STUDY OF EXPANSIVITY OF A SUITE OF QUARTZWACKES, ARGILLITES AND QUARTZ ARENITES

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ABSTRACT

The expansivity of a suite of quartzwackes, argillites and quartz arenites has been evaluated by the concrete prism test, the mortar bar test (ASTM C227) and the miniature rock prism test. In determining the composition of the rocks by petrographic methods, it was found that expansivity is related to porosity and the percentage of microcrystalline material (matrix) present.

The slope of the regression line fitted to the curve for the expansion of concrete prisms made with these aggregates and high alkali cement gives a measure of the expansivity of the aggregate. It is probable that the expansion of concrete prisms made with most of the aggregates is largely controlled by expansion of the aggregate due to reaction between it and the alkalies in the cement.

Introduction

When cracking typical of alkali reactivity was observed in several concrete structures in the Sudbury area of Ontario, Figure 1, samples were taken from operating pits in an extensive fluvoglacial deposit. The study was designed to determine which rock types are expansive and the mechanism of expansion. The average composition of the coarse gravel (19 to 6 mm grain size) taken from stockpiles of the five pits is shown in Figure 2. Similar rocks from Nova Scotia came under investigation some years ago (1).

Initially, the potential expansivity of the gravel was evaluated by the chemical method of ASTM C289 (2), by the concrete prism test, and by petrographic examination. The chemical test indicated that the aggregate is nonexpansive; the concrete prism test, that the aggregates are marginally expansive, having an average expansion of 0.075 per cent after 900 days storage at 100 per cent relative humidity and 38°C; petrographic examination, that some of the rocks in the aggregate might be potentially expansive. It was decided to collect large boulders representing the different rock types in the gravel to test them for alkali-expansivity. The norites and granitic rocks proved to be nonexpansive by the concrete prism test, but most of the quartz arenites and quartz argillites were found to be expansive.

Experimental Methods

Systematic testing by the chemical method of ASTM C289 was not used as previous work (3) had shown it to be unreliable. Earlier research (3) had shown that the mortar bar test, ASTM C227, also was inappropriate for use with quartzites, quartz arenites and quartzwackes, but a limited number of aggregates were subjected to this test. The results confirm earlier observations.

The concrete prism test is a modified form of CSA A23.2.24 (4). The prisms are 7.6 × 7.6 × 25.4 cm, and grading of the aggregate is shown in Table I. Water:cement ratio varied from 0.40 to 0.45, the exact value depending on the porosity of the aggregate and the cement. The concrete prisms were stored at 100 per cent RH and 38°C for the duration of the test.

The miniature rock prism test (3), is an alternative to the rock cylinder test, ASTM C586, giving results generally in good agreement with the data from the concrete prism test.

A number of complementary test procedures are described under the heading, petrographic examination. Its basic purpose is the characterization of the rock.

- Thin sections were examined with the petrographic microscope and estimates made of composition, using an automatic point count apparatus.
- Grains of crushed rock were examined by means of petrographic microscope, SEM, and electron-microprobe.
- Crushed grains were examined by XRD and by electron diffraction in a TEM.
- Measurements were taken of pore size distribution using an American Instrument Company, 60,000 psi Mercury Porosimeter.

Surface areas were not determined because preliminary experiments had shown that the values obtained were too low for the differences to be of any significance.

Statistical Treatment of Expansion Data

Examination of expansion curves of concrete prisms from expansive aggregates (Figure 3) shows that expansion takes place in two phases: an early phase with a high rate of expansion, and a later, much lower one. The transition from the high to the low rate occurs at about 300 days. Separate regression lines may be fitted to the two halves of the expansion curves by the method of least squares, and the expansivity of the samples expressed by the rate of expansion per day - the slope of the regression line fitted to the expansion curve. The slope may be calculated from

$$s = \frac{\sum xy - \sum x \sum y/n}{\sum x^2 - [\sum x]^2/n} \tag{1}$$

The rate of expansion of the concrete prisms for the early phase of expansion largely controls the final expansion of the samples. From this it follows that the slope of the regression line of the early phase of expansion can be used as a measure of expansivity of the samples. It is possible to differentiate between expansive and innocuous aggregates by defining the mean slope and its lower 95 per cent confidence limit for all expansive aggregates and the mean and upper 95 per cent confidence limit for all innocuous aggregates (Figure 4). A typical expansive concrete prism might have regression lines for the curve of expansion with slopes of 50×10^{-5} and 5.3×10^{-5} for the early and late stages of expansion, respectively. Equations for the regression lines take the form $y = a + bx$. Lines with slopes of 50×10^{-5} and 5.3×10^{-5} are expressed by equations (2) and (3):

$$y = 50 \times 10^{-5} + (-0.023)x \tag{2}$$

$$y = 5.3 \times 10^{-5} + (0.011)x \tag{3}$$

Concrete Prism Test

The most reliable method of determining the potential alkali expansivity of an aggregate in concrete is the concrete prism test. Other test procedures are evaluated against it. A summary of the results of the concrete prism test may be seen in Table II. For purposes of comparison, a number of known expansive aggregates from other areas are included: 76-15, an argillite described by Dolar-Mantuani (5), and 73-50, a quartzwacke sample AP34/JA14 examined by Swenson (6).

Pairs of concrete prisms were made from each aggregate with high and low alkali cement, Table III. The large number of prisms involved in this study precludes showing the graphs of expansion for all of them, and instead, a number of typical expansion curves are shown in Figure 3. Regression lines corresponding to the mean expansion of the population of curves of both expansive and nonexpansive aggregates are shown in Figure 4.

