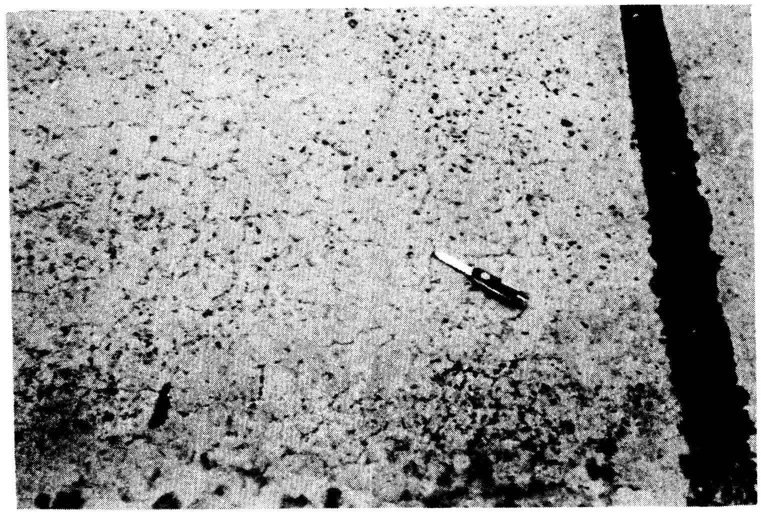

Figure 3. Typical view of pattern cracking on northern project.

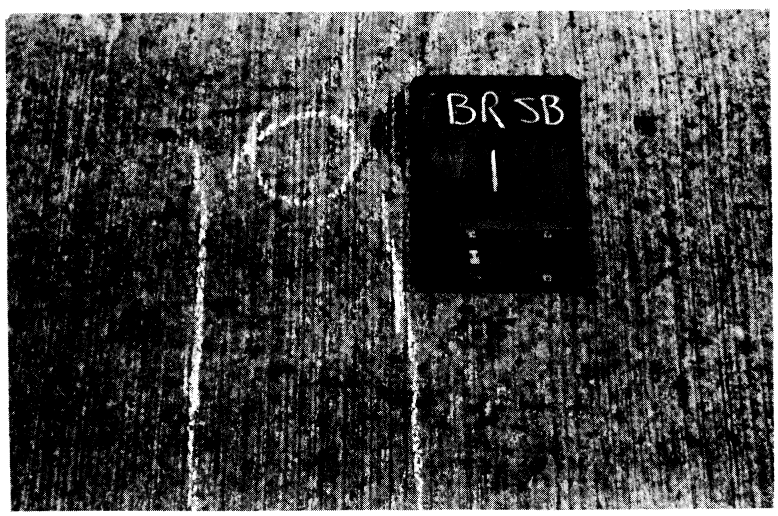

Figure 4. Typical view of pavement condition in southern project.

1998

TABLE III

NUMBER OF DECKS AFFECTED BY PATTERN CRACKING AND SCALING ON NORTHERN AND SOUTHERN PROJECTS

Project	No. of Decks Not Affected, %	No. of Decks Affected, %		% Area of Decks Affected		
				>25	>50	>75
N	15	85	No. of Affected Decks (%)	56	27	15
S	90	10	No. of Affected Decks (%)	0	0	0
		SCALING		>25	>50	>75
N	12	88	No. of Affected Decks (%)	47	27	9
S	65	35	No. of Affected Decks (%)	15	10	5

EXAMINATION OF HARDENED CONCRETE

Seventeen of the total number of cores taken from bridges on both projects were designated for petrographic examination. Ten were taken specifically to represent a particular condition, either poor or good, and seven were taken in an unbiased manner by selecting the coring locations with a table of random numbers. The cores were subjected to various examinations. Pertinent information about the cores is summarized in Table IV.

