ALKALI - AGGREGATE REACTION
1981
ALKALI - AGGREGAATREAKSIE
S252

# A REVIEW OF THIRTY YEARS OF INVESTIGATION OF THE ALKALI-AGGREGATE REACTION IN NEW ZEALAND

by R A Kennerley*, D A St John* and L M Smith*

## SYNOPSIS

New Zealand has many potentially reactive rock types that have been used in major structures and because of this it has been necessary to carry out investigations of aggregates to ensure adequate durability for these structures. This paper reviews the work carried out to date on the use of a variety of tests.

An attempt is made to assess the results obtained from the investigations and relate them to the performance of the structures. The test methods for predicting alkali-aggregate reactivity are also discussed on the basis of their use in New Zealand.

## SAMEVATTING

Daar kom talle potensieel reaktiewe rotstipes in Nieu-Seeland voor wat in belangrike strukture gebruik is en dit het gevolglik nodig geword om ondersoek in te stel na aggregate ten einde voldoende duursaamheid vir sodanige strukture te verseker. Hierdie referaat gee 'n oorsigtelike verslag oor die werk wat tot op hede ivm die gebruik van 'n verskeidenheid toetse uitgevoer is.

Dit is 'n poging om die resultate, wat uit die ondersoeke verkry is, te evalueer en met die gedrag van die strukture in verband te bring. Die toetsmetodes om alkali-aggregaatreaksie te voorspel, word bespreek op grond van die aanwending daarvan in Nieu-Seeland.

**S252/12**

Conference on alkali-aggregate reaction in concrete
Cape Town - South Africa
March 30 - April 3, 1981

Konferensie oor alkali-aggregaatreaksie in beton
Kaapstad - Suid-Afrika
30 Maart - 3 April, 1981

Secretariat: NBRI of the CSIR
P O Box 395, Pretoria 0001, South Africa
Telephone (012) 86-9211 Telegrams Navorsbou
Telex SA 3-630

Sekretariaat: NBNI van die WNNR
Posbus 395, Pretoria 0001, Suid-Afrika
Telefoon (012) 86-9211 Telegramme Navorsbou
Teleks SA 3-630

* *Chemistry Division, DSIR, Petone, New Zealand*

## 1. INTRODUCTION

In New Zealand investigations on the reaction of cement alkalis with aggregates began in 1943. Since that date Chemistry Division DSIR has carried out extensive work[1-6] in response to requests from the Ministry of Works and Development and other agencies responsible for major public works. Recently there has been renewed interest in alkali-aggregate reactivity as the New Zealand cement industry moves to replace the wet process kilns with modern suspension pre-heater kilns which may make the production of low alkali* cement less economic at some works.

In this paper we briefly review the work carried out to date, discuss current work, and attempt to assess the results obtained in relation to the performance of some structures. A complete record and discussion of all test results is being published[7].

## 2. NEW ZEALAND CONCRETE AGGREGATES

The rock types used for concrete aggregate in New Zealand, in order of importance, are:

| *Most used rock types* | *Less used rocks* |
|---|---|
| greywacke-argillite sequence | phonolite |
| basalts | quartzites |
| andesites | granite and gneisses |
| dacites | schist |
| rhyolites (incl ignimbrite) | limestone |

Greywacke-argillite probably represents over half of all the aggregates produced. It is widely distributed throughout the country except in Taranaki where andesites are the only available rock for concrete aggregate. It is to be noted that the term greywacke-argillite covers a complex and variable, sequence of rocks consisting of indurated, poorly sorted sandstone/siltstone/mudstone materials which are heavily faulted and often deeply weathered. Good quarries eliminate most argillite and badly weathered material by careful selection and processing but a varying amount of siltstone is always present. While it is possible petrographically to categorise the greywacke sequence from individual localities, experience is showing that this is not meaningful when applied to concrete aggregates because physical properties are more important than composition.

Basalt, andesite, dacite and to a lesser extent rhyolite from the rocks of the central North Island volcanics find extensive use in these areas. The remaining aggregates listed are of very localised use. Limestone, because of its poor physical qualities, is rarely used. Flints and cherts are not common and rocks containing opaline type materials are also limited in occurrence. New Zealand rocks of this type are not used for aggregate and are not likely to be used for this purpose in the future.

## 3. PETROGRAPHY

Petrographic examination of aggregates is carried out by the New Zealand Geological Survey. It provides a valuable first grouping of the aggregates by rock type. Petrographers describe the rocks and report the presence of any appreciable amounts of (a) fine grained acid-intermediate matrix, whether glassy or crystalline, (b) cristobalite, (c) tridymite. Experience has shown that for New Zealand rocks it is unrealistic to expect any further diagnostic information from the petrographer. Some specialised work on the greywacke sequence reported later in this paper tends to confirm this statement.

