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BUILDING CANADIAN AGGREGATES FOR ALKALI EXPANSIVITY

by P.E. Grattan-Bellew and G.G. Litvan

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On discute des applications de l'essai chimique ASTM C289, l'essai sur une barre de mortier C227 (mortar bar test), une modification de l'essai chimique, l'essai sur un prisme de pierre (rock prism test), et l'essai sur un cylindre de pierre C586 (rock cylinder test) en utilisant des aggrégats canadiens choisis. Il est démontré que l'essai chimique C289 est insatisfaisant. L'essai sur un prisme de ciment a démontré qu'il était le plus satisfaisant mais deux années se sont écoulées avant d'obtenir des résultats et son usage est donc peu pratique dans bien des cas. Un nouvel essai accéléré est proposé - l'essai sur un prisme de pierre - une forme modifiée de la norme ASTM C586. De petits prismes de pierre sont saturés sous vide dans un alcali et le changement de longueur avec le temps est enregistré; les résultats sont obtenus après environ trois mois. Les essais sur des pierres semblables en utilisant la méthode du cylindre de pierre C586 ont demandé jusqu'à deux années. Le nouvel essai serait utile pour le choix préliminaire des aggrégats afin de déterminer ceux qui devraient être mis à l'essai plus longuement en utilisant les méthodes de la barre de mortier ou du prisme de mortier.

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TESTING CANADIAN AGGREGATES FOR ALKALI EXPANSIVITY

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ABSTRACT

The applications of the chemical test ASTM C289, the mortar bar test C227, a modification of it, the rock prism test, and the rock cylinder test C586 to selected Canadian aggregates are discussed. The chemical test C289 is shown to be unsatisfactory. The concrete prism test proved to be the most satisfactory, but it took up to two years to obtain results and its use is therefore impractical in many instances. A new accelerated test is proposed--The Rock Prism Test--a modified form of ASTM C586. Thin prisms of rock are vacuum saturated in alkali and the length change with time is recorded; results are obtained in about three months. Tests on similar rocks by the rock cylinder method C586 took up to two years. The new test would be useful for preliminary screening of potential aggregates to determine which would need further testing by the mortar bar or concrete prism methods.

Introduction

Canadian aggregates generally perform quite satisfactorily but there have been a number of reports of alkali-reactivity from various parts of the country. (The broad physiographic regions of Canada are shown in FIG. 1.) In the Western Cordilleran Region and on the Prairies cases of

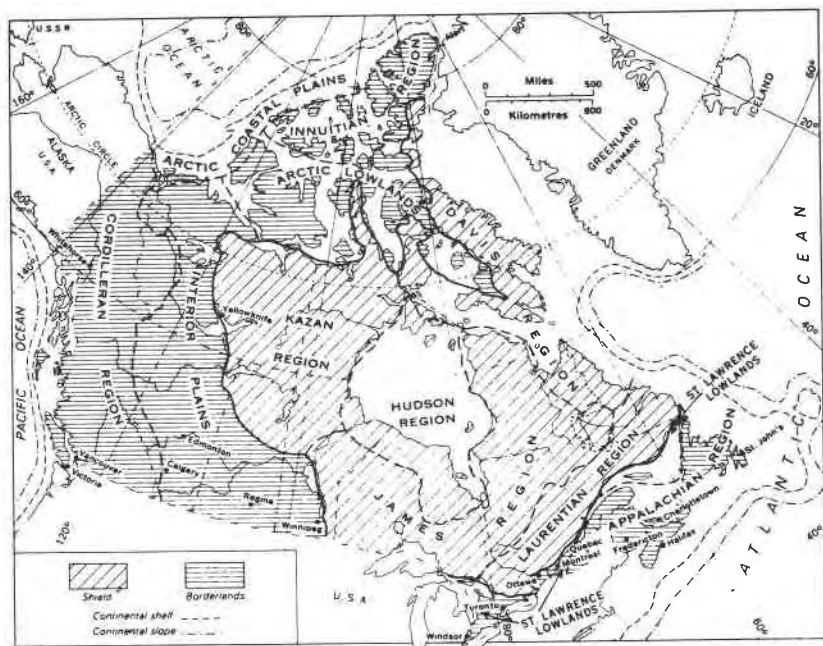


FIG. 1

Map of Canada showing the physiographic regions (from
Geology and Economic Minerals of Canada, GSC, 1970)

alkali-silica reactivity due to the presence of cherts and opaline silica in gravels are on record. Some impure dolomitic limestones from the St. Lawrence lowlands are alkali-carbonate reactive (Dolar-Mantuani (1,2), Swenson and Gillott (3), Gillott and Swenson (4)). In the Appalachian and Shield areas, precambrian granites, volcanics, schists, greywackes and quartzites are the most common rock types. Studies of the alkali reactivity of these rocks have been carried out by Dolar-Mantuani (5), Duncan et al (6), and Gillott et al (7). This paper deals with the alkali-silicate reactivity of rocks from the Canadian Shield and the

Appalachian regions.