TABLE IV

AIR VOID SYSTEM AND PETROGRAPHIC INFORMATION
NORTHERN PROJECT

Core No.	Designation and Estimated Condition	Total Void Content %	Entrained Air (< 1 mm)	Specific Surface $in2/m^3$ $in2/in^3$	Coarse Aggregate [1]	Other Features
0150	Specific poor rotten	0.6	0.2	324	Black, light and dark gray angular to subangular, crushed dolomitic limestone, occasionally visibly argillaceous, pyritiferous, and fossiliferous	Hairline cracks parallel to pavement surface through paste and coarse and fine aggregate. Internal cracks in coarse aggregate. Incipient boundary separations. Paste dull, chalky, opaque, absorptive. Fracture not through very much aggregate. Water voids and entrapped air voids extremely sparse.
0151	Specific good	5.6	3.7	532	"	Hairline cracks in pavement surface continue below to display crack pattern in paste along which leaching has taken place. There are few cracks in the paste in the lower part of the core. Internal cracks in aggregate and boundary separations.
0152	Specific good	4.6	2.6	515	"	Interior aggregate cracks, some extend into paste, not well developed. Aggregate/paste interface tight with a few separations.
0153	Specific light scale	1.0	0.3	274	"	System of cracks parallel to pavement surface, marked boundary openings, internal cracks in aggregate especially in upper core.
0154	Specific good (best)	4.1	3.0	713	"	Fine cracks in surface and upper core which are not abundant. Minor amount of internal aggregate cracks. No well developed paste/aggregate separations.
0171	Specific scaled	4.7	2.9	528	"	Few cracks in paste especially near steel. Boundary separations more abundant at bottom of core.
0172	Random good	4.5	2.5	509	"	Fine cracks in paste, a few emanating from reactive aggregate particles.
0173	Random good	3.6	2.1	633	"	Fine paste cracks and boundary separations.
0174	Specific scaled area	6.2	3.0	473	"	Many fine cracks in paste, many water voids.
0175	Random good	5.1	2.7	497	"	Poor bond
0176	Specific random cracking	1.5	0.3	189	"	
0177	Random good	5.9	3.3	616	"	Fine cracks in surface and upper core which are not abundant. Numerous internal aggregate cracks. No well developed aggregate/paste separations.
					SOUTHERN PROJECT	
0163	Random good	3.8	2.5	699	"Crystalline" dolomite, slightly sandy partly brecciated and recemented.	Minor amount of very fine boundary separations at bottom.
0164	Random good	3.8	1.9	702	"	Fine boundary separations at bottom of core.
0165	Random good	3.5	1.6	485	"	Discontinuous cracks in paste at bottom of core.
0166	Specific scaled area	3.3	1.7	621	"	Many fine cracks in top of core, open fractures in large aggregate at bottom of core.
0170	Random slight scale	4.5	2.3	556	"	Some boundary separations and weak bond.

1/ The fine aggregate in all the cores is a subangular to subrounded natural sand, mostly quartz but with some feldspar and some crushed quartz particles.

1999

Air Void System

The average total void content of the hardened concrete, as determined in accordance with ASTM C457, for randomly taken samples on the northern project is 3.9% and for similar samples from the southern project is 3.8% (Table IV). There are no significant differences in the amounts of air in the hardened concrete, in the properties of the void systems, nor in the characteristics of the mortar fractions of the northern and southern concretes which would account for the difference in the performance of the two groups of bridges. Examination of the pattern cracking and scaling in a dry condition, which tends to minimize its severity, would in all likelihood lead an observer to the conclusion that it was a case of common scaling caused by freezing and thawing.

Petrographic Examination

Twelve cores from the northern and five from the southern project were examined petrographically using conventional techniques. Relevant features of the examinations of the concrete from the two projects are summarized below.

Southern Project

Core samples from undistressed pavement surfaces on the southern project show the finishing marks still well preserved with strong lineation and good relief as shown in Figure 5. The fine aggregate is firmly held, the paste somewhat carbonated and hard and dense. There are no hairline cracks or similar features of distress. Observation of at least 4 horizontal interior polished surfaces for each core from the southern project reveal only that the paste has a few isolated, fine, discontinuous cracks,which do not transect either coarse or fine aggregate particles.

The coarse aggregate used in the southern project is a typical example of a rock of its particular kind; a nearly pure "crystalline" dolomite, which is a coarse grained mosaic of generally equigranular interlocked dolomite subhedra, with a small amount of quartz, feldspar and opaque minerals. The total acid insoluble residue comprises about 6% of the rock(see Figure 6).

Almost all of the dolomite coarse aggregate particles have internal fractures and veins which are intrinsic to the stone but which do not extend into the paste. An example is shown in Figure 7.

In summary, the concrete from the sourthern project is of good quality and exhibits no features of distress. The minor, isolated, discontinuous cracking in the paste does not connect with the cracks and fractures intrinsically present in the coarse aggregate.

Figure 5. Typical view of pavement surface of core from southern project. Note finishing marks still visible.

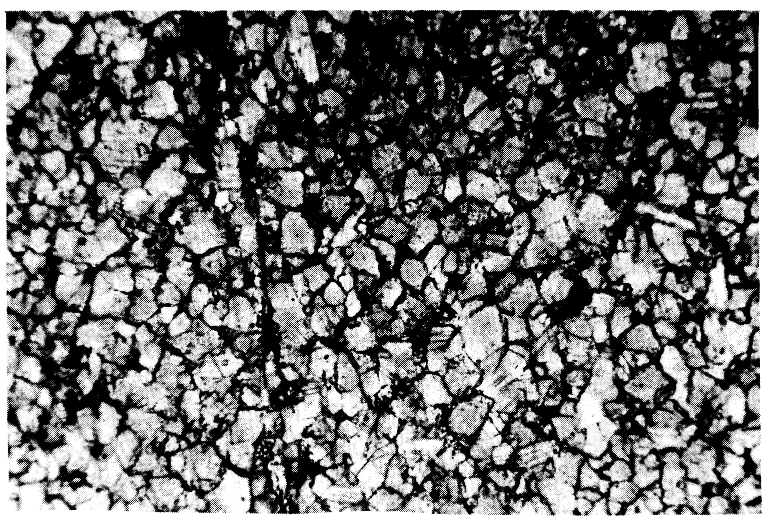

Figure 6. Typical view of crystalline dolomite. Explanation in text. Field is 1.3 mm. plane polarized light.