However, concrete petrography has proved to be a valuable tool both for the examination of samples from failed structures and laboratory studies. Using large area thin sections (up to 150 x 125 mm) with close control of thickness and with complete edge retention[8-10], it has been possible to make a thorough examination of the nature of the alkali-aggregate reaction in concrete. It is our considered opinion that the more usual type of petrological thin section (25 x 25 mm) covers too small an area and destroys too much information for satisfactory petrographic examination of concrete. Figures 1 and 2 illustrate the type of information obtainable and also the typical morphology of reactive andesite in concrete. It is surprising how little of the aggregate appears to be involved in the reaction and how restricted are the sites where expansion

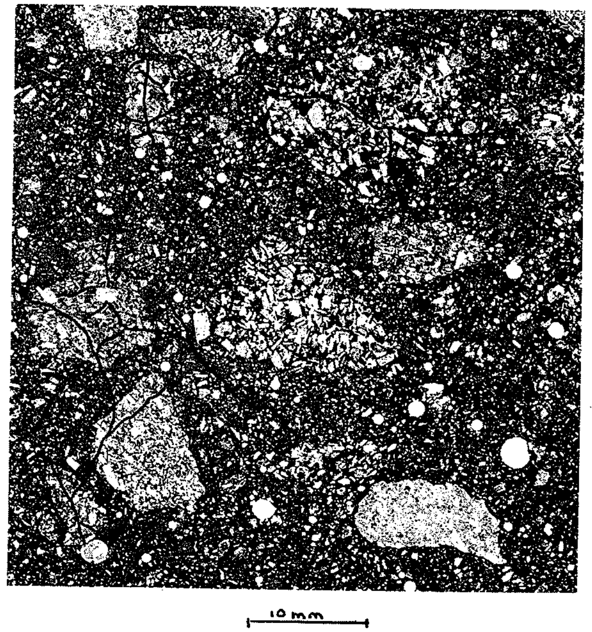

FIGURE 1: Petrographic thin section of the full cross section (75 x 75 mm) of a nine-year-old prism containing Egmont andesite. T15/1 from exposure site. (Cement content 594 kg/m$^3$, alkali content 1,20%, expansion 1,11%). Pattern of cracks has been delineated. Lighter areas of cement paste are due to absorption into aggregates.

---

* For brevity, the term alkali is used to signify $Na_2O$ equivalent in cement, unless otherwise stated.

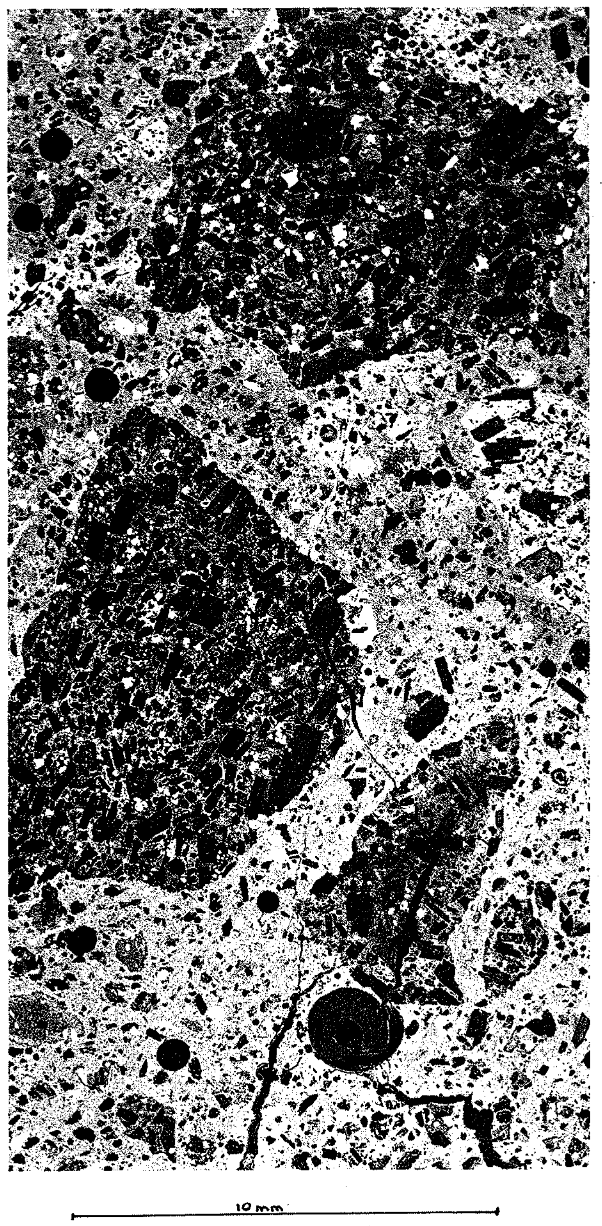

FIGURE 2: Enlarged portion of section shown in Figure 1 produced by using thin section as negative and enlarging directly onto photographic paper. Pore and cracks in lower portion of figure contain gel. Aggregate at top centre is badly cracked and part of its fabric disintegrating.

appears to be occurring. A similar pattern was found when we examined some concretes containing Canadian greywacke/argillite from the Maskinong and Lady Evelyn dams in Ontario[11]. This type of observation raises the question as to whether these reaction sites are concentrating alkali and how general is the type of concentration of alkali already reported by Poole[12].

## 4. QUICK CHEMICAL TEST (ASTM C289)

ASTM C289 has generally proved to be a reliable method for indicating the potential reactivity of New Zealand rocks with cement alkalis. The main problem encountered has been that for some rock types it has been difficult to wash all the dust from the 300-150 µm fraction of the aggregate and this has affected reproducibility. The chemical test effectively sorts igneous rocks into order of potential reactivity which is not possible by other petrographic methods. For instance it has revealed a wide range of potential reactivity for andesite rocks and has indicated that generally, the andesites from the Tongariro area are more reactive than those from the Egmont area. It is assumed that this difference in reactivity is due to the higher glass content and internal surface area of the Tongariro materials. This hypothesis has not been proven because it is impossible to define glass matrices and, additionally, even the so called 'fresh' andesites are partially devitrified.

