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THE AGGREGATE SHORTAGE AND HIGH ALKALI CEMENT IN A CHANGING ENERGY SITUATION

by P. E. Grattan-Bellew, L. M. M. Dolar-Mantuani and P. J. Sereda

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The aggregate shortage and high alkali cement in a changing energy situation

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Shortages of good quality concrete aggregate may be experienced in the larger urban areas, across Canada, during the next 25 years. The potential shortfall in the supply of aggregate will be aggravated in many regions by legislation restricting the operation of pits and quarries. Potential supplies of aggregate will also be affected by the increasing cost of energy. The rising cost of fuel will result in higher haulage costs, which will make transport of aggregate from remote areas, where it is more plentiful, increasingly uneconomic. Some aggregates react with alkalis and are therefore unsuitable for use with high alkali cement. The increased cost of operating a cement kiln due to rising energy costs may be offset by increasing the alkali content of the raw mix, which then clinkers at a lower temperature and produces a cement with a higher alkali content. In some regions this might result in some aggregates, now acceptable, becoming unsatisfactory for use in concrete that is exposed to moist conditions. Potential shortages of good quality concrete aggregate point to the need to conserve supplies; one way of doing this would be to make concrete last longer by improved quality control of concrete exposed to harsh environments.

On peut s'attendre à souffrir d'une pénurie en agrégats à béton de bonne qualité dans les grandes zones urbaines canadiennes au cours des 25 prochaines années. Bien plus, l'insuffisance potentielle de l'approvisionnement en agrégats sera aggravée dans plusieurs régions par des législations restrictives touchant l'exploitation des carrières. Cet approvisionnement sera également affecté par les coûts croissants de l'énergie, dont le pétrole, ce qui entraîne des coûts de transport toujours plus élevés et rend de moins en moins économique le transport d'agrégats en provenance des régions éloignées où on en retrouve en abondance. Quelques agrégats se révèlent chimiquement réactifs aux alcalis; ils sont donc impropres à former des bétons avec des ciments hautement alcalins. L'augmentation, due au coût croissant de l'énergie, du coût d'exploitation d'un four à ciment peut être compensée par une augmentation du contenu alcalin de la matière première qui se transforme en clinker à plus basse température et fournit un ciment à teneur plus élevée en alcalis. Dans certaines régions, il pourra s'ensuivre que des agrégats, présentement satisfaisants, deviendront impropres à utiliser dans un béton exposé à une atmosphère humide. Les pénuries possibles d'agrégats de bonne qualité mettent en relief la nécessité de préserver les réserves; un moyen d'atteindre ce dernier objectif consiste à fabriquer des bétons de plus grande durabilité grâce à un contrôle de la qualité accrue pour les bétons destinés à des environnements rigoureux.

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Introduction

It may seem surprising to many that there could be a potential shortage of aggregate in a country with about half its land mass made up of that great mass of Precambrian rock, the Canadian Shield, and which also contains the Rocky Mountains with huge rock masses towering to 4000 m. Proctor & Redfern Ltd. nevertheless concluded, in a recent report (1974), that "with the present conditions, the Central Ontario Planning Region could only remain self-sufficient in mineral aggregate for perhaps 20 years." The projected aggregate supply and demand for central Ontario is shown graphically in Fig. 1. It must be realized, however, that potential aggregate shortages will generally occur only within about a 50 mi (80 km) radius of large urban areas, which comprise less than 10% of the Canadian land mass.

Potential shortages of aggregate are not unique to Canada. A study by Witczak *et al.* (1971) showed that aggregates were potentially in short supply in about one third of the states in the USA. In the United Kingdom, Verney (1972) in a report to the government concluded that by the early 1990's almost all the gravel-bearing land in the southeast of England, which was not agriculturally or environmentally precious, would have been worked out.

Definition of Aggregate

The definition of aggregate, modified from ASTM (American Society for Testing and Materials) D8-1975, is "a granular material of mineral composition such as sand, gravel, slag or crushed stone used with a cementing medium to form mortar, concrete or asphalt paving or alone as base course, ballast or

FIG. 1. Projected accumulated demand and current potential available supply of all types of aggregate in the Central Ontario Region (from Proctor & Redfern Ltd. 1974).

fill." Aggregates discussed in this study are naturally occurring sands, gravels, and crushed rocks, which, when mixed with cement and water in proportions of approximately 5:1:0.5, produce concrete.

