THE UHTHOFF QUARRY ALKALI-CARBONATE ROCK REACTION: A LABORATORY AND FIELD PERFORMANCE STUDY

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This report, concerned with alkali-carbonate rock reaction in concrete, is a laboratory and field study of the performance of aggregate from one of the largest commercial quarries in Ontario. Laboratory studies included the fabrication of sets of concrete prisms containing a high alkali content by the addition of sodium hydroxide to the concrete mix. Field performance studies of highway structures included taking cores for petrographic examination, summarizing pattern cracking, and testing of selected structures by pulse-velocity techniques. It is concluded that the presence of approximately 20 percent reactive rock in the quarry material was responsible for widespread surface pattern cracking of the structures. Such cracking has apparently reduced the potential durability of some concrete exposed to almost continuously moist conditions but to date has not affected the serviceability of high-quality reinforced concrete. When applied, existing specifications concerned with the expansion of carbonate rocks, will in all probability produce durable concrete, although some of the symptoms of reactivity—namely, surface pattern cracking—may still occur in field concrete exposed to moist conditions.

•IN the last 15 years it has been established beyond doubt (1, 2, 3) that, when incorporated in concrete as the coarse aggregate, some rocks of the middle Ordivician period of the Black River (Gull) formation near Kingston, Ontario, produce excessive expansion and cracking of the concrete due to an alkali-carbonate reaction.

In the early 1960s, attention was focused on the performance of other aggregate sources in the same geological formation, in particular, the Uhthoff Quarry near Orillia, Ontario. The familiar map-pattern cracking observed in the Kingston area was present in some structures containing the Uhthoff aggregate, but, fortunately, this was not accompanied by the deep, wide, destructive cracks noted at Kingston. This observation of apparent deterioration in the field concrete led to a comprehensive laboratory test program started in 1963 to determine the expansion characteristics of the various layers of rock in the quarry and in two local gravel pits. The main reactive rock in the quarry was identified quickly, and a change in the method of working the quarry to exclude the reactive material permitted continued use of the Uhthoff rock for concrete coarse aggregate.

Long-term data on the length change of concrete prisms made with rock from each quarry layer were compared with shorter term rock cylinder tests, and the performance of concrete in the field was observed as it related to how the quarry was worked and the inclusion, or otherwise, of reactive material.

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GEOLOGY OF UHTHOFF QUARRY

The geology of the quarry was described in 1960 by Hewitt (4). The present quarry face is shown in cross section in Figure 1. The limestone of the Uhthoff Quarry, produced as coarse aggregate for concrete, from the Middle Black River (Gull) bed belongs to the same geological formation as the reactive Kingston aggregates identified in the Pittsburg and Frontenac Quarries (3). The Uhthoff stone is quite distinctive; it has a dense whitish-grey appearance and extremely fine texture and tends to have a higher proportion of flat and elongated particles than most other quarried aggregates in Ontario. Characteristics of the stone are given in Table 1.

GRAVEL SOURCES

Coarse aggregate from the two gravel pits (Ennis S&G and Uren S&G) close to the Uhthoff Quarry was included in the laboratory evaluation and the field performance surveys. These two gravel sources contained large amounts of the Uhthoff type of limestone (45 to 55 percent).

CONCRETE PRISM TESTS

Stone prepared from handpicked rock pieces from each layer within the Uhthoff Quarry was used in three sets of prisms for testing. Layer U4D consisted largely of shale and was not sampled.

Specimens with the suffix L contained a low-alkali (0.46 percent) cement (calculated as $Na_2O + 0.658\ K_2O$). Specimens N and F contained a typical Ontario normal portland cement (type 1) with an alkali content of 0.96 percent. In addition, for specimens F, sodium hydroxide was added to the concrete mix water in an amount to produce an alkali content in the mix equivalent to 3 percent by weight of the cement.

Prisms were also tested for the top lift of the Pittsburg Quarry at Kingston, the two gravel pits close to the Uhthoff Quarry, and a control nonreactive dolomite aggregate from Nelson Quarry at Burlington. In addition, prisms were tested using material from two production stockpiles of the Uhthoff Quarry rock. One sample (UAF) represented the whole 36-ft (11-m) face above the quarry floor; the other (UAP) represented material above layer U2.

The fine aggregate was an Ontario natural sand known to be nonreactive. Aggregates were oven-dried on arrival at the laboratory and saturated in water for 24 hours prior to incorporation in the concrete batch.

Concrete mixes were non-air-entrained, with a cement content of 525 ± 5 lb/yd^3 (311 ± 3 kg/m^3) and slump of 3 ± ½ in. (76 ± 13 mm).