## 5. ROCK PRISM TESTS

With rocks containing opaline-type silica or acid-intermediate glass or its alteration products, there is agreement among most workers that the principal reaction involves the formation and expansion of alkali-silica type gels. However, for other potentially reactive rock types such as greywacke/argillite, phyllite, quartzites etc, the reaction is less well understood and it is claimed that the Quick Chemical Test ASTM C289[13] and the Mortar Bar Test ASTM C227 do not give reliable results[14]. Grattan-Bellew[14] has published results that suggest that a modification of the Rock Prism Test ASTM C586 does indicate the potential reactivity of these latter rock types. The major New Zealand concrete aggregate is sandstone/siltstone grades of greywacke not dissimilar to some rocks reported as being reactive by other workers[13, 14]. Some early laboratory testing[6] had suggested that Rangitaiki River argillite was undergoing an unexplained, slow expansion, therefore a research programme involving the use of the Rock Prism Test was initiated. Tests have been carried out on greywacke from the two main urban areas, Auckland and Wellington, and also the Rangitaiki River. The results are shown in Figures 3a and b, (page 3).

From the results it is evident that Grattan-Bellew's findings are not applicable to the New Zealand greywacke sequence of rocks. His largest rock prism expansion coincides with the lowest expansion obtained in our tests. In spite of the fact that rock prisms of some of our greywackes have large, rapid expansions in alkali solution, there is no record of deleterious expansion having occurred in any structure or in mortar bar tests. Currently tests on concrete prisms containing up to 370 kg/m³ of cement and up to 2,3 per cent alkali are in progress. Early results are merely tending to confirm the general unreactivity of New Zealand greywacke.

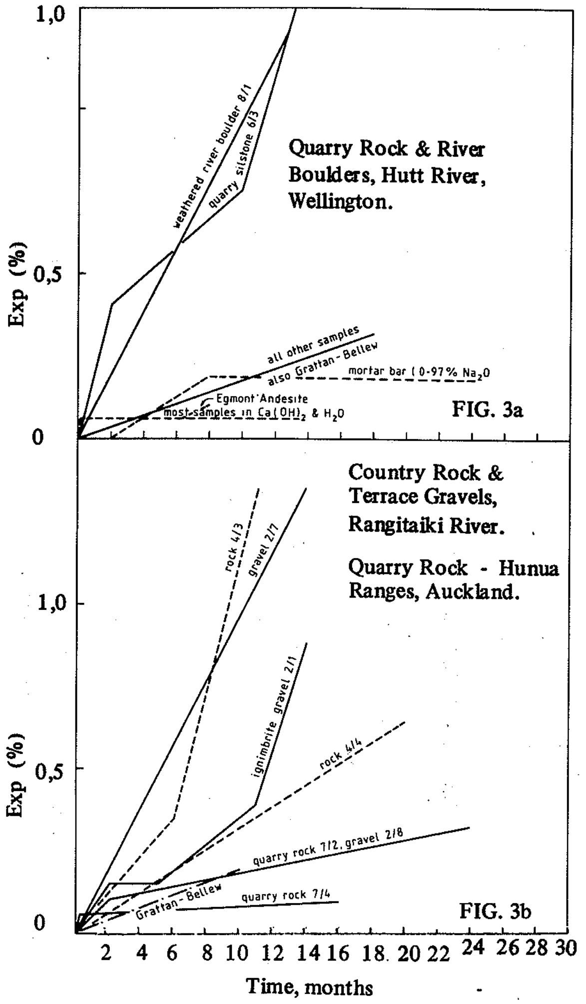

FIGURE 3a: Expansion of rock prisms (2 M NaOH solution) from Wellington greywacke sequence. Quarry siltstone and weathered river boulders expand rapidly. All other samples expand at a slower rate approximately equal to Grattan-Bellew's highest result. The same samples in saturated $Ca(OH)_2$ solution and in water do not expand. A mortar bar test (C227) and a result in Egmont andesite are also included.

3b: Expansion of rock prisms from Rangitaiki River (series 2 and 4) and Hunua Ranges Auckland (series 7). Samples from Rangitaiki River are spread from lowest result 2/8 to highest result 4/3. Samples from Auckland have smallest and lowest expansions and fall within a narrow range.

Also included in the rock prism tests are samples of rhyolitic ignimbrite, rhyolitic pumice, (both present in Rangitaiki River gravels) and Egmont andesite. Ignimbrite expands rapidly, pumice disintegrates rapidly while Egmont andesite has a slow, if somewhat irregular expansion. Parallel tests on selected samples of greywacke in distilled water and calcium hydroxide solutions, are also in progress. After a small rapid expansion these samples have stabilised and show no signs of further reaction. It would appear that Van Aardt and Visser's hypothesis[15], that reaction between feldspar and calcium hydroxide solution causes expansion, is not tenable for the New Zealand greywacke rock sequence.

Extensive petrographic analyses of the rocks are in progress and some details are given in Table 1 (page 4) together with some results of analyses of the alkali solutions containing material dissolved from the rock prisms. The only parameter found that has any correlation with rock prism expansion is the water absorption of the rock and even this does not apply to sample 6/4. There is some suggestion that, given the necessary water absorption, the matrix content and degree of weathering may have some effect. In spite of extensive SEM examination of fracture surfaces no exfoliation of matrix clay layer structures has been detected as found by Gillott[13]. However vermiculite type clays are generally not found in the New Zealand greywacke. The amounts of silica, alumina and other constituents dissolved in the alkali solutions bear no relation to expansion and merely suggest that, while some preferential dissolution of silica occurs, general attack by the alkali solutions on the rocks is occurring. Limited thin-sectioning of expanded prisms has failed to identify any alkali-silica gel. The nature of the reaction is quite similar to that previously found from examination of two Canadian concretes containing argillite[11]. The texture of the aggregates appears to be attacked along a reaction fissure without signs of reaction rims or alteration at any margins. However, alkali-silica gel was present in these old Canadian concretes.

