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REPORT ON A LABORATORY INVESTIGATION INTO THE ALKALI-AGGREGATE REACTION POTENTIAL OF VOLCANIC ROCKS FROM ANDERSON ROAD QUARRIES

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FOREWORD

In mid-1991, at the request of the Quarries Section of the Office, the Public Works Central Laboratory (PWCL) of the Materials Division commenced an investigation into the alkali-aggregate reaction potential of the volcanic rocks from the Anderson Road Quarries. The main objective of the investigation is to provide information for the evaluation of the suitability of the use of such rocks as aggregates in concrete.

This report presents the results obtained from petrographic examination, chemical tests, mortar bar tests and accelerated mortar bar tests.

The early stage planning of this investigation was carried out by Mr P.C. Wong. Mr W.C. Leung took over the management of the project in January 1993. This report was prepared by Mr Leung in conjunction with Mr W.L. Tse, who supervised the mortar bar tests, Mr C.S. Mok, who supervised the chemical tests and Mr S.T. Gilbert, who carried out the petrographic examination.

The report was reviewed by Dr T.Y. Irfan as well as the Subcommittee on AAR of the Standing Committee on Concrete Technology.

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1. INTRODUCTION

The Anderson Road Quarries are located at Anderson Road, on the north-eastern part of Kowloon, where aggregates are being produced for both road and building construction. Quarrying at Anderson Road has been in operation since 1956. The K. Wah Quarry Co. Ltd works the northern part of the quarry site (the Tai Sheung Tok Quarry) and Pioneer Quarries (HK) Ltd on the southern part (the Anderson Road Area 3 Quarry). The original contracts of these operators, which commenced in 1974 (Pioneer) and 1978 (K. Wah) respectively, were for 12 years only and have subsequently been extended.

The geology of the quarry site has been mapped by the Hong Kong Geological Survey and is documented in Strange & Shaw (1986). The majority of the site is underlain by fine- to medium-grained granites. Volcanic tuff of Upper Jurassic Age occupies the upper levels of the quarry site. The volcanic tuff when first formed would have contained abundant volcanic glass and possibly other silica phases such as tridymite and cristobalite. These minerals are thermodynamically unstable and will recrystallise with time. As the volcanic tuff was formed some 150 million years ago, the recrystallisation process would have proceeded to a point where little discernible volcanic glass would be left (Workman, 1985).

The quarrying at Anderson Road has been mainly carried out on the granite and has currently reached the final landform specified in the contracts. In their 1993 report, Ove Arup & Partners (1993) have recommended the progressive restoration of the quarry through extending the quarrying rights. It is intended that the developed platform will be handed back to the Government for future development. It is anticipated that the restoration works may take about 20 years to complete and a large quantity of volcanic rocks will be produced. Although the physical and mechanical properties of the volcanic aggregates are at least as good as granite aggregates (Gilbert & Irfan, 1990; Irfan, 1994), there is considerable concern that certain types of volcanic aggregates may be prone to react with the alkalis that exist in the concrete paste. The reaction can cause expansion of the concrete, which may result in 'map cracking' of the construction.

In order to assess whether the volcanic rocks at Anderson Road are suitable to be used in concrete, the Quarries Section of the Office has requested the Materials Division to carry out laboratory testing on selected volcanic rock samples obtained from the Anderson Road Quarries. The laboratory works commenced in late 1992.

2. LITERATURE REVIEW

2.1 Alkali-Aggregate Reaction in Concrete

In many parts of the world, concrete deterioration occurs due to a reaction between some minerals in certain aggregates and the soluble alkaline components in the concrete which come mainly from the Portland cement. This reaction is known as the alkali-aggregate reaction (AAR). This reaction can result in detrimental expansion of the concrete characterised by a well-defined crack pattern commonly identified as 'map cracking'. The cracking process due to AAR in concrete is generally very slow; in most cases the cracks will start to appear in about ten to fifteen years after construction. In some extremely reactive aggregates, the cracks may appear within a few years after construction.

For alkali-aggregate reaction to occur in concrete, there must be reactive minerals present in the aggregates, as well as sufficient alkali and moisture in the concrete to support the reaction process (Concrete Society, 1987; Hobbs, 1980).

Two forms of alkali-aggregate reaction have been known to exist, namely alkali-silica reaction and alkali-carbonate reaction. The most commonly encountered form of AAR is the alkali-silica reaction which occurs with aggregates containing various forms of reactive silica. The alkali-carbonate reaction occurs mainly in aggregates from dolomitic limestones.

2.2 Reactive Minerals in Aggregates

The common forms of minerals regarded by most researchers as likely to cause the occurrence of AAR include opal, tridymite, cristobalite, microcrystalline to cryptocrystalline quartz, chalcedony, strained quartz and volcanic glasses (DOT, 1991; RILEM, 1993). These constituents are known to occur in a wide variety of quartz-bearing rocks including granite and volcanic rocks. For AAR to occur, the reactive minerals must be present in sufficient quantities. Table 1 gives a summary of the national threshold values of potentially reactive forms of silica in seven countries (RILEM, 1993).

Many authors have expressed opinions that the reactivity of minerals are related principally to their grain size and the amount of disorder in their crystal structures. Opal, which is amorphous has the highest disordered crystal structure and is considered to be the most reactive form of silica (Smith & Collis, 1993). At the other end of the scale is well ordered unstrained quartz which is normally considered to be innocuous.

Rocks containing strained quartz have frequently been recognised by petrographic examination as being potentially reactive and previous research has focused on developing quantitative petrographic methods to determine the degree of strain in individual quartz crystals (Dolar-Mantuani, 1983). More recent research (Andersen & Thaulow, 1989; French, 1992; Grattan-Bellew, 1992; Smith et al, 1992) has suggested that the measurement of degree of strain to determine reactivity in strained quartz can be misleading. Additional factors such as grain size, degree of crystal disorder and texture of the strained quartz crystals are now considered to have a greater influence on the potential for reaction.

2.3 Reactive Alkalis in Concrete

Alkali-aggregate reaction is a chemical reaction between the hydroxyl ions in the pore solution of the concrete and the aggregates. Therefore, the concentration of hydroxyl ions in the pore solution of concrete has a major influence on the occurrence of AAR.

The main source of alkalis in concrete is usually from the cement. Alkalis derived from other sources such as mixing water, alkali salts in the aggregates or concrete admixtures usually have a much lesser contribution. The alkali content in cement is usually expressed as percentage Na_2O equivalent which is equal to the sum of percentage Na_2O and 0.658 times the percentage K_2O present.