Each set of prisms consisted of three 3 × 4 × 16-in. (76 × 102 × 406-mm) specimens with a ¼-in. (6-mm) diameter stainless-steel measuring pin at each end. Immediately after being cast, the concrete prisms were covered with a layer of polyethylene film and placed in the moist room (73 F, 100 percent relative humidity). The prisms were taken out of their molds the day after casting, measured for length, and returned to the moist room. Additional length measurements were made at 3, 7, and 28 days and periodically up to 7 years. The average length change, in percent based on the length at 7 days, for each set of three prisms is summarized in Figure 2.

ROCK CYLINDER TESTS

Specimens were prepared from handpicked rock samples taken at 6-in. (15-cm) intervals from layers U2 and U3, and at each 12-in. (30-cm) interval from the remainder of the Uhthoff Quarry face. Testing was carried out in accordance with ASTM C 586 except that the included angle on the conical ends was 90 deg. One test consisted of three rock cylinders. Rock cylinders were measured for length change 7 days after reaching constant length and at regular intervals for 1 year thereafter (Figure 3).

DISCUSSION OF CONCRETE PRISM TESTS

The long-term expansion criteria for nonreactive rocks in a moist-cured concrete

Figure 1. Section of Uhthoff Quarry.

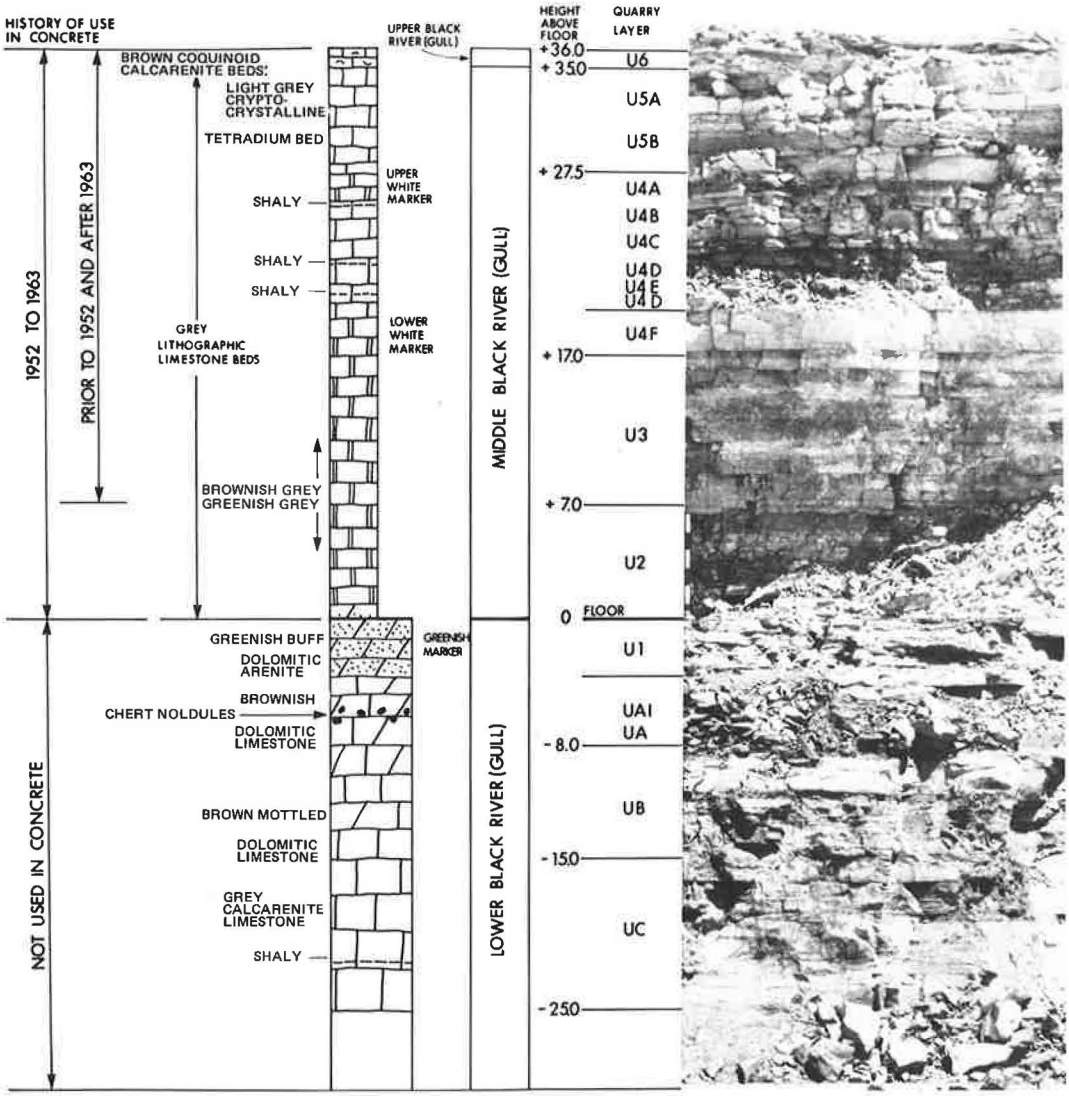
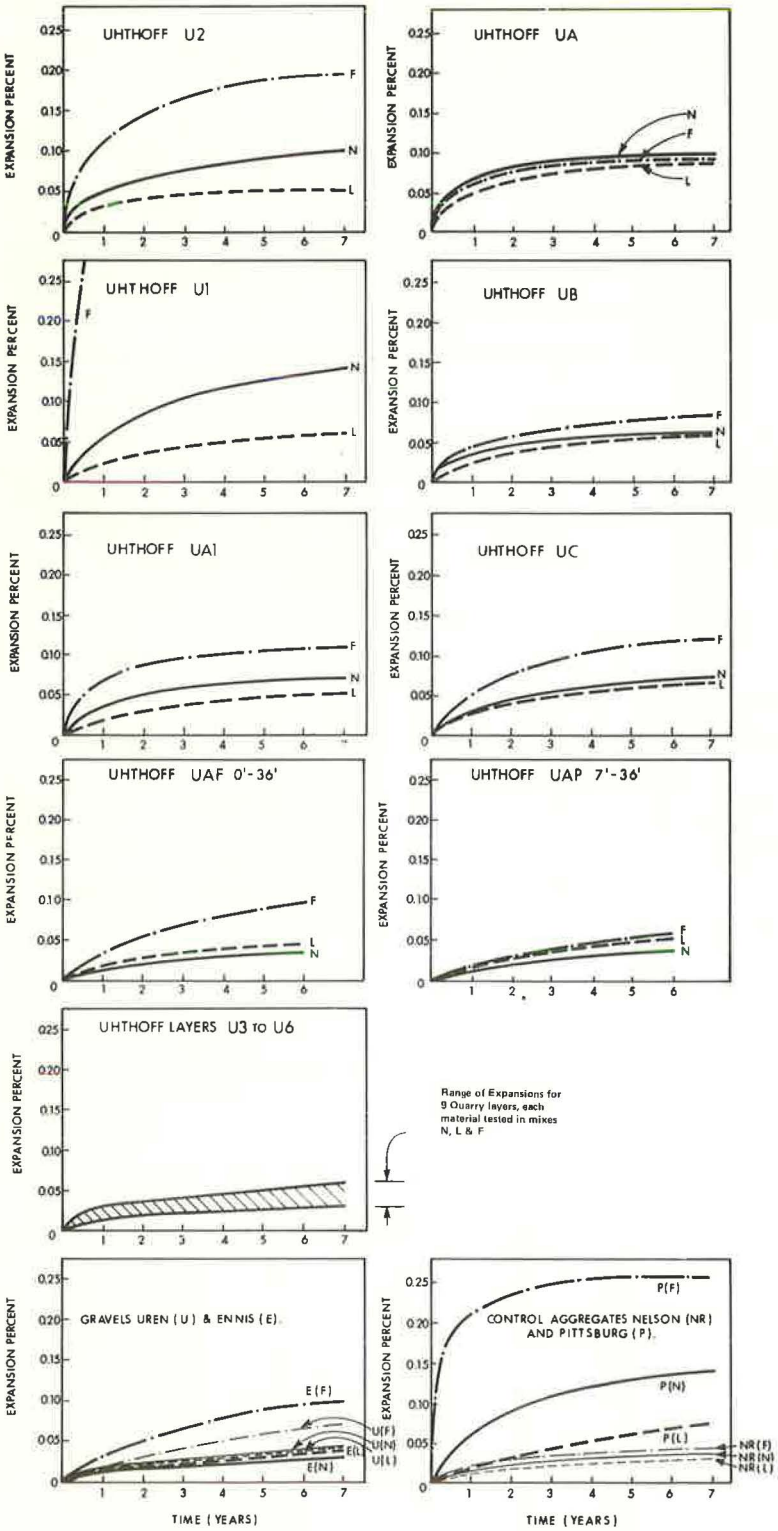


Table 1. Characteristics of rock samples from Uhthoff Quarry.

Quarry Layer	Calcite (percent)	Dolomite (percent)	Insoluble Residue (percent)	Clay Mineralogy	
				Illite	Chlorite
U6	95.6	2.8	1.6	Major	Major
U5A	90.2	4.6	5.2	Major	Minor
U5B	94.2	2.3	3.5	Major	Minor
U4A	96.4	1.8	1.8	Major	Trace
U4B	95.4	2.3	2.3	Major	Minor
U4C	94.2	2.8	3.0	Major	Trace
U4D	96.1	2.3	1.6		
U4E	93.8	3.2	3.0	Major	Minor
U4F	96.3	2.3	1.4	Major	Trace
U3	92.1	3.7	4.2	Major	Major
U2	83.3	7.4	9.3	Major	Trace
U1	10.8	44.2	45.0	Major	Trace
UA1	59.9	37.1	3.0	Major	Major
UA	64.9	31.7	3.4	Major	Minor
UB	91.4	6.0	2.6	Major	Major
UC	88.8	3.7	7.5	Major	Minor

Figure 2. Length change of concrete prisms with time.