In summary, the rock prism data we have obtained indicates that the test may not be reliable for indicating the potential reactivity of rock types such as greywacke/argillite. Some New Zealand varieties expand rapidly in alkaline solution by an unknown mechanism, but do not exhibit expansion when mixed with concrete containing large amounts of alkali. Further tests using rock prisms are in progress.

## 6. MORTAR BAR TESTS (ASTM C227)

The first series of aggregates tested involved the use of 50 x 50 x 300 mm prisms with alkali contents of 0,55 per cent and 1,0 per cent, stored at 21 °C. The US Bureau of Reclamation criteria[16] were used for determining reactivity. These first tests indicated that a basalt and a quartzite were reactive but that the rate of expansion was relatively slow. Rhyolite, a Waikato River sand consisting of mixed rhyolite and andesite, and a greywacke showed no significant expansion after 2¼ years.

Tests on composites of Waikato River gravels and sands each graded to comply with ASTM C227, and with variable removal of the naturally occurring fine pumice present, did not give appreciable expansion at alkali contents of 0,45 per cent and 0,70 per cent. These same aggregate combinations were further tested at 38 °C and at an alkali content of 0,97 per cent with and without the use of three pozzolans. Significant expansion occurred within 18 months where the pumice content was less than 1 per cent. This expansion was reduced when the natural pumice content was 3-6 per cent and eliminated when pozzolans consisting of 25 per cent pumicite and 12,5 per cent diatomaceous pumicite cement replacement was used.

The next series of mortar bar tests included a wide range of aggregates, selected because the quick chemical test showed them to be either deleterious or potentially deleterious. Prism dimensions were standardised at 25 x 25 x 285 mm, storage was at 38 °C and alkali contents were 0,89 per cent, 1,20 per cent and 1,50 per cent. Some lower alkali contents were used when considered necessary. Andesite was shown to be the most reactive rock type. However rhyolite and dacite, both of which gave high $S_C$ and $R_C$ values in the quick chemical test did not expand significantly within one year. On the basis of these results single samples of each of Egmont andesite, Tongariro andesite, rhyolite and dacite were selected and tested in combination with Wellington greywacke to determine the 'pessimum' proportions. It has been previously reported[2] that, except for Egmont andesite whose expansion is directly proportional to the amount present, all the other aggregates showed definite 'pessimum' proportions, their reactivity decreasing markedly with decreasing alkali content.

Some of the specimens in the above tests, especially those involving combinations with greywacke were retained for periods of up to four years. In several cases specimens which had not expanded significantly by 6 or 12 months, expanded considerably at later ages (Figure 4). The above results suggest that present ASTM C227 criteria (0,05 per cent at 3 months and 0,10 per cent at 6 months) may be under-estimating reactivity by not taking account of the slower expanding rocks. This appears to have been recognised in Denmark where an aggregate is considered potentially harmful where expansion exceeds 0,1 per cent at 24 months[17]. In earlier tests, an important commercial aggregate, Tirohia hypersthene-augite andesite, gave $S_C/R_C$ values of 336/157 and 446/107 in the quick chemical test. Mortar bars containing this aggregate with a 0,89 per cent alkali were discarded because they did not reach the Bureau of Reclamation criterion of 0,1 per cent expansion at 12 months. We have little doubt that the bars would have expanded if they had been kept for longer periods. Thus, important information on the reactivity of aggregates can be lost by not retaining test bars to check for slow, long-term expansion.

While both laboratory testing and structural experience has shown that New Zealand rocks do not expand in concrete where the alkali content of the cement is less than 0,6 per cent, one of our tests indicates that some aggregates may be potentially reactive even at low alkali contents. It was found that when 3 per cent of Wellington greywacke was replaced by California State Division of Highways aggregate No 28039 (a siliceous magnesian limestone) in mortar bars at an alkali content of 0,4 per cent, expansion reached 0,4 per cent by 12 months.

Cracking may occur in mortar bars with low alkali content although no significant expansion is recorded. An example of this is shown in Figure 5. Because in this case petrographic sectioning was not carried out, it can only be hypothesised that cracking was confined to surface layers and was due to concentration of alkalis at the surface of the bars. The conditions of storage in large metal cans did allow some surface drying to occur and this probably accounts for the above effect. Apart from these results, our studies have shown an association between crack development and the expansion of mortar bars. Generally crack development has been found to precede expansion and expansion appears to be essentially due to the widening of the cracks[18].

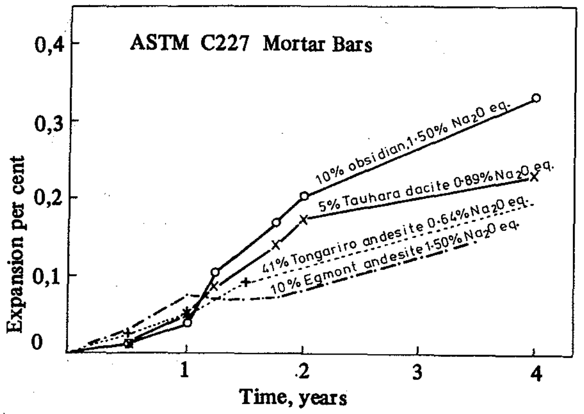

FIGURE 4: Examples where significant expansion occurred at ages later than 6 or 12 months