For a cement containing 1.0 % Na_2O equivalent, the pH of the pore solution under sealed condition is about 13.9, whereas the pH of saturated calcium hydroxide (i.e. with zero contribution from cement alkali) is around 12.5 (Shayan, 1991). As an increase in one pH unit is equal to tenfold increase in hydroxyl ion concentration, the alkali content of the cement has a direct influence on the alkali content of the pore solution in concrete and hence has a direct influence on the extent of AAR.

The extent of AAR is governed by the total amount of alkali present in the concrete. Cement with a high alkali content (0.6 % Na_2O equivalent or above) can still be used provided that the total amount of alkali in the concrete is within the safe limit.

The Hippo Quarries Ltd of South Africa carried out an extensive study on the AAR potential of South African aggregates and published safe alkali limits for a number of their aggregates (Hippo Quarries, 1991). The safe alkali limit for the aggregates used in concrete has to be first evaluated and the maximum acceptable cement content that may be used in concrete can then be calculated using the following equation:

$$\begin{array}{l}\text{Maximum acceptable}\\ \text{cement content of}\\ \text{concrete (kg/m}^3\text{)}\end{array} = \frac{\text{Safe alkali limit in kg per m}^3\text{ concrete} \times 100}{\text{Percentage Na}_2\text{O equivalent of cement}} \qquad \text{.......}\ (1)$$

2.4 Laboratory Methods for Evaluating the Potential Reactivity of Aggregates

2.4.1 Types of Methods

Various researchers have proposed testing methods for determining the potential reactivity of aggregates. The methods may generally be classified into the following types:

(a) Petrographic examination
(b) Chemical tests
(c) Expansion tests
(d) Accelerated mortar bar tests

2.4.2 Petrographic Examination

Petrographic examination is the description of rocks in hand specimen and thin section. It is an essential first step in evaluating the potential reactivity of an aggregate. It provides information on the type or types of rock comprising the aggregate. The information provided will enable a decision to be made as to whether further testing is necessary. In the recent RILEM Technical Committee TC106 survey (RILEM, 1993), it was found that most countries rated the petrographic examination as an essential screening test. The ASTM C295-85 procedure (ASTM, 1985) is the most commonly used standard for petrographic examination of aggregates.

Although petrographic evaluation is rapid and convenient, many researchers (CSA, 1993) have reported difficulties in quantifying the potential alkali-reactivity of an aggregate from its petrographic examination results. This is partly due to the very fine grain sizes and low concentrations of some of the reactive minerals which make it very difficult to identify their existence by using conventional microscope. Very often, more advanced and costly techniques such as SEM and X-ray diffraction need to be used.

2.4.3 Chemical Tests

A number of chemical tests are available to test the potential reactivity of aggregates. These include the ASTM C289-87 chemical test (ASTM, 1987a) the gel-pat test (Jones & Tarleton, 1958), the German dissolution test (German Committee for Reinforced Concrete, 1986), and the osmotic cell test (Stark, 1983).

In the ASTM chemical test, the reactivity of the aggregates is evaluated by measuring the amount of dissolved silica and the reduction in alkalinity in the reaction alkali solution. The gel pat test is basically a screening test for highly reactive aggregates by observing the formation of gels on the aggregate surface after immersion in an alkali solution. The German dissolution test measures the reduction in weight of the aggregates after reacting with an alkali solution. The osmotic cell test evaluates the reactivity of aggregates by measuring the difference in osmotic pressure of alkali solutions across a cement paste membrane, one side of which contains a solution that has reacted with the aggregates and the other side contains a solution that has not reacted with the aggregates.

The RILEM survey (RILEM, 1993) indicated that the most commonly used chemical test was the ASTM C289-87 test. This is a rapid test which takes only a few days to complete. However, the same survey also indicated that no country had found the chemical tests to be worth rating as a primary test. Most countries regarded the chemical tests as secondary and supporting tests.

2.4.4 Expansion Tests

Expansion tests are widely used to assess the AAR potential of aggregates. The commonly used expansion tests are the mortar bar test as described in ASTM C227-87 (ASTM, 1987b) and the concrete prism test (CSA, 1993).

The mortar bar test is one of the earliest test methods developed to evaluate the potential reactivity of aggregates and hence it has been widely used. It involves the casting of a mortar bar and storing it at 38°C and 100% humidity. The expansion of the mortar bar is then monitored. It has been found that the results from mortar bar tests tend to underestimate the potential reactivity of certain aggregates (Grattan-Bellew, 1989). The low expansions obtained for some of the known reactive aggregates may be caused by the lack of sufficient alkalis in the cement (Rogers & Hooton, 1991). A cement alkali content of between 1% and 1.2% is often used (Hobbs, 1988). In Canada, it has been found that use of a cement with an alkali content of 1.25% and testing for at least one year is necessary in order to identify successfully the majority of alkali-silica reactive aggregates (CSA, 1993).

The concrete prism test is a relatively new test developed to evaluate the potential reactivity of aggregates. Canada has produced a draft standard (CSA, 1993) on the concrete prism test. RILEM is in the process of producing its own standard test procedure. BSI is also drafting a British version of the concrete prism test. The concrete prisms of these draft standards are very similar and are generally about 75 x 75 x 300 mm in dimension. In the test, the prism is cured at 38°C and approximately 100% humidity for up to two years, during which the expansion of the prism is monitored. Up to now, the expansion criteria for distinguishing deleterious aggregates from innocuous aggregates have not been firmly established.

2.4.5 Accelerated Mortar bar Tests

As the conventional expansion tests take about one to two years to complete, many researchers (Grattan-Bellew, 1990; Oberholster & Davies, 1986; Shayan, 1989) have proposed accelerated versions of the expansion tests in the hope that conclusion on aggregate reactivity may be obtained within a short time. Canada has produced a draft standard (CSA, 1993) on the accelerated mortar bar test. The accelerated expansion test methods proposed by Oberholster & Davies (1986) and Shayan (1989) are very similar to that in the draft Canadian Standard. Basically, they all propose to measure the expansion of a mortar bar immersed in 1M NaOH solution at 80°C. If the expansion exceeds 0.1% over a standard time, the aggregate is classified as deleterious.

3. LABORATORY INVESTIGATION

3.1 Collection and Description of Samples

Two samples of volcanic tuff (viz. AR4 and AR5) were obtained from the upper quarry face at the Anderson Road Area 3 Quarry (Pioneer) in April 1992. Another two samples of volcanic tuff (viz. AR6 and AR7) were collected from the same area one year later to obtain more material for additional tests. The results to be described later indicate that the two batches of samples are petrographically similar and give similar expansions in the mortar bar and accelerated mortar bar tests.