Quartzwacke 74-57 (Figure 3) is very expansive. Prisms made from it and high alkali cement expanded by 0.166 per cent in 600 days; but with low alkali cement the expansion was 0.061 per cent in the same length of time. The slopes of the regression lines drawn through the curve of expansion for early and late stages of expansion, for prisms made with high alkali cement, are 50×10^{-5} and 7.2×10^{-5}, respectively. Regression lines similar to those for sample 74-57 are typical of all expansive aggregates. The corresponding slopes of the regression lines for concrete made from sample 74-57 and low alkali cement are 15×10^{-5} and 3.5×10^{-5}.

Feldspathic quartz arenite, 74-45, made into concrete with high alkali cement had an expansion of 0.113 per cent after 600 days, proving to be a moderately expansive aggregate. The slopes of the regression lines fitted to the expansion points are 28×10^{-5} and 6.3×10^{-5} for high alkali cement concrete and 19×10^{-5} and 2.9×10^{-5} for low alkali cement concrete.

Quartz arenite 74-52 is nonexpansive. There is virtually no difference in the amounts of expansion found with high and low alkali cement. The slopes of the regression lines for the expansion curves are 4.3×10^{-5} and 1.8×10^{-5} for concrete made with high alkali cement, and 7.4×10^{-5} and 0.39×10^{-5} for that made with low alkali cement.

From the results of the expansion experiments shown in Figure 3, it is evident that there is a relation between the expansiveness of concrete made with reactive aggregate and high alkali cement and the slope of the regression line drawn through the curve of expansion for the first 200 to

300 days. The expansivity of the samples is clearly related to the slope of the regression line for the early stage of the expansion curve. This slope expresses the rate of expansion in per cent linear expansion per day. Concrete prisms made with high alkali cement and aggregate 74-57 have an expansion of 0.166 per cent in 600 days and a slope of 50×10^{-5}. Concrete made with aggregate 74-45 has a 600-day expansion of 0.113 per cent and a slope of expansion of 28×10^{-5}. That made with non-expansive aggregate 74-52 has a 600-day expansion of 0.024 per cent and an expansion slope of 4.3×10^{-5}.

Figure 4 shows two sets of regression lines for expansion of concrete made with high alkali cement. One set shows the mean expansion of the population of curves for all prisms made with expansive aggregates; the other, the mean of all those made with nonexpansive aggregates. A similar set of curves for concretes made with low alkali cement is shown in Figure 5.

The slopes of the mean regression lines drawn through the expansion curves for concrete prisms made with expansive aggregate and low alkali cement are about the same as those for nonexpansive aggregates made with high alkali cement. This indicates that reducing the alkali content from 1.08 per cent Na_2O equivalent to 0.68 Na_2O equivalent reduced the expansion of most of the concrete prisms to a safe level.

Cracks were observed in most concrete prisms after 200 to 300 days of storage, i.e., at about the same time that the break occurred in the slope of the expansion curves. Microcracking is certain to occur before cracks become large enough to be visible by casual inspection. It is probable that microcracking had already occurred in those expansive concrete prisms in which no cracks were visible. The effect of crack formation is to relieve the stress caused by the expansion of the aggregate in the concrete. The low slope of the regression line, which was found for all samples after the break in the expansion curve, is probably due to creep of the concrete and possibly to some residual expansion where cracking has not entirely relieved the stress in the concrete.

The long-term expansion of a few concrete prisms was measured. When the slopes of the expansion curves were extrapolated from 600 days to 1665 days, the values obtained were in good agreement with measured expansions. For example, sample 73-50 expanded by 0.215 per cent in 1665 days, and the value determined by extrapolation from 600 days was 0.214 per cent.

Differentiation of Deleterious and Nonexpansive Concretes

It is difficult to place the cut-off between expansive and nonexpansive concretes. The upper 95 per cent confidence limit for the slope of the regression line drawn through the expansion curve for the first 200 days for concrete made with expansive aggregate and low alkali cement is 23×10^{-5}. The lower 95 per cent confidence limit for the same aggregates used with high alkali cement is 15×10^{-5}. A slope of 20×10^{-5} might be considered the borderline between expansive and nonexpansive aggregates.

Mortar Bar Test

The mortar bar method, ASTM C227, is not a satisfactory method for assessing the potential expansivity of concrete made with either quartz arenite or quartzwackes. For example, mortar bars made with high alkali cement and aggregate 74-57 expanded only 0.05 per cent in 600 days. Concrete prisms made with the same material expanded by 0.165 per cent. These differences are also reflected in the slopes of the expansion curves. For mortar bars made with sample 74-57 and high alkali cement, the slope of the regression line of the expansion curve is 21×10^{-5}; that for concrete prisms, 50×10^{-5}.

It was assumed that the difference in expansion observed for mortar bars and concrete prisms was due to differences in the grading of the aggregate. In order to demonstrate this, three sets of mortar bars and one pair of concrete prisms were made from sample 73-50, a feldspathic quartzwacke. The grading of the aggregate used for the samples is shown in Table I.

The first pair of mortar bars was made with Mix 1, unwashed. For the second set, Mix 1 was washed to remove fine material. The third pair was made with Mix 2, containing coarse material without -0.3 + 0.15 mm fines. The concrete prisms were made with Mix 3. Results of the expansion experiments are shown in Figure 6: The coarse mortar mix showed almost the same expansion as was found with the concrete, but concrete prisms made with this aggregate generally showed much higher expansions than were observed in the test (see Table II). There seems to be a definite relation between the expansion observed and the grain size of the aggregate used in the beams.

With argillite 76-15, although they expanded less than the concrete (Figure 7), the mortar bars were sufficiently expansive for Dolar-Mantuani (5) to conclude that the aggregate was expansive. A relation exists between the amount of expansion observed in mortar bars made with high alkali cement and the amount of microcrystalline material in expansive argillites and quartzwackes (Figure 8).

