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THE APPLICATION AND RELIABILITY OF STANDARD TESTING PROCEDURES FOR POTENTIAL ALKALI-REACTIVITY

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SYNOPSIS

The assessment of concrete aggregates for potential alkali-reactivity often requires the application of standardised tests, the results of which are frequently used as pass-fail criteria. The reliable evaluation of aggregates for alkali-reactivity potential is usually based upon local experience of materials, application of the most appropriate tests and the direct observation of existing concretes made with the same aggregates. It is common for the available standard tests to be mis-applied or specified for inappropriate materials. These practical difficulties are illustrated by reference to numerous case studies involving assessments of engineering significance and test programmes carried out on aggregates from many parts of the world, including the United Kingdom.

SAMEVATTING

Die waardebepaling van betonaggregate vir potensiële alkali-reaktiwiteit vereis dikwels die aanwending van standaardtoetse waarvan die resultate herhaaldelik as slaag-faalkriteria gebruik word. Die betroubare evaluering van aggregate vir potensiële alkali-reaktiwiteit word gewoonlik gegrond op plaaslike ondervinding van materiale, aanwending van die mees toepaslike toetse en die direkte waarneming van bestaande beton wat met dieselfde aggregate vervaardig is. Die beskikbare standaardtoetse is in die algemeen soms foutief aangewend of vir ontoepaslike materiale gespesifiseer. Hierdie praktiese probleme word geïllustreer deur verwysing na talle gevallestudies waarby waardepalings van betekenis vir die ingenieurswese en toetsprogramme wat uitgevoer is op aggregate uit baie wêrelddele, insluitend die Verenigde Koninkryk, betrokke is.

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1. GENERAL DISCUSSION

The importance of alkali-aggregate reactivity as a potential threat to concrete durability is now recognised worldwide. Examples of structural distress arising from alkali-reactivity have now been reported from many countries, including the United Kingdom[1, 2, 3]. As a result of this recognition, the assessment of concrete aggregates for potential alkali-reactivity has become a normal requirement of many materials evaluation programmes or contract specifications.

Research has shown that the alkali-aggregate reaction actually embraces a number of dissimilar mechanisms, each of which are controlled by variable parameters that are interrelated in a complex manner. Consequently it is often inappropriate to base an assessment upon isolated tests which appear to provide precise results. Instead it is usually necessary to undertake a balanced and complete appraisal, considering many factors both separately and in combination, and taking into account where possible local experience of using the materials under consideration. In this context several standardised tests are available for use, where appropriate, as indicators to assist in making an overall and informed judgement.

Unfortunately this is an ideal situation that is rarely satisfied in commercial investigations. The standardised tests are too frequently regarded as being definitive, and as providing results that can be used as *pass or fail* criteria, which is rarely the case. Consequently, contract specifications or consulting engineers sometimes call for the aggregate assessment to be based upon specific tests, which may or may not be appropriate to the materials in question, and which in any case are unlikely to provide sufficient unambiguous evidence in isolation. In one recent example, the author, having completed an appraisal of a pure carbonate rock material for alkali-reactivity potential, was required additionally to carry out an inappropriate chemical test intended for siliceous rocks (ASTM C289–71[4]) because the Middle Eastern government department concerned would accept only the results of the test cited in the contract specification; the more apposite consideration was rejected as being outside the scope of the contract document.

A knowledge of the nature of the materials being considered is central to the assessment programme, and some form of petrographic examination should never be omitted. In some cases the petrographic appraisal may obviate the need for any further testing, and in most cases the most pertinent indicative testing sequence will be identified. This would avoid the blind application of often inappropriate tests; particular confusion seems to arise over the distinction between siliceous and carbonate rocks. Petrography also recognises in advance the presence of constituents that may give rise to misleading results, such as some cherts in the ASTM C289–71 test, or results that are difficult to interpret reliably, such as opaline limestones or metaquartzites in the mortar bar test (ASTM C227–71[5]), or which are not adequately covered by any of the existing standard tests, such as expansive phyllosilicate rocks.

At present, there is little practical guidance regarding the assessment of potential alkali-aggregate reactivity given in the various national standards. The current British Standard specification for concrete aggregates (BS.882:1973[6]) does not mention alkali-reactivity, and nor are there any British Standard tests available. The German standard specification (DIN 4226, 1971[7]) sensibly states that aggregates should be assessed for alkali-silica reactivity *by a competent test institute, taking into account those aspects of the concrete and of the structure that come into question and also giving due regard to the performance of concrete, containing the same kind of aggregate, in structures already completed*, but does not give any standard tests.

The American Society for Testing and Materials (ASTM) provides the most comprehensive advice and also the standard test procedures that are most frequently used in all parts of the world. The specification for concrete aggregates (ASTM C33–78[8]) includes an appendix on the methods for evaluating potential reactivity. This appendix is prefaced by a precautionary statement that is insufficiently heeded: *A number of methods for* detecting *potential reactivity have been* proposed. *However, they do* not *provide quantitative information on the degree of reactivity to be expected or tolerated in service. Therefore,* evaluation *of potential reactivity of an aggregate should be based upon* judgement *and on the* interpretation *of test data and examination of concrete structures containing a combination of fine and coarse aggregates and cements for use in the new work. Results of the following test will* assist *in making the evaluation* (author's emphasis). In the listing that follows in the standard, it is interesting to note that it is not made clear that the ASTM C289–71 test is not intended to detect alkali-carbonate reactive rocks; this may be a source of much misunderstanding.

In making these assessments for alkali-reactivity potential, the commercial materials engineer is frequently hampered by two recurring problems: insufficient time to carry out the more reliable long-term tests or time-consuming case studies, and insufficient sample to ensure acceptable representability or to supply a comprehensive test programme. Enquiries regarding suitable sample quantities almost invariably follow, rather than precede, the sample collecting and transporting exercise. Apart from sample quantity, the difficulty of obtaining adequately representative samples has been mentioned elsewhere[9].

The time problem is frequently resolved by the questionable expedient of accepting earlier indications than those recommended, such as considering the two- and three-month length change measurements in the mortar bar test instead of waiting for the six-month results. Acceleration of standardised tests has been suggested and is sometimes possible. The simple gel pat test[10] has been run at an elevated storage temperature with reasonable success (Plate 1)[11]. Application of the mortar bar test at higher storage temperatures has usually been avoided for fear of

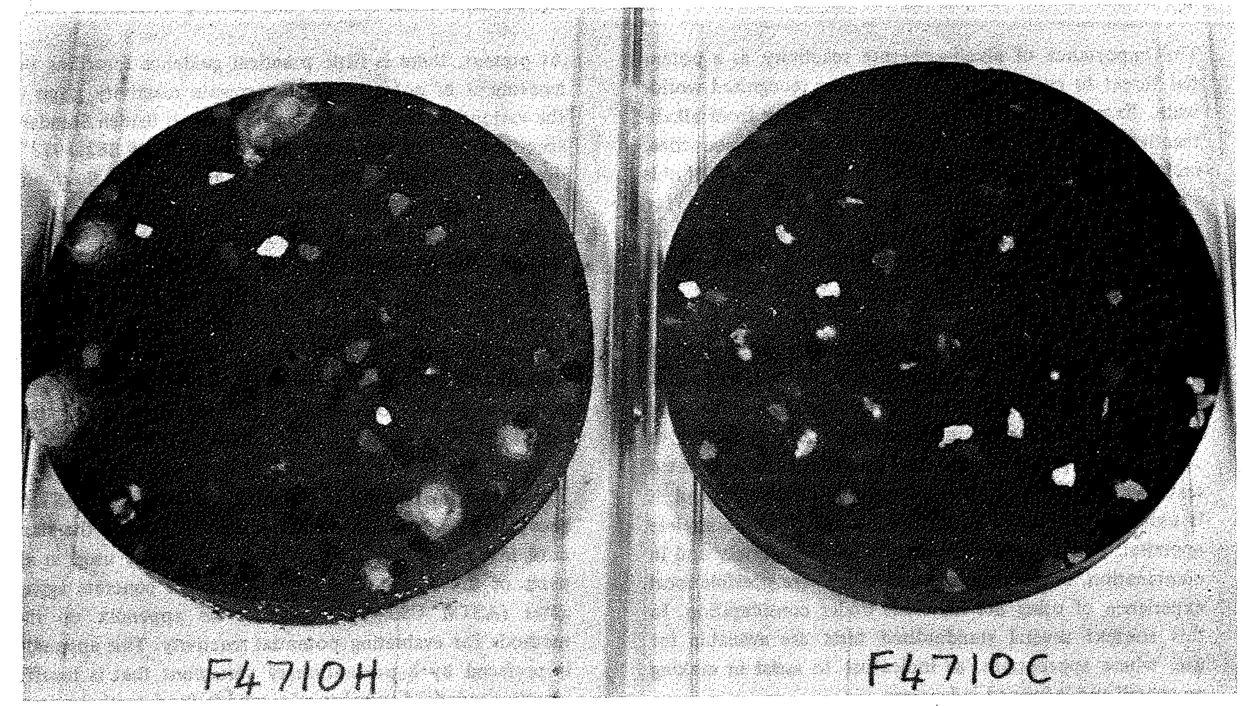


PLATE 1: Gel pat testing of a Cyprus aggregate containing a proportion of opaline limestone. The pats have each been immersed in alkaline solution for three days, but the left hand specimen has been stored at the elevated temperature of 38°C, whilst the right hand specimen has been stored at 20°C.

modifying the properties of any gel produced[12], but a recent method of acceleration has combined increased temperature with immersion in sodium chloride solution[13]. In the case of certain alkali-silic*ate* reactive rocks, it has been found necessary to 'accelerate' standard tests in order to counteract slower-than-usual rates of expansion[14]. The advisability of 'accelerating' tests by the deliberate addition of alkalis has recently been discussed with regard to some UK materials[15].

2. PETROGRAPHIC EXAMINATION

A procedure for the petrographic examination of aggregates for concrete is given in ASTM C295–65[16], although a rather less exhaustive approach is often regarded as adequate. The degree of inspection detail is commonly dictated by the type of material encountered; for example, carbonate rocks can often be most usefully assessed on the basis of the detailed analysis of mineralogical composition and microscopic texture. Visual examination may need to be supplemented by analytical techniques, such as the use of X-ray diffraction to help identify the possible presence of opaline silica in chert materials[17]. The principal function of the petrographic examination is to identify any constituents that are potentially susceptible to alkali-reactivity, to derive a preliminary view of the likelihood of deleterious reaction by informed consideration of the relative proportions, and to indicate the most appropriate form of subsequent testing when this is deemed to be necessary.

The practical problem for the commercial petrographer is to balance two opposing responsibilities. On the one hand, there is the need to be technically competent and so to recognise, and report to the client, all possible forms of potentially reactive material present, however obscure. The diversity of materials that have been described as occasionally taking part in a form of alkali-reaction is now so great that such a thorough approach would classify relatively few aggregates as completely without suspicion. On the other hand, however, there is the need to prevent the spread of unfounded alarm by drawing undue attention to details believed at present to be of only hypothetical or academic interest.

A case in point arose some years ago when, quite inexplicably, serpentinites in the Arabian Gulf area were believed by some to be potentially alkali-reactive. In the absence of contrary evidence, it became necessary to make especial comment about the presence of serpentinite in aggregate, but also adding the rider that no actual examples of reaction had been observed. Fortunately, the non-reactive character of serpentinite has recently been demonstrated[18].

Another example of difficulty concerns the type of alkali-carbonate reaction first identified in Bahrain, which has been described elsewhere[19, 20]. These Middle Eastern dolomitic rocks are different in character to the North American dolomites described in the appendix to ASTM C33–78, but they frequently develop calcitic reaction rims when used as aggregate in concrete (Plate 2). The

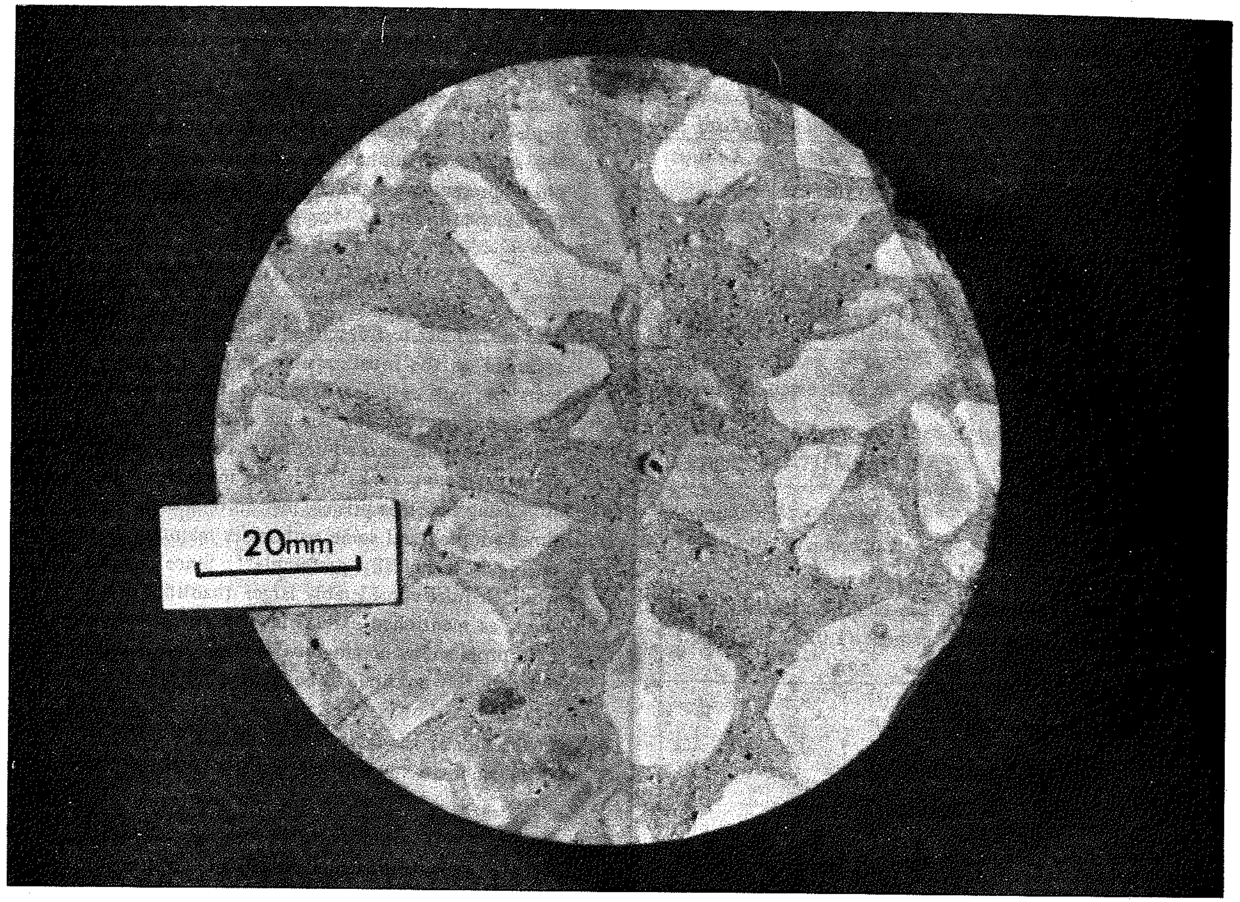


PLATE 2: A section across concrete from the Arabian Gulf area showing dolomitic limestone particles encircled by calcitic reaction rims (these appear in the photograph). This is not believed to be an expansive reaction.

development of these rims is not believed to be an expansive reaction, but the effect on the cement:aggregate bond has been questioned[11, 21]. Since the latter aspect has been neither verified nor disproved as yet, it is frequently necessary to forewarn intending users of these dolomitic aggregates that such visually obvious but apparently non-expansive reactions may occur in due course. To many, such advice is equivocal, and yet it would be irresponsible not to direct attention to previous experience with similar materials. In one such case, a guarantee of non-expansion and a strong statement refuting the likelihood of durability failure was requested; it was not possible to provide such an assurance.

3. CHEMICAL TESTING

The most familiar and widely used chemical test is that described in ASTM C289–71[4]. The gel pat test[10] may also be regarded as a chemical method, and the procedure published by the German Committee for Reinforced Concrete (Deutschen Ausschusses für Stahlbeton)[22] involves primarily chemical treatment.

The ASTM C289–71 method is attractive because it is relatively rapid, requires only small quantities of sample for the test itself, and gives apparently clear and unambiguous results in the majority of cases. It is not an appropriate method of test for materials suspected of being alkali-carbonate reactive or alkali-silic*ate* reactive as described by Gillott[23]. It is a rigorous test and even certain types of silica that have performed satisfactorily in service or in the expansion tests may be shown as 'deleterious' or 'potentially deleterious' by this method. In the UK, for example, most of the flint (a term for English Cretaceous chert) – bearing aggregates give a positive response in the ASTM C289–71 test, which is usually regarded as a misleading result. A typical comparison of chemical and mortar bar test results for Thames Valley flint gravel and sand is shown in Figure 1.

Gel pat testing, at normal and elevated temperature, has been used successfully, as an alternative to the ASTM C289–71 test, for monitoring flint-bearing aggregate supplies at several large construction sites in the south-east of England. Whilst basically a simple qualitative test, the gel pats can furnish much information when employed with repetitive sampling and subjected to regular, detailed and comparative inspections; it is thought possible that the differing morphologies of the gel growths produced could

ASTM C289–71. Chemical Test		
Typical flint gravel/sand material:	Coarse, +5 mm	Fine, –5 mm
	Millimoles per litre	
Mean Reduction in Alkalinity, R_c:	130	60
Mean Dissolved Silica, S_c:	567	145
Designation:	Potentially deleterious	Deleterious

ASTM C227–71, Mortar Bar Test

├--- ASTM maxima guidelines

○–○ (1) 67% Coarse/33% Fine blend of the above materials, using a low-alkali cement (0,50% Na_2O eq.)

●–● (2) 70% Coarse/30% Fine blend of similar materials, using a high-alkali cement (1,02% Na_2O eq.)

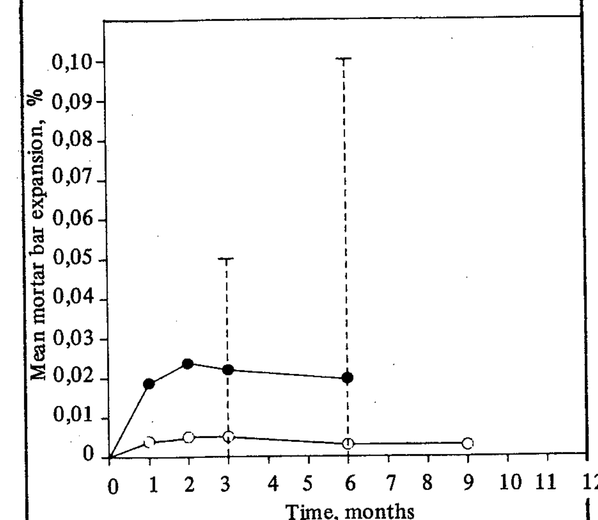


FIGURE 1: Typical chemical and mortar bar test results for Thames Valley flint-bearing aggregates

yield more useful information than is currently realised. Furthermore, in polymictic aggregates the gel pat test enables the reacting particles to be identified.

In Germany, a modification of the ASTM C289–71 test was devised for use with flint aggregates[24], but this does not appear to have become internationally accepted for regular usage.

It is known that calcium carbonate can induce a significant error in the ASTM C289–71 test if the dissolved silica and alkalinity reduction values indicate a marginal result (see interpretation section of ASTM C289–71). No mention is made, however, of the possible effects of other contaminants such as sulphate. A set of trachytic tuff samples, taken from an island in the Arabian Gulf that was formed by gypsum (hydrous calcium sulphate) diapir, were analysed for acid soluble sulphate and also tested for potential alkali-reactivity by the ASTM C289–71 method (Table 1). Since these rocks were petrographically similar apart from the secondary sulphate contents, it seems that the sulphate present substantially affected the potential alkali-reactivity test results.

4. PHYSICAL EXPANSION TESTING

The mortar bar test described in ASTM C227–71 is widely regarded as the most reliable of the indicative standard tests. A rock cylinder expansion test is given in ASTM C586–69[25] specifically for use with carbonate rocks, but variants of the procedure have been applied to alkali-silicate reactive rocks[14, 26]. The measurement of expansion using concrete prisms, instead of mortar bars, is sometimes adopted and some authorities maintain that concrete testing is technically preferable[27]. Since concrete testing would require considerably larger quantities of sample, and since, as mentioned earlier, insufficient sample is a recurrent problem in commercial testing, the mortar bar test will probably continue to be favoured in practice.

In the mortar bar test, the identification of cement: aggregate combinations definitely capable of harmful expansion

TABLE 1: A comparison of sulphate contents and the results of the chemical test for alkali-reactivity for a series of similar trachytic tuff samples from the Arabian Gulf area.

Sample Ref:	A	B	C	D
CHEMICAL ANALYSIS FOR SULPHATE CONTENT				
	% by mass			
Acid soluble sulphate SO_3:	10,4	12,6	3,6	0,4
ASTM C289–71, CHEMICAL TEST				
	Millimoles per litre			
Mean reduction in alkalinity, R_c:	890	900	650	73
Mean dissolved silica, S_c:	Nil	Nil	2	71
Apparent designation:	Innocuous	Innocuous	Innocuous	Marginally deleterious

is based upon recording expansions in excess of 0,10 per cent at six months, or alternatively 0,05 per cent at three months. Although these figures are helpful guidelines, it is unfortunate that they are frequently and erroneously regarded as being 'limits' to be passed or failed. In fact, many examples have been described of materials that exhibit slow but progressive expansions, often well within the ASTM C227–71 guidelines at three and six months, but proceeding to deleterious expansions at later ages; examples are, the Nova Scotia rocks[14], the Ontario pelitic rocks[26], the Malmesbury aggregate in South Africa[28], and the opaline limestone of Cyprus[11].

ASTM C227–71 Mortar Bar Test

├--- ASTM maximum guidelines

○–○ (1) Metaquartzite coarse aggregate blended with 34% quartz sand, using high-alkali cement (1,19% Na_2O eq.)

●–● (2) Metamorphic quartz sand tested alone, using high-alkali cement (1,19% Na_2O eq.)

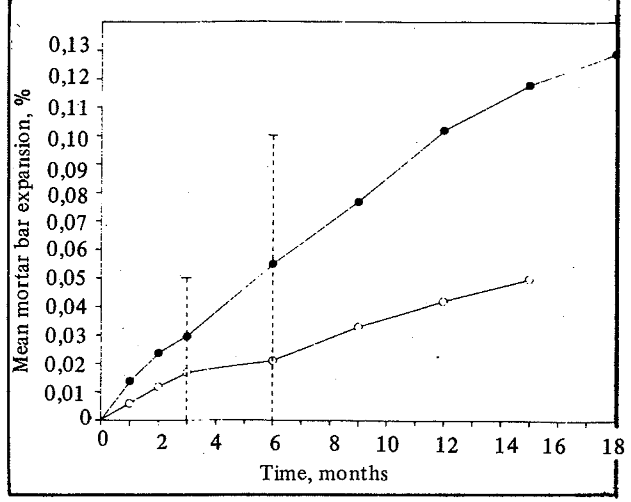


FIGURE 2: Mortar bar test results showing the slow but progressive expansion of a metaquartzite aggregate from Ireland and a metamorphic sand from the Himalayas.

Two new examples are given here of slow but progressive mortar bar expansions that have proved difficult to interpret satisfactorily, one being a metaquartzite aggregate from Ireland and the other being a metamorphic quartz sand from the Himalayas (Figure 2). In both cases the expansions at three and six months were significantly below the ASTM C227–71 guideline values but continued to increase up to and beyond twelve months. The metamorphic sand exhibited an expansion equal to the six month guideline value after twelve months. Both combinations have exhibited increasing expansion up to the present and the tests are being continued. For interest, both materials had been categorised as 'deleterious' in the ASTM C289–71 chemical test. It will be appreciated that such examples, whilst interesting, are extremely difficult to evaluate reliably on commercial time scales; the Malmesbury aggregate, for example, was still expanding after nearly two years[28].

The section on interpretation in ASTM C227–71 recognises that deleterious alkali-carbonate rocks *may not produce notable expansion in this method.* It follows that the guidelines given in ASTM C227–71 are intended to apply to siliceous rocks, but that is not always appreciated. The interpretation of the results for carbonate rocks in the mortar bar test is thus made difficult and the longer time scales required are certainly commercially unacceptable. One possible solution is by comparison with the results for materials of known performance. In that respect, the dolomitic limestone from certain horizons at Kingston, Ontario, is well documented[29]. In this study, mortar bar expansion curves up to six months have been produced for three of the Kingston Ontario rocks, and are here compared with those obtained for Middle East rocks that are similar to those that develop weak calcitic reaction rims (Figure 3).

ASTM C227–71, Mortar Bar Test

├--- ASTM maxima guidelines

○–○ (1) 7 ft level ★–★ (2) 12 ft level ●–● (3) 21 ft level	}	Dolomitic limestone from Kingston, Ontario, used with high-alkali cement (1,02% Na_2O eq.)
△–△ (4) Sample A ▲–▲ (5) Sample B	}	Middle Eastern Carbonates similar to those that develop weak calcitic reaction rims, used with high-alkali cement (1,19% Na_2O eq.)

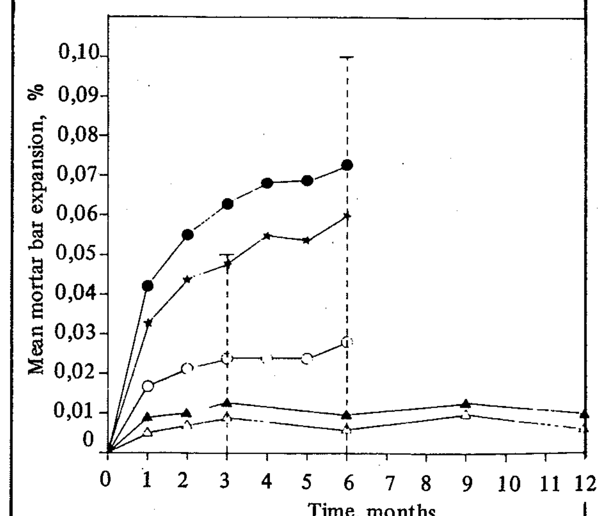


FIGURE 3: Mortar bar results showing the comparison between a North American alkali-carbonate reactive rock and the Middle Eastern type of reactive carbonate.

Experience shows that the majority of aggregates produce negligible expansion in the mortar bar test, especially with moderate to low-alkali cements. All behaviour that is notably different to this is therefore of interest and of potential significance. In this respect, as shown above, an aggregate that exhibits marked expansion which is less than the guidelines given in ASTM C227–71 may nevertheless be capable of disruption and should not be regarded as unimportant. Even if an interim judgement has to be made, the mortar bar testing should at least be continued until either the rate of length change becomes negligible or the expansion passes a predetermined 'critical' level.

In a few cases, mortar bars produce anomalous results that are hard to explain. The opaline limestone gravels of Cyprus, for example, which are known to have been involved in deleterious alkali-reactivity affecting structures in Dhekelia[30], Limassol and elsewhere (Plate 3), do not always produce remarkable expansions in the mortar bar test; they sometimes exhibit slow and progressive expansion, but not always. In another case, involving volcanic rocks from Korea, the mortar bars persistently indicated contraction rather than expansion (Figure 4), despite the fact that aggregate shrinkage testing placed the material into the lowest category given by the Building Research Establishment[31] in the UK.

The significance of a mortar bar result is always strongly dependent upon the combination of cement and aggregates being tested. The alkali content of the cement is of vital importance and ASTM C33–78 recommends the use of a cement with a total (acid soluble) alkali content preferably in excess of 0,8 per cent (as Na_2O equivalent). However, recent research[32] has re-emphasised that *water soluble* alkalis have a better correlation to the performance in mortar bars than the *acid soluble* alkalis usually considered. Furthermore, it is becoming realised that other aspects of cement composition, such as the contents of calcium hydroxide and tricalcium silicate, may exercise controlling influences over alkali-reactivity[33, 34, 35]. An adaptation of the mortar bar method to test the reactivity of *cements* has been proposed[36]. For these reasons, whenever possible it would seem to be sensible to employ the cement actually proposed for use in any given contractual situation. In many cases it will be thought desirable to repeat the test using a laboratory stock cement of higher alkali content, or even enhancing the alkalis still further, for the reasons discussed earlier (see section 1) or to make due allowance for an uncertain cement supply[11].

Single aggregate materials are often tested by the mortar bar method, but this can give misleading results in practice. In general terms, the 'pessimum' concept is now well established, whereby, in a given concrete mix, a certain 'critical reactive aggregate content' produces the maximum amount of expansion and the shortest time to cracking[32]. The critical content may be as little as 1 per cent (by mass of total aggregate) or less[16]. Therefore, it follows that an aggregate which contains a proportion of potentially alkali-reactive material could give an acceptable result when tested alone, but an unacceptably expansive result when diluted in combination with another and different aggregate. Many real concretes do comprise such a blend of coarse and fine aggregates which are petrographically different, and it is not unusual for the coarse or fine aggregates themselves to be blended for various reasons (such as workability improvement etc.). For example, the flint-bearing aggregates of south-east England invariably give mortar bar results that give no cause for concern (see Figure 1). and

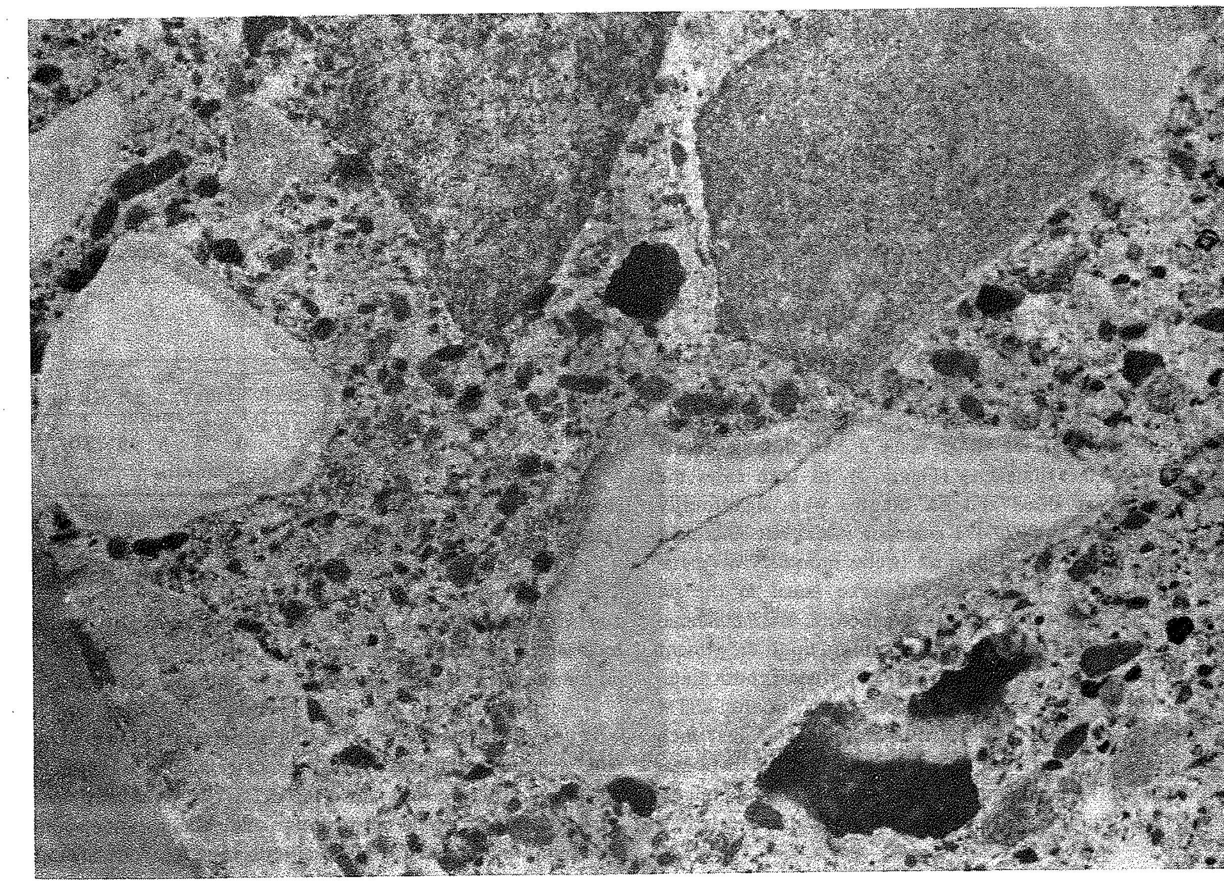


PLATE 3: A detail of a concrete from southern Cyprus showing dark reaction rims around opaline limestone particles. The concrete was only two years old and no distress was yet apparent in the structure. (The larger particle is approximately 15 mm across).

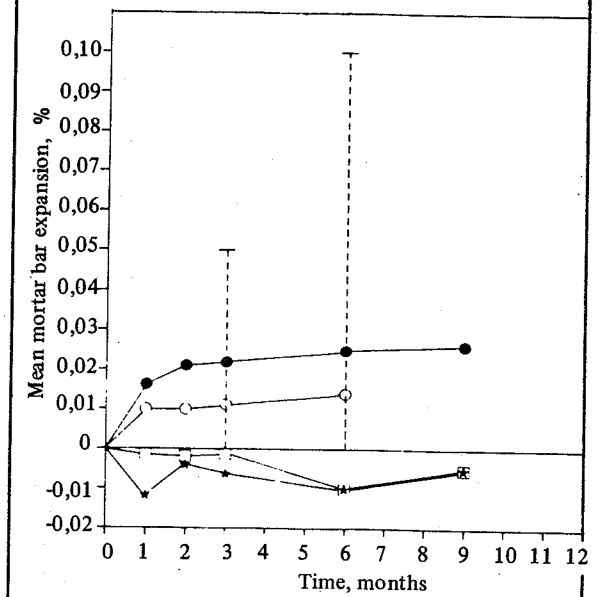
ASTM C227–71, Mortar Bar Test

⊢--- ASTM maxima guidelines

1) Repeat tests, volcanic rock materials, tested using high-alkali cement (1,19% Na_2O eq.)

2 Similar rock material blended with 33% quartz sand, tested using high-alkali cement (1,19% Na_2O eq.)

3 Similar rock material blended with 33% quartz sand, tested using high-alkali cement (0,99% Na_2O eq.)



BRE DIGEST 35, Aggregate Shrinkage Test (cf. Curves 1 and 2 above)	
Mean drying shrinkage:	0,032%
Classification:	< 0,045%, lowest category

FIGURE 4: Unexplained contraction of mortar bars made using a volcanic rock from Korea, compared with the more normal behaviour for some similar materials from the same area.

yet the deleterious alkali-reactivity in the south-west of England has mostly concerned similar materials which are blended with other innocuous rocks and are thereby present in very much smaller proportions (incidentally, the cement types were usually high-alkali and there were sometimes other exacerbating factors). Again, therefore, it would seem more important and relevant to test the actual aggregate combinations proposed for use on particular contracts, rather than the individual aggregates alone.

The identification of potentially reactive carbonate rocks by the ASTM C586–69 rock cylinder test is based upon recording expansions in excess of 0,10 per cent. No definite time to achieve this expansion is given, but it is stated that *usually expansive tendencies are evident after 28 days.*

Again, this expansion figure and the time period mentioned have been wrongly used as a *limit* to be satisfied. In fact this guideline is much less well established than those given for mortar bars, and this is reflected in the cautious wording of the interpretation section of ASTM C586–69. Furthermore, the guideline is based upon the North American reactive dolomites, which as we have seen earlier, differ considerably from the reactive Middle East carbonate rocks.

The rock cylinder test works well for the dolomitic limestone from Kingston, Ontario (Figure 5). In the example shown, for the twelve foot horizon, all four cylinders exceed the guideline at twenty eight days, and the two

ASTM C586–69, Rock Cylinder Test

⊢--- ASTM maximum guideline

Dolomitic limestone, Kingston, Ontario, Canada. 12 ft level.
(approximately 48% dolomite, 43% calcite, 9% insoluble residue)

cylinders drilled parallel to bedding.

cylinders drilled normal to bedding.

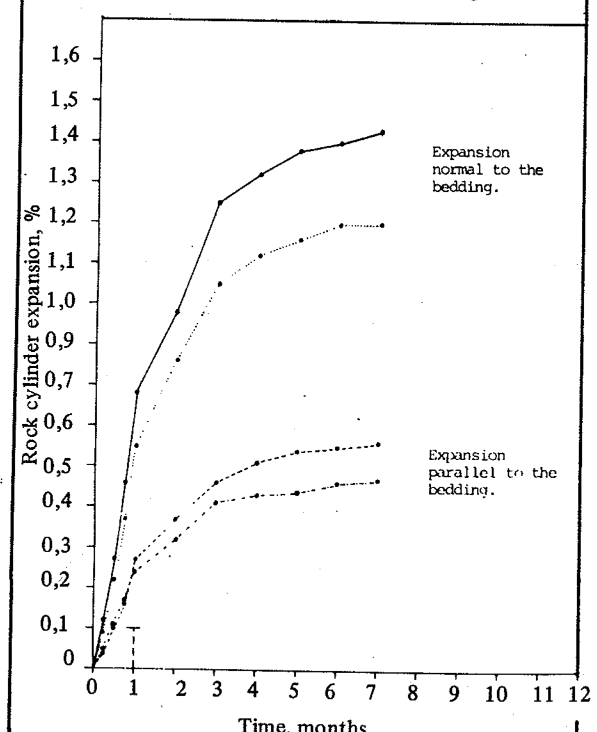


FIGURE 5: Rock cylinder test results for dolomitic limestone from Kingston, Ontario, Canada.

PLATE 4: A detail of concrete from Leicestershire, England, showing a chert particle 7 mm across with a reaction rim and associated gel-infilled voids. The chert represented only a small proportion of the total aggregate. No distress was apparent in the concrete.

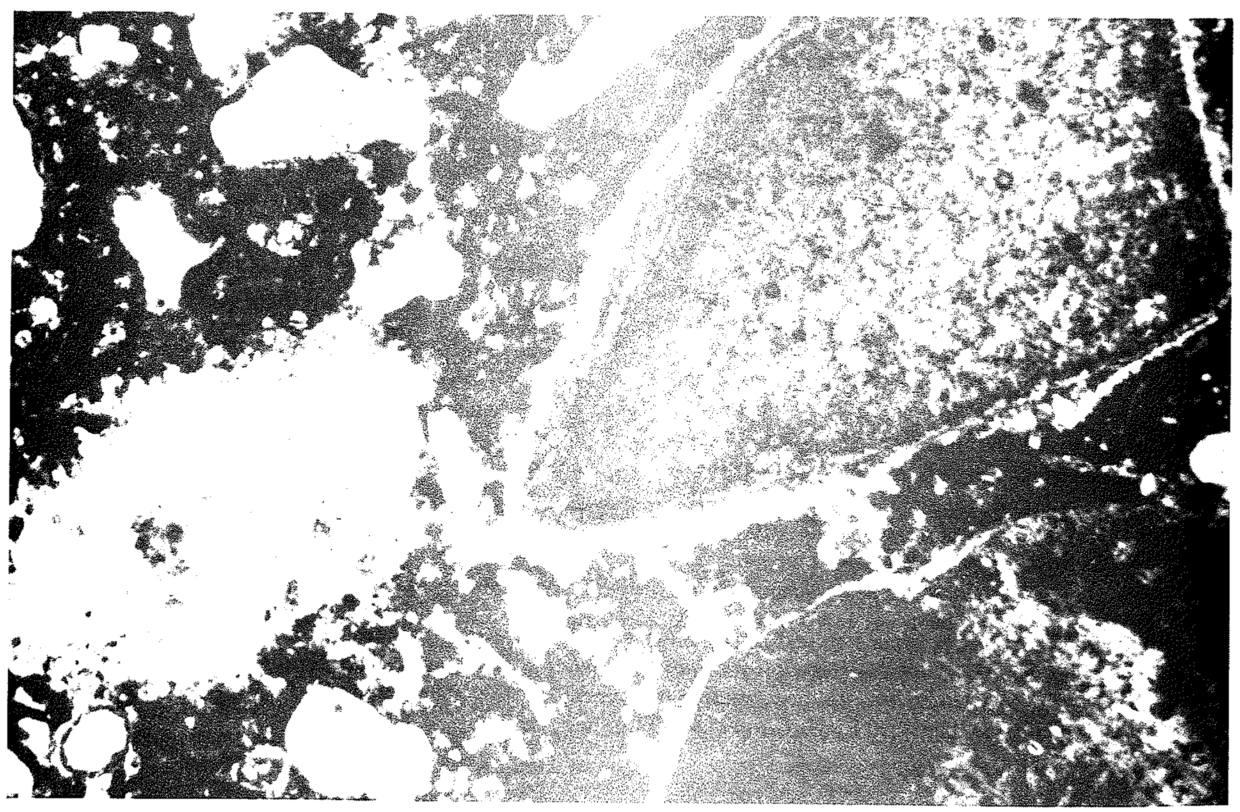


PLATE 5: Photomicrograph in plane polarised light of concrete from an early twentieth century structure in London, England. A piece of flint about 5 mm across exhibits a reaction rim and is surrounded by a peripheral crack infilled with gel; the void to the left is also infilled with gel. In this case, flint was the principal aggregate constituent and many of the larger particles were also affected.

cylinders drilled normal to the layering show markedly larger expansions. By contrast, many rock cylinder tests carried out on Middle Eastern dolomites, even those found to be petrographically similar to the reactive Bahrain rocks, provide results which are difficult to interpret. The main difficulty is that they tend to produce negative results indicative of contraction over the first 28 days and often over a period of several months (Figure 6). In some cases, for example a dolomitic limestone from North Africa, the customary initial contraction was followed at a much later age by a small but progressive expansion which may be continuing at the present time (Figure 6).

The rock cylinder test has been adapted for use with alkali-silic*ate* reactive rocks from Nova Scotia, by using stronger alkaline solutions and higher storage temperatures[14]. The expansion of the phyllosilicate minerals present in the Nova Scotia rocks was also successfully monitored by X-ray diffraction and electron microscopy[37]. A sample of phyllite from Nepal, which is thought to be mineralogically similar to those from Nova Scotia, is currently being tested at the Messrs Sandberg Laboratories using the X-ray diffraction procedure described by Gillott et al[37].

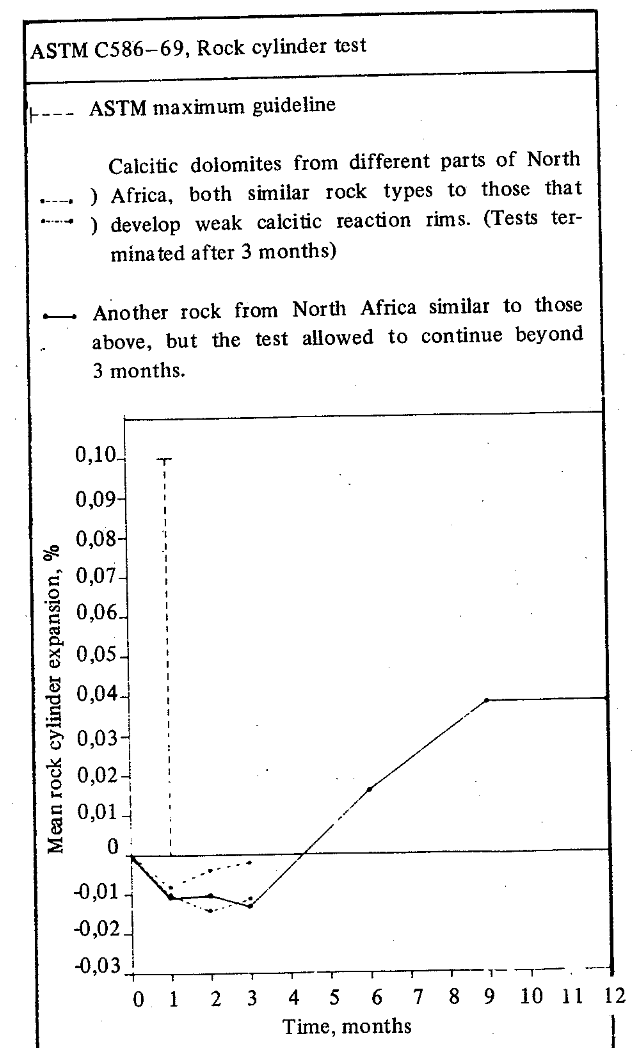


FIGURE 6: Typical rock cylinder test results for Middle Eastern rocks similar to those that develop weak calcitic reaction rims, showing later age slight expansion following earlier age contraction.

5. PREVENTIVE AND REMEDIAL MEASURES

This paper is primarily intended to draw attention to some of the practical problems encountered in evaluating aggregates for alkali-reactivity potential. However, it is appropriate to mention briefly some of the allied problems involved in recommending preventive measures when potentially deleterious combinations have been identified, and in recognising the seriousness of a reaction that is identified in retrospect after the concrete has been made, and in suggesting possible remedial measures in such cases.

A large number of possibly effective preventive measures have been described for application when alternative materials are not available, of which the use of a 'low-alkali' cement (total alkali content of less than 0,60 per cent Na_2O equivalent) is the most frequent. This solution is not always appropriate because alkalis are sometimes available from other sources[13, 15, 38] and in some localities cement supplies may be unpredictable[11]. Another commonly advocated method of prevention is the deliberate addition of finely-ground materials that modify the cement hydration reactions, and some of the latest suggestions include pulverised fuel ash (fly-ash)[34, 35] and blastfurnace slag[39]. The hypothetical general benefit of these admixtures is often well demonstrated by laboratory experiments, but in practice it remains difficult to provide the necessary assurances of durability that are understandably required. There are some examples of pozzolanic admixtures that have not been effective; a material, believed to be a pumicite, used with opaline limestone aggregate in Cyprus actually led to greater expansion being recorded in the mortar bar test[11]. The test programme that would be suitable for proving the effectiveness of a given additive in a specific contractual situation would usually require an unacceptably long time to complete.

Recognition of the operation of alkali-reactivity within a hardened concrete is relatