BRIDGE DECK DETERIORATION PROMOTED
BY ALKALI-CARBONATE REACTION:
A DOCUMENTED EXAMPLE

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Fifteen Interstate bridges in Virginia were constructed within the same time period in the same general locality and with the same materials and engineering design, except for differences in the lithologies of the coarse aggregate. In 9 of the structures an argillaceous dolomitic limestone was used, in 6 a crystalline dolomite. Both aggregates meet abrasion and soundness specifications. The limestone has a rock prism expansion in alkaline solution of 1 percent at 6 months; the dolomite under the same conditions shows no expansion. Recent surveys of the 15 bridges, opened to traffic in July 1960, show 90 percent of the slabs of the 6 containing dolomite to be free of pattern cracking and scaling, but only 15 percent of the slabs of the 9 bridges containing limestone to be 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 that 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 distress. 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 cement alkali content.

•ALTHOUGH the reaction between certain carbonate aggregates and the alkalies in cement has been extensively studied (1), documented reports of detrimental field performance are comparatively few. Such performance information is available from 15 bridges of the Interstate system in Virginia that were opened to traffic on July 1, 1960; all were constructed during the same 9-month period on two separate but connecting projects in the same geographic and climatic zone. The 15 were built with the same engineering design and construction techniques. All have 8-in.-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 and natural siliceous fine aggregate from the same geologic source were used in all of the concrete. 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 a situation 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, which will be called the northern project, contain a dark, argillaceous, dolomitic limestone. Six, designated the southern project, contain a pure crystalline dolomite.

Both coarse aggregates met conventional soundness requirements and Virginia Department of Highways specifications for abrasion resistance (AASHO T 62) of maximum loss at 400 revolutions of 35 percent and $MgSO_4$ soundness (AASHO T 104) of maximum loss at 5 cycles of 8 percent. The important characteristics of these aggregates and the main requirements for the concrete are given in Tables 1 and 2 respectively.

The soundness loss of the aggregate for the northern project was higher than that for the southern (Table 1). Although both aggregates passed the tests required by the specifications, it might be argued that the sensitivity of the northern project aggregate to freezing and thawing was greater than that of the aggregate in the southern project and that the distress (described later) was due to that fact. The effects of freezing and thawing and alkali reactivity on the durability of the aggregate are discussed at the conclusion of the paper.

Rock prisms of the northern aggregate have an average expansion in alkaline solution of about 1 percent at 6 months, whereas the southern aggregate has no expansion for the same length of time. The northern aggregate was from the source that contained the stone designated "1-8" in previous Virginia Highway Research Council reports of studies of alkali-carbonate reactivity (2, 3, 4). 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 0.45 and 0.55 percent expressed as Na_2O equivalent. In addition, data from random samplings from various construction projects during this period (Figure 1) show that 80 percent of the samples from the cement source were between 0.40 and 0.60 percent total alkalies. The remaining 20 percent were greater than 0.60 percent alkalies, although in general the cement would conventionally be referred to as "low alkali".

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 8 years old. The survey revealed two principal types of distress: scaling (Figure 2) and map or pattern cracking (Figure 3), which in most cases was 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. On the southern project, 90 percent of the decks were free of pattern cracking, and of the 10 percent affected all had less than 25 percent of the area affected. Some 65 percent of the decks in the southern project were free of scaling. Of those not free, 85 percent had less than 25 percent of the area affected. Figure 4 is a typical view of the pavement condition in the southern area.

In contrast, in the northern area only 15 percent of the decks were free of pattern cracking, and of the 85 percent affected more than two-thirds had over 25 percent of the area affected. Only 12 percent 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 percent of the area affected. Table 3 gives a more complete representation of the percentage of affected decks and the area of those decks affected.

EXAMINATION OF HARDENED CONCRETE

Of the total number of cores taken from bridges on both projects, 17 were designated for petrographic examination; 10 were taken specifically to represent a particular condition, either poor or good, and 7 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 4.

Table 1. Aggregate characteristics.

Property	Northern Project	Southern Project
Bulk specific gravity (ASTM C 127)	2.74	2.82
Absorption, percent at 24 hours (ASTM C 127)	0.32	0.50
Dolomite/total carbonate, percent	63	100
Insoluble residue, percent	28	6
Prism expansion, percent at 6 months (ASTM C 586)	+0.95	-0.02
Magnesium sulfate soundness loss, percent at 5 cycles (ASTM C 88)	5.59	2.60
L.A. abrasion loss, percent (ASTM C 131)	15.8	28.6

Table 2. Concrete specifications.

Property	Requirement
Cement content, minimum lb/yd^3	588
Water/cement, maximum	0.49
Slump, range, in.	0-5
Air content, range, percent	3-6
Maximum aggregate size, in.	1

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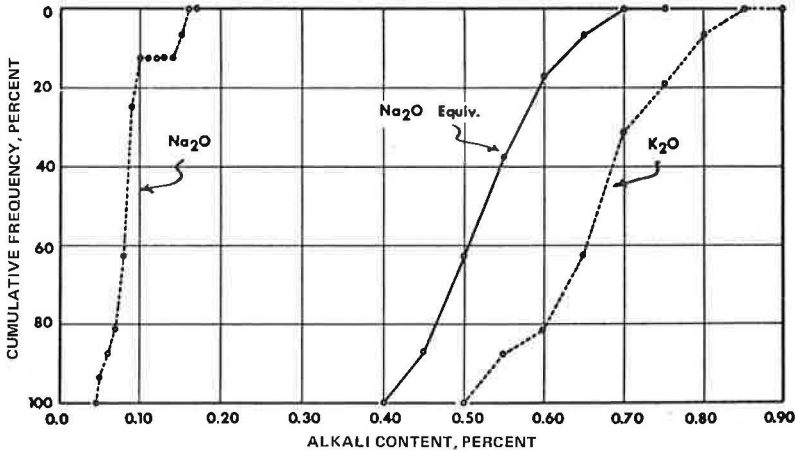

Figure 2. Typical view of severely scaled area in northern project.

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

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

Table 3. Proportion of decks affected by pattern cracking of northern and sourthern projects.

Description	Northern Project	Southern Project
Pattern cracking		
Percentage of decks not affected	15	90
Percentage of decks affected	85	10
Percentage of affected decks with		
>25 percent of area affected	56	0
>50 percent of area affected	27	0
>75 percent of area affected	15	0
Scaling		
Percentage of decks not affected	12	65
Percentage of decks affected	88	35
Percentage of affected decks with		
>25 percent of area affected	47	15
>50 percent of area affected	27	10
>75 percent of area affected	9	5

Air Void System

The average total void content of the hardened concrete, as determined in accordance with ASTM C 457, for random samples taken on the northern project was 3.9 percent, and for similar samples from the southern project it was 3.8 percent (Table 4). There were no significant differences in the amounts of air in the hardened concrete, in the properties of the void systems, or in the characteristics of the mortar fractions of the northern and southern concretes that 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 an example of common scaling caused by freezing and thawing.

Petrographic Examination

Twelve cores from the northern and 5 from the southern project were examined petrographically using conventional techniques. Relevant features of the examinations are summarized in the following paragraphs.

Southern Project—Core samples from undistressed pavement surfaces on the southern project had finishing marks still well preserved, with strong lineation and good relief (Figure 5). The fine aggregate was firmly held and the paste was somewhat carbonated and hard and dense. There were no hairline cracks or similar features of distress. Observation of at least 4 horizontal interior polished surfaces for each core from the southern project revealed only that the paste had a few isolated, fine, discontinuous cracks that did not transect either coarse or fine aggregate particles.

The coarse aggregate used in the southern project was 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 (Figure 6). The total acid-insoluble residue comprised about 6 percent of the rock.

Almost all of the dolomite coarse aggregate particles had internal fractures and veins that were intrinsic to the stone but did not extend into the paste. An example is shown in Figure 7.

In summary, the concrete from the southern project was of good quality and exhibited no features of distress. The minor, isolated, discontinuous cracking in the paste did not connect with cracks and fractures that were intrinsically present in the coarse aggregate.

Northern Project—The concrete specimens from the northern project were taken to sample two conditions: (a) presumably "good" areas that exhibited no scaling or pattern cracking and (b) scaled and pattern-cracked areas. Pavement surfaces on core samples taken to represent the latter condition typically showed no visible lineations or finishing marks but instead displayed deep scale with a maximum relief of about 15 mm and well-exposed coarse aggregate—some particles of which were disrupted and broken apart as shown in Figure 8. There was a network of vertical-trending hairline cracks transecting, parallel to, and radial to coarse aggregate particles.

Interior polished surfaces of the core showed essentially the same crack pattern as did the pavement surface (Figure 9). If some lateral shifting with the depth of the cracks is allowed for, the surface pattern could be superimposed on the trace of the pattern on the interior surface with good agreement, and in many cases cracks could be traced down the sides of the cores to the interior surfaces. These observations established that the cracks were not isolated and discontinuous but were a continuous 3-dimensional network through the mortar and coarse aggregate particles and that the pavement surface cracks were extensions of cracks from below.

Interestingly, the interior polished surfaces of concrete cores from the so-called good areas of the northern project (Figure 10) showed 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 shown in Figures 11 and 12.