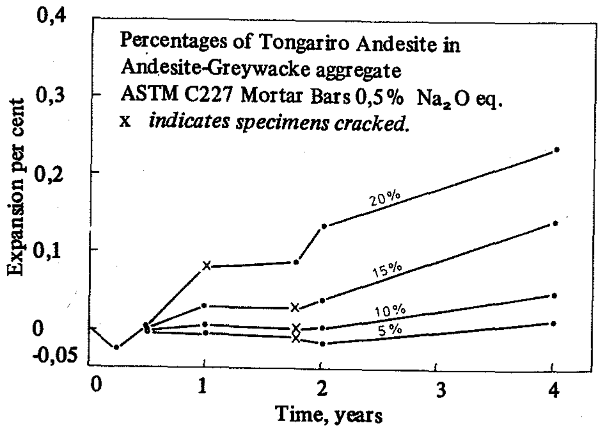

FIGURE 5: Indications of cracking prior to expansion

TABLE 1 : Some results of tests on rock prisms

| | % Expansion NaOH 12m | % Expansion Ca(OH)$_2$ 6m | Rock composition* Matrix % | Rock composition* Feld % | Rock composition* Quartz % | Analysis of alkali soln SiO$_2$ (ppm) | Analysis of alkali soln Al$_2$O$_3$ (ppm) | Analysis of alkali soln K$_2$O (ppm) | Analysis of Ca(OH)$_2$ soln SiO$_2$ (ppm) | Analysis of Ca(OH)$_2$ soln Al$_2$O$_3$ (ppm) | Analysis of Ca(OH)$_2$ soln K$_2$O (ppm) | Analysis of Ca(OH)$_2$ soln Na$_2$O (ppm) | Water abs % mass |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **WELLINGTON-HOROKIWI QUARRY** | | | | | | | | | | | | | |
| 6/1 | 0,24 | | 17 | 50 | 16 | 390 | 35 | 20 | | | | | 0,39 |
| 6/2 | 0,22 | | 10 | 53 | 14 | 500 | 40 | 20 | | | | | 0,38 |
| 6/3 | 0,70 | 0,15 | 80 | 14 | | 900 | 45 | 25 | <50 | <20 | <5 | 30 | 0,98 |
| 6/4 | 0,21 | | 10 | 47 | 20 | 250 | 85 | 15 | | | | | 1,07 |
| **AUCKLAND QUARRIES, HUNUA RANGES** | | | | | | | | | | | | | |
| 7/1 | 0,09 | | 3 | 26 | 6 | 100 | 15 | 10 | | | | | 0,22 |
| 7/2 | 0,23 | | 81 | 22 | 16 | 420 | 30 | 15 | | | | | 0,37 |
| 7/3 | 0,09 | | - | - | - | 170 | 30 | 10 | | | | | - |
| 7/4 | 0,06 | | 28 | 21 | 3 | 120 | 15 | 10 | | | | | 0,25 |
| 7/5 | 0,09 | | 30 | 27 | 5 | 190 | 20 | 10 | | | | | 0,37 |
| 7/6 | 0,16 | 0,07 | 79 | 20 | 9 | 550 | 25 | 15 | <50 | <20 | <5 | 45 | 0,46 |
| 7/7 | 0,13 | | 70 | 23 | 7 | 300 | 25 | 15 | <50 | <20 | <5 | 80 | 0,21 |
| 7/8 | 0,13 | 0,05 | 77 | 22 | 7 | 320 | 25 | 15 | <50 | <20 | <5 | 80 | 0,22 |
| 7/9 | 0,09 | 0,05 | 70 | 30 | 2 | 280 | 20 | 15 | <50 | <20 | <5 | 80 | 0,34 |
| **WELLINGTON-WEATHERED BOULDER, HUTT RIVER** | | | | | | | | | | | | | |
| 8/1 | 1,25 | 0,10 | | | | 900 | 165 | <5 | 65 | <10 | <5 | | 0,91 |
| 8/2 | 0,80 | 0,10 | | | | 950 | 165 | <5 | 100 | <10 | <5 | | 0,91 |
| 8/3 | 1,16 | 0,05 | | | | 850 | 165 | <5 | 50 | <10 | <5 | | 0,91 |
| **WELLINGTON-QUARRIES, WESTERN HUTT HILLS** | | | | | | | | | | | | | |
| 9/1 | 0,12 | 0,03 | 25 | 42 | 11 | 630 | 50 | 20 | <50 | <20 | <5 | 40 | 0,24 |
| 9/2 | 0,20 | 0,06 | - | - | - | 1050 | 65 | 30 | <50 | <20 | <5 | 10 | 0,31 |
| 9/3 | 0,29 | 0,07 | 78 | 9 | 7 | 2650 | 40 | 10 | <50 | <20 | <5 | 35 | 0,32 |
| 9/4 | 0,13 | 0,01 | 11 | 49 | 16 | 480 | 50 | 20 | <50 | <20 | <5 | 30 | 0,29 |

* Matrix defined as rock less than 30 μm. Matrix is quartz, feldspar and micas grading into chlorite, illite and minor kaolinite and rare montmorillonite clays. Feldspar principally potassic feldspar and sodic plagioclase

## 7. USE OF POZZOLANS

A diatomaceous pumicite (approximate composition 30 per cent diatomite, 55 per cent pumicite, 15 per cent clay, specific surface air permeability method 2700 $m^2/kg$) has been used extensively in dams and other important structures in New Zealand at 12½ per cent replacement by mass of low alkali cement. The aggregates involved have frequently been andesites, and while the pozzolan was used initially as an additional safeguard against expansive reactivity, its later use was primarily to provide enhanced concrete workability. Thus the effect of this pozzolan in suppressing alkali-aggregate reactivity is solely known from laboratory testing because it has only been used with low alkali cement which in itself is an effective suppressor of the reactivity of New Zealand rocks in concrete.