Effect of the Changing Energy Situation on the Supply of Aggregate

The increasing costs of oil and natural gas affect the supply of usable concrete aggregate, mainly in two ways:

(i) By increasing haulage costs. Increased fuel costs would make hauling from greater distances increasingly uneconomic at a time when the currently worked aggregate pits near or within municipal boundaries are rapidly being used up.

(ii) By increasing the costs of firing cement kilns with oil or natural gas. The increased costs of firing cement kilns due to rising oil and gas prices can be offset in two ways: (a) by reducing the firing temperature, which can be accomplished by increasing the alkali content of the cement, or (b) by using cheaper coal as fuel. Changing from firing with oil or gas to coal may result in an increase of the alkali content of the cement. It can thus be seen that both these methods result in an increase in the alkali content of the cement.

All aggregates react to some extent with the alkalis in cement but in some instances the reaction causes deleterious expansion of concrete made with high alkali cement. A significant increase in the alkali content of a cement could result in some satisfactory or borderline aggregates becoming alkali-expansive and thus unsuitable for use as normal concrete aggregate. This could cause local shortages, until alternative sources of supply were developed.

Demand and Availability of Aggregate in Canada

Concrete is used in greater amounts than any other building material; the amount of cement used per capita can be used as an index of a country's industrial development. Cembureau (1975) lists world per capita consumption of cement for 1974 at 172 kg. The figure for Canada is 433 kg, that for all of North America 344 kg; the figure for Europe is 495 kg. Approximate figures for annual concrete aggregate production can be obtained by multiplying the cement per capita value by 5 times the population. (One part cement and 5 parts aggregate makes normal concrete.) This calculation yields a value of about 50×10^6 tons (5×10^{10} kg) of aggregate for the annual Canadian consumption. The population of Canada is expected to increase from 23 million to about 30 million by the year 2000. Using the above calculation for a population of 30 million yields a value of 65×10^6 tons (6×10^{10} kg) of aggregate for the year 2000. This figure may be modified by a number of factors but it does, however, give some idea of the expected growth in the demand for concrete aggregate.

To determine the current position of aggregate supply and demand in Canada, the authors solicited information from each province. Detailed information was only obtained for parts of Ontario (Proctor & Redfern Ltd. 1974; Proctor & Redfern Ltd. and Gartner Lee Associates Limited 1976), Manitoba (Underwood McLellan and Associates 1976), and New Brunswick (Hamilton and Carroll 1975). Much of the statistical data presented in this paper are based on this information.

Central Canada

The potential shortfall in aggregate supply over demand is generally only a problem in the more industrialized and populated urban areas. The usual problem in the large cities is that urban sprawl has covered many potential aggregate sources and because of the high volume of aggregate required even large reserves within a 10–20 mi (16–32 km) radius of the cities are rapidly depleted. Proctor & Redfern (1974) (Fig. 1) show that most of the currently available sources of aggregate, of all types, within a reasonable distance from cities in central Ontario will have become exhausted within the first decade of the next century. Inquiries made during the course of the present survey indicate that a similar situation exists in many other urban centres in Canada. It must, however, be borne in mind that, to some extent at least, shortages will be artificially created by social pressure for legislation restricting the operations of aggregate plants to certain areas (Yundt 1975). Rising haulage costs (Fig. 2) will make

FIG. 2. Truck haul cost-distance relationship for central Ontario region, 1974 (from Proctor & Redfern Ltd. 1974) and Ottawa, 1977.

it increasingly uneconomic to bring aggregate from greater distances where usable reserves may exist. For example, in the Ottawa area in 1977 aggregate delivered 10 mi (16 km) from the plant cost about \$2.70/ton (1 ton = 907 kg), that delivered 50 miles \$6.65. The problem of potential shortages of aggregate is particularly acute in Ontario as not only does it have the highest population of any province, about 8 million, but also the largest number of major urban areas, all of which are expanding.