2002

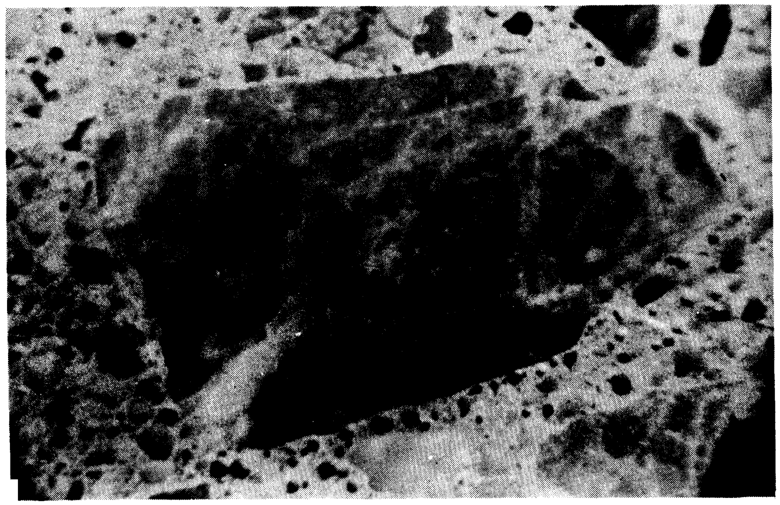

Figure 7. Detail view of coarse aggregate particle from southern project in cut and polished surface. Note internal fractures and veins in particle.

Northern Project

The concrete specimens from the northern project, as previously indicated, were taken to sample two conditions: (1) presumably "good" areas which exhibited no scaling or pattern cracking, and (2) scaled and pattern cracked areas.

Pavement surfaces on core samples taken to represent the latter condition typically show no visible lineations or finishing marks, but instead display deep scale with a maximum relief of about 15 mm and well exposed coarse aggregate — some particles of which are disrupted and broken apart as shown in Figure 8. There is a network of vertical trending hairline cracks through the plane transecting, parallel to, and radial to coarse aggregate particles.

As shown in Figure 9, interior polished surfaces of the core show essentially the same crack pattern as does the pavement surface. Allowing for some lateral shifting with the depth of the cracks, the surface pattern may be superimposed on the trace of the pattern on the interior surface with good agreement, and in many cases cracks may be traced down the sides of the cores to the interior surfaces. These observations establish that the cracks are not isolated and discontinuous but are a continuous three-dimensional network through the mortar and coarse aggregate particles, and that the pavement surface cracks are extensi of cracks from below.

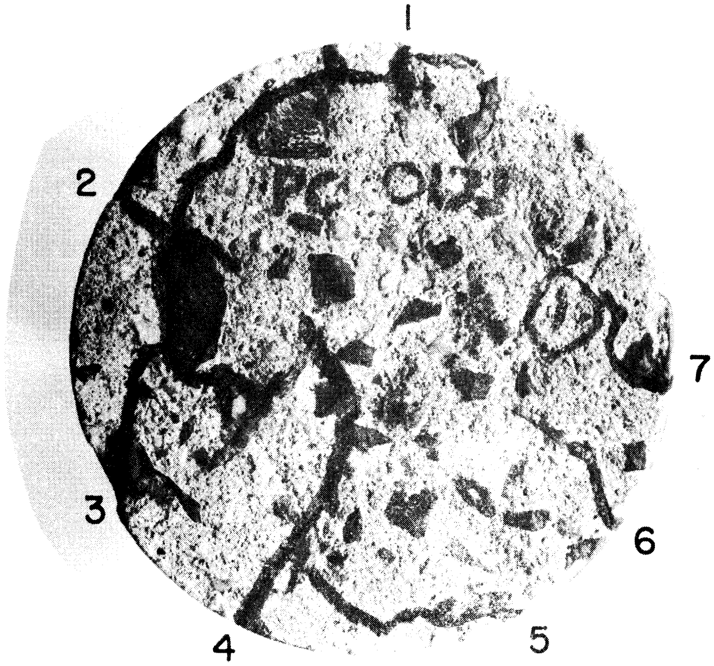

Figure 8. Top slice of core from scaled and pattern cracked area in northern project. Note exposed coarse aggregate (dark gray to black) and cracks (outlined in ink) across core and alongside coarse aggregate particles.