ASTM C441 tests on the diatomaceous pumicite indicated that a 10 per cent replacement by mass of cement was required to achieve the specified $R_c$ value of 75 per cent. With an uncontaminated pumicite, the greatest $R_c$ value obtainable was 60-70 per cent. However, in mortar tests both pozzolans effectively prevented expansion of reactive aggregate suggesting that the $R_c$ value of 75 per cent specified in ASTM C441 could be conservative. There is a problem in deciding how the pozzolan effects the reduction in expansion. The replacement of 25 per cent of cement containing 0,97 per cent alkali with 25 per cent pumicite effectively lowers the alkali content to 0,73 per cent. This reduction in alkali is in itself sufficient to account for much of the reduction in reactivity obtained.

## 8. CONCRETE TESTS

A detailed study has been made of concrete containing Egmont andesite, an aggregate of known reactivity. Cement contents of 300, 450 and 600 $kg/m^3$ were used with alkali contents ranging from 0,32 to 1,20 per cent. Concretes were mixed at slumps of either 30 or 100 mm which generally resulted in water to cement ratios of approximately 0,3 to 0,6. Specimens consisted of 292 x 76 x 76 mm beams and 152 x 76 mm cylinders which were stored either under continuously moist conditions at 21 °C or on an outdoor exposure site[3].

The results shown in Figure 6 confirm those obtained from the mortar bar tests carried out on this aggregate, ie expansion increases with alkali content. It is to be noted that conditions of storage have a marked effect on expansion. With continuous moist storage expansions tend to level out at approximately five years. On the other hand, with outdoor exposure, expansion is still occurring after ten years. Probably, movement of alkali is occurring in the concrete giving localised concentrations which would be absent under moist curing conditions. The outdoor exposure site more truly represents structural conditions and very clearly indicates some of the problems in translating results of laboratory testing into field practice.

These are not the only problems in testing. Compressive strength tests did not clearly reveal any regression in strength due directly to alkali-aggregate reaction, but well defined reductions in strength did occur with increases in alkali content (Figure 7, page 7). A similar effect of alkali on the strength of cement pastes has been reported[19]. Similarly, neither splitting tensile nor dynamic modulus tests showed any clear trends. This is especially the case for longitudinal measurements of dynamic modulus where even severely cracked beams showed no reduction in modulus. It is possible that transverse measurements[20] may have given some better indication of any strength losses. However this lack of correlation between cracking and strength is understandable when we examine the petrographic cross section of the beam T15/1 shown in Figure 1. This beam is one of two beams whose expansion is represented by curve E 7.15 in Figure 6. Petrographic examination of this beam shows that cracking takes place in localised reaction centres. It is likely that sufficient sound concrete still remains so that strength and other properties are not significantly affected. Thus measurement of expansion appears to still be the best method of measuring alkali-aggregate reactivity.

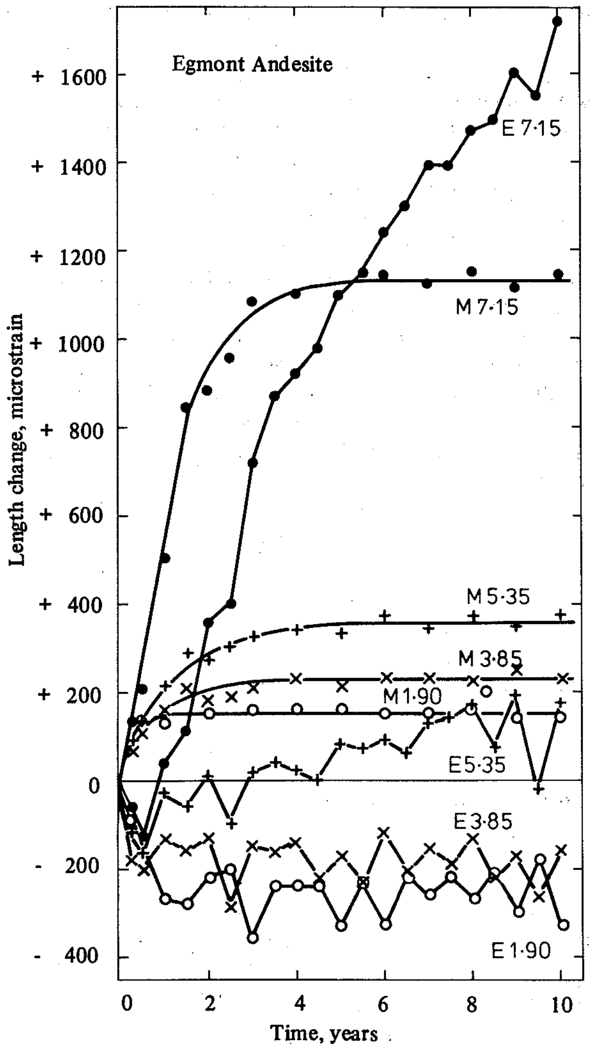

FIGURE 6: Length change versus time for concretes with indicated alkali contents ($kg/m^3$) and subjected to continuous moist conditions (M) and to outdoor exposure (E). Cement content 600 $kg/m^3$.