Although Ontario has large reserves of limestone suitable for use as crushed aggregate, many rural counties have bylaws without provision for pits and quarries. A good case could probably be made for the suggestion in *A policy for mineral aggregate resource management in Ontario* (Ministry of Natural Resources 1977) that "The Minister of Natural Resources should have the power and authority to order that a municipal official plan or by-law be amended to allow for aggregate extraction in regional or county municipalities which refuse to accept responsibility for a reasonable output of aggregate." Crushed limestone is used extensively in the province of Quebec. In Montreal much of the limestone used is quarried within the city limits but, within the next 5 years, legislation for environmental protection may cause closure of these quarries.

Another possible solution to potential aggregate shortages in some areas would be the underground mining of aggregate. In addition to alleviating the shortage of aggregate, underground mining would almost totally eliminate the dust and noise pollution normally associated with open pit operations, if the crushing and screening plant was put underground. The costs of underground mining are discussed in Proctor & Redfern Ltd. (1974, Appendix D). They

conclude that if costs were written off over a 10 year period, the net cost f.o.b. (free on board) pit head would be \$3.65/ton. To this figure freight and transport charges would have to be added. This has to be compared with a figure of \$1.21 f.o.b. pit for open pit aggregate production (Statistics Canada 1973b). A rough calculation using 1977 haulage figures suggests that aggregate mined underground and delivered 30 mi (50 km) away would be competitive with aggregate from open pits delivered by road 70 mi (112 km) away. Long distance delivery costs could be reduced if larger tractor trailers would replace the trucks now normally in use. The cost of underground mining could also be reduced by finding a use for the space created for warehouse operations, energy, storage, etc. However, other problems with underground mining of aggregate would be the high capital cost to get it started and the highly skilled work force needed to carry on underground mining. Acquiring mining rights within city limits also raises a difficult problem.

A number of other possibilities exist to help alleviate the potential aggregate shortage in central Ontario:

(i) *Dredging of Gravel from Lake Ontario*

Sand and gravel deposits exist in Lake Ontario but dredging in the shallow coastal waters where it would be most feasible would be objected to on environmental grounds because of the risk of shoreline erosion. The gravels in Lake Ontario near the mouth of the Niagara River contain concentrations of chert, which could give rise to alkali expansion if it were used in concrete. The possibility that other gravel deposits in Lake Ontario would also be alkali-expansive due to the presence of reactive carbonate rocks such as those found in the Kingston area cannot be excluded. Any gravels from Lake Ontario would need to be tested for alkali expansivity prior to use as concrete aggregate.

(ii) *The Use of Manufactured Aggregates*

At present there seems little possibility that manufactured aggregates, made perhaps from waste products, e.g. rubble, broken brick, or mine waste, would have a significant effect on the potential supply of concrete aggregates.

(iii) *Classifying Aggregate Deposits for Specific Uses*

High quality aggregate is needed for use in concrete and asphalt, but currently much of it is used as fill or as the base course in roads for which a poorer grade of material would suffice. If the better grades of aggregate were reserved for use in concrete and asphalt, as is done in the Winnipeg region, reserves could be made to last longer. About 20% of the total aggregate used in Ontario goes into concrete.

FIG. 3. Projected accumulated demand and current potential available supply of aggregate in the Winnipeg region of Manitoba (from Underwood, McLellan and Associates 1976).

Maritime Provinces

The aggregate supply in the Maritime Provinces is generally adequate because of the relatively low population density. However, because alkali-expansive rocks occur in the area (see Duncan *et al.* 1973), potential concrete aggregates would need to be tested for expansivity before being used. Hamilton and Carroll (1975) in a recent report on sand and gravel in New Brunswick state that sand and gravel are in short supply in the Moncton area and have to be trucked from about 40 mi (64 km) away. In New Brunswick, crushed stone, mostly granite, comprises nearly 90% of the coarse aggregate used in concrete although it covers only about 20% of the total aggregate used, for all purposes, in the province.

Prairies

Aggregate resources are adequate in the Prairie Provinces where there are few cities of even medium size (0.25–0.5 million people). The only comprehensive aggregate survey in the Prairies was made on the Winnipeg region by Underwood, McLellan and Associates (1976). This study shows that between 85 and 90% of all the aggregate used for residential construction in the province of Manitoba is used in the Winnipeg region.