N denotes Normal Alkali Cement; L denotes Low Alkali Cement; F denotes Fortified Alkali Mix

Figure 3. Length change of rock cylinders from Uhthoff Quarry at 16 weeks and 1 year.

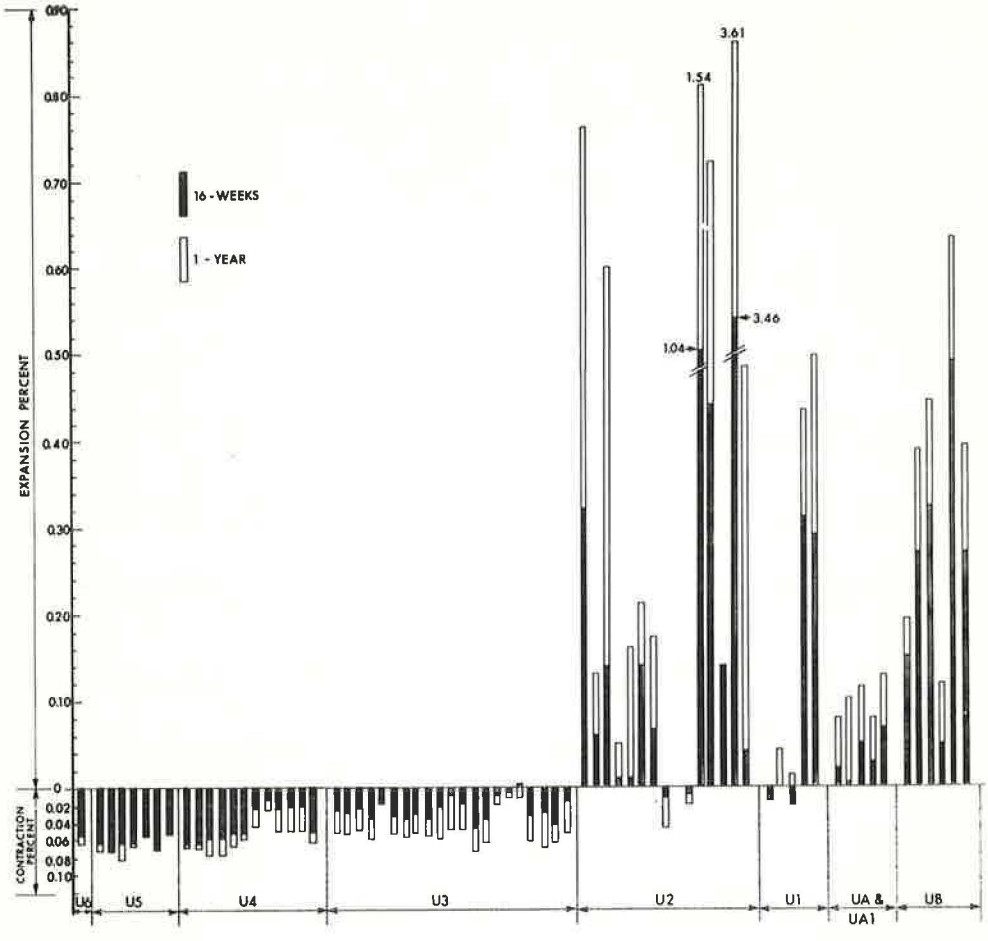


Table 2. Characteristics of rock samples from layer U2 of Uhthoff Quarry.

U2 Layer	Calcite (percent)	Dolomite (percent)	Insoluble Residue (percent)	Absorption (percent)
15* (top)	83.3	6.9	9.8	0.29
14	86.1	6.9	7.0	0.15
13*	87.7	6.9	5.4	0.18
12	87.2	6.9	5.9	0.10
11	85.9	7.4	6.7	0.13
10	79.5	10.1	10.4	0.15
9	87.1	7.4	5.5	0.13
8	91.6	4.1	4.3	0.05
7	90.9	4.6	4.5	0.08
6	89.3	6.0	4.7	0.07
5*	84.9	8.7	6.4	0.20
4*	83.0	8.3	8.7	0.18
3	79.5	9.2	11.3	0.28
2*	53.7	27.1	19.2	0.52
1* (bottom)	23.2	54.3	22.5	2.00

* Indicates substantial expansion in rock cylinder test.

prism test suggested by Newlon et al. (5, 6) is 0.03 percent maximum at 1 year and 0.05 percent maximum at 5 years. This was equaled or exceeded only by each of the six Uhthoff Quarry layers below U3 and material from the Pittsburg Quarry when tested with a normal-alkali cement (0.96 percent). Applying the current MTC standard of 0.02 percent maximum at 12 weeks, only three of these six Uhthoff layers and the Pittsburg Quarry could be identified as reactive. The production samples UAF and UAP, the two gravel pits, and the Nelson Quarry are nonreactive by any of the above criteria.