Thus for both surface conditions, i.e., scaled and unscaled, typically there were internal cracks or fractures that presumably originated from the coarse aggregate

Table 4. Air void system and petrographic information.

Core No.	Designation and Estimated Condition	Total Void Content (percent)	Entrained Air (percent <1 mm)	Specific Surface (in.$^{-1}$)	Other Features
Northern Project					
0150	Specific poor, rotten	0.6	0.2	324	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 through very few of coarse aggregate particles; 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; few cracks in paste in lower part of core; internal cracks in aggregate and boundary separations around coarse aggregate particles.
0152	Specific good	4.6	2.6	515	Interior aggregate cracks; some extend into paste, not well developed; aggregate-paste interface tight with few separations.
0153	Specific light scale	1.0	0.3	274	System of cracks parallel to pavement surface, noticeable boundary openings; internal cracks in aggregate, especially in upper portion of core.
0154	Specific good (best)	4.1	3.0	713	Fine cracks in surface and upper core, 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 cement-to-aggregate 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, not abundant; numerous internal aggregate cracks; no well-developed aggregate-paste separations.
Southern Project					
0163	Random good	3.8	2.5	699	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.

Notes: 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. 2. For the northern project, the coarse aggregate is black, light and dark gray, angular to subangular, crushed dolomitic limestone, occasionally visibly argillaceous, pyritiferous, and fossiliferous. 3. For the southern project, the coarse aggregate is "crystalline" dolomite, slightly sandy, partly brecciated and recemented.

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

Figure 6. Typical view of crystalline dolomite coarse aggregate from southern project; field is 1.3 mm across, plane polarized light.
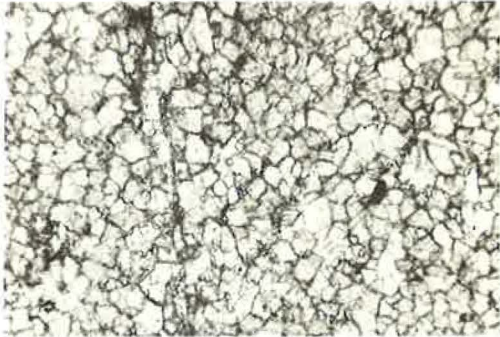
Figure 7. Detail view of coarse aggregate particle from southern project in cut and polished surface; note internal fractures and veins within the particle.

Figure 8. Top slice of core (pavement surface) from scaled and pattern-cracked area in northern project; note exposed coarse aggregate (dark gray to black) and crack across core and alongside coarse aggregate particles.

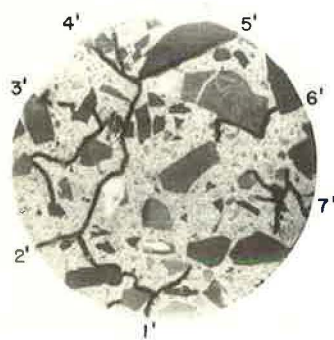Figure 9. Interior polished surface of core with same crack pattern as the pavement surface (underside of slice in Figure 8).

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 outlined in black.

Figure 12. Detail view of crack in Figure 11.

particles, extended into the paste (sometimes only a short distance), and dwindled to fine cracks or ended as radial cracks against other coarse aggregate particles. More often, the cracks extended through the paste a greater distance, transected coarse and fine aggregate particles, and ultimately connected with other cracks of similar origin (Figure 13).

At least some of the internal coarse aggregate cracks were intrinsic to the material, since a few (about one-tenth as many as in the aggregate in the concrete) could 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 had coarse aggregates that had internal fractures intrinsic to the material. But in the case of the northern stone, the expansion, presumably due to alkali reactivity, had exploited the intrinsic weakness, which was subsequently further exploited by freezing and thawing.

In any case, for the concrete of the northern project it was difficult, at best, to separate the distress due solely to reactivity from that due to freezing and thawing, but the general mechanism was almost certainly that internal fractures were produced within the aggregate (Figure 14), later extended to its edges (and eventually into the paste), propagated through the coarse and fine aggregate particles, and finally connected 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.

EXPERIMENTAL EVIDENCE

At the time the distress was observed it was not possible to obtain materials that would precisely represent the two aggregate sources involved. However, as part of a research program on potentially reactive carbonate aggregates, material from the quarry that supplied the northern project was extensively studied during the period that the decks were being constructed. No similar studies were made of the aggregate from the quarry that supplied the southern project because preliminary samplings of that quarry had indicated no potential reactivity. Thus direct experimental comparisons could not be made. Materials from the same vicinity and containing the same type of nearly pure "crystalline" dolomite were included in the testing program to determine resistance to freezing and thawing using ASTM procedure C 291 in concretes made with cements of varying alkali contents. The resistance to freezing and thawing of concrete with aggregate like that used in the southern project was good and unrelated to alkali content. The resistance to freezing and thawing of aggregate "1-8" was poorer and furthermore was shown to be a function of the alkali content of the cement. In that experiment the northern stone was diluted with a granite control aggregate and mixed with cements of varying alkali contents. The results of that experiment are shown in Figure 16.