In order to obtain results for comparison purposes, three samples of granite (viz. AR1 to AR3) were also taken from the Anderson Road Tai Sheung Tok Quarry (K. Wah). One of these was collected from the aggregate stockpile and the other two were obtained from the quarry face.

The samples were examined and described by a geologist and the sample sizes and descriptions are given in Table 2.

Specimens were obtained from both the volcanic and granite samples for the study, and the examination and tests carried out are described below.

3.2 Test Procedure and Results

3.2.1 Petrographic Examination

The petrographic examination carried out generally followed the procedure of ASTM C295-85 for identification of potential AAR constituents. Six rock thin sections were made from the volcanic tuff samples and two rock thin sections were made from the granite samples. The petrographic examination results are summarised in Table 3. Similar rock thin sections made by the Hong Kong Geological Survey were also examined. The results are also summarised in Table 3.

Two specimens of volcanic tuff were sent to the British Geological Survey (BGS) in United Kingdom for mineralogical analysis using the X-ray diffraction technique to confirm the presence and quantity of potential reactive constituents. The X-ray diffraction results are summarised in Table 4.

3.2.2 Chemical Tests

Two types of tests were carried out, viz. the gel pat test and the ASTM C289-87 chemical test.

The gel pat test was carried out in accordance with the method described in the National Building Studies Research Paper 25 (Jones & Tarleton, 1958). In the test, the aggregates were crushed and incorporated in cement pats. The pats were then immersed in a solution containing 20g/L of NaOH, 28g/L of KOH and saturated with CaO at 20°C. If the aggregates are reactive, gels will be formed on the surface of the pat within a few days of immersion. A total of five volcanic tuff samples and three granite samples were tested. After seven days of immersion, none of the samples showed any gel formation.

Seven samples of volcanic tuff were tested in accordance with the ASTM C289-87 procedure. The results are given in Table 5 and plotted on a Dissolved Silica versus Reduction in Alkalinity (Sc-Rc) correlation graph in Figure 1.

3.2.3 Expansion Tests

Both the volcanic tuff and granite rocks were tested for AAR reactivity using the ASTM C227-87 mortar bar test method. The concrete prism test was not carried out because at the time of commencement of this investigation, standard test procedure was not yet available.

The mortar bars were prepared in accordance with the procedure given in ASTM C227-87. A total of 12 mortar bars made from volcanic tuff aggregates and four mortar bars from granite aggregates were tested. The cement used in this test had a reactive alkali content of 0.7%. Two series of tests were carried out. In the first series, the alkali content of the mortar bars was 0.7%. In the second series, an alkali content of 1.2% was used. The higher alkali content was made possible by the addition of suitable quantities of sodium hydroxide in the mixing water.

The bars were demoulded at 24 hours and initial measurement of their length was taken immediately. The bars were then wrapped in moist towels and placed in a humidity chamber in which the temperature was maintained at 38°C and the relative humidity at approximately 100%. The bar expansion was measured at ages of 1, 2, 3, 4, 6, 9, and 12 months.

The expansions of the mortar bars are summarised in Tables 6 and 7. Curves showing the average expansions of the mortar bars are shown in Figures 2 and 3.

3.2.4 Accelerated Mortar Bar Tests

At the commencement of this investigation, no standard test procedure for the accelerated mortar bar test was available. However, it was considered worthwhile to carry out the test to obtain results for reference. It was decided that the Australian procedure as proposed by Shayan should be adopted. The mortar bars were prepared in accordance with

Australian Standard AS1141-38 (SAA, 1974). This is very similar to that of ASTM C227-87. The main difference being that the flow of the mortar mix is improved in the Australian method. The reactive alkali content of the cement used in the mix was 0.85%.

After casting, the moulds were stored at an environment of 23°C and at a relative humidity above 90%. The moulds were demoulded after 24±2 hours and were further cured for three days. At this stage, the lengths of the bars were measured. The bars were then placed above a water bath and the temperature of the water was slowly raised. The temperature of the air above the water bath was slowly raised to 80°C and maintained constant for 30 minutes. The length of each bar was measured again and these were taken as the initial length. The bars were then immersed in a bath of 1M NaOH solution at 80°C. The expansions of the mortar bars were monitored for a period up to three months. The test results are given in Table 8 and curves showing the average expansions are shown in Figure 4.

3.3 Discussion of Results

3.3.1 Petrographic Examination

The petrographic examination of thin sections of volcanic tuff from the Anderson Road Area 3 Quarry indicated the presence of potentially reactive microcrystalline to cryptocrystalline quartz and strained quartz in all of the samples examined. The results of the X-ray diffraction analyses indicated total quartz contents, for the samples examined of 29% and 40% which, as a result of the very low quartz crystal contents of these rocks, can be assumed to represent the quantity of microcrystalline to cryptocrystalline quartz in the rock matrix. These quantities of microcrystalline to cryptocrystalline quartz are well in excess of the national threshold limits for potential reactivity for these constituents (See Table 1). Other known forms of reactive silica such as opal, chalcedony, cristobalite and tridymite were not identified in thin section or by the X-ray diffraction analyses.

It was not possible with the conventional polarising microscope to quantify the degree of potential reactivity of strained quartz, present in both the crystals and the matrix of all of the thin sections examined, because of the low crystal content and the very fine grained nature of the rocks which was at times beyond the resolution of the petrographic microscope used in the examination.

Comparative petrographic examination of thin sections of granite from the Anderson Road Tai Sheung Tok Quarry indicated the presence of potentially reactive strained quartz in some crystals in all the samples examined. However, the straining is generally slight and, in view of the relatively large grain size of the quartz crystals in these rocks, is not considered to constitute a strong potential for AAR.

The ASTM C295-85 method was employed in the study as it is the most widely used method internationally for the petrographic examination of aggregates for AAR. The method has been specifically designed for the assessment of the suitability of aggregates for use in concrete. It is also sufficiently flexible in its approach to permit petrographic examination for particular purposes such as the investigation of AAR potential, for which some guidance is given, by use of additional techniques such as X-ray diffraction analysis and other appropriate methods. In this respect the method therefore is seen as being more appropriate for the investigation of AAR in aggregates than other petrographic methods which are more inflexible in their approach. The method does not however permit the quantitative determination of mineral constituents and can only determine relative mineral proportions by qualitative means.

Quantitative determination of potentially reactive components of aggregates is important to allow the proportions of these constituents to be compared against the established national threshold limits for assessing the degree of potential reactivity. The most commonly used method for determining the proportions of mineral constituents in aggregate is by point counting mineral constituents in thin sections to establish the percentage of each mineral present. However, careful consideration should be given to the extent of the point counting coverage in relation to the grain size of the samples otherwise the assessment will not be statistically representative. This method is however not suited for the assessment of very fine grained rocks such as the volcanic tuffs of the Anderson Road Area 3 Quarry the mineral constituents of which are too small to be quantitatively assessed in thin section using a conventional polarising microscope with point counting stage.

Some success has been gained during the study in determining the quantitative proportions of reactive constituents present in the volcanic tuffs using X-ray diffraction methods although difficulties will arise in the resolution of reactive components when these are present in very low quantities (<2%). It is therefore considered that the ASTM C295-85 method in conjunction with X-ray diffraction analysis, for quantitative assessment, is an appropriate petrographic method for the assessment of the AAR potential of the volcanic tuffs at Anderson Road. In contrast, the granites as a result of their coarser grained nature can be adequately assessed by the ASTM C295-85 method in conjunction with point counting for quantitative determination of mineral constituents.

3.3.2 Chemical Tests

The gel pat test is a preliminary screening test and only very reactive aggregates will give gel formation within a few days. The absence of gel in the eight test specimens indicates that the aggregates tested were not highly reactive.

Thirty specimens have been tested by the ASTM C289-87 chemical test method and the results are considered to be innocuous according to the ASTM C289-87 Sc-Rc correlation diagram (see Figure 1). Nevertheless it can be seen that some of the test results cluster near the innocuous/deleterious boundary line of the correlation diagram.

The ASTM C289-87 method was based on a study of about 100 reactive and non-reactive materials (Mielenz et al, 1947; Mielenz & Witte, 1948) and the correlation diagram was originally prepared on the basis of a correlation between the results of the chemical tests, the mortar bar tests, petrographic examination and the service history of the aggregates. The curve that divides innocuous and deleterious aggregates was in fact drawn from expansion data of mortar bars at 38°C, where expansion over 0.1% in one year was considered to be reactive, and by petrographic examination results (Jones & Tarleton, 1958). It should be noted that other expansion criteria have been adopted to interpret the reactivity of aggregates (Grattan-Bellew, 1983).

The ASTM C289-87 method is widely used because the test provides useful data to indicate potential reactivity of aggregates and the results can be obtained quickly compared to the expansion tests. Nevertheless, the chemical test as well as the mortar bar expansion test have been reported by many researchers to lack reliability and are inappropriate for confirming reactivity of aggregates (Grattan-Bellew, 1983; Shayan et al, 1988; Sorrentino et al, 1988).

It has also been reported that the chemical test is not applicable to a number of rock types, especially reactive rocks containing carbonates such as calcite and dolomite, or silicates of magnesium, such as serpentine (ASTM 1987a).

Slowly reactive aggregates may not be detected as potentially reactive by the chemical test either because the amount of reactive material is low, or because the amount of dissolved silica is underestimated due to precipitation by certain elements in the constituent materials. The results of chemical tests indicate that potentially reactive aggregates may be classified as innocuous by the method (Shayan, 1991). In view of the limitation of the chemical method in quantifying the reactivity of aggregates, and the fact that some of the test results for the aggregates under study are close to the boundary line between innocuous and deleterious aggregates, the reactivity of the aggregates needs to be further assessed by other methods.

3.3.3 Expansion Tests

At the age of one year, the mortar bars having a cement alkali content of 0.7% gave an average expansion of 0.013% (Figure 2). This is rather low in comparison with the criterion proposed by Jones & Tarleton (1958), viz. 0.1% expansion in one year. Furthermore, there is very little difference in the expansion characteristics between the granite aggregates and the volcanic aggregates, indicating that the 0.7% alkali content limit may be too low to be effective for the testing. The same conclusion has been drawn by other researchers as reviewed in Section 2.4.4.

For bars made with a 1.2% cement alkali content, the average expansion at one year is 0.047% for fine ash vitric tuff (Figure 3). The one year expansion data of the granite aggregates has yet to be obtained but at the age of nine months, the granite mortar bars gave an expansion which is equal to about half the expansion of the volcanic tuff mortar bars. Using the 0.1% expansion criterion, both the volcanic and granite aggregates would be classified as innocuous by the ASTM C227-87 method.

As discussed in Section 2.4.4, many researchers have cast doubt on the effectiveness of the mortar bar test despite it being the most widely used test for determining the potential alkali-aggregate reactivity of aggregates. It has been reported that this test tends to underestimate the potential reactivity of certain aggregates (Grattan-Bellew, 1989).

3.3.4 Accelerated Mortar bar Tests

The accelerated mortar bar test carried out was based on the Australian method as proposed by Shayan. The criteria used by Shayan to distinguish potentially reactive aggregates is 0.1% expansion at 22 days. Any aggregate giving an expansion of more than 0.1% is classified as potentially reactive.

The average expansion of the Anderson Road volcanic tuff aggregates at 22 days varies from 0.45% for fine ash vitric tuff to 0.34% for fine ash tuff. Both values well exceeded the 0.1% expansion limit and the aggregates can therefore be classified as potentially reactive based on the accelerated mortar bar test.

The results of the accelerated tests on the Anderson Road aggregates are shown in Figure 4 together with the results for a number of locally available aggregates as well as of aggregates from overseas. It can be seen that the Anderson Road fine ash vitric tuff aggregates exhibited the highest expansion at 22 days. The expansions of the granite aggregates are well below those of the volcanic aggregates. Figure 4 also shows the expansions of the two Canadian and one Australian reference aggregates (known to be reactive) under the same test conditions. The Sudbury aggregates expanded by 0.393% and the Spratt aggregates expanded by 0.338%. The expansions of the Anderson Road volcanic aggregates are of the same order as those of these reactive aggregates from Canada.

The test results seem to indicate that the Anderson Road volcanic tuff aggregates are potentially reactive. The accelerated mortar bar test can give results in 25 days and appears to be suitable to be used as a quick standard test to screen out potentially reactive aggregates. More work is needed before this can be confirmed.

4. CONCLUSIONS AND RECOMMENDATIONS

In response to the request of the Quarries Section, the PWCL carried out a laboratory investigation of the alkali-aggregate reaction potential of volcanic rocks from the Anderson Road Quarries. A total of eight rock thin sections were prepared and examined. The gel pat test was carried out on eight rock specimens and thirty other specimens were tested using the ASTM C289-87 chemical test method. A total of fourteen mortar bars were prepared and their expansions monitored under standard test conditions. Ten other mortar bars were prepared and tested using the accelerated method. Based on the results of these tests, the following conclusions can be drawn:

(a) The petrographic examination of thin sections of volcanic tuffs from the Anderson Road Quarries indicated the presence of potentially reactive microcrystalline to cryptocrystalline quartz and strained quartz in all of the samples examined.

(b) The X-ray diffraction analyses results carried out on two samples of volcanic tuff indicated that the quantity of microcrystalline to cryptocrystalline quartz in the volcanic tuff well exceeded the established national threshold limits for potential reactivity for these constituents.

(c) Because of the very fine grain sizes of some of the local rocks, such as the volcanic tuffs of the Anderson Road Quarry, and the difficulties encountered in quantifying the reactive minerals, it is considered that the petrographic examination should only be used as a preliminary screening test for identifying the presence of potentially reactive minerals. The results of petrographic examination will assist in determining the extent and type of further testing that needs to be carried out.

(d) Gel formation was not observed in the gel pat test for all of the samples tested.

(e) The ASTM C289-87 chemical test gave results which indicate little distinction between the AAR potential of the volcanic tuff and granite aggregates of Anderson Road. Both rock types would be classified as innocuous by this test.

(f) From the mortar bar tests carried out, it was found that the recorded expansions of the Anderson Road aggregates were low even after a testing duration of one year.

(g) The results of the accelerated mortar bar test indicated that the potential reactivity of the volcanic tuff aggregates at Anderson Road is up to about four times that of granite aggregates and, according to available guidelines, the volcanic tuff aggregates would be classified as potentially reactive. The results also indicated that the reactivity of the volcanic tuff aggregates is similar to that of the reference reactive aggregates from Canada.

From this study, it appears that the accelerated mortar bar test can differentiate the relative reactivity of different rock types with respect to AAR. Therefore, it is recommended that the effectiveness of the accelerated mortar bar test in classifying potentially reactive aggregates should be further investigated.

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Table 1 - National Threshold Values of Potentially Reactive Forms of Silica in Aggregates (after RILEM, 1993)

Country	Potentially Reactive Forms of Silica Found in Aggregates	Threshold of Reactivity
Belgium	Opal, chalcedony, microcrystalline & cryptocrystalline quartz.	<2%
Canada	Opal, tridymite, cristobalite volcanic glasses, beekite. Chalcedony, microcrystalline to cryptocrystalline quartz, macrogranular quartz with deformed crystal lattice.	As little as 1% As little as 5%
Denmark	Opal, cryptocrystalline quartz.	<2%
Ireland	Opal, cristobalite and tridymite chalcedony, microcrystalline & cryptocrystalline quartz, volcanic glass.	Opal, cristobalite and tridymite = 0% Chalcedony, microcrystalline quartz, volcanic glass <0.5% Strained Quartz <30%
Norway	Microcrystalline quartz.	<2%
Russia	Opal, microcrystalline quartz, volcanic glass, cristobalite, tridymite, chalcedony.	<5%
UK	Opal, cristobalite and tridymite. Microcrystalline & cryptocrystalline quartz, strained quartz, opal, chalcedony, volcanic glass. Strained quartz.	Opal, cristobalite and tridymite = 0% Microcrystalline to cryptocrystalline quartz (in flint) <2% and >60% in coarse aggregate; <5% in fine aggregate. Strained Quartz <30%

Table 2 - Description of Samples from the Anderson Road Quarries

Source of Sample	Date of Sampling	Sample No.	Size of Sample	Description of Rock Type in Hand Specimen
Anderson Road Tai Sheung Tok Quarry (K. Wah)	23.4.92	AR 1 AR 2 AR 3	Boulder Boulder 20 mm	Medium-grained GRANITE Medium-grained GRANITE Medium-grained GRANITE (occasional fragments of dyke rock)
Anderson Road Area 3 Quarry (Pioneer)	23.4.92	AR 4 AR 5	Boulder Boulder	Fine ash TUFF (occasional rock fragments) Fine ash vitric TUFF
Anderson Road Area 3 Quarry (Pioneer)	20.4.93	AR 6 AR 7	Boulder Boulder	Fine ash TUFF Fine ash vitric TUFF

Table 3 - Summary of Petrographic Examination Results on Rock Samples from Anderson Road Quarries

Specimen/Thin Section No.	Rock Type	Major Constituents	Minor Constituents	Potentially Reactive Constituents
AR1	Medium grained GRANITE	Quartz K-feldspar plagioclase	Mica & chlorite	Strained quartz with lattice defects
AR2	Medium grained GRANITE	Quartz & K-feldspar (dominant) plagioclase	Mica & chlorite	Strained quartz with lattice defects
AR6a	Fine ash TUFF	Quartz (dominant) K-feldspar	Mica, chlorite, iron pyrites/oxides	Microcrystalline quartz Strained quartz
AR6b	Fine ash TUFF	Quartz, K-feldspar plagioclase	Mica, chlorite	Microcrystalline quartz Strained quartz
AR6c	Fine ash TUFF	Quartz K-feldspar	Mica, chlorite, iron pyrites/oxides	Microcrystalline quartz Strained quartz
AR7a	Fine ash vitric TUFF	K-Feldspar (dominant) quartz	Mica, chlorite, iron pyrites/oxides	Microcrystalline to cryptocrystalline quartz
AR7b	Fine ash vitric TUFF	K-feldspar (dominant) quartz, mica	Mica, chlorite, iron pyrites/oxides	Microcrystalline to cryptocrystalline quartz, strained quartz
AR7c	Fine ash vitric TUFF	K-feldspar (dominant) quartz, mica	Mica, chlorite, iron oxides/pyrites	Microcrystalline to cryptocrystalline quartz
HK 1042	HORNFELS	--	--	Microcrystalline quartz Strained quartz

Table 3 - Summary of Petrographic Examination Results on Rock Samples from Anderson Road Quarries (Cont.)

Specimen/Thin Section No.	Rock Type	Major Constituents	Minor Constituents	Potentially Reactive Constituents
HK 1044	Fine ash TUFF	Quartz and K-feldspar (dominant) plagioclase	Chlorite, mica, iron pyrites/oxides, zircon	Microcrystalline quartz Strained quartz
HK 7021	Fine ash TUFF	Quartz K-feldspar	Chlorite, mica, iron oxides/pyrites, zircon	Microcrystalline to cryptocrystalline quartz
HK 7022	Fine ash TUFF	Quartz & K-feldspar (dominant) mica	Chlorite, mica, iron oxides/pyrites, zircon	Microcrystalline quartz
HK 7024	Fine ash vitric TUFF	K-Feldspar (dominant) quartz	Mica, chlorite, iron oxides	Microcrystalline to cryptocrystalline quartz
HK 8723	Medium-grained GRANITE	Quartz, K-feldspar & plagioclase (dominant) Mica	Mica, chlorite, iron oxides	Strained quartz with lattice defects
HK 8724	Medium-grained GRANITE	Quartz, K-feldspar & plagioclase	Mica, chlorite, iron oxides	Strained quartz with lattice defects
HK 8725	Medium-grained GRANITE	Quartz, K-feldspar & plagioclase (dominant), mica	Chlorite, mica, iron oxides	Strained quartz with lattice defects
HK 8726	Fine-to medium-grained GRANITE	Quartz (dominant) K-feldspar, plagioclase, mica	Chlorite, mica	Strained quartz with lattice defects
HK 8727	Medium-grained GRANITE	Quartz, K-feldspar & plagioclase (dominant) mica	Chlorite & mica	Strained quartz with lattice defects
Note: Specimen No. HK 1042, 1044, 7021, 7022, 7024, 8723 to 8727 were sample specimens obtained by Hong Kong Geological Survey.				

Table 4 - X-ray Diffraction Analysis Results of Volcanic Aggregates

Specimen No.	X-Ray Diffraction Results
AR7a	AR7a contains dominant quartz (29 wt %), major Na-feldspar and K-feldspar, minor chlorite and mica and trace magnetite. The presence of pyrite was not confirmed. The 4.26A peak width was 0.16°2θ.
AR7b	AR7b contains dominant quartz (40 wt %), major K-feldspar and Na-feldspar, and minor chlorite and mica. The presence of pyrite and iron oxides was not confirmed. The 4.26A peak width was 0.15°2θ.

Table 5 - Chemical Test Results of Anderson Road Aggregates (based on ASTM C289-87)

Sample No.	Silica content in the original filtrate (Sc) (millimoles per litre)		Reduction in alkalinity (Rc) (millimoles per litre)	
	Results	Mean	Results	Mean
AR3	19.3 19.4 19.1	19.3	18.5 18.5 20.5	19.2
AR4	26.1 26.6 25.7	26.1	27.0 23.0 24.0	24.7
AR5	25.7 25.5 25.8	25.7	25.0 24.0 29.0	26.0
AR8a	27.6 27.6 28.4	27.9	25.5 30.5 30.6	28.9
AR8b	32.0 34.0 33.0	33.0	25.5 17.9 15.3	19.6
AR8c	21.8 22.0 22.4	22.1	66.4 63.8 71.5	67.2
AR8d	25.6 25.4 25.2	25.4	28.1 30.6 33.2	30.6
AR8e	26.9 25.1 27.1	26.4	17.3 18.3 15.3	17.0
AR8f	23.2 22.2 20.9	22.1	20.4 15.3 19.3	18.3
AR8g	21.1 22.1 22.1	21.8	18.5 20.5 21.5	20.2

Note: (1) The descriptions of sample nos AR3 to AR5 are given in Table 2.
(2) The AR8a to AR8g samples were delivered to the PWCL by the Mines and Quarries Division of GEO in August 1991.

Table 6 - Mortar Bar Expansion Test Results of an Anderson Road Aggregates at Alkali Content of 0.7%

Rock Types	Specimen No.	Expansion (%)						
		1 month	2 months	3 months	4 months	6 months	9 months	12 months
Granite (AR3)	AR3a AR3b	0.007 0.006	0.008 0.008	0.010 0.008	0.010 0.009	0.014 0.013	0.013 0.012	0.015 0.013
Fine ash tuff (AR4)	AR4a AR4b	0.005 0.004	0.008 0.008	0.009 0.008	0.010 0.008	0.013 0.011	0.013 0.010	0.015 0.012
Fine ash vitric tuff (AR5)	AR5c AR5d	0.005 0.006	0.008 0.010	0.010 0.010	0.010 0.011	0.013 0.013	0.011 0.013	0.011 0.012

Notes : The mortar bars were cured in an environment of 100% R.H. at 38°C.

Table 7 - Mortar Bar Expansion Test Results of an Anderson Road Aggregates at Alkali Content of 1.2%

Rock Types	Sample No.	Expansion (%)						
		1 month	2 months	3 months	4 months	6 months	9 months	12 months
Granite (AR3)	AR3i AR3j	0.008 0.010	0.014 0.014	0.014 0.016	0.018 0.020	0.021 0.021	0.022 0.023	
Fine ash tuff (AR4)	AR4k AR4l	0.009 0.011	0.017 0.019	0.021 0.023	0.022 0.023	0.025 0.025	0.023 0.025	
Fine ash vitric tuff (AR5)	AR5e AR5f	0.017 0.017	0.028 0.029	0.034 0.031	0.041 0.035	0.051 0.037	0.053 0.038	0.054 0.040
Fine ash vitric tuff (AR7)	AR7k AR7l	0.011 0.012	0.018 0.021	0.028 0.026	0.034 0.032	0.038 0.035	0.041 0.038	

Notes : The mortar bars were cured in an environment of 100% R.H. at 38°C.

Table 8 - Accelerated Mortar Bar Test Results of Anderson Road Aggregates

Rock Types	Specimen No.	Expansion (%)									
		2 days	5 days	8 days	11 days	14 days	18 days	22 days	1 month	2 months	3 months
Granite (AR3)	AR3e	0.006	0.023	0.032	0.047	0.070	0.096	0.113	0.165	0.280	0.367
	AR3f	0.003	0.015	0.027	0.039	0.061	0.085	0.105	0.151	0.260	0.346
	AR3g	0.007	0.016	0.026	0.044	0.064	0.093	0.117	0.162	0.283	0.398
	AR3h	0.009	0.021	0.031	0.046	0.064	0.091	0.114	0.160	0.282	0.393
Fine ash tuff (AR4)	AR4g	0.026	0.094	0.152	0.210	0.257	0.307	0.348	0.447	0.680	0.867
	AR4h	0.020	0.088	0.145	0.204	0.250	0.299	0.342	0.439	0.665	0.850
Fine ash vitric tuff (AR5)	AR5i	0.038	0.130	0.211	0.286	0.340	0.397	0.446	0.553	0.795	1.009
	AR5j	0.036	0.132	0.217	0.293	0.350	0.408	0.459	0.569	0.816	1.032
Fine ash vitric tuff (AR7)	AR7e	0.024	0.089	0.157	0.215	0.280	0.336	0.373	0.464	0.700	0.886
	AR7f	0.022	0.089	0.155	0.213	0.280	0.334	0.372	0.462	0.699	0.883
Notes : The mortar bars were cured in a 1M NaOH solution at 80°C.											

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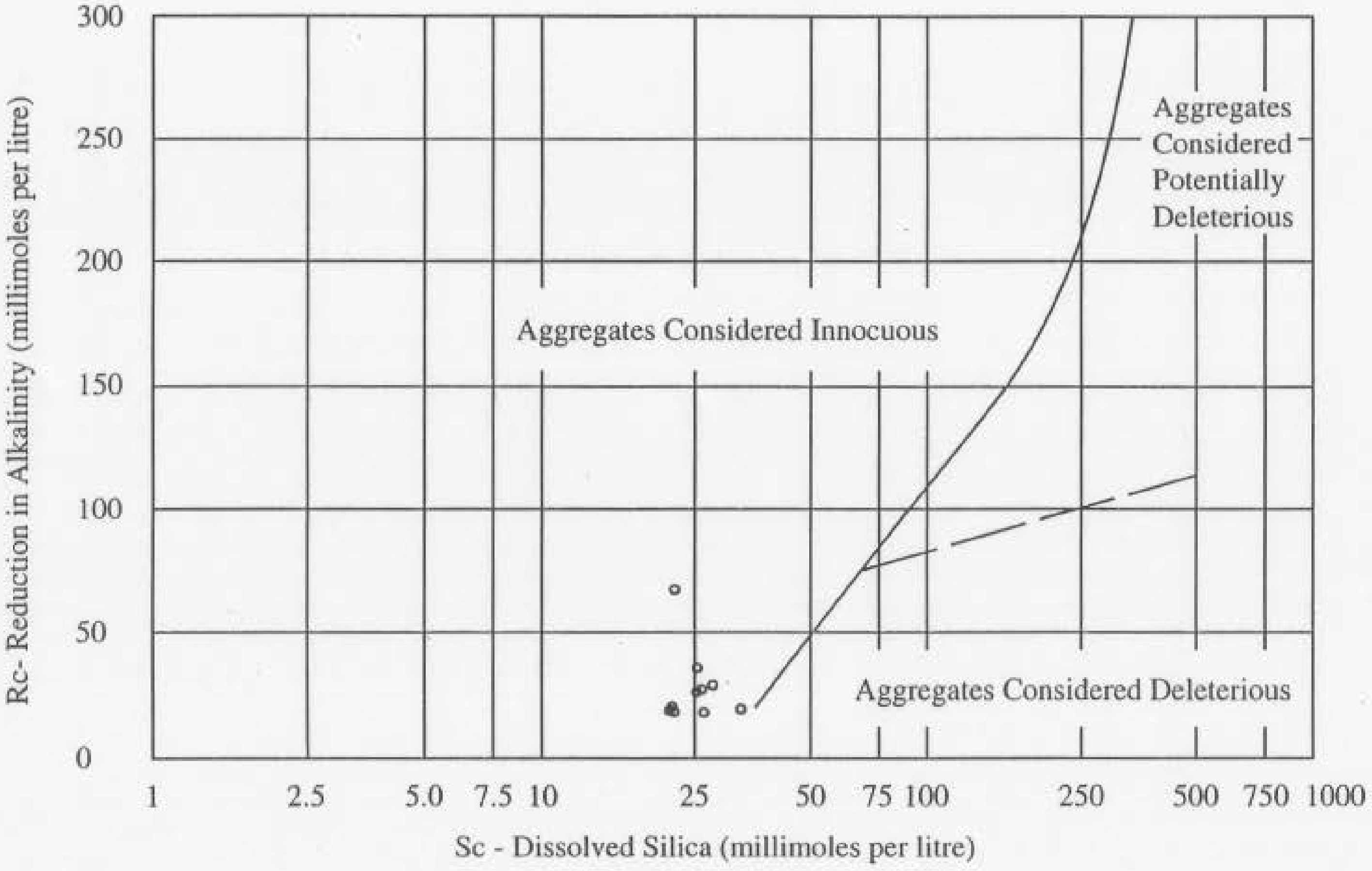
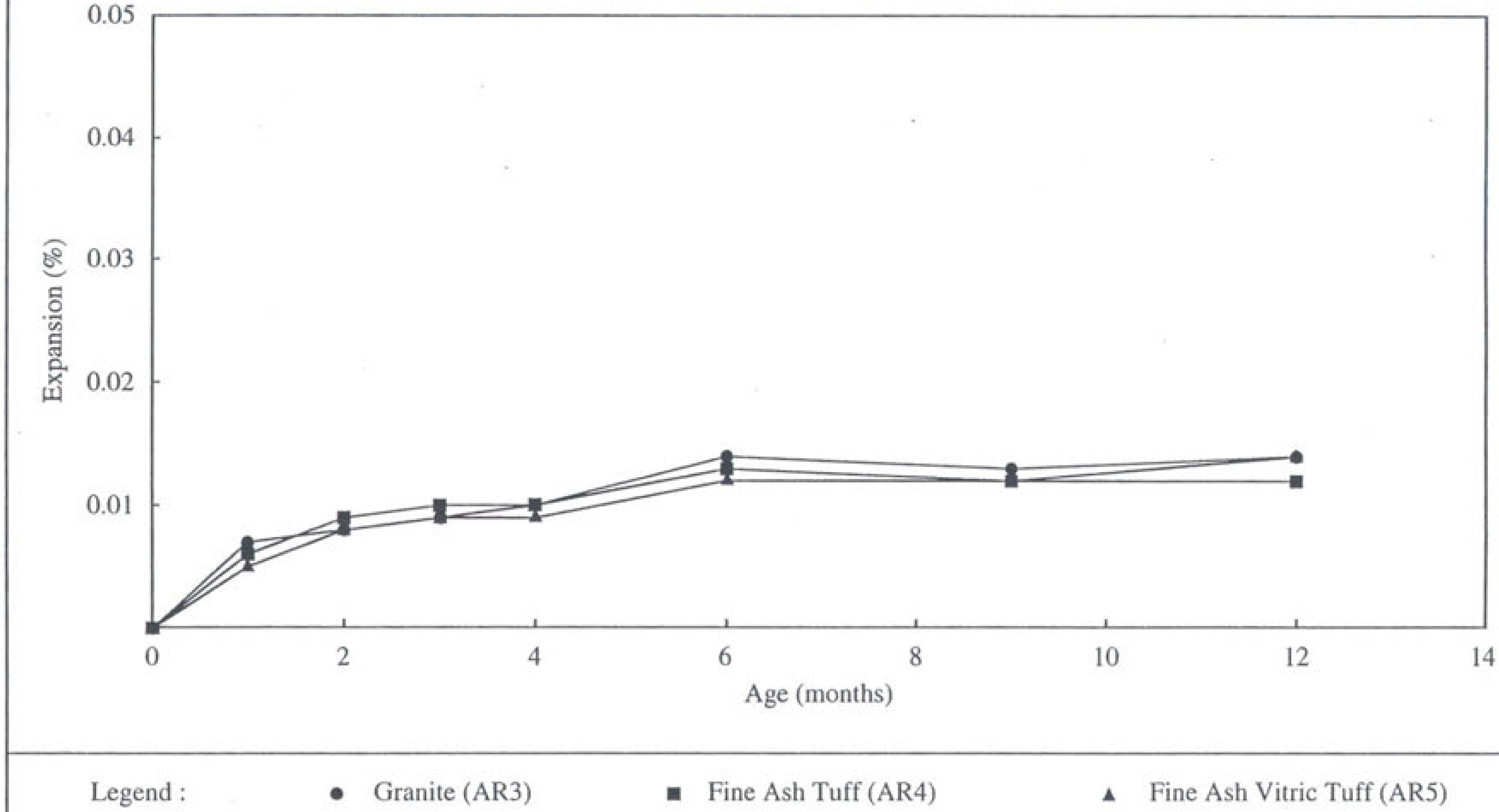