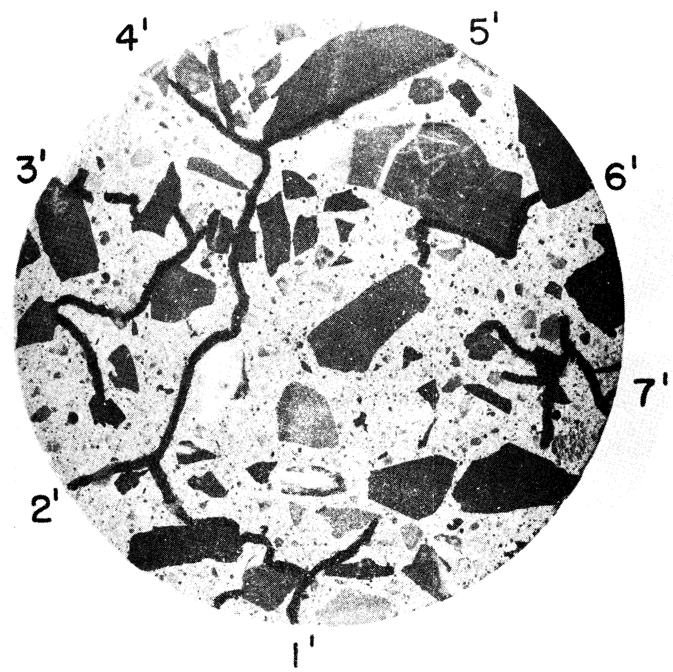

Figure 9. Interior polished underside of core shown in Figure 8 showing same crack pattern as pavement surface. Cracks corresponding to those numbered in Figure 8 are evident.

Interestingly, the interior polished surfaces of concrete cores from the first group, the so-called good areas from the northern project, such as that illustrated in Figure 10, show exactly the same features as those from the scaled areas the main difference between the concretes being the presence of surface scaling. These features are seen in Figures 11 and 12.

Therefore for both surface conditions, i.e., scaled or unscaled, typically there are internal cracks or fractures that presumably originate from the coarse aggregate particles, extend into the paste (sometimes only a short distance), and dwindle to fine cracks or end as radial cracks against other coarse aggregate particles. More often, the cracks extend through the paste a greater distance, transect coarse and fine aggregate particles, and ultimately connect with other cracks of similar origin as seen in Figure 13.

At least some of the internal coarse aggregate cracks are intrinsic to the material since a few (about one-tenth as many as in the aggregate in the concrete) may be found in sectioned and polished particles from stockpiles of current production.

This property may be viewed as another factor of similarity between the concretes from the northern and southern projects. That is, both of the concretes have coarse aggregates which have internal fractures intrinsic to the material, but in the case of the northern stone expansion, presumably due to alkali reactivity, has exploited the intrinsic weakness, which has been subsequently further exploited by freezing and thawing.

In any case, at this stage in the history of the concrete of the northern project it is difficult, at best, to separate the distress due solely to reactivity from that due to freezing and thawing, but the general mechanism is almost certainly that internal fractures are produced within the aggregate (see Figure 14), later extend to its edges (and eventually into the paste), propagate through the coarse and fine aggregate particles, and finally connect with cracks of a similar history.

Petrographically, the coarse aggregate used in the northern project is very like the prototypical alkali reactive carbonate rock (ASTM C 294). As seen in Figure 15, it is composed of isolated or "floating" dolomite euhedra and subhedra in a matrix of turbid, fine grained, partially sparry but mainly micritic, calcite and indistinct material, that on the basis of acid insoluble residue determinations, is presumably clay.

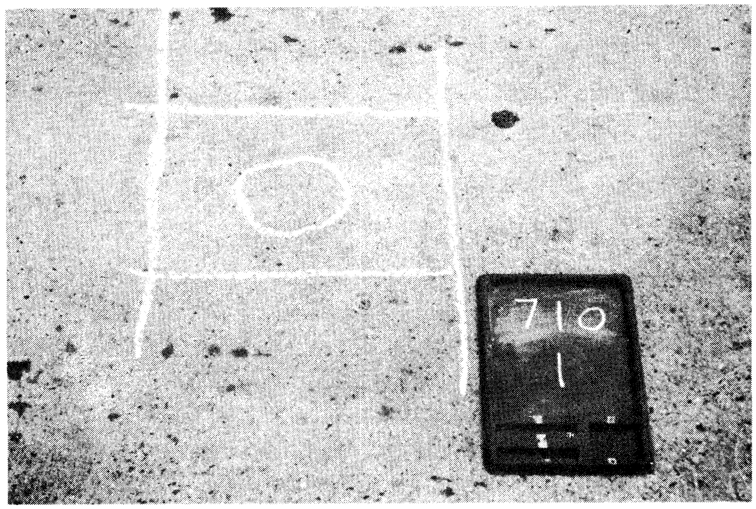

Figure 10. Core location on northern project showing healthy looking pavement, apparently free of scaling and cracks.

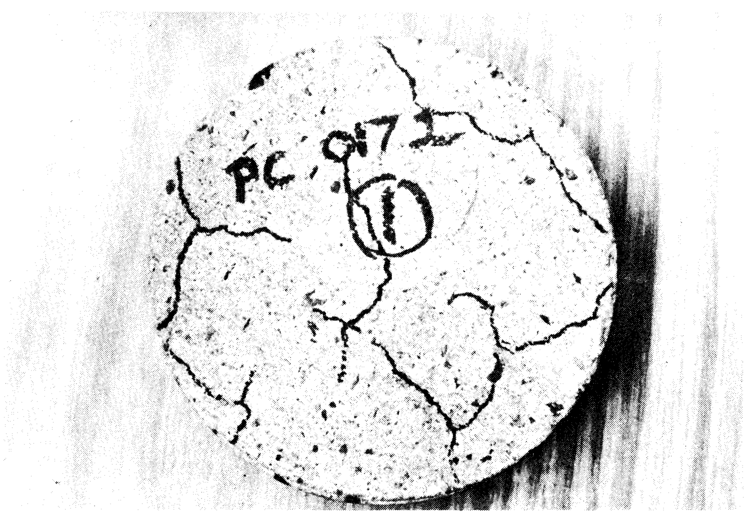

Figure 11. Core from location in Figure 10 showing system of hairline cracks which have been outlined in black.