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

As noted previously, the rock prism expansion of the northern stone in an alkaline solution indicated that it was 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.

CONCLUSIONS

The differences in the appearances and performances of the concretes in the northern and southern projects were due to the difference in the coarse aggregates used, since all other factors were the same. While the aggregate used in the northern project had

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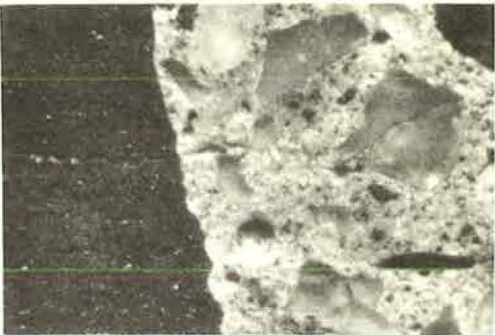

Figure 14. Family of internal cracks in coarse aggregate particle in concrete from northern project; scale divisions are 0.1 in.
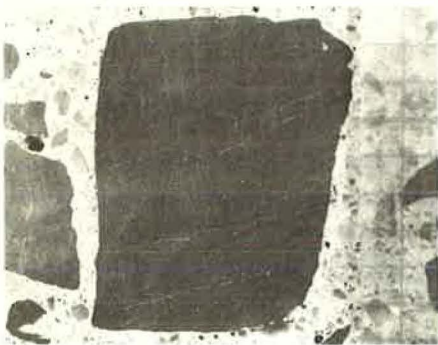
Figure 15. Detail view of argillaceous dolomitic limestone from northern project showing interstitial clay and dolomite rhombs; field is 0.3 mm across, plane polarized light.
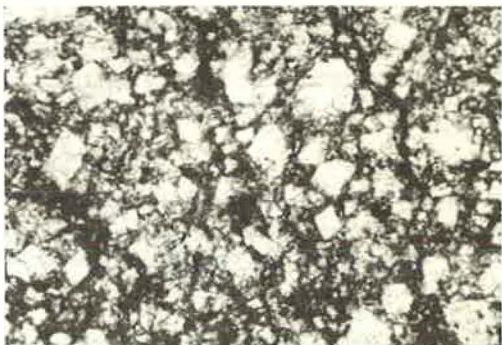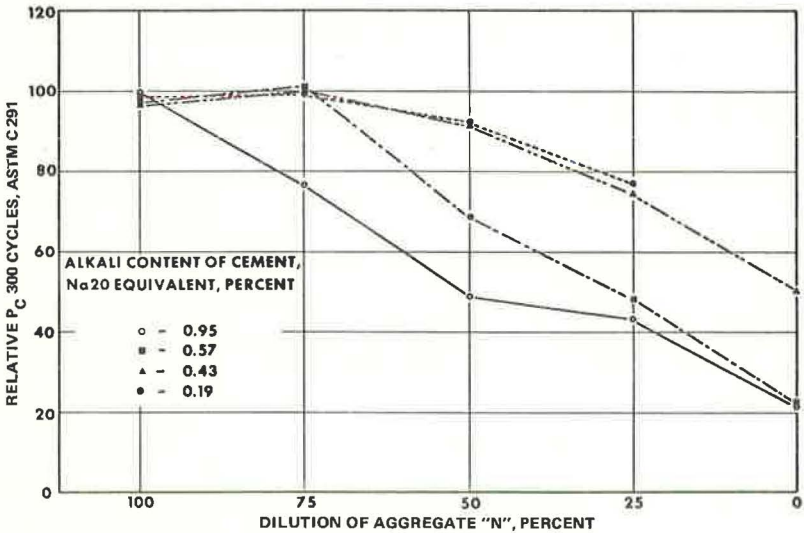

Figure 16. Freeze-thaw durability of dolomitic limestone (aggregate N) with varying concentrations of granite reference aggregate and varying percentages of alkalies.

a lower resistance to freezing and thawing, results from freezing and thawing tests (with varying dilution of reactive stone versus alkali content) suggest that alkali-carbonate reactivity, due to increasing alkali content, was a strong determinant of performance, whatever freeze-thaw sensitivity the stone may have had.

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