Glacial and fluvo-glacial gravels and sands are found overlying the bedrock in many regions but the deposits are usually quite localized. These gravels are a major source of aggregate but a variety of crushed rocks are also used.

Raw material for cement is found in most regions of Canada and cement plants are located adjacent to large urban centres. The composition of the cement varies but, with the exception of the West Coast region where low alkali cement is manufactured, normal Type I cement is a high alkali type with a total alkali content, expressed as Na_2O equivalent of between 0.6 and about 1%*.

Alkali-Silicate Reaction

In North America the term "alkali-silicate reaction" has come to be used to differentiate between the classical alkali-silica reaction as exhibited by opaline rocks and the reaction that occurs with quartzites, greywackes and phyllites that do not contain opaline or chalcedonic silica (see Gillott (8)). The expansion mechanism of alkali-silicate reactive rocks is not fully understood and although there is some evidence to the contrary, it is not at present clear that the mechanism is different from that of the classical alkali-silica reaction. The rate of the alkali-silicate reaction is slower than that of alkali-silica and the shapes of the expansion curves of rock cylinders of the two types in alkali may differ (FIG. 2). These differences may be due, however, to variations in the amount of reactive material present in the two rocks. The weight loss of the (alkali-silica) agate after 400 days was 35%; that of the alkali-silica reactive quartzite was less than 1% (9). It has also been suggested (7) that the expansion of some alkali-silicate rocks, e.g., argillite, may be due to the exfoliation of certain phyllosilicates but it is not clear at present if this is the only cause of expansion.

Test Methods

The following ASTM test methods have been and are used in the laboratory of the Division of Building Research, NRC, and by most Canadian workers:

C289 Quick Chemical Test	Modified C227 Concrete Prism Test
C227 Mortar Bar Test	Modified C586 Rock Cylinder Test

*American Society for Testing and Materials, Standard Specification for Portland Cement Designation C150 (1970).

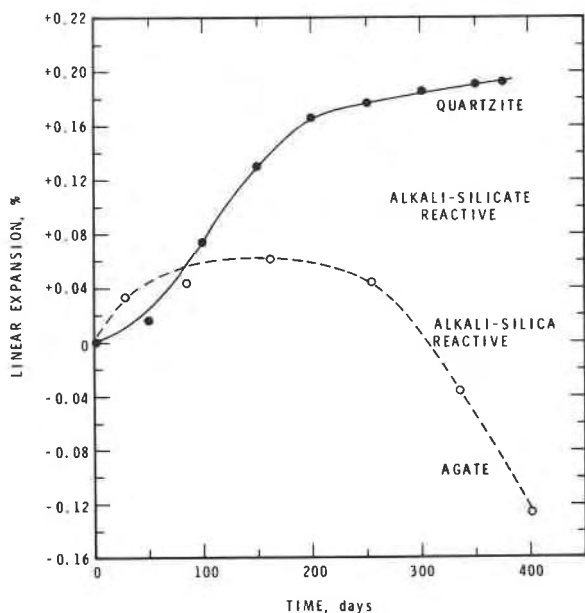


FIG. 2

Comparison between the expansion and contraction of alkali-silica and alkali-silicate rock prisms immersed in 2N NaOH at 20°C. Agate curve plotted from data from Duncan (9).

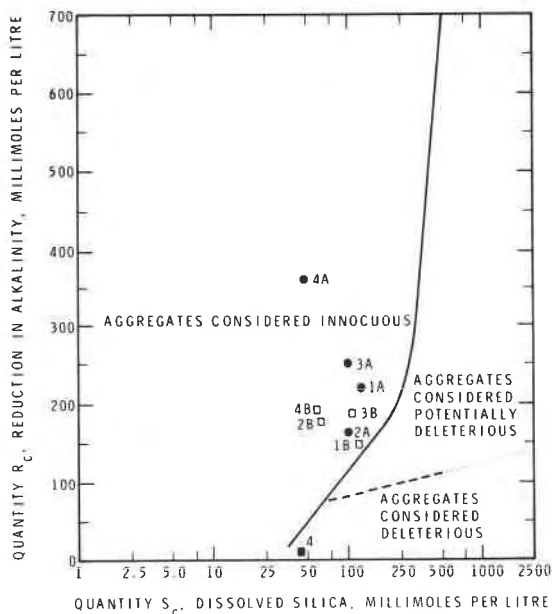


FIG. 3

Plot of results of quick chemical test C289 for a reactive sand of volcanic origin, Samples 1A, 2A and 3A and 4A and for a quartzite, Sample 5. 1B, 2B 3B and 4B are results of duplicate runs.