2006

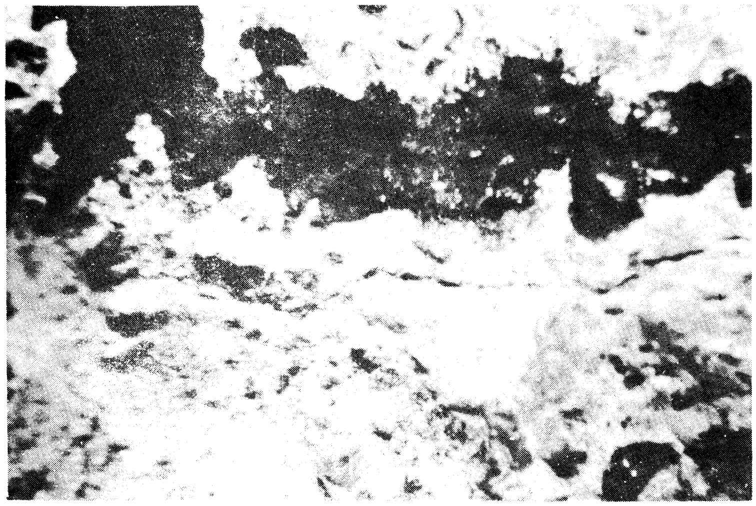

Figure 12. Detail view of crack in Figure 11.

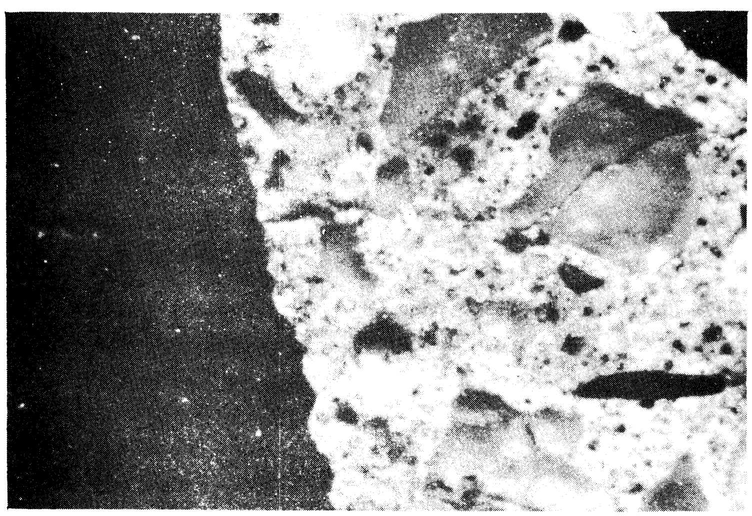

Figure 13. Detail view of coarse aggregate particle from northern project showing internal crack extending into paste and through fine aggregate particle.

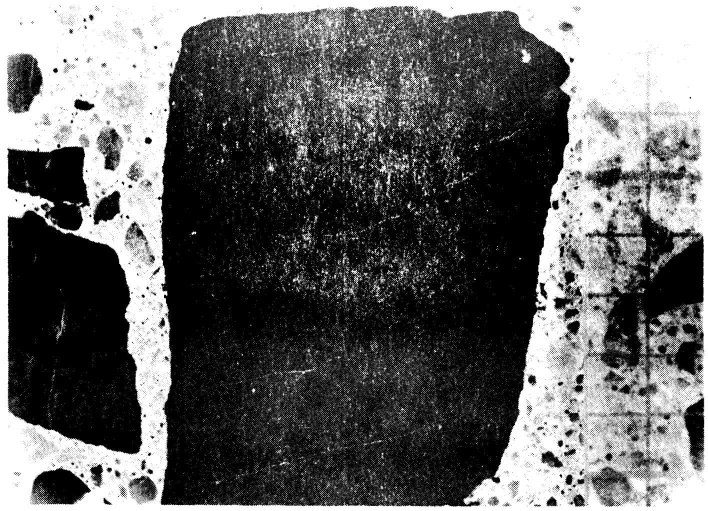

Figure 14. Family of internal cracks in coarse aggregate particle in concrete from northern project. Scale = . 1".