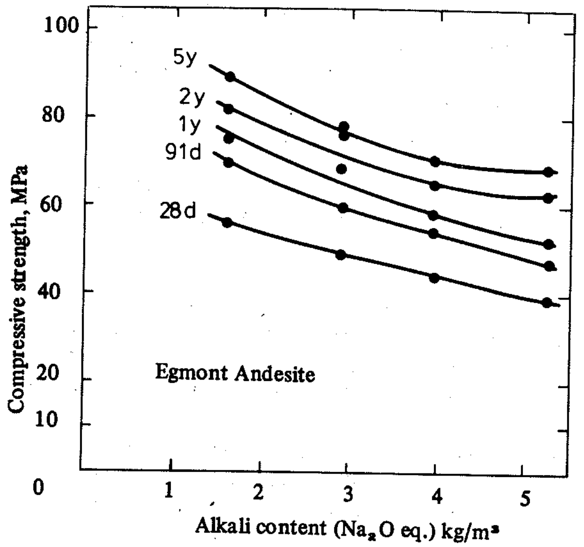

FIGURE 7: Compressive strength versus alkali content for concrete containing 450 $kg/m^3$ of cement, 100 mm slump, w/c = 0,39 continuously moist cured for the indicated times.

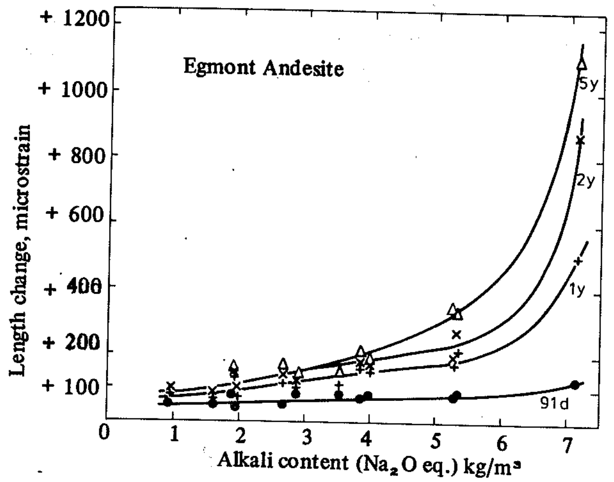

FIGURE 8: Length changes versus alkali content for concrete continuously moist cured.

The effect of the total alkali content of the concrete on expansion is shown in Figure 8. Significant expansion commences in the range 5-6 $kg/m^3$ and increases markedly at higher levels. If we assume a maximum cement content of 450 $kg/m^3$ in practice, this corresponds to a cement alkali content of 1,11 per cent - 1,33 per cent. The proposed new limit[6] of 0,8 per cent alkali for New Zealand cements translates into a total alkali content in the concrete of 3,5 $kg/m^3$, at a cement content of 450 $kg/m^3$. On the basis of the results in Figure 8 this would give an adequate safety margin and appears even more conservative when we consider the results of the outdoor exposure tests given in Figure 6. However it is expected that some engineers will still expect protection against unexpected conditions and it is proposed that these would be adequately covered by the use of a Portland pozzolan cement where considered necessary.

## 9. ECONOMICS OF LOW ALKALI CEMENT USAGE

It has been fortunate for New Zealand that, in the areas where the reactive rocks are located low alkali cement has always been available. Additionally, imported cements have also tended to be of the low alkali type. However, of the four cement plants presently operating, at least two may have incurred direct cost penalties of up to 10 per cent due to the blanket requirement to produce only low alkali cement. One works is presently re-equipping with a modern suspension pre-heater kiln and another is expected to rebuild within the near future. If more stringent stack emission requirements are to be met and the full economic benefits and energy reductions of the new systems are to be realised, some overall increase in the alkali content of New Zealand cements must occur.

In retrospect, it is probably fair to comment that the blanket use of low alkali cement has been economically justified. In a rapidly growing country such as New Zealand with shortages of capital for major works, the durability of structures has a high economic value. Thus the use of low alkali cements has allowed the safe use of reactive aggregates. Where inadvertent use of high alkali cement at a total alkali content of 4,45 - 5,10 $kg/m^3$ of concrete with Egmont andesite has occurred, cracking of three rail bridges resulted[4]. Such cracking provides a sharp and necessary reminder to that portion of the construction industry in New Zealand which still considers alkali aggregate reactivity as an unreal effect of mainly academic interest.

## 10. CONCLUSIONS

(a) Petrographic examination of aggregates is only useful for initially grouping rocks into potentially reactive or non-reactive types.

(b) Petrographic examination of large area thin sections of concrete is a valuable method for investigating the alkali-aggregate reaction. The smaller thin sections normally used by geologists are not suitable for this purpose.

(c) The quick chemical test ASTM C289 has proved to be a reliable method of indicating potential reactivity of New Zealand aggregates.

(d) The modified rock prism test ASTM C586 is not applicable to the New Zealand greywacke sequence of rocks since it is indicating high potential reactivity which is not occurring in either laboratory testing or service concretes.

(e) Where rock prisms of New Zealand greywacke are attacked in alkaline solution the whole fabric of the rock appears to be attacked. The mechanism of expansion has not been determined.

(f) Rock prisms of New Zealand greywacke do not expand in either saturated calcium hydroxide solution or distilled water.

(g) Mortar bar tests (ASTM C227) have effectively predicted that New Zealand rocks do not expand with low alkali cement. However, some testing indicates that a very highly reactive Californian aggregate, when used at a critical 'pessimum' proportion may expand with low alkali cement.

(h) Experience from using the ASTM C227 test indicates that tests should be run for at least two years and that the ASTM criterion of 0,1 per cent expansion at six months may be conservative. The Danish criterion of 0,1 per cent at two years appears more applicable to some slower reacting types.