C289 Quick Chemical Test

This test was developed to assess aggregates believed to be susceptible to the classical alkali-silica reaction, although it has been demonstrated that it also works with some alkali-silicate rocks, e.g., a quartzite sample 5 (FIG. 3). Duncan et al (6), found only a 50% confidence factor for tests done on 14 rocks from Nova Scotia and concluded, therefore, that test C289 was inappropriate for rocks from the Appalachian Region.

If the mechanism of the alkali-silicate reaction is different from the classical reaction of alkali-silica, it is to be expected that the amounts of dissolved silica and reduced alkalinity observed in C289 should also be different. For example, a river gravel of volcanic origin which is known to be reactive was submitted to the C289 test. The results of runs on three pairs of samples are shown in FIG. 3, Nos. 1, 2 and 3, all of which

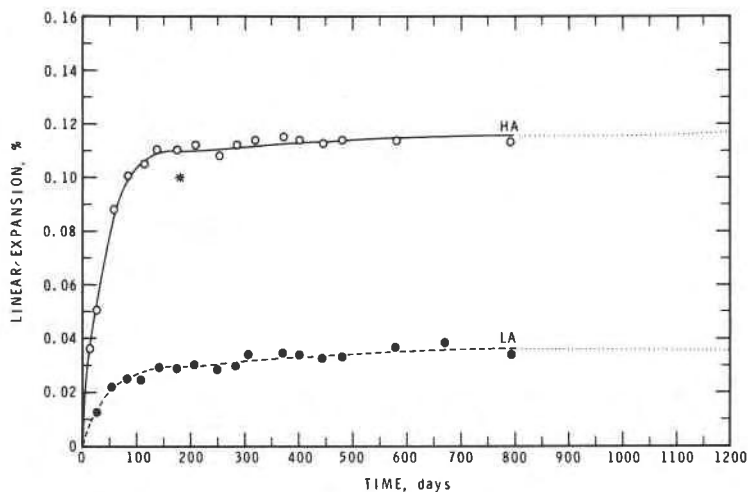


FIG. 4

Expansion of mortar bars, made from a reactive gravel of volcanic origin, with high and low alkali cement (H.A. & L.A.).

*Indicates borderline between reactive and non-reactive aggregates as specified in ASTM Test C227.

plot in the non-reactive part of the diagram. The results of the mortar bar test (C227) on this gravel, shown in FIG. 4, clearly demonstrate that the gravel is expansive. The sand fraction of the material consists mainly of volcanic glass; the gravel-size fraction is composed of fragments of acid to intermediate volcanic rocks.

From tests carried out in the DBR laboratory and elsewhere, Duncan et al (6), it is evident that considerable caution is necessary in interpreting the results of the quick chemical test C289 when it is applied to potentially alkali-silicate reactive rocks.

Mortar Bar Test C227 and Concrete Prism Test

To overcome the objection to the mortar bar test, i.e., that mortar and not concrete is being tested, the concrete prism test was devised. It has been used extensively in Canada (6, 10) and in the DBR laboratory. The effective dimensions of the concrete prisms are $7.6 \times 7.6 \times 25.4$ cm ($3 \times 3 \times 10$ in.). At DBR concrete prisms and mortar bars are routinely stored at 38°C and 100% relative humidity to accelerate the expansion. We have found the concrete prism test is the most satisfactory method of testing aggregates for alkali-reactivity but it has one major disadvantage which probably prevents its wider acceptance - the large amount of space needed to store the prisms. Only four prisms can be sealed in a container 28 cm in diameter by 47 cm high.

In the work at DBR there have been several instances when concrete prisms showed an aggregate to be expansive when the mortar test C227 did not; an example is shown in FIG. 5. The cement used is a normal Type I containing 0.34% Na_2O and 1.13% K_2O giving an Na_2O equivalent of 1.08%. The amount of soluble Na_2O and K_2O was determined by a modification of ASTM C114, about 30% of the sodium was soluble after ten minutes hydration; virtually all the potassium was soluble. This cement is classed as a high-alkali type according to ASTM Specification C150 but with an Na_2O content of 0.34% it is not very reactive. In future work, a cement with a higher Na_2O content will be used as it is known that Na_2O is more reactive than K_2O . A lower expansion for mortar bars than for concrete prisms has also been reported (10). (The work reported in this paper was also done in the DBR laboratories.) The reason for the discrepancy between the results of the mortar bar and concrete prism tests is still being investigated; the possibility that it may be due to the effect of grain size is being considered. Vivian (11) showed that the maximum expansion caused by

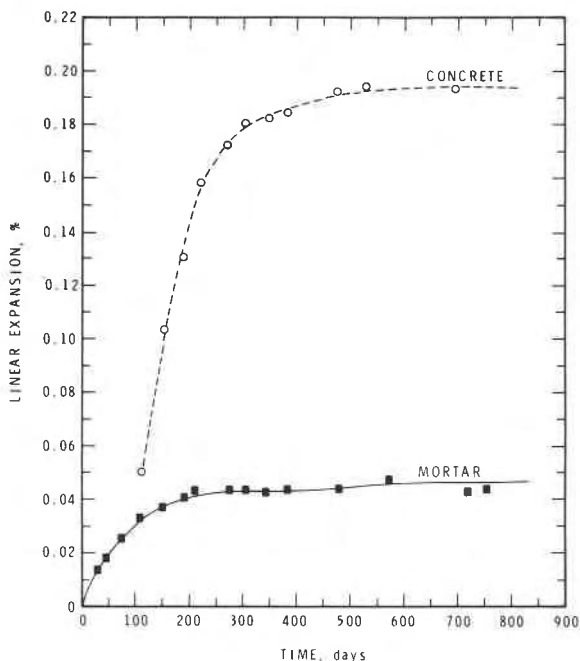


FIG. 5

Comparison of the amount of expansion of a mortar bar and a concrete prism made from a reactive feldspathic quartzite and high alkali cement.

additions of 5% opal to a non-expansive aggregate occurred where the grain size of the aggregate was in the range of 50 to 300 μm . It might also be expected that the maximum expansion of aggregate exhibiting alkali-silicate reactivity would also occur in the 50 to 300 μm range but Duncan (9) found that the amount of expansion increased as the average particle size was increased. For example, a calcareous argillite expanded 0.077% in 48 weeks when a normal grading (ASTM C227) was used but it expanded by 0.164% when the grading was altered by adding 65% of -9.5 + 4.76 mm material. This addition also increased the amount of the coarser material in the smaller screen sizes to give a total of 65% of coarser fractions compared to the standard grading.

In addition to the discrepancy noted between the expansion of mortar bars and concrete prisms, another problem was encountered. Mortar bars made from both high and low alkali cement showed the same (small) amount of expansion (FIG. 6). There is usually a significant difference in the amount of expansion observed in mortar bars made from reactive aggregate with high alkali and low alkali cement; for example FIG. 4 shows the expansions of mortar bars made from a reactive sand of volcanic origin.

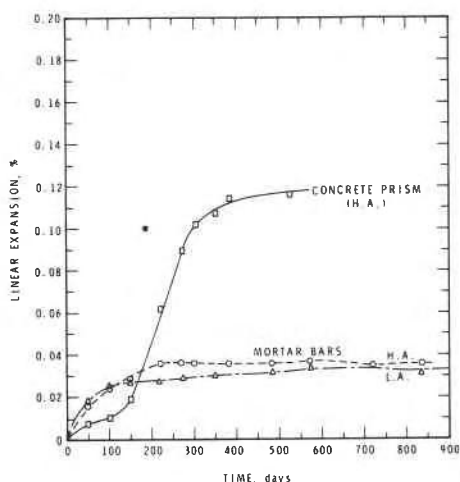


FIG. 6

Comparison of the expansion of mortar bars, of a reactive rhyolite, made with high and low alkali cement. For comparison, the expansion of a concrete prism made with high alkali cement is also shown.

H.A. High alkali cement

L.A. Low alkali cement

The reason why some mortar bars made with high alkali cement did not show more expansion than those made with low alkali cement has so far not been determined, but it may be due to the distribution of the alkalis in the cement - 0.34% Na_2O and 1.13% K_2O , Na_2O equivalent 1.08. Although this would be classed as a high alkali cement based on its Na_2O equivalent it may not behave as such in mortar. At DBR, for the past few years, washing the aggregate as specified in ASTM C227 has been omitted. In normal field practice the aggregate is not washed and it was thought that the test would better simulate normal usage if washing were omitted. The effect of omitting the washing of the aggregate is that about 0.8% more fine material is present, most of it in the 150 to 300 μ range. Experiments are currently in progress to determine if the small percentage of fines added to the mortar bars as a result of not washing the aggregates could act as a pozzolan and inhibit the expansion.

ASTM Test C227 specifies that expansion in excess of 0.1% at six months or 0.05% at three months be considered deleterious. This specification may be satisfactory for aggregates showing the classical alkali-silica reaction but is not reliable for concrete prisms made from aggregates that exhibit the alkali-silicate reaction. FIG. 7 shows the expansions of three concrete prisms made with high alkali cement and quartzites from the Canadian Shield. Samples 1 and 2 are excessively expansive; sample 3 is marginal. Quartzite 1 would be deemed excessively expansive by ASTM C227 specification but quartzite 2 would not, although it expanded more than 0.14% in two years and cracks had appeared in the prisms. Concrete prisms

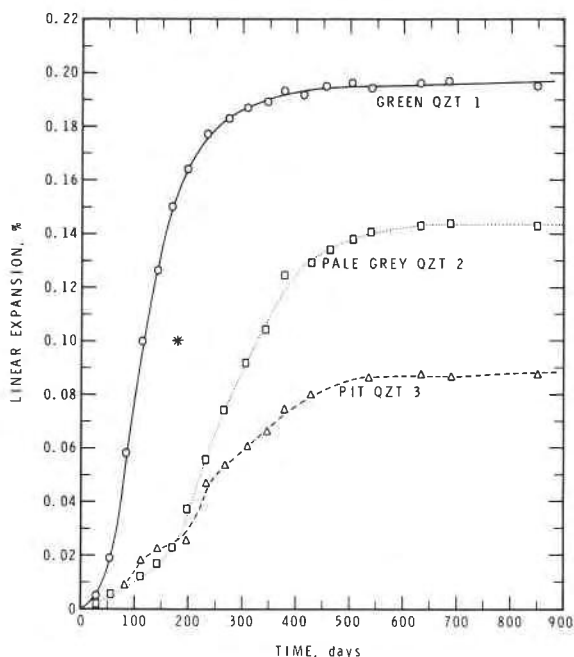


FIG. 7

Expansion curves of three concrete prisms made with quartzites and high alkali cement. Quartzites 1 and 2 are excessively expansive, number 3 is marginal. * Indicates borderline between reactive and non-reactive aggregates as specified by ASTM Test C227.

and mortar bars made with alkali-silicate reactive aggregates expand more slowly than those made from reactive alkali-silica rocks. Instead of setting a limit of 0.1% at six months as the boundary between reactive and non-reactive aggregates it would be better to specify the maximum expansion that should have occurred when the slope of the plot of percentage linear expansion vs time, as shown in FIG. 7, has flattened out. For the quartzites shown in FIG. 7, this occurred after about 600 days.

Modified Rock Cylinder Test, ASTM C586

Test C586 is to determine the potential expansivity of carbonate rocks, but Dolar-Mantuani (5) showed it to be applicable to a variety of Canadian alkali-silicate rocks. Duncan et al (6) found that the results of mortar bar and rock cylinder tests differed in only 11% of the samples studied, about the same disagreement as they found between the results of mortar bar and concrete prism tests. Recent results (6, 10) supported by DBR studies, show that the modified rock cylinder test is a satisfactory method to determine the potential expansivity of aggregates which may be expected to exhibit alkali-silicate reactivity. The modified rock cylinder test, when applied to potentially alkali-silicate rocks, has the

same drawback as the mortar bar and concrete prism tests applied to these rocks, i.e., the length of time required to obtain results, frequently from one to two years. To be of practical value the rock cylinder test would have to be much more rapid.

Accelerated Test: The Rock Prism Test

Some time ago it was decided to try to develop an accelerated rock cylinder test. This was achieved by making small rock prisms $20 \times 3.175 \times 6.35$ mm instead of the rock cylinders. The rock prisms were vacuum saturated with 2N NaOH solution at the start of the experiment. This new method, the Rock Prism test, will be described in more detail in a later publication. The length change of the rock prisms can be measured by one of two methods: (1) by a differential transformer giving a continuous chart readout; or (2) by means of a Huggenberger gauge which is read at selected intervals. (A rock prism and this gauge are shown in FIG. 8a. For comparison a regular rock cylinder is shown on a Tesa measuring apparatus in FIG. 8b.) Small metal studs are attached to the rock prisms to permit measurement with the Huggenberger gauge; these are visible in FIG. 8a. The studs are cemented to the rock with epoxy. Some problems

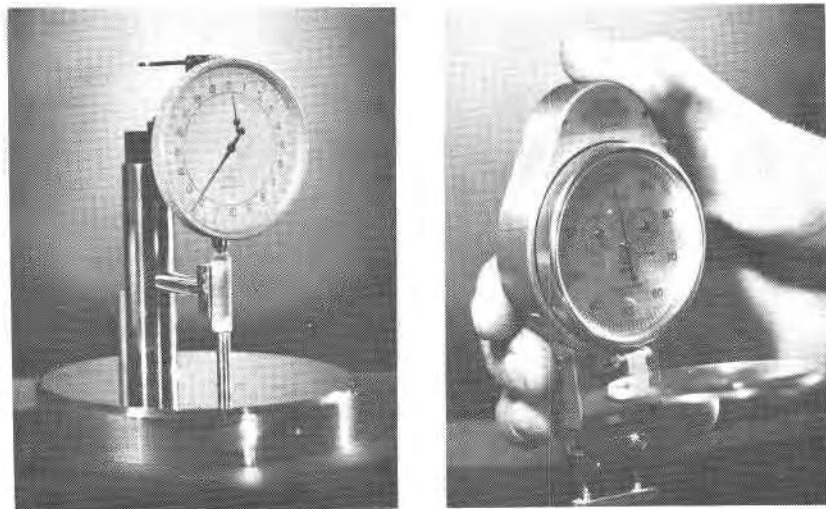


FIG. 8

- a) Huggenberger gauge to measure length of rock prism. Note the two studs attached to the prism into which the prongs of the apparatus fit.
- b) Tesa gauge to measure a rock cylinder.

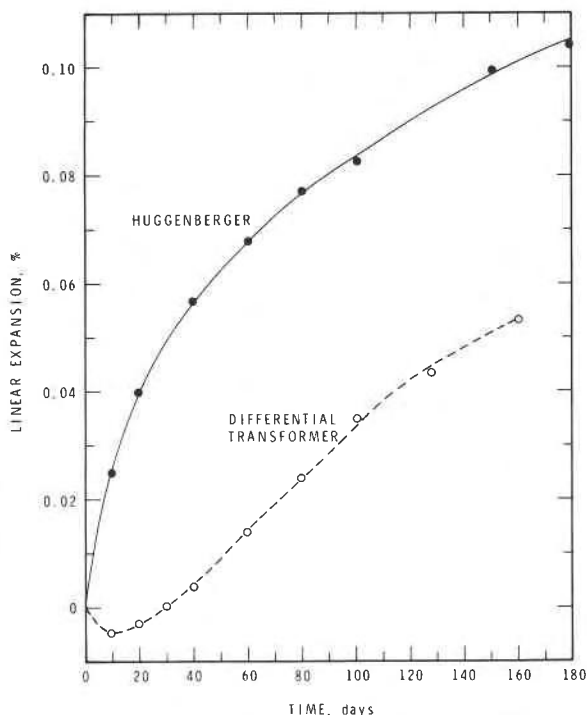


FIG. 9

Comparison of expansions measured on prisms of a reactive quartzite in 2N NaOH solution with a Huggenberger gauge and a differential transformer

were encountered due to the studs coming off, particularly on the more expansive samples but nonetheless satisfactory results were obtained. The differential transformer is capable of more accurate measurement, but it has the disadvantage that one apparatus is needed for each sample. In the transformer apparatus the sample is clamped in small jaws so there is no problem with epoxy becoming detached as sometimes happens to the studs on samples when the Huggenberger gauge is used. The results of expansion experiments with this gauge and transformer apparatus are shown in FIG. 9. Both curves show about the same slope but the amount of expansion after 100 days measured by the transformer is less than half that measured by the Huggenberger gauge. The discrepancy between the two samples may be due to differences in the two prisms or to friction in the transformer or

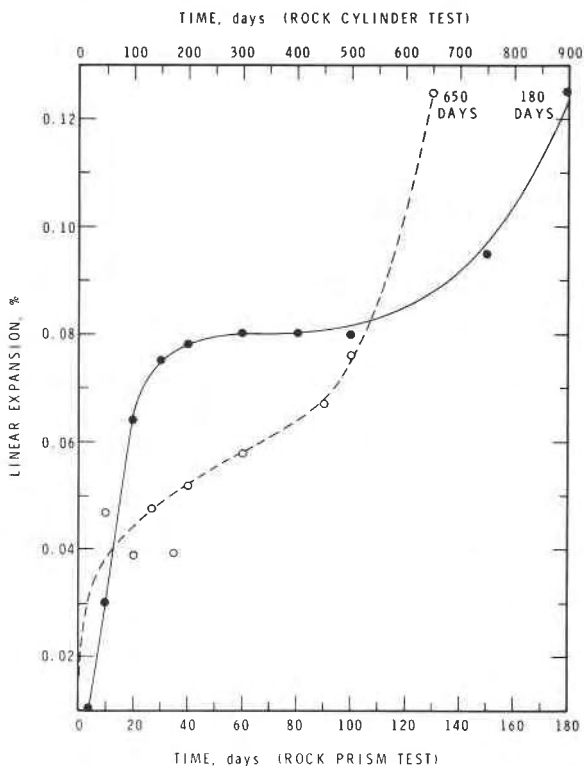


FIG. 10

Comparison of the rate of expansion observed on a rock prism and a rock cylinder of reactive quartzite immersed in 2N NaOH at 20°C.

both. The use of the differential transformer has been discontinued as the Huggenberger is more convenient.

The rate of expansion of a reactive quartzite measured with a Huggenberger gauge on a $20 \times 3.175 \times 6.35$ mm rock prism and that measured on a rock cylinder 9 mm in diameter by 35 mm long with the Tesa gauge are shown in FIG. 10. The rock prism expanded by 0.08% in 60 days. This amount of expansion was not reached by the rock cylinder until after 500 days. There was almost a tenfold increase in the rate of expansion of rock prisms compared with rock cylinders.

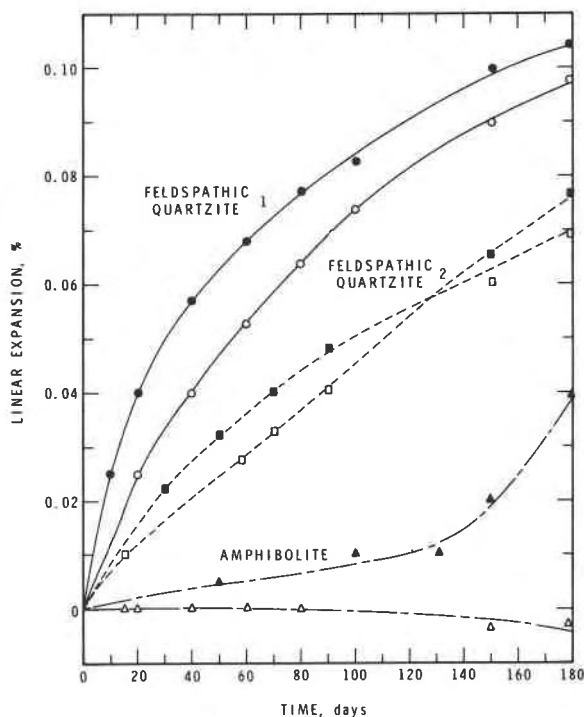


FIG. 11

Rock prism test on duplicate samples of aggregate immersed in 2N NaOH solution.

Pairs of cylinders, even though cored from the same piece of rock and immersed in alkali frequently show different rates of expansion due to lack of homogeneity in the sample. To try to reduce to a minimum this inhomogeneity in the pairs of rock prisms they were sawn side by side from the same slab of rock. Despite this, however, considerable variation in expansion was found between the pairs. Typical expansion curves for three pairs of rock prisms are shown in FIG. 11. The uncertainty that may arise in the interpretation of the rock prism test can be reduced by measuring three or more prisms from each sample. The effect of the lack of homogeneity of the rocks can be minimized by testing sets of prisms from a number of pieces of aggregate.

The problem of determining the dividing line between normal and expansive rocks, which was encountered with the mortar bar and concrete prism tests, also exists with the rock prism method. The two feldspathic quartzites shown in FIG. 11 are known from concrete prism tests to be expansive; the amphibolite is non-expansive. The problem is how to designate rocks that have curves lying between the quartzites and the amphibolite (FIG. 11). The dividing line between expansive and non-expansive rocks and the minimum duration of expansion experiments cannot be established with certainty until more experiments have been done on rock types that have previously been tested in concrete; work on this project is still in progress.

The rock prism test as outlined in this paper shows promise of providing a relatively rapid method of screening aggregate which may be potentially alkali-silicate reactive.

Discussion

Research on the problem of alkali-reactivity has been carried out for more than a quarter of a century but there is still no clear understanding of the exact mechanism by which the expansion of concrete occurs, even in the case of the classical alkali-silica reaction. The alkali silicate reaction, which was defined recently, presents a more complex problem. There is some evidence that expansion may occur due to several mechanisms. (For recent discussions on these topics see Diamond (12) and Gillott (8)). In studying the expansion of concrete made with reactive aggregate and high alkali cement there are two major questions to be answered: (1) How do rock prisms expand when immersed in alkali or in concrete, and (2) Why does the concrete itself expand and crack when made with reactive aggregate.

Gillott et al (7) demonstrated that some phyllosilicates expand when immersed in alkaline solution. The alkali dissolved out the interlayer precipitates thus increasing the surface area and allowing the adsorption of water which in turn caused the mineral to swell. This mechanism does not, however, explain the expansion of quartzites observed by the present authors. The quartzites consisted of large grains of quartz surrounded by interstitial fine quartz and silica.