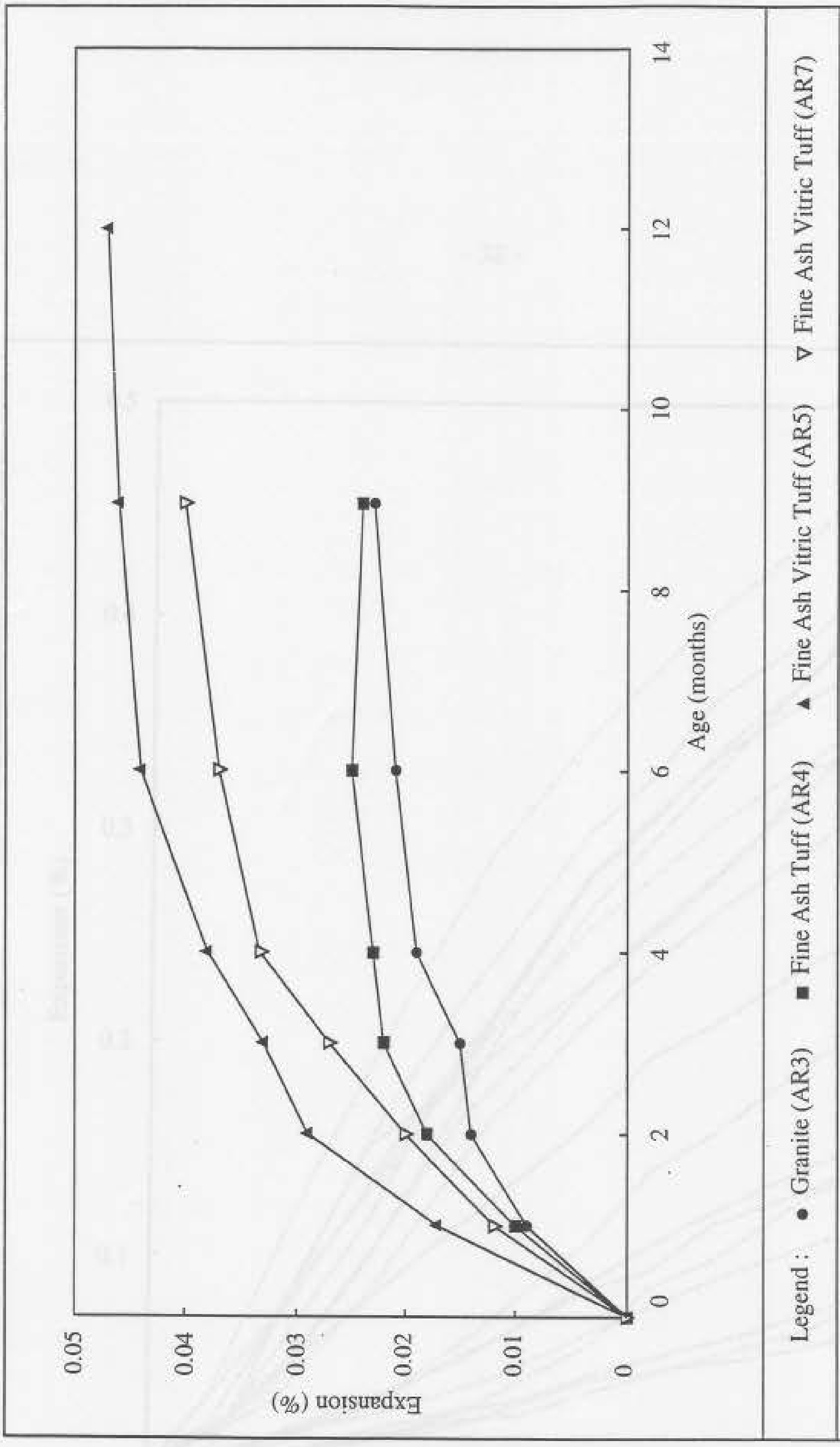
Note : The data in this figure are taken from the mean of the test results given in Table 5.

Figure 1 - ASTM C289 Chemical Test Results of Anderson Road Aggregates



Note : The expansion data in this figure are taken from the mean of the expansion results given in Table 6.

Figure 2 - Expansion of Motar Bars Made from Anderson Road Aggregates an Alkali Content of 0.7% and Subjected to Curing Environment of 100% RH at 38°C



Note : The expansion data in this figure are taken from the mean of the expansion results given in Table 7.

Figure 3 - Expansion of Mortar Bars Made from Anderson Road Aggregates at an Alkali Content of 1.2% and Subjected to a Curing Environment of 100% RH at 38°C

Legend :

AR5 - Fine Ash Vitric Tuff, Anderson Road Quarry
CH6 - Fine Ash Tuff, China
SB - Sudbury Agg., Canada
CH3 - Mylonite, China
AR7 - Fine Ash Vitric Tuff, Anderson Road Quarry
AR4 - Fine Ash Tuff, Anderson Road Quarry

SR - Spratt Agg., Canada
HK5 - Rhyolite, HK
AU - Ignimbrite, Australia
HK1 - Fine-grained Granite, HK
CH2 - River Sand, China

CH1 - Granodiorite, China
HK3 - Granite, HK
HK2 - Basalt, HK
AR3 - Granite, Anderson Road Quarry
HK4 - Granite, HK
CH4 - Granite, China
CH5 - Granite, China

Figure 4 - Expansion of Mortar Bars Made from Anderson Road Aggregates Cured in 1M NaOH Solution at 80°C