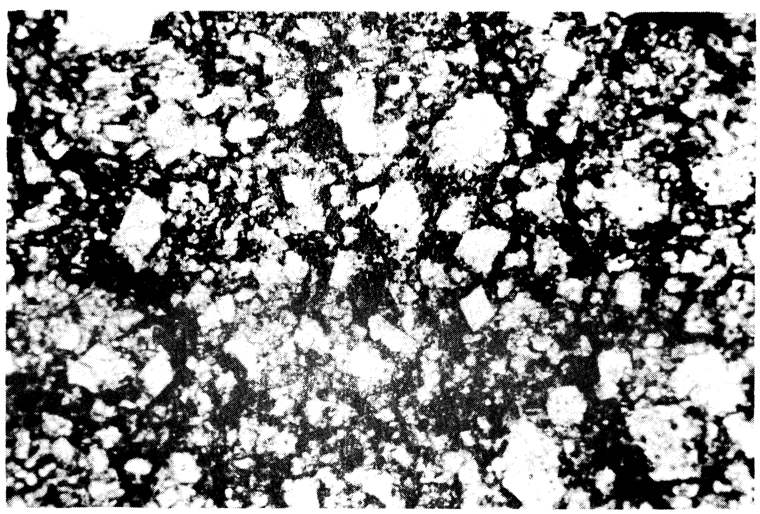

Figure 15. Detail view of argillaceous dolomitic limestone from northern projec showing interstitial clay and dolomite rhombs. Field is . 3 mm, plane polarized light.

2003

EXPERIMENTAL TESTS

The question of whether the concrete distress in the northern project could possibly be entirely due to the lack of freezing and thawing resistance of the stone is answered by results from scaling-block tests and from freezing and thawing tests.

Scaling Blocks*

Concrete blocks 12" x 12" x 6" were made in two series: one using the northern stone, and the second using a granite control aggregate. Both series were combined with cements of high and medium-low alkali contents. A total of twelve blocks, three for each aggregate-cement combination, were available. The blocks were fabricated so as to permit the ponding of water on the surface and were placed in an outdoor exposure area. After each freeze of the ponded water approximately two percent by weight of the water of granular NaCl or flake $CaCl_2$ respectively was spread on each of two of the duplicates. The resulting salt solution was allowed to freeze and thaw one time, after which the surface was rinsed and covered with plain water that was allowed to freeze, and then the cycle was repeated. Thus half the freezes of these specimens were with a salt solution. The remaining set of four blocks was treated only with plain water.

Freezing and thawing was judged by daily visual observation rather than according to temperature and in some cases ice remained on the surface for several days. The samples were exposed for four winters and at the final inspection had undergone 172 cycles of freezing and thawing, approximately half of which were with salt.

A rating system was developed to express the degree of surface scaling quantitatively as follows:

Rating	
0	No distress, no scaling
2	$<$10% light scaling $<$10 popouts
3	5-50% light to moderate scaling; $<$10 popouts
4	5-50% light to moderate scaling; $>$10 popouts
5	40-90% light to moderate scaling; $>$10 popouts
6	30-60% moderate scaling; $<$10 popouts
7	30-60% moderate scaling; $>$10 popouts
8	30-60% moderate to deep scaling
9	70-100% deep scaling
10	100% deep scaling

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* The following test is similar in scope, procedure and method of evaluation to the new ASTM Designation C672-71T, and was intended in this particular application to evaluate qualitative by visual examination the effect of different aggregates on resistance to scaling.

The results, presented in Table V, show a definite relationship between the type of aggregate and the occurrence of scaling, all other things being approximately equal. There is some inconsistency in the results in that the northern aggregate sometimes performed worst with the medium-low alkali cement (.43%) than with the high (.95%) alkali.

No argument is proposed to account for this other than that the test is somewhat subjective in nature and would probably yield more reliably quantifiable results had a greater number of samples been used. The amount of entrained air is probably not a factor in accounting for the difference since the air contents (plastic conditions) were 3.4 vs. 3.5, 3.6 vs 4.4, and 5.0 vs. 4.9 for medium-low vs. high alkali cement with water, NaCl, and $CaCl_2$ treatment, respectively.

The conditions of some of the samples after 14 months exposure and treatment are shown in Figures 16-19 for comparative purposes. These comparisons have been selected or "weighted" to favor the northern aggregate with respect to alkali and air contents.

TABLE V

PERFORMANCE OF SCALING BLOCKS WITH DIFFERENT AGGREGATES

Aggregate	Cement Alkali Content Na_2O Equiv. %		RATING NUMBERS[a] Water			$CaCl_2$			NaCl			40 Month's Expansion of Moist Stored Concrete, %
		No. of cycles	18	49	172	18[b]	49[c]	172[d]	18[b]	49[c]	172[d]	
Northern	.95		0	3	5	1	3½	4	2	5	6	0.17
Northern	.43		0	3½	4	2	4½	6	2	4	5½	0.07
Control (Granite)	.95		0	0	0	0	2	2	0	3	3	0.05
Control (Granite)	.43		0	0	0	0	2	2	0	2	2	0.04

a/ Fractional values of 1/2 occur due to averaging and do not imply precision to one-half a rating number
b/ 9 Cycles with salt
c/ 25 Cycles with salt
d/ 79 Cycles with salt

2010

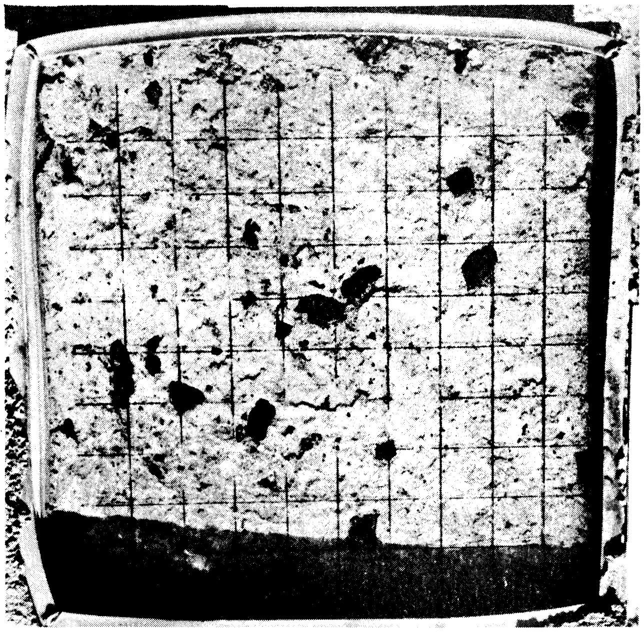

Figure 16. Age 14 months, granite aggregate, med-low alkalies, 4.4% air, $CaCl_2$ treatment — compare with Figure 17.

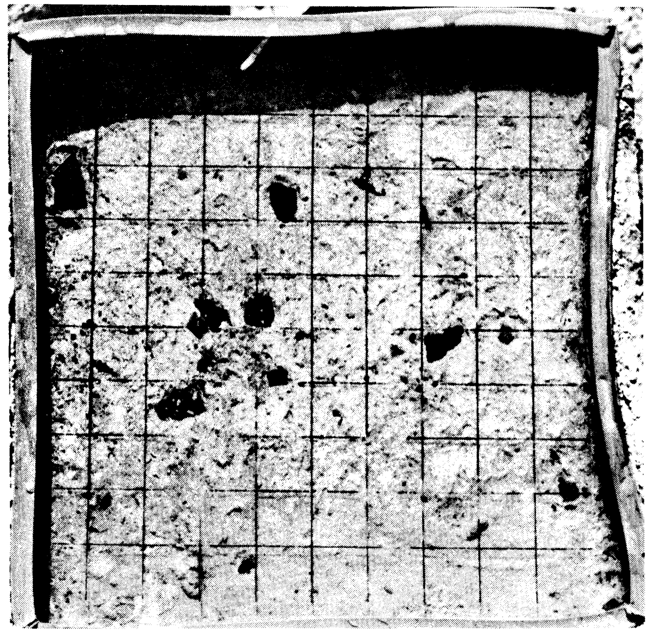

Figure 17. Age 14 months, northern aggregate, med-low alkalies 4.9% air, $CaCl_2$ treatment — compare with Figure 16.

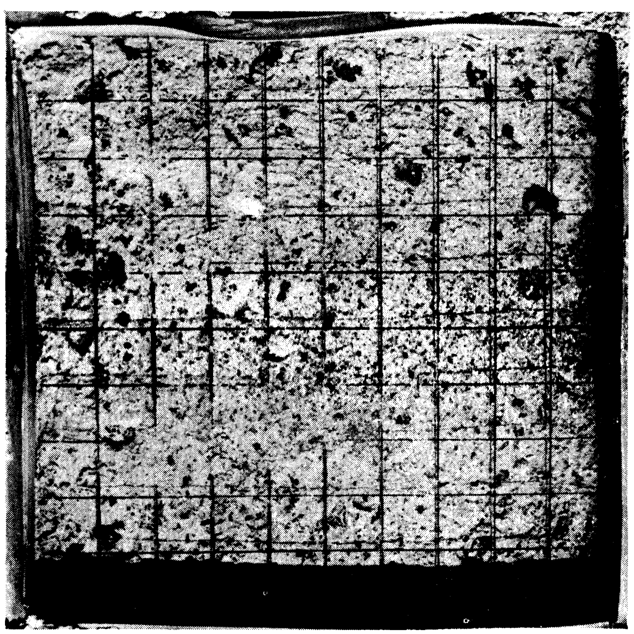

Figure 18. Age 14 months, granite aggregate high alkalies, 4.0% air, NaCl treatment -- compare with Figure 19.

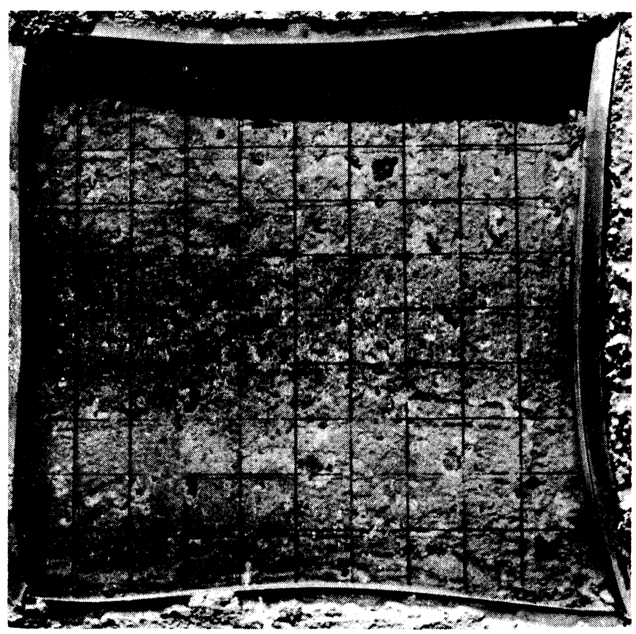

Figure 19. Age 14 months, northern aggregate, med-low alkalies, 4.4% air, NaCl treatment — compare with Figure 18.