Figure 3 shows the forecast supply and demand for aggregate in the Winnipeg area. Reserves of good quality aggregate will become exhausted early in the 21st century; however, if the better grades of aggregate were reserved for use in concrete and asphalt, supplies could be considerably extended as only about 40% of the total aggregate is used for these purposes.

British Columbia

British Columbia is the third most populated and developed province but it has only two large cities, Vancouver and Victoria. There are adequate supplies of aggregate on Vancouver Island, some of which are shipped to Vancouver. Gravel is the main source of aggregate in the Vancouver area but sources within a 40 mi radius of the city may become exhausted by the year 2000. After that, gravel will have to be shipped from further up the coast. Quarrying of granite from the nearby mountains will possibly then be economically feasible. Some gravels in the Vancouver area contain chert, which could cause alkali-expansion problems in concrete if the alkali content of the cement is raised. At present, low-alkali cement is the normal portland cement used in Vancouver and Victoria.

Summary of Statistical Data on Cement and Aggregate Production and Consumption in Canada

It is difficult to obtain accurate statistics on aggregate production as the data available from Statistics Canada often do not represent the true situation. For example, in the Report of the Ontario Mineral Aggregate Working Party (Ministry of Natural Resources 1977), the authors write that the tonnage removed from 124 townships in southern Ontario in 1974 and 1975 was equal to or greater than that reported for all of Ontario by Statistics Canada. Part of the problem is that data are only collected from a limited number of producers and many small pit operators evidently do not report to Statistics Canada. In Nova Scotia data are collected

TABLE 1. Amount of crushed stone and sand and gravel (10^6 tons*) used by the provinces as concrete aggregate (Statistics Canada 1973a)

	Nfld.	N.S.	N.B.	Que.	Ont.	Man.	Alta.	Sask.	B.C.	Total
Crushed rock for concrete	0.14	—	0.29	9.0	5.1	0.035	—	—	0.038	14.7
Sand and gravel	0.33	0.84	0.10	5.2	16.1	1.8	3.5	0.35	5.2	33.6
Total concrete aggregates	0.47	0.84	0.39	14.2	21.2	1.84	3.5	0.35	5.24	47.3

*1 ton $\approx$ 907 kg.

NOTE: Individual figures may not add up exactly to the totals due to rounding off of numbers.

from only seven aggregate producers but there are probably over 50 producers in the province.

An estimate by Statistics Canada of the amount of aggregate used in concrete, broken down into sand and gravel and crushed stone, is shown on Table 1. Ontario and Quebec together account for about 75% of the total aggregate used. From Table 1, it can be seen that Quebec and New Brunswick are the only provinces using more crushed rock than sand and gravel. In Quebec, 9 million tons (8×10^9 kg) of crushed rock and 5.2 million tons (5×10^9 kg) of the sand and gravel are used. From these figures it may be seen that supplies of sand and gravel near the larger urban centres of Montreal and Quebec city are not able to meet the demand.

Types of Rocks used as Crushed Aggregate in Concrete

As shown in Table 2, 90% of the crushed aggregate used in Canada is limestone and most of this is used in Ontario and Quebec, the two most industrialized provinces. The term limestone is used to refer loosely to carbonate rocks varying from pure limestone to dolostone and shale. Pure limestone makes good quality aggregate but problems have been noted with impure limestones (Dolar-Mantuani 1975; Swenson and Gillott 1964) and with shale (Bérard *et al.* 1975). Entire rock formations may be unsuitable for use as concrete aggregate, because of the high clay content e.g. Verulam and Lindsay formations in southern Ontario (Dolar-Mantuani 1975). If further increases were to occur in the alkali contents of cements used in southern Ontario and Quebec, some carbonates that are now marginally alkali-expansive might become deleteriously expansive in concrete. When sand and gravel deposits become depleted, more reliance will have to be placed on crushed rock for concrete aggregate and so the demand for it may be expected to rise.

Life Cycle Costs of Concrete

Increasing costs of labor, fuel, and transportation mean that the cost of concrete aggregate may be expected to continue to rise. In 1974, aggregate cost about \$1.32 per ton compared with about \$2.15 per ton in 1977 (Ottawa price). As the costs of

TABLE 2. Amount of crushed stone (10^6 tons*) used as concrete aggregate classified by rock types (Statistics Canada 1973b)

Granite	Limestone	Sandstone	Shale	Total
0.82	13.3	0.48	0.38	14.7

*1 ton $\approx$ 907 kg.

aggregate and, hence, concrete continue to rise, 'life cycle cost' is going to be increasingly important. Obviously, if a concrete sidewalk has to be replaced after 5 years, the initial cost of its construction in no way reflects the true cost over the expected life time of that sidewalk, which might be 25 years. Good quality concrete should last more or less indefinitely unless it is exposed to an extremely harsh environment.

Any increase in the alkali contents of cements that might lead to the production of less durable concrete due to the effects of alkali expansivity would obviously increase the life cycle cost of that concrete.

Statistics Canada (1974) estimates repairs and maintenance to all types of building materials, including wood, at 17% of the construction costs or about \$3 billion. Records that would enable this huge economic loss to be broken down are not available but the cost of repair and maintenance of concrete would probably be much lower than 17% as it is generally a durable material. T. G. Clendenning, in a personal communication (1976), indicated that in Ontario Hydro the annual cost of repair and maintenance of concrete was under 1%. It must be realized, however, that in an organization like Ontario Hydro the quality control of concrete is probably much better than in most organizations or municipalities and the average figure for the repair and maintenance of concrete is certainly higher than 1%. A walk around most cities will reveal many cases of deteriorated concrete in need of repair. For example, some concrete curb stones, placed in an Ottawa street in 1976 are already showing severe deterioration after only 1 year, and will certainly need to be replaced within the next few years.

The actual benefits of improved materials and better quality control, and the associated energy conservation, will only be apparent when life cycle costs are available.

FIG. 4. Variation in the observed expansion of concrete made with an expansive aggregate and cements with different alkali contents.

FIG. 5. Map cracking developed on concrete curb due to alkali expansivity of the aggregate.

Alkali Expansivity of Concrete Aggregate

Some reaction between the aggregate and the cement paste is desirable because it adds strength to the bond between the aggregate and the surrounding cement paste. The amount of expansion occurring in concrete made with a particular expansive aggregate usually depends on the alkali content of the cement (Fig. 4). In some cases, however, the use of a low-alkali cement will not prevent expansion due to alkali reactivity because alkali is supplied to the system from external sources. The effects of alkali

expansivity usually first show up as map cracking in the concrete (Fig. 5). There is a direct relationship between the alkali content of the cement and the amount of expansion that has occurred after 18 months in a concrete made with expansive carbonate aggregate (Fig. 6).

The alkali content of cement is controlled by a number of factors: (i) the alkali content of the raw material; (ii) the design and method of operation of the kiln; (iii) the amount of alkali fed back into the kiln from dust collected from the stack; (iv) the

FIG. 6. Graph showing relationship of the observed expansion of concrete prisms at 18 months to the alkali content of the cement.

alkali content of coal, when this is used to fire the kiln. All these factors are, theoretically, under the control of the operator. In practice, however, there may be no raw materials available with low-alkali contents; environmental considerations may necessitate putting all the alkali recovered from the flue dust back into the kiln. Many modern kilns tend to produce a higher-alkali cement than the older ones they replace. The presence of alkali in the kiln also acts as a flux, reducing the firing temperature and thus the energy required to make the cement (Alsted Nielsen 1975). In the USA, for economic reasons, some kilns, previously fired by oil or natural gas, have been converted to burn coal. The coal contains sulfides and sulphates; and alkaline earths in these cause an increase in the alkali content of the cement, which, in some cases, is as high as 1.3%. In Nova Scotia, Alberta, and British Columbia, where coal is produced locally, some cement plants may convert the existing oil-fired kilns to coal. This could increase the alkali content of the cement, which could result in some currently acceptable aggregates becoming excessively expansive and therefore unacceptable, if no remedial material is added. It should be noted that alkali expansion of concrete made with a reactive aggregate is generally only a problem when the concrete is exposed to moist conditions. It is estimated that about 50% of concrete is normally exposed to such conditions.

The alkali contents of cements currently produced in Canada are shown in Table 3. They range from 0.16% produced by plant A to 1.18% produced by plant W. Cements with an alkali content below 0.60% (Na_2O equivalent) are considered to be of the low alkali type. The cements manufactured in B.C. are usually of this type because such cements are specified in Seattle, a major user of the B.C. product.

TABLE 3. Alkali content of Canadian portland cements, 1975 (data supplied by W. S. Weaver, Canada Cement Lafarge Ltd.)

Plant code	Equivalent Na_2O (%)
A	0.16
B	0.47
C	0.49
D	0.56
E	0.68
F	0.68
G	0.74
H	0.75
I	0.78
J	0.81
K	0.83
L	0.87
M	0.90
N	0.93
O	0.94
P	0.96
Q	0.97
R	1.03
S	1.04
T	1.10
U	1.14
V	1.16
W	1.18

In certain regions the supply of concrete aggregate is limited due to the potential alkali expansivity of some rock formations. In these regions an increase in the alkali content of the cement would necessitate testing the aggregates to ensure that they were not excessively expansive with the new cement. It must be borne in mind that some commonly performed tests, such as the province-wide megascopic examination of aggregates to determine the petrographic number, used in Ontario, Quebec, and British Columbia and specified in CSA A23-2-30 (Canadian Standards Association 1973) does not detect alkali-expansive aggregates as it is impossible to identify reactive material by visual examination with a hand lens or binocular microscope. Also, in many instances, some of the ASTM (American Society for Testing and Materials) tests designed specifically to detect alkali-expansive aggregates fail to do so. For example, ASTM C227, the Mortar Bar Test, does not work with the carbonates from Kingston (Swenson 1957). Neither C227 nor C289, the chemical method, is effective for detecting some expansive silicate rocks (Grattan-Bellew and Litvan 1976). In many cases the expansion of concrete made with reactive aggregate can be controlled by replacing about 25% of the cement with a pozzolan. This method was found to be ineffective, however, for the

expansive carbonates at Kingston (Swenson and Gillott 1964).

Case Histories

It is not possible to make any kind of a generalization concerning the amount of aggregate that is potentially expansive in Canada. In two well-surveyed regions, Nova Scotia and the Kingston region of Ontario, about 10% of the aggregates are thought to be potentially expansive. Alkali-expansive aggregates have been identified from Nova Scotia in the east to Vancouver in the west and from Alert, N.W.T., in the north to Kingston and St. Catharines in southern Ontario (Dolar-Mantuani 1976).

Southern Ontario and Quebec

Southern Ontario and Quebec are underlain by paleozoic sediments. Several potentially alkali-expansive horizons have been identified in this region. The best known case is probably that of the Gull River formation near Kingston (Swenson and Gillott 1964). Expansive aggregates in the Gull River formation occurring in a line running from Kingston west to Georgian Bay have been reported by Dolar-Mantuani (1975). Excessive expansion of concrete made with the Potsdam sandstone, obtained from a region southwest of Montreal, was recorded by Bérard and Lapierre (1977); concrete made with deformed dacite aggregate, from southeast of Montreal was recorded by Dolar-Mantuani (1976).

Central Ontario

Some fine-grained quartzite boulders from the gravel in the Sudbury region are alkali-expansive and argillites and greywackes from the Cobalt area were also reported to be expansive (Dolar-Mantuani 1969).

Nova Scotia

A field survey of concrete in Nova Scotia and in neighbouring parts of New Brunswick (Fig. 7) (Swenson undated) showed that structures in many parts of these provinces were probably affected by alkali expansivity. Subsequent laboratory tests showed that some quartzites, greywackes, phyllites, argillites, showed and rhyolites were expansive with the alkali in cement. The affected concrete typically showed pattern cracking and exudations. This was particularly obvious in older structures.

Alert, Ellesmere Island, N.W.T.

A problem of concrete deterioration was found at a military base at Alert, Ellesmere Island, N.W.T. Subsequent laboratory studies (Gillott and Swenson 1973) showed it to be due to alkali expansivity of a greywacke containing chert. The reaction would have been very slow in this case if the concrete was

exposed to low temperature, which slows the rate of reaction, but in heated buildings with high humidity, the reaction would be moderately rapid.

Prairies

Most of the sands in the Prairies are not alkali-expansive but some dune sands containing opal and chalcedony caused excessive expansion in mortar bars made for test purposes. This suggests that some caution is necessary when using aggregate from newly opened pits from which concrete has not been made.

British Columbia

In the Vancouver and Victoria regions, normal cement has an alkali content of 0.60% (Na_2O equivalent) and thus is a low-alkali cement. Chert, a potentially reactive rock, occurs in the gravel deposits of B.C. and hence the gravels should be regarded as potentially expansive if used with high-alkali cement. Problems could arise if the alkali content of the cement were raised. Mindess and Gilley (1973) showed that mortar bars made with Mary Hill aggregate and high-alkali cement were moderately expansive.

Frost Resistance of Concrete

Some aggregates are unsuitable for use as concrete aggregate due to a lack of resistance to frost damage. The resistance of concrete made with frost-susceptible aggregate to cycles of freezing and thawing is not directly related to the alkali content of the cement, but a relationship exists between alkali expansivity and freeze-thaw deterioration. For example, in the Ottawa region where some of the carbonates are marginally alkali-expansive, the problem is sometimes exacerbated due to the presence in the aggregate of shale particles that are susceptible to frost action. Cracks caused by frost action permit the access of moisture to the interior of the concrete where it accelerates the alkali-expansion reaction. The quality of concrete made with such an aggregate would obviously worsen if the marginally expansive aggregate were to become deleterious due to an increase in the alkali content of the cement.

Quality Control of Aggregate Production

The quality control methods currently used to assess potential sources of concrete aggregate, for example, the megascopic, petrographic number method used widely in Ontario, assess only the physical quality of aggregate. The ASTM C295 standard practice for examination of concrete aggregate suggests that the "presence of constituents known to cause deleterious chemical reactions in concrete" should be noted (Section 7.4.1.9, recent

FIG. 7. Map showing results of a survey of the condition of concrete structures in Nova Scotia and southern New Brunswick (from Swenson undated).

revision due for publication in 1979). Rocks and minerals that are potentially alkali-expansive are listed with short descriptions in ASTM C294. Although this list is not complete because other aggregates have been found to be potentially alkali-expansive, this list, together with Appendix C33 (A1. Methods for Evaluating Potential Reactivity of an Aggregate), provides a guide for detecting most of the common reactive aggregates.

If the alkali content of certain cements were to be raised, it would be advisable to test potentially reactive aggregates to determine if they would cause excessive expansion of concrete made from them and high alkali cement. At present there is no rapid test method applicable to all rock types. The quick chemical method, ASTM test C289 is generally considered to give unreliable results, as shown repeatedly by various researchers. The mortar bar method, ASTM C227, was shown by Swenson (1957) to be inapplicable to expansive carbonate rocks in the

Kingston area and, more recently, Grattan-Bellew and Litvan (1976) found that excessive expansion of some silicate rocks from the Canadian Shield was also not detected by this method.

The rock cylinder test C586 works well for carbonate rocks and also for some silicate rocks (Dolar-Mantuani 1969). However, with some rocks this test takes too long to be practical. The concrete prism test (Swenson and Gillott 1960), works well with all types of rock but in many instances the test is too slow. It is generally recommended that several specific tests be used to determine the potential alkali expansivity of an aggregate (Newlon *et al.* 1972). A petrographer experienced in concrete aggregate work would be able on the basis of composition and texture of the rock, to separate many rocks into those that would be satisfactory and those that might be potentially alkali-expansive and that would therefore require testing.

If extensive testing of Canadian aggregates were

to become necessary, there would be an inadequate number of trained petrographers. The training of petrographers in universities does not specifically include the identification of potentially alkali-expansive rocks. A manual for the petrographic examination of concrete aggregate is being prepared by one of the authors (Dolar-Mantuani), and it is hoped that it will be acceptable for training petrographers in this specialty. If a more thorough system of concrete aggregate testing were to be set up, there would also be a need to train petrographic assistants to help speed up the work of the petrographer. A training program for petrographic assistants could possibly be set up in some community colleges.

No single quick test exists that could be used to evaluate potential alkali-expansivity of all rock types although there is some hope that the new miniature rock prism test currently being tested by Grattan-Bellew and Litvan (1976) may fill this role. More research is needed to develop better test methods and to catalogue potentially expansive aggregates. At present, there are possibly a dozen laboratories where research into the problem of alkali-expansivity is carried out, but only intermittently. This research usually involves one person. If more rapid progress is desired, more manpower and resources would have to be devoted to the task. More research is surely justified in an industry with an annual value of about a half billion dollars; an expenditure of about four times the current level might be appropriate.

Potential Sources of Additional Concrete Aggregate

In some areas, expected shortages of aggregate can be eliminated by utilizing alternate sources, which could be exploited when changes in the economy of the industry make this possible. Transportation of aggregate from remote areas where it is plentiful is unlikely to be economic, in the future, due to rising fuel costs, so a number of alternatives closer to the markets have to be considered. (These have already been discussed in this paper.)

(i) Lake and river dredging. It is probable that dredging of aggregate would only be feasible in the Great Lakes and along the eastern and western seaboard. Dredging, however, is unlikely to provide a significant volume of aggregate in Ontario and Quebec where there is the greatest demand.

(ii) Underground mining of aggregate. An example of underground mining of aggregate practiced in Kansas City has been reported by Legget (1973). In the future, underground mining of aggregate may become economic in major cities like Toronto, Montreal, and Vancouver.

(iii) Use of manufactured aggregate. This is unlikely to be significant in the foreseeable future.

(iv) Classification of aggregate deposits for use in various areas of construction. The purpose of classification would be to identify and reserve the better and most suitable grades of aggregate for use in concrete.

(v) Fuller exploitation of known resources. Changes in municipal by-laws would be necessary to permit the extraction of aggregates on a large scale from deposits in southern Ontario and Quebec. If rail transport were feasible, large volumes of aggregate could be transported to depots on the outskirts of major cities from considerable distances, at an economic price. This would permit the exploitation of deposits that are too far from the market to be economically transported by road.

Summary and Conclusions

This paper presents a brief overview of the current and future situation regarding the supply and demand of concrete aggregate in Canada. It is clear that by the end of the century there will be a shortage of aggregate in many large urban centers. Any increase in the alkali content of cements, which might be brought about in order to reduce the energy requirements of cement kilns, would almost certainly result in some potentially alkali-expansive aggregates, which currently make satisfactory concrete, becoming deleteriously expansive. This would reduce the amount of good quality concrete aggregate available in that region. It is not possible, at present, to estimate what percentage of potential aggregate sources would contain alkali-expansive material.

It is recorded that high-alkali cement (alkali content over 0.6% Na_2O equivalent) is produced in most parts of the country, western Canada being the exception. Those plants now producing low-alkali cement may eventually change to manufacturing a high-alkali type for a variety of economic and environmental reasons.

Crushed rock comprises about 31% of the aggregate used in Canada and 90% of the crushed rock is limestone and other carbonates; most of this is used in Ontario and Quebec.

As gravel deposits become depleted, more crushed rock will have to be used. This will consist mainly of carbonate rocks and so it follows that research on concrete aggregate needs to be concentrated on these rocks.

It is estimated that 50% of concrete used is exposed to high moisture conditions where alkali expansivity can be a problem if the aggregates are potentially alkali-expansive.

This paper presents cost estimates applicable to 'first cost' of construction but emphasizes the importance of estimating 'life-cycle costs' in order to show the benefits of better quality control of concrete

aggregate. With steadily increasing costs, the benefits of quality control will become more evident and this will result in a greater need to obtain 'life-cycle cost' estimates.

Contacts were made with experts on concrete aggregate in all provinces, except Prince Edward Island, which imports aggregate from nearby provinces, to obtain first-hand information on the current supply and demand of aggregates across Canada. Four detailed and a number of limited studies were found. The detailed studies covered the most densely populated parts of Ontario and Manitoba, and all of New Brunswick.

It would be desirable for all provinces that have not done so to commission studies to establish the availability of concrete aggregate, both now and in the future in the developed regions where demand is greatest. In this way it would become possible to make a national aggregate inventory, which would enable measures to be taken now to ensure the long-term supply of concrete aggregate so vital for industrial development.

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