(i) There is good correlation between cracking and expansion of mortar bars with cracking usually preceding expansion.

(j) In New Zealand pozzolan has always been used in concrete in combination with low alkali cement. Thus it is not possible to estimate its effect in suppressing the alkali-aggregate reaction.

(k) Laboratory testing of pozzolans indicates that the ASTM C441 requirement of an $R_c$ value of 75 per cent may be conservative.

(l) Concrete tests on Egmont andesite confirmed results found from mortar bar tests. That is, expansion increases with increasing alkali content of the cement and is directly controlled by the total alkali content present in the concrete.

(m) Methods of storage and exposure of concrete specimens have a strong influence on the degree and duration of expansion.

(n) Strength and modulus testing of expanded concretes do not correlate with either expansion or cracking. Measurement of expansion appears the only method of directly determining alkali-aggregate reaction in concrete.

(o) Concrete tests using a highly reactive andesite indicate that the alkali content of New Zealand cements can safely be raised from 0,60 per cent to 0,80 per cent $Na_2O$ equivalent.

(p) In retrospect the extra cost of manufacturing only low alkali cements in New Zealand appears to have been economically justified as no alkali-aggregate problems in concrete structures are known where low alkali cement has been used. However on the basis of energy consumption and present day economics it is doubtful if this argument can now be sustained.

## REFERENCES

1. HUTTON C O *The problem of reaction between aggregate materials and high alkali cement.* NZ J Sci Tech *26B,* 1945.
2. KENNERLEY R A and ST JOHN D A *Reactivity of aggregates with cement alkalis.* Proc of Conference on Concrete Aggregates, Hamilton, NZ, June 1969.
3. KENNERLEY R A ST JOHN D A and SMITH L M *Alkali-aggregate reactivity in New Zealand.* Symposium on Alkali-aggregate Reaction, Preventive Measures. Reykjavik, Iceland, August 1975.
4. ST JOHN D A *Confirmation of alkali-aggregate reaction in the Te Henui Bridge.* NZ J Sc *18,* 1975.
5. ST JOHN D A and SMITH L M *Expansion of concrete containing NZ argillite. The effect of alkalis on the properties of concrete.* Proc of Symposium held in London, Sept 1976.
6. ST JOHN D A and SMITH L M *Alkali-aggregate studies in NZ - Progress report.* Proc of 4th Int Conf on the Effects of Alkalis in Cement and Concrete. Purdue University, USA, June 1978.
7. KENNERLEY R A ST JOHN D A and SMITH L M *Reactivity of NZ aggregates with cement alkalis - Review of work.* CD Report No 2310 in publication. Chemistry Division, DSIR, Private Bag, Petone, NZ, 1981.
8. ANDERSEN P E and PETERSEN B H *Drilling of concrete cores and preparation of thin sections.* RILEM Bulletin, 11: 1961.
9. JONES T G HAWES R W M and DYSON J R *Semi-automatic preparation of ultra-thin and large-area petrological sections.* Trans Brit Ceram Soc, 65: 1966.
10. ABBOTT J H and ST JOHN D A *The preparation of specimens for the examination of concrete.* CD Report No 2311. In preparation, 1981.
11. ST JOHN D A *Report to the Ontario hydro-electric commission.* Canada, 1979.
12. POOLE A B *Electron probe microanalyses of reaction zones at cement/opal interfaces. The effects of alkalis on the properties of concrete.* Proc of Symposium held in London, Sept 1976.
13. GILLOTT J E DUNCAN M A G and SWENSON E G *Alkali-aggregate reaction in Nova Scotia. IV. Character of reaction.* Cement and Concrete Research, *3* (5), 1973.
14. GRATTAN-BELLEW P E *Study of expansivity of a suite of greywacke, argillite and quartz arenites.* Proc of 4th Int Conf on Effects of Alkalis in Cement and Concrete, Purdue University, USA, June 1978.
15. VAN AARDT J H P and VISSER S *Calcium hydroxide attack on feldspars and clays : Possible relevance to cement-aggregate reactions.* Cement and Concrete Research, 7 (6), 1977.
16. BLANKS R F and MEISSNER H S *The expansion test as a measure of alkali-aggregate reaction.* J Amer Concr Inst *17,* 1964.
17. BREDSDORFF P IDORN G M KJAER A PLUM N M and POULSEN E *Chemical reactions involving aggregates.* Proc Fourth Int Symp on Chemistry of Cement, Washington DC, 1966.
18. McGOWAN J K and VIVIAN H E *Studies in cement-aggregate reaction XX. The correlation between crack development and expansion of mortar.* Aust J Appl Sci *3* (3), 1952.
19. ALEXANDER K M and DAVIS C E S *Effect of alkali on the strength of Portland cement paste.* Aust J Appl Sci *11* (1), 1960.
20. STUTTERHEIM N LOCHNER J P A and BURGER J F A *A method for determining the dynamic Young's modulus of concrete specimens developed for corrosion studies.* Proc Int Symp on the Non-Destructive Tests of Materials and Structures. Paris. Paper A-2: 1955.

## DISCUSSION

Dr P E Grattan-Bellew (NRC, Ottawa, Canada) referred to the comments about the method of attack accounting for the expansion of greywacke in sodium hydroxide solution. He felt that it did not differ greatly from the classical alkali-silica reaction mechanism. The main difference was that in the case of rocks such as the greywackes, hornfelses and quartzites, only a small proportion of the quartz in the rock was reactive. The reaction probably occurred along the grain boundaries where there were many defects which increased the free energy and consequently the solubility of the silica.