Freezing and Thawing Tests

To further refine the answer to the question of the effect of alkalies (which is suggested in the foregoing scaling block experiment) by a method which would allow more definite quantitative results, freezing and thawing tests were conducted in accordance with ASTM C291 — Rapid Freezing in Air and Thawing in Water. In this experiment the northern stone was diluted with the same granite control aggregate as used in the scaling block test and mixed with cements of varying alkali contents — two of which (.43 and .95% alkalies) were the same as used in the scaling block test. The results of this experiment are presented in Figure 20.

Note that after 300 cycles, for concrete with 100% reference aggregate, the relative dynamic modulus, P_c, is 100 but that for instance, at 50% northern aggregate and high alkali cement, the P_c is about one-half of what it was before, and further that the lower the alkali content, the better is the performance in the freezing and thawing tests.

As noted previously the rock prism expansion of the northern stone in an alkaline solution indicates that it is of the alkali-carbonate reactive type.

Apparently the resistance to freezing and thawing of the aggregate in concrete is related to the alkali content of the cement; the relation is that increased alkalies increase expansion from alkali-carbonate reaction and cause cracking, which in turn lowers the relative modulus.

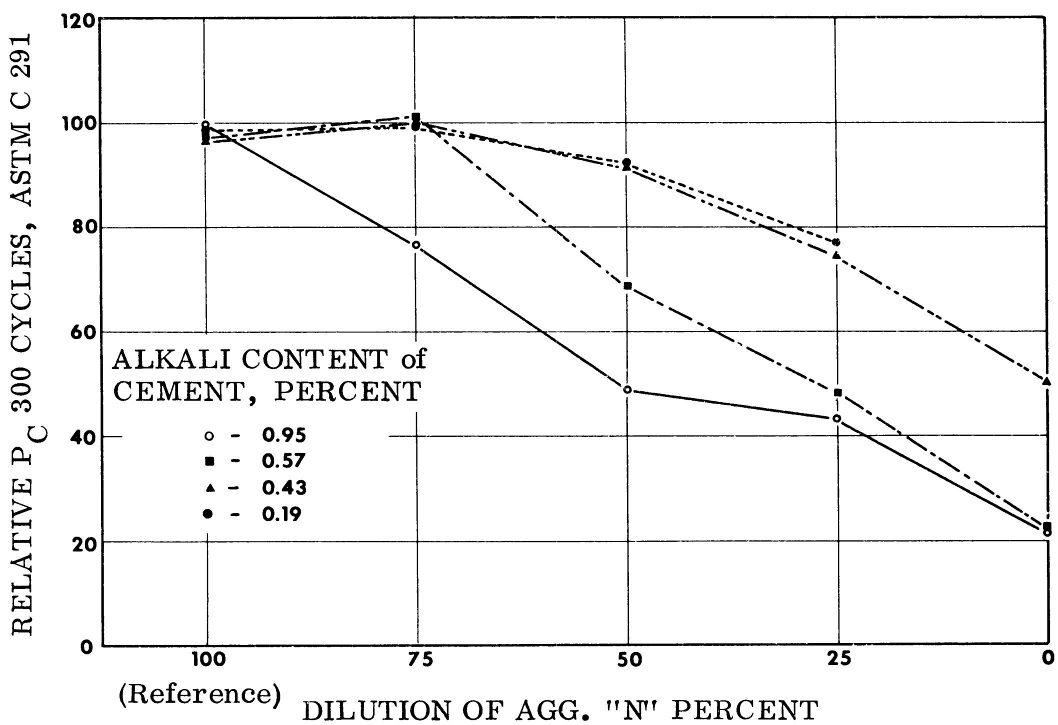

Figure 20. Freeze-thaw durability of dolomitic limestone (Aggregate 'N') with varying concentrations of granite reference aggregate and varying percentages of alkalies.

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CONCLUSIONS

The differences in the appearances and performances of the concretes in the northern and southern projects are due to the difference in the coarse aggregates used — since all other factors are the same.

Scaling block tests were used to simulate or reproduce the distress as seen in the field; results from these tests suggest that the increasing distress could be related to the increasing alkali content of the cement.

Further, results from freezing and thawing tests (with varying dilution of reactive stone vs. alkali content) confirmed that alkali-carbonate reactivity, due to increasing alkali content, is a stronger determinant of performance than whatever freeze-thaw sensitivity the stone may have.

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REFERENCES

1. Newlon, H. H., Jr., and W. C. Sherwood, "An Occurrence of Alkali Reactive Carbonate Rock in Virginia," HRB Bull. 355, Highway Research Board, Washington, D. C., (1962).