Miniature Rock Prism Test

The miniature rock prism test (3) was used in place of the rock cylinder test, ASTM C586, because the latter was found to take too long and frequently yield erratic results. Results for the miniature rock prism test are summarized in Table IV. The concrete prism test showed samples 74-45 and 74-59 to be expansive, but this test indicated that they are not. For the first 200 days the slope of the mean regression line through the expansion curves for all the expansive rock prisms was 41×10^{-5} and the lower 95 per cent confidence limit was 17×10^{-5}. The slopes of the expansion curves for samples 74-45 and 74-54 were 14×10^{-5} and 9×10^{-5}, respectively, values that lie outside the 95 per cent confidence limits for expansive aggregates. It is probable but not certain that these prisms were inadvertently cut parallel instead of normal to the bedding of the rocks.

The effect of the direction in which rock prisms are cut, in relation to layering in the rocks, is shown by prisms made from argillite 76-15. The slope of the regression line for expansion of prisms cut normal to the layering was 69×10^{-5}, that for prisms cut parallel to the layering, 19×10^{-5}. The rock prism test indicated that the two nonexpansive samples, 74-52 and 74-56, were expansive. This discrepancy is probably due to variations in the composition of the aggregate. There is considerable variation in grain size of these aggregates and it is possible that some layers may be expansive. This hypothesis is substantiated by the expansivity of sample 74-53, which is broadly similar to the above two samples in both composition and appearance.

The slope of the curve representing the mean expansion of all the expansive aggregate prisms in 2N . NaOH solution was 41×10^{-5}. A line with this slope is shown in Figure 4 for comparison with a slope of 47×10^{-5} for the expansion of concrete prisms made with the same aggregates. From these results it is concluded that the miniature rock prism test gives a good indication of the potential expansivity of aggregates, although care must be taken to ensure that the prisms tested are truly representative of the rock to be evaluated.

Petrographic Examination

The results of petrographic examination of the aggregates, using a point count apparatus on a petrographic microscope, are shown in Table V, which also shows porosities, ratio between porosity and volume of microcrystalline material in the samples (P/M ratio), and the slope of the regression line of the expansion curve, for the first 200 days, for concrete prisms made with the various aggregates and high alkali cement. The slopes are listed to give a measure of the expansivity of the aggregates.

Based on content of microcrystalline material, the aggregates may be divided into four groups; nomenclature follows Pettijohn et al (7).

- Argillite 76-15, with 82 per cent microcrystalline material;
- Quartzwackes 72-85, 74-55, 74-46 and 74-57, with from 52 to 71 per cent microcrystalline material;
- Quartz arenites with 13 to 16 per cent microcrystalline material, samples 74-47 to 53 inclusive;
- Sample 74-45 feldspathic quartzite, with 2 per cent microcrystalline material (could also be termed quartz arenite).

There is a gradation between the quartz arenites and the quartzwackes.

Optical micrographs considered to be representative of each of the four groups of aggregates are shown in Figure 9.

The slope of the curve of expansion of the concrete prisms for the first 200 days appears to be related to the content of microcrystalline material and porosity of the rocks. A graph showing slope versus P/M ratio (porosity divided by microcrystalline content) is shown in Figure 10.

Aggregate 74-53 is an expansive quartz arenite similar in grain size and composition to the two nonexpansive samples, 74-52 and 74-56 (Table I), but it is readily distinguished from them since it plots in a different area of the graph (Figure 10). Samples 74-52 and 74-56 have P/M ratios of 0.24 and 0.13, respectively; sample 74-53 has a P/M ratio of 0.05.

Expansive aggregate 74-45 has a P/M ratio of 0.60, suggesting that it should be nonexpansive if the borderline between expansive and nonexpansive aggregates is taken at a P/M value of 0.12. This aggregate, a feldspathic quartzite, contains only 2 per cent microcrystalline material and hence is of somewhat different composition from the other rocks.

Microstructure

The microcrystalline portion of the rocks not resolved by the petrographic microscope was analysed by XRD, SEM and electron microprobe analysis. The microcrystalline material was found to consist mainly of illite and a mixture of microcrystalline quartz similar in appearance to the chert illustrated by Gillott and Swenson (8). Feldspar was also present in many samples and a few contained chlorite. A typical area of microcrystalline material in contact with a macro quartz grain is shown in Figure 11(a). A typical grain of microcrystalline quartz of 7 μm diameter is shown in the centre of Figure 11(b). Crystals of illite, chlorite and feldspar are shown in Figure 11(c), (d) and (e), respectively. Chlorite was identified in aggregates 73-50, 74-46, 74-57 and 76-15. The composition and microstructure of the microcrystalline material in argillite is almost identical to that in the quartz arenites, apart from the occurrence of some chlorite.

The ratio of silicon to aluminum and potassium determined by microprobe analysis of many grains is much too high for illite, but at the same time the amounts of aluminum and potassium are too high for quartz. As precautions were taken to ensure that silicon counts were not arising from neighboring grains, it is concluded that the anomalous silicon values are real. It is thought that the grains giving rise to anomalous values may be composed dominantly of quartz in which there are inclusions of illite. Mielenz (9) reported illite as a common inclusion in quartz, and Hirsch et al (10) have shown that the presence of a second phase in a crystal gives rise to streaks in electron diffraction patterns. Although streaks were observed in electron diffraction patterns of some quartz grains, interpretation is a rather complex procedure and further study to confirm this hypothesis is still in progress.