The expansion of limestone and porous 96% silica glass was studied by Feldman and Sereda (13); the mechanism that they proposed to account for the expansion may well also apply to the quartzites. Essentially what

happens is that the alkali reacts with silica or silicate to form an alkali-silicate hydrate which precipitates as a gel in the fine pores of the rock. This material has a high surface area and readily adsorbs water which causes it to expand (13). The characteristics of the adsorption and expansion isotherms confirm that the alkali-silicate hydrate is in the gel form.

The possibility of developing a reliable and rapid test for alkali-silicate reactive aggregates would be greatly enhanced if the mechanism or mechanisms of expansion were understood. Determining the cause of the expansion of concrete made with reactive aggregate and high alkali cement is complicated by three factors, in addition to the alkali-silicate reaction: temperature, moisture content, and hydration reaction. The aim of the test for alkali-expansivity is to determine the effect of the alkali-silicate reaction alone on the expansion of the concrete. This is never a simple task; it is often an impossible one. In the initial period just subsequent to fabrication all four parameters change simultaneously and feed-back problems arise. As hydration proceeds the temperature rises and the moisture content decreases due to changes of relative humidity. It is very important to keep these facts in mind both in the design and evaluation of test procedures.

Acknowledgements

The authors are indebted to P.J. Sereda for discussions concerning the reaction mechanism, and to J.P. Lefebvre and H. Schultz for the care with which they made and measured the samples.

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Mr. B. Mather

I suggest that the term "alkali-silicate reaction" be reserved for reactions with phyllosilicates as will be suggested by S. Diamond (in press) rather than used for reactions that involve the classical alkali-silica physical chemistry - differing only in rate of development and shape of curve.

Dr. G.M. Idorn

In order to distinguish between the different types of reactivity we are concerned with one must consider the character of the reactive rock closely.

Tense and porous flints are 100 percent mono-mineralic silica rocks. Dense flint particles often have interior regions less compact than other parts and are thus attractive for alkali-silica reaction to start in. Expansion therefore often perform as sudden crack formation within the rock particles and then continuing out through the surrounding paste. Porous flint particles often become completely transformed to gel, before expansive pressure from the remaining "gel-body" is exerted upon the surrounding paste and makes it crack (or makes the gel escape out as a diluted liquid into the pores of the paste without causing cracking).

Polymineralic rocks - phyllites, greywackes etc. behave differently. The reacting constituents are silica and maybe also silicates occurring as interstitial minerals, and the reaction with alkalies affect only their areas of the rock particles. Cracking therefore also originates in reactive areas of the particles.

Crushing of coarse aggregate specimens in order to make sand for standard mortar bars will make the dense flint sand consist of more and less readily reactive particles, porous flint to remain unchanged with regard to reactivity, and polymineralic rocks to consist of reactive and innocuous sand particles, respectively. Accordingly the mortar bar test experiments must be interpreted with great care, if intended to reveal information on the nature, characteristics and designation of alkali-reactivity.

Dr. G.M. Idorn (cont.)

I do not think this is in opposition to P. Gratton-Bellew's designation. Alkali-silica and alkali-silicate reaction, but that thoroughness and consistency is called for when such designation is to be established.

Mrs. K. Mather

The point made by Dr. Idorn is excellent because he reminds us that we should pay attention to the minute geography of the aggregate particles. I am also reminded by Dr. Gratton-Bellew's comment of the aggregate in Fontana Dam; the aggregate graded from coarse-grained greywacke to fine-grained phyllite without much change in composition. We counted the number of coarse aggregate particles associated with gel pockets, reaction rims, and internal cracking, and we sorted these by lithologic variety. We found that there was more gel and more internal cracking associated with the coarse-grained rocks rather than with the fine-grained rocks. This is not the condition that exists with rocks from the Canadian shield.

Dr. P. Gratton-Bellew

In reply to questions and comments on our paper.

Mrs. K. Mather and Dr. Idorn raised the problem of the effect of grain size of rock aggregate on the expansion of mortar bars and concrete prisms, and of pore size and distribution and surface area. unaffected by grain size in the range considered (3mm - 0.1mm). However in reactive quartzites large grains are surrounded by finer siliceous material and fine quartz, possibly in the coarser material more of the fine interstitial material (thought to be the reactive component) may occur on the surface of quartz grains and so enhance the reactivity of the rock.

In discussion with B. Mather and G. Idorn on use of the term alkali-silicate reaction. This term I used loosely to refer to a variety of rock types - this usage is probably misleading and I agree with B. Mather that the term alkali-silicate reaction should be reserved for the explanation of phyllosilicates reported by Gillot if this is indeed the cause of expansion of the aggregate in these cases. The term alkali-silicate should also surely be applied and reactions such

Dr. P. Gratton-Bellew (cont.)

as the one I described as the paper concerning the expansion of concrete made with a sand of volcanic origin and consisting largely of volcanic glass - a silicate material.