Used with a low-alkali cement (0.46 percent), the materials in the Uhthoff Quarry below U3 and the Pittsburg Quarry would generally meet the criteria for a nonreactive rock with the exception of Newlon's 5-year requirement of 0.05 percent maximum, whicl in most cases is slightly exceeded.

Data analysis to correlate prism expansion (N and F mixes) at various early ages, with 5-year expansions of the N mixes, did not indicate that a single early test criterion can be developed that will identify all the expansive aggregates found in this study. Linear regression analysis using 4- and 12-week data to predict 5-year expansion resulted in correlation coefficients between 0.77 and 0.86 when using data from both reactive and nonreactive materials and between 0.77 and 0.89 when using data from only expansive aggregate mixes. In general, early F beams (fortified alkali mix) were no better than early N beams (normal alkali cement) in predicting long-term expansions. No single expansion limit applied to the F and N beams at an age of 4 weeks to 1 year would reject all the reactive material while at the same time accepting all the rock identified as nonreactive.

The F prisms containing a reactive aggregate in all cases but one expanded at a much faster rate than the prisms containing the normal-alkali cement. This is particularly evident in the case of the highly expansive aggregates U2, U1, and Pittsburg. The nonreactive rock from layer U3 and above in the Uhthoff Quarry and from the Nelson Quarry displayed generally little difference in prism expansions regardless of the alkali content of the concrete mix.

The performance of the F prisms containing a portion of reactive materials is interesting. The two gravel sources containing approximately 50 percent Uhthoff-type limestone and the Uhthoff Quarry sample UAF containing the reactive layer U2 all displayed increased expansion in the F prisms, particularly after 1 year. Thus, although a decision on the acceptance of an aggregate source at an early age cannot be based on the performance of the F prisms alone, fabrication of such specimens has a number of potential advantages. Test data allow early rejection, perhaps as soon as 4 weeks, of aggregates with a high rate of expansion in concrete. If the F prisms expand at a noticeably faster rate than the N prisms, this indicates the presence of some reactive material in the sample and provides a warning that the test period of the N prisms should be extended before making a final decision on the acceptability of the aggregate.

Most highway structures in Ontario built with concrete containing the Uhthoff Quarry limestone were constructed when the working of the quarry face included approximately 20 percent of reactive material, i.e., the layer U2. Although such dilution of reactive to nonreactive aggregate has apparently produced an acceptable material, in that the expansion of specimens UAF, representing the whole 36-ft (11-m) face of the quarry, is well within the criteria for nonreactive aggregate, the field surveys revealed that pattern cracking on the concrete surface of the type often associated with alkali-concrete reactions is a common occurrence. Thus, although carbonate rocks that meet existing tentative concrete prism expansion specification requirements will in all probability produce durable concrete, some of the symptoms of alkali-carbonate reactivity may still occur in such concrete when exposed to continuously moist conditions.

DISCUSSION OF ROCK CYLINDER TESTS

Specimens of nonreactive material from layers above layer U2 underwent contraction throughout the test. Generally the amount of contraction increased with time.

Most rock cylinders from layer U2 and below had expanded substantially by 1 year. The rate and degree of expansion varied considerably. Using the criteria of 0.1 percent expansion at 12 weeks or 0.2 percent at 16 weeks, 14 out of the 31 rock samples tested

are reactive. The 0.2 percent requirement at 16 weeks appears somewhat more tolerant than the 12-week requirement. At 2 weeks significant expansion had occurred in only half the samples identified as expansive at a later age.

Most specimens with significant expansions at 1 year could be identified on the basis of a 0.1 percent expansion at 12 weeks, but there were exceptions. For example, the cylinders obtained from the bottom of layer U2 expanded 0.03 percent at 12 weeks, 0.16 percent at 6 months, and 0.49 percent at 1 year. Conversely, some layers that exhibited substantial expansion after 12 weeks displayed almost constant length for the remainder of the test.

If a criterion of 0.2 percent maximum expansion at 16 weeks is used for a nonreactive rock, the rock cylinder test, in general, predicts the behavior of the aggregate in the concrete prisms. The material identified in the concrete prism test as nonreactive is nonreactive in the rock cylinder test. More than one-third of the rock cylinders from the reactive layers U2, U1, and UB indicate the aggregate to be reactive. Rock cylinders were not tested from layer UC.

In layer UA, subdivided into UA without chert and UA1 with chert, the concrete prisms showed substantial expansion, although in the case of UA1 it is a slow mechanism. However, the five sets of rock cylinders from these layers did not produce significant expansions and normally would be labeled as nonreactive. An extension of the rock cylinder test beyond 1 year probably would have produced additional useful data on the expansion mechanism of the rocks from layers UA and UA1.

Rock cylinders were not tested from the Pittsburg and Nelson Quarries and from the two gravel pits referred to in this study because a very large number of test specimens would be needed to properly evaluate each aggregate source.

PETROGRAPHIC STUDY

Handpicked samples of rock from the Uhthoff Quarry were subjected to numerous tests, which included chemical analysis and studies of thin and polished sections.

The U2 layer is the most unusual because it contains nonreactive to extremely reactive beds. The layer has, in general, a very fine matrix of calcite intermixed with clay in which small euhedral crystals of dolomite are "afloat". The rock contains from 4.1 percent to 54.3 percent dolomite and from 4.3 percent to 22.5 percent insoluble residue. It varies from limestone to dolomitic limestone (Table 2). The reactive layers have over 5 percent dolomite and contain at least 2 percent clay, which when present as illite is sufficient to trigger the expansion mechanism.

The U2 layer is underlain by the U1 layer, which, apart from the noted expansion, is not acceptable for use as a concrete aggregate because of its poor physical characteristics. The matrix of beds UA and UA1 is very fine-grained and tends to have zonal concentrations of larger sized dolomite crystals with, apparently, sufficient amounts of clay to be reactive.

Layer UB has a very fine calcitic matrix with small crystals of dolomite and a texture similar to the other reactive rocks. It expanded to unacceptable levels but less than other reactive layers. Rock from this layer with larger dolomite crystals showed only moderate expansion in the rock cylinder test, the difference in expansion characteristics presumably being due to its heterogeneous character.

Layers U3 to U6 are characterized by dense fine-crystalline limestone containing up to 5.2 percent insoluble residue but no dolomite crystals and are considered as nonreactive.

A review of the literature on alkali-carbonate reactive rocks indicates that they are argillaceous dolomitic limestones, extremely fine-grained, particularly the calcite matrix. In general, this description also applies to the reactive rocks from the Uhthoff Quarry. The dolomitic crystals, which are almost perfect rhombohedrons with a maximum size of 0.25 mm, have a tendency to be concentrated in some spots or lenses and quite often are associated with clayey or shaley seams or stylolites. This characteristic is probably responsible for the wide variation in expansion of cylinders cut from the same rock specimen that was sometimes experienced in this project.

EXAMINATION OF CONCRETE PRISMS AND FIELD CORES

Microscopic examination of laboratory prisms and field cores did not reveal a widespread network of cracks, although some of the specimens had undergone considerable expansion. The formation of new minerals and features of the alkali reaction process were in some cases difficult to determine because of the specimen preparation. Reactive features were more easily observed on fractured faces.

Prism U2-F, containing aggregate from the U2 layer, exhibited very narrow hairline surficial cracks. On a polished cross-sectional surface, about one-quarter of the aggregate particles contained fine disoriented cracks, with some peripheral cracks restricted to the particular aggregate particle. No aggregate reaction rims were noted, and the mortar was free of cracks. Most of the small voids were encrusted but not completely filled with calcite, and portlandite and ettringite crystals were observed. Prisms prepared with normal-alkali and low-alkali cement and aggregate from the U2 layer cracked and formed minerals in the voids but to a lesser degree.

Typical field cores (Vernon Narrows Structure, Huntsville) contained rock from the entire 36-ft (11-m) Uhthoff quarry face with some aggregate from the U1 layer. About half of the aggregate particles contained minor cracks, among which radial cracks predominate. Peripheral cracks are quite common but are localized around single particles. No cracks were observed in the cement paste below the immediate surface layer. A few particles have narrow discoloration rims, and many of the small voids are encrusted with calcium hydroxide and occasional formations of microscopic crystals of ettringite and portlandite. In general, field cores exhibited similar reactive features regardless of their surface condition.

FIELD SURVEYS

In 1965 and 1966, field condition surveys were carried out at 71 structures known to contain coarse aggregate from the Uhthoff Quarry and the two local gravel pits. Structures were inspected for severity of pattern cracking, scaling, surface pop-outs, etc., with more detailed testing, including pulse velocity surveys and core sampling for petrographic examination, on several typical bridges. The riding surface of all bridge decks is a bituminous layer and, in general, the top surface of the concrete deck slab was not investigated.

Three groups of structures were established: 21 completed prior to 1952, 39 built in the period from 1952 to 1959, and 11 completed in the period from 1960 to 1963. The year 1952 is significant because records indicate that only the top 30 ft (9.1 m) of the quarry (i.e., above U2) was worked prior to that time. The year 1959 was arbitrarily chosen as the date after which there is reasonable assurance that the structural concrete is properly air-entrained. Pattern cracking, which may be indicative of alkali-carbonate reactivity, on the 71 structures is summarized in the following:

Construction Period	No. of Structures Inspected	No. of Structures Affected by Pattern Cracking
1947-1951	21	9
1952-1959	39	27
1960-1963	11	0

In each of the 21 structures built prior to 1952 there is evidence of deteriorated concrete. The distinct pattern cracking observed on 9 structures most commonly affects retaining walls and concrete above the deck. Considering the age, exposure, and lack of entrained air in the concrete, the overall condition of the structures in this group is excellent.

In all, 23 structures containing Uhthoff rock and 16 structures built with local gravels represent the 1952 to 1959 construction period. Clearly defined pattern cracking was observed on 70 percent of these structures, with exposed portions—particularly where moisture is most abundant—commonly affected, with more than 50 percent of the sur-

face pattern cracked. In most cases the cracks are shallow and have not led to general disintegration of the concrete.

The concrete in the 11 structures built after 1959 is generally in excellent condition, with very fine pattern cracking affecting only isolated areas of 4 structures.

VERNON NARROWS BRIDGE

The 9-span Vernon Narrows structure, completed in 1959 and by far the largest bridge containing Uhthoff stone, affords an interesting comparison between the incidence of pattern cracking in concrete that is normally in a dry condition and concrete that is wet for much of its service life. Thus, pier 6 (Figures 4 and 5), beneath an open bridge deck expansion joint, exhibits clearly defined pattern cracking that covers from 50 to 100 percent of each exposed concrete face. However, pier 7, situated beneath a continuous portion of the deck slab, is affected by barely discernable pattern cracking over approximately 5 to 10 percent of the concrete surface. Cracking also affects poorly consolidated concrete in the south abutment wall saturated by water seeping through from the backfill.

A pulse velocity survey, consisting of 600 tests on a 1-ft (0.3-m) grid, was carried out on the north half of piers 6 and 7. The data are given in Table 3.

The tests on the columns and column top beams indicate that the concrete quality in piers 6 and 7 is good and apparently unaffected by the network of shallow surface cracks. In the partly submerged column foundations, pulse velocity test values on pier 6 are somewhat lower and more scattered than on pier 7. The significance of these lower tests, particularly the 30 percent below 12,000 ft (3658 m) per second, is not clear because the core samples indicate that the concrete below the immediate surface is sound. Continued monitoring of the condition of this concrete will indicate whether the serviceability of the column foundations is impaired.

The pulse velocity survey of the top beam of pier 7 includes approximately 10 percent of test results below 12,000 ft per second. This negative skew in the test distribution curve is reflected in the high standard deviation of 1,276 ft (389 m) per second. The lower pulse velocity values on this section of the structure are in an area affected by vertical and random cracks in the concrete that appear to be associated with the freezing of water in bolt holes during construction.

FIELD SURVEY CONCLUSIONS

Some form of pattern cracking on the surface of concrete highway structures is a relatively common occurrence in Ontario. In extreme cases, particularly with a dolomitic limestone at Kingston, expansion of the concrete has resulted in extensive deterioration.

The overall effect on the durability of the structures containing reactive aggregates from the Uhthoff Quarry and local gravel pits appears to be small. Cracks in the concrete that presumably result from the alkali-carbonate reaction are confined to the immediate surface of the concrete, and, in isolated cases where the cracks are accompanied by partial disintegration of the concrete, other factors appear to be involved.

Incorporating the reactive Uhthoff Quarry layer U2 in concrete aggregate from 1952 to 1963 has almost doubled the number of structures on which distinct pattern cracking is present in the concrete. Considering that many of the structures containing the U2 layer were built some time after 1952, the incorporation of the reactive layer in the concrete has increased significantly the incidence of pattern cracking. The lower pulse velocity characteristics of some concrete in pier 6 of the Vernon Narrows Bridge indicate that under continuously moist conditions some reduction in durability may occur without apparently affecting the serviceability of high-quality reinforced concrete.

CONCLUSIONS

Laboratory tests have clearly demonstrated that some lower lifts of the Uhthoff Quarry contain expansive carbonate material that will ultimately produce cracks in concrete. The expansion, after 6 years of continuous moist storage, of such material,

Figure 4. Vernon Narrows Bridge, columns of pier 6 (left) and pier 7 (right). Pier 6 is situated beneath an open bridge deck expansion joint.

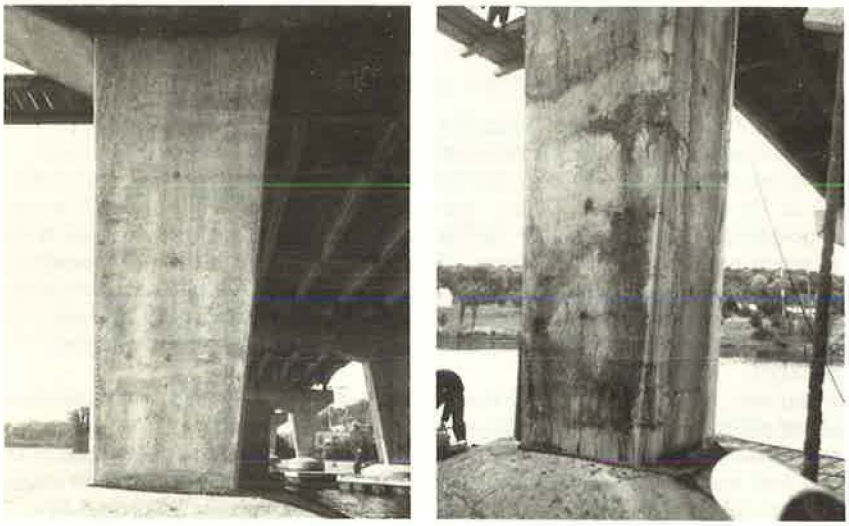


Figure 5. Vernon Narrows Bridge, pier 6, pattern cracking of column foundation. Black and white strip is in 1-in. increments.

Table 3. Pulse velocity tests (in feet per second).

Location	Pier 6 (wet)	Pier 7 (dry)
Column foundation		
Average	12,330	14,160
Standard dev.	589	328
Column		
Average	14,530	14,840
Standard dev.	322	266
Column top beam		
Average	14,260	13,820
Standard dev.	423	1,276

Note: 1 ft = 0.3048 m.

measured in concrete prisms made with cement containing an alkali content of 0.96 percent, varied from 0.07 percent to 0.13 percent. In contrast, a dolomite material used as the control aggregate, with a long history of excellent performance in concrete highway structures, had an expansion value of 0.04 percent.

The top 36-ft (11-m) lift of the quarry, worked for many years to produce coarse aggregate for concrete, had a 6-year expansion of 0.04 percent. Within this lift, layer U2, which constitutes approximately 20 percent of the face, exhibited an expansion of 0.11 percent.

Newlon's suggested criterion for concrete expansion of not greater than 0.03 percent at 1 year is more effective in identifying expansive rocks than the current MTC requirement of 0.02 percent at 84 days.

Expansive rocks tested in concrete prisms made with a low-alkali cement (alkali content 0.46 percent) exhibited expansions generally less than the limits noted above.

Concrete prisms containing sodium hydroxide, to produce a high alkali content (3 percent) in the mix, have a number of advantages in the evaluation of aggregate sources. The extra cost of fabricating such test specimens appears justified by results.

Rock cylinders representing expansive carbonate material in the beds of the quarry below layer U3 showed wide variations in expansion within each layer. Comparison between such specimens and the expansion of concrete prisms containing aggregate representing the whole layer is therefore difficult. Rock cylinder tests of the nonexpansive material above layer U2 exhibited contractions after 1 year, which indicates an apparent zero risk of rejecting acceptable material with this test.

A rock cylinder expansion criterion of 0.2 percent at 16 weeks suggested by Newlon identified most of the expansive layers as containing some reactive material, but some specimens with an expansion below 0.2 percent showed significant expansion after 1 year of testing.

The rock cylinder test cannot be viewed as the sole basis for rejection of material for use in concrete. Aggregate sources shown to contain potentially reactive material in this test should be evaluated in concrete prisms, with portland cements of varying alkali content where appropriate, before a decision is made on their acceptability or otherwise.

Thin-section petrographic studies of rock specimens from the quarry indicated that the expansive carbonate material—i.e., layer U2 and below—possesses the textural characteristics for reactive rocks as identified by other investigators. In general, the texture is a very fine calcitic matrix containing some clay and scattered crystals of dolomite. The layers in the Uhthoff Quarry identified in this investigation as reactive usually contain more than 5 percent dolomite and an insoluble residue content that results in at least 2 percent clay in the aggregate.

Concrete structures built with coarse aggregate that included the reactive layer U2 generally exhibited more pattern cracking than structures constructed when the reactive layers of the quarry were not worked.

The pattern cracking on exposed surfaces in most cases appears unlikely to affect the expected service life of the structures. The cracks are confined to the surface and have not produced general disintegration of the concrete matrix. Cracking is most pronounced on those portions of the structure exposed to periodic wetting, such as sidewalks, handrail posts, retaining walls, and vertical columns beneath open deck expansion joints.

The 4:1 dilution of good to expansive material that formed the normal working face of the quarry prior to 1964 produced negligible expansion of moist-cured concrete prisms in the laboratory. Nevertheless, the occurrence of pattern cracking in structures containing this material indicates a potential durability level of the concrete below what might be considered normal. Of the potential solutions to the problem, working the upper part of the quarry so as to exclude all material below layer U3 for use as concrete aggregate was deemed more satisfactory than using a low-alkali cement with rock containing some reactive material.

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