Summary and Conclusions

(1) It has been demonstrated that the slope of the regression line drawn through the expansion curve for concrete prisms is, for the first 200 to 300 days, directly related to the expansivity of the samples. Samples with slopes greater than 20×10^{-5} are considered deleteriously expansive. Examination of the expansion curves in Figure 3 shows that, provided readings are taken at frequent intervals for the first 100 to 150 days, the slope of the expansion curve and hence the expansivity of the samples can be established. Without this method it would take much longer to establish expansivity. Readings would have to be continued until the slope of the expansion curve flattened out.

(2) The slope, 41×10^{-5}, of the mean expansion curve of rock prisms in 2N . NaOH is close to the value of 47×10^{-5} found for expansion of concrete prisms made with the same aggregates. This indicates that expansion of these concrete prisms is largely controlled by expansion of the aggregate when it reacts with alkalies in the cement paste.

(3) Mortar bars made from expansive quartzites, quartz arenites or quartzwackes and high alkali cement did not expand excessively, confirming earlier findings (3). The amount of expansion of mortar bars made with these aggregates was proportional to the grain size of the aggregate; the larger the grain size, the greater the expansion. The reason for the reduction in expansivity with decreasing grain size is not clear, but it is probably due to a combination of reduced localized volume expansion resulting from the smaller volume of the grains and an increase in the restraining force applied to them by the relatively larger volume of cement paste. Large grains of coarse aggregate are surrounded by only a narrow rim of cement paste, but small ones are surrounded by a volume of cement paste much greater than the volume of the grains. The greater volume of cement paste exerts a greater restraining force.

An exception to the lack of expansion of mortar bars found in this study is argillite 76-15, which contains only 16 per cent of quartz grains greater than 0.01 mm. The fact that, in this case, reduction in grain size of aggregate does not prevent expansion of mortar bars indicates that expansion of mortar and concrete made with this argillite and high alkali cement must, in part at least, be due to some factor other than expansion of the aggregate. This hypothesis is supported by other observations:

(1) Although expansive, mortar bars were much less so than concrete prisms. The slope of the expansion curve for concrete prisms is 212×10^{-5}, and that for mortar bars 50×10^{-5}.

(2) Concrete prisms expanded much more than the rock prisms, which have a slope of expansion of 69×10^{-5}. This observation tends to confirm that expansion of concrete prisms is not entirely controlled by expansion of the aggregate, as appeared to be the case with the other samples. Some additional mechanism must be operative. It seems probable that the calcium sodium silicate formed by reaction of silica with alkalies in the cement may be causing expansion of the cement paste. This, combined with expansion of the aggregate, could lead to the excess expansion observed in the concrete prisms over that in the rock prisms.

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TABLE I

COMPOSITION OF CONCRETE AND MORTAR MIXES USED IN STUDYING THE EFFECT OF GRAIN SIZE ON EXPANSION

1. Normal Mortar

300 g cement + aggregate

67.5 g	-4.7	+ 3.2	mm
168.75 g	-3.2	+ 1.0	mm
168.75 g	-1.0	+ 0.59	mm
168.75 g	-0.59	+ 0.3	mm
101.25 g	-0.3	+ 0.15	mm

water 133 ml

2. Coarse Mortar

300 g cement + aggregate

67.5 g	-9.5	+ 4.7	mm
67.5 g	-4.7	+ 3.2	mm
168.75 g	-3.2	+ 1.0	mm
168.75 g	-1.0	+ 0.59	mm
202.5 g	-0.59	+ 0.3	mm

water 126 ml

3. Concrete

1500 g cement + 2800 g sand passing 3.2 mm + coarse aggregate

2438 g	-19	+ 12.5	mm
1688 g	-12.5	+ 9.5	mm
750 g	-9.5	+ 6.4	mm

water 600 ml

TABLE II

SUMMARY OF RESULTS OF CONCRETE PRISM EXPERIMENTS

Sample No.	(1) Expansion Slope × 10^5 for 0 to 300 days	(2) Break in Slope at (days /% Exp)	(3) Expansion Slope × 10^5 for 300 to 600 days	(4) % Expansion at 600 d
76-15 HA	212	-	-	-
72-85 HA	43	400/0.13	1.3	0.14
74-55 HA	54	275/0.14	3.5	0.15
74-55 LA	11	200/0.02	3.5	0.03
74-46 HA	39	350/0.12	10.2	0.14
74-46 LA	11	175/0.02	5.3	0.04
74-57 HA	50	350/0.15	7.2	0.165
74-57 LA	15	350/0.05	3.5	0.06
74-47 HA	48	225/0.09	8.0	0.12
74-47 LA	14	200/0.026	2.4	0.05
72-92 HA	87	325/0.21	0.17	0.21
74-51 HA	51	250/0.11	1.85	0.115
74-51 LA	22	275/0.05	1.90	0.06
74-50 HA	30	350/0.085	1.6	0.09
74-50 LA	13	200/0.02	1.2	0.025
73-50(A) HA	72	300/0.185	1.3	0.19
73-50(B) HA	34	200/0.06	7.5	0.09
74-52 HA	4	200/0.015	1.9	0.02
74-52 LA	7	200/0.015	0.4	0.015
74-54 HA	50	225/0.075	4.4	0.09
74-54 LA	16	300/0.04	3.3	0.05
74-56 HA	17	200/0.02	2.8	0.03
74-56 LA	11	200/0.02	1.9	0.025
74-53 HA	37	250/0.07	5.7	0.095
74-53 LA	18	200/0.03	2.5	0.035
74-45 HA	28	375/0.10	5.3	0.11
74-45 LA	19	200/0.035	2.9	0.05

(1) The slope of the curve of expansion, for the first 300 days, of concrete prisms made with the listed aggregates and high (HA) and low (LA) alkali cement.
(2) The number of days to the break in the slope of the expansion curve and the percentage expansion that had then taken place.
(3) The slope of the expansion curve from (300 days) the break in the slope to 600 days.
(4) The percentage expansion after 600 days. (This gives a measure of the expansivity of the concrete.)

TABLE III

ALKALI CONTENT OF CEMENTS

	Na_2O	K_2O	Na_2O (Equiv)
High Alkali:	0.34	1.13	1.08
Low Alkali:	0.15	0.81	0.68

TABLE IV

SUMMARY OF EXPANSIONS OF ROCK PRISMS IN 2N . NaOH AT 38°C

Sample No.	(1) Expansion Slope for 0 to 300 days $\times 10^5$	(2) % Expansion at 300 days	(3) Porosity of Aggregate %
76-15	69	0.18	0.82
74-55	-	-	0.97
74-46	30	0.087	1.05
74-57	49	0.093	1.03
74-47	42	0.117	1.20
72-92	48	0.15	1.31
74-51	42	0.135	1.31
74-50	34	0.107	1.85
73-50	60	0.100	1.7
74-52	53	0.180	3.8
74-54	9	0.043	1.45
74-56	31	0.087	1.85
74-53	25	0.08	0.67
74-45	14	0.037	1.10

(1) The slope of the regression line for the curve of expansion of rock prisms in 2N . NaOH.

(2) Observed expansion at 300 days.

(3) Porosity of the aggregate.

TABLE V

TABLE V

SUMMARY OF PETROGRAPHIC ANALYSES OF AGGREGATES

Sample No.	(1) Porosity	(2) P/M Ratio	(3) Slope of Expansion of Concrete prisms × 10^5	(4) Composition of Rock, % Micro-crystal-line Material	Quartz >0.05 mm	Quartz <0.05 mm	Feldspar	Hema-tite	Oxides, Mica, etc.
76-15	0.82	0.01	212	82	0	16	-	-	2
72-85	-	-	43	71	10	18	-	-	1
74-55	0.97	0.02	54	64	-	33	-	-	3
74-46	1.05	0.02	39	55	13	27	2	-	3
74-57	1.03	0.02	50	52	15	29	2	-	2
74-47	1.20	0.04	48	31	45	17	6	<1	1
72-92	1.31	0.05	87	27	62	10	-	-	1
74-51	1.31	0.06	51	22	58	19	-	-	1
74-50	1.85	0.08	30	20	58	18	4	<1	-
73-50	1.70	0.11	(A) 72 (B) 34	15	43	40	2	-	-
74-52	3.80	0.24	4	16	78	3	-	2	1
74-54	1.45	0.10	50	14	77	9	-	-	-
74-56	1.85	0.13	17	13	62	10	6	9	-
74-53	0.67	0.05	37	13	69	11	5	-	2
74-45	1.1	0.55	28	2	77	12	6	3	-

(1) Porosity of aggregates

(2) P/M ratio (Porosity divided by % microcrystalline material in the aggregate)

(3) Expansivity of the aggregate as shown by the slope of the regression line for the expansion curve of concrete prisms.

(4) Mineral composition of aggregates as revealed by the petrographic microscope.

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FIGURE CAPTIONS

Fig. 1 Map showing location of Sudbury area in Central Ontario, Canada.

Fig. 2 Histogram showing the mean distribution of rock types identified visually in stock piles of Sudbury gravel. Subsequent investigation showed that these rocks should properly be called quartzwackes and quartz arenites.

Fig. 3 Graph showing expansions of some typical concrete prisms made with expansive and nonexpansive aggregates and high and low alkali cements. Each point on the graph represents the average expansion of a pair of prisms.

Fig. 4 Regression lines for early and late stages of expansion of the means of all curves for concrete prisms made with high alkali cement. (Separate lines are shown for expansive and nonexpansive aggregates; for purposes of comparison, the slope of the regression line for the expansion of the mean of all rock prisms in alkali is also shown.)

Fig. 5 Regression lines representing mean expansion of all concrete prisms made with low alkali cement.

Fig. 6 Effect of variation in grain size of aggregates on expansion of concrete prisms and mortar bars made with high alkali cement. Slopes of the regression lines of the expansion curves vary from 18×10^{-5} to 55×10^{-5} with increasing grain size of aggregate.

Fig. 7 Expansions of concrete prisms and mortar bars made with argillite 76-15 and high and low alkali cements. (The slope of expansion curve for rock prisms in NaOH is also shown; for comparison, the slope of expansion of mortar bars made with cement containing 0.96 per cent Na_2O equivalent by Dolar-Mantuani (5) is also shown, line LDM.)

Fig. 8 Graph showing relation between content of microcrystalline material in expansive argillites and quartzwackes and expansion of mortar bars made with them and high alkali cement. The expansivity of the samples is shown by the slope of the regression line of the expansion curve.

Fig. 9 Optical micrographs of some typical aggregates

(a) Argillite 76-15 showing quartz (Q) 16 per cent in a microcrystalline matrix (M).

(b) Quartzwacke 74-46 showing quartz (Q) and feldspar (F) in a fine microcrystalline matrix which comprises 55 per cent of the material.

(c) Quartz-arenite 74-50 showing macrocrystalline quartz 60 per cent and microcrystalline material filling interstices between the quartz grains. The rock contains 22 per cent microcrystalline material.

(d) Feldspathic quartzite 74-45 consisting of quartz (Q), 6 per cent (F) and 2 per cent microcrystalline material.

Fig. 10 Plot showing relation between the ratio of porosity to microcrystalline content (P/M ratio) of aggregates and expansivity of concrete made with those aggregates and high alkali cement.

Fig. 11 SEM micrographs of microcrystalline portion of aggregates.

(a) Low magnification view showing microcrystalline material (M) in contact with a macrocrystalline quartz grain (Q).

(b) Microcrystal of quartz (Q) in the microcrystalline material.

(c) Illite (I) in the microcrystalline material.

(d) Chlorite (C) in the microcrystalline material.

(e) Feldspar (F) rectangular shaped crystals with good cleavage in a matrix of quartz and illite.

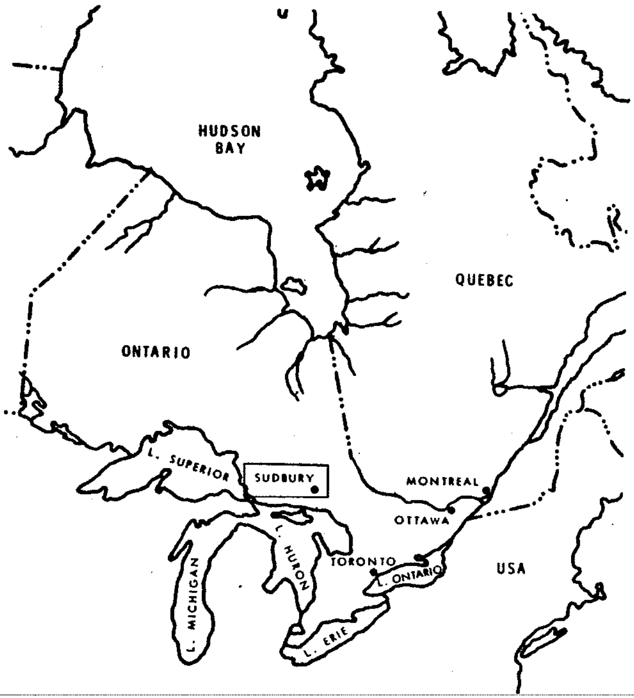


Fig. 1 Map showing location of Sudbury area in Central Ontario, Canada

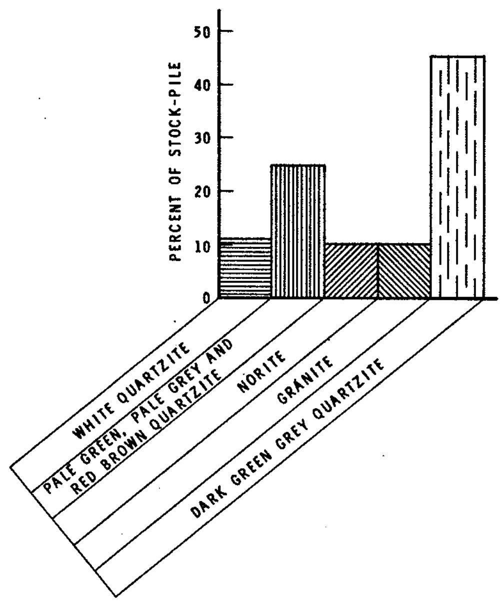


Fig. 2 Histogram showing the mean distribution of rock types identified visually in stock piles of Sudbury gravel. Subsequent investigation showed that these rocks should properly be called quartzwackes and quartz arenites

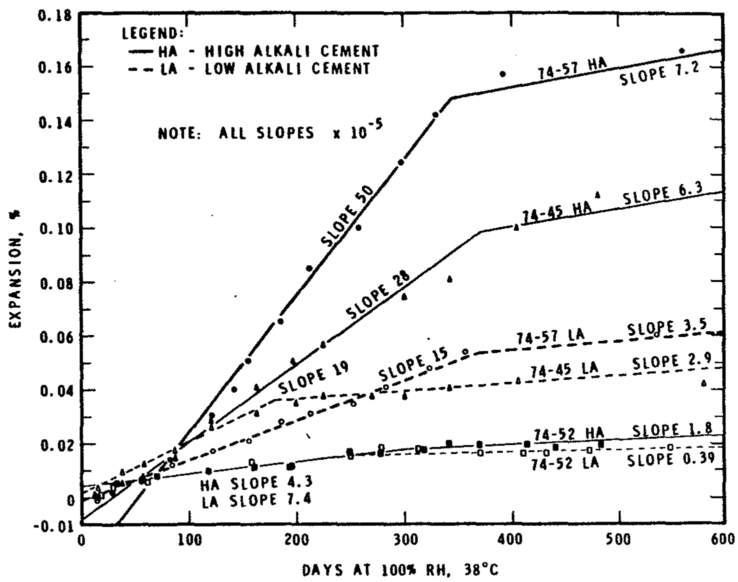


Fig. 3 Graph showing expansions of some typical concrete prisms made with expansive and nonexpansive aggregates and high and low alkali cements. Each point on the graph represents the average expansion of a pair of prisms

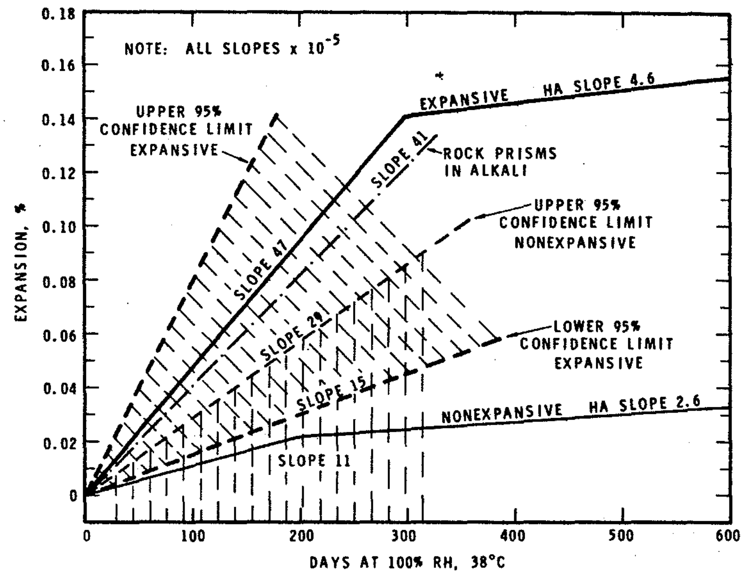


Fig. 4 Regression lines for early and late stages of expansion of the means of all curves for concrete prisms made with high alkali cement. (Separate lines are shown for expansive and nonexpansive aggregates; for purposes of comparison, the slope of the regression line for the expansion of the mean of all rock prisms in alkali is also shown.)

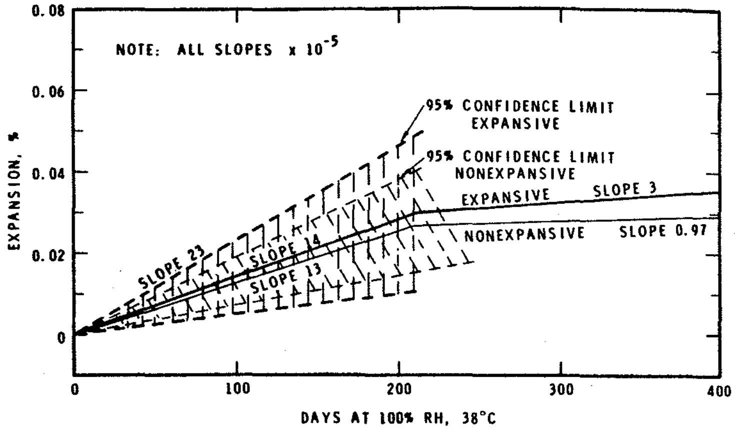


Fig. 5 Regression lines representing mean expansion of all concrete prisms made with low alkali cement

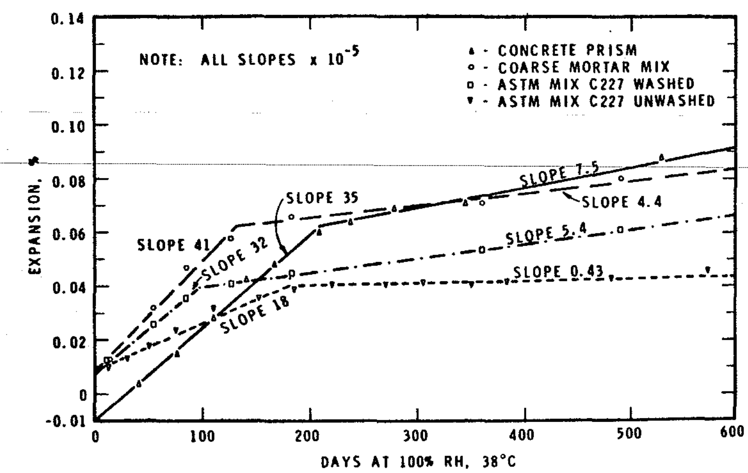


Fig. 6 Effect of variation in grain size of aggregates on expansion of concrete prisms and mortar bars made with high alkali cement. Slopes of the regression lines of the expansion curves vary from 18×10^{-5} to 55×10^{-5} with increasing grain size of aggregate.

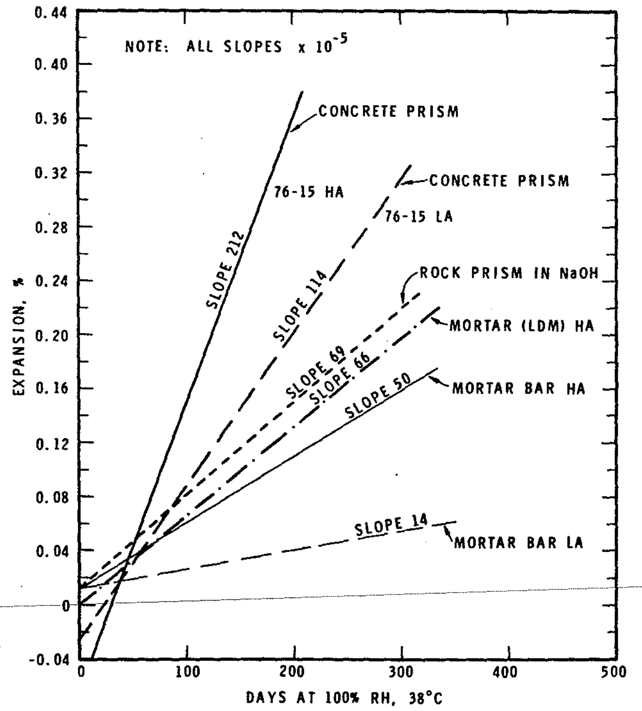


Fig. 7 Expansions of concrete prisms and mortar bars made with argillite 76-15 and high and low alkali cements. (The slope of expansion curve for rock prisms in NaOH is also shown; for comparison, the slope of expansion of mortar bars made with cement containing 0.96 per cent Na_2O equivalent by Dolar-Mantuani (5) is also shown, line LDM.)

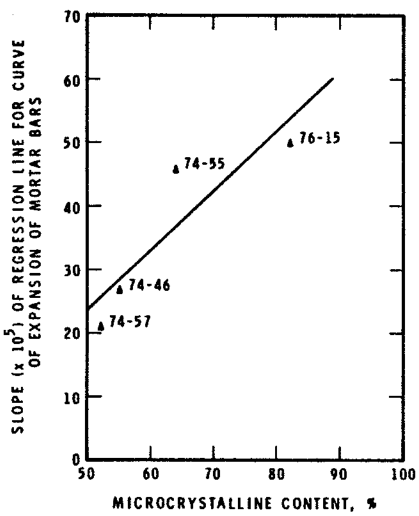
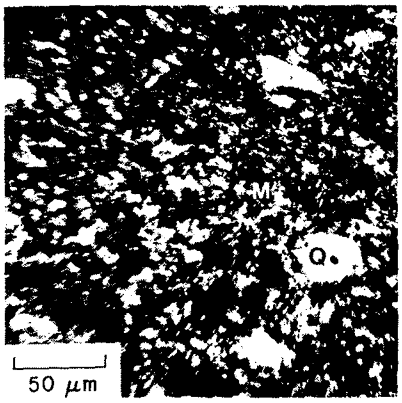
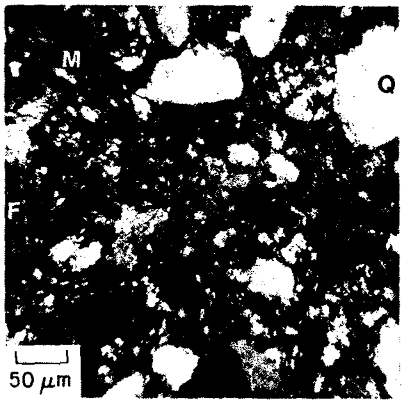


Fig. 8 Graph showing relation between content of microcrystalline material in expansive argillites and quartzwackes and expansion of mortar bars made with them and high alkali cement. The expansivity of the samples is shown by the slope of the regression line of the expansion curve



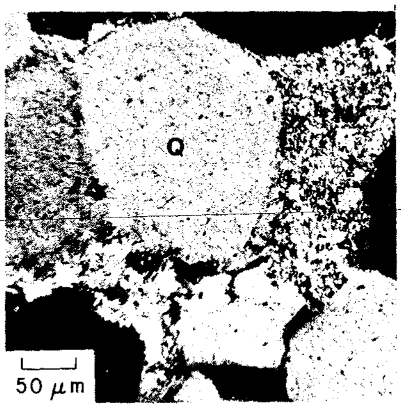
(a)

Argillite 76-15 showing quartz (Q) 16 per cent in a microcrystalline matrix (M)



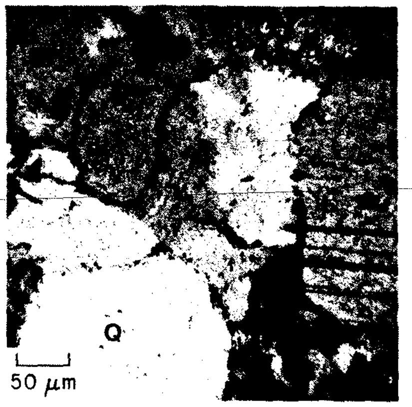
(b)

Quartzwacke 74-46 showing quartz (Q and feldspar (F) in a fir microcrystalline matrix which comprises 55 per cent of the material



(c)

Quartz-arenite 74-50 showing macrocrystalline quartz 60 per cent and microcrystalline material filling interstices between the quartz grains. The rock contains 22 per cent microcrystalline material



(d)

Feldspathic quartzite 74-45 consisting of quartz (Q), 6 per cent (F) and 2 per cent microcrystalline material

Fig. 9 Optical micrographs of some typical aggregates

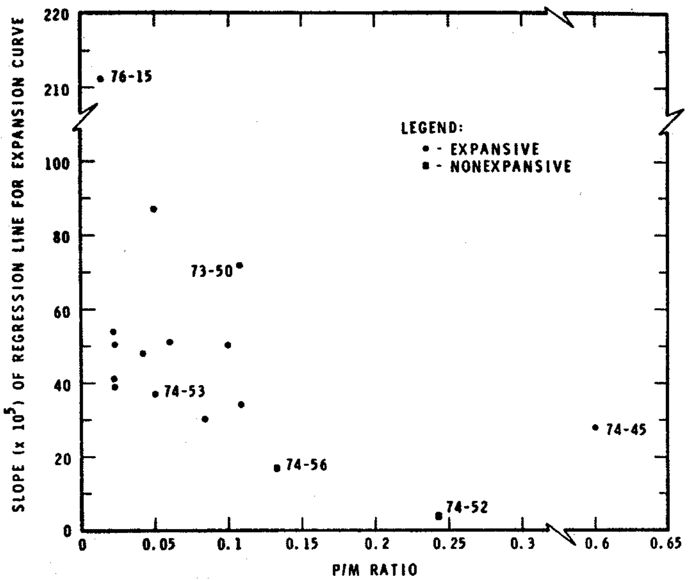


Fig. 10 Plot showing relation between the ratio of porosity to microcrystalline content (P/M ratio) of aggregates and expansivity of concrete made with those aggregates and high alkali cement.

(a)

(b)

(c)

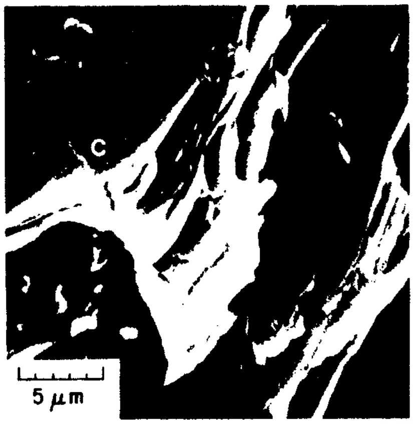
Fig. 11 SEM micrographs of microcrystalline portion of aggregates

(a) Low magnification view showing microcrystalline material (M) in contact with a macrocrystalline quartz grain (Q)

(b) Microcrystal of quartz (Q) in the microcrystalline material

(c) Illite (I) in the microcrystalline material

(Cont'd)



(d)

(e)

Fig. 11 SEM micrographs of microcrystalline portion of aggregates (Cont'd)

(d) Chlorite (C) in the microcrystalline material

(e) Feldspar (F) rectangular shaped crystals with good cleavage in a matrix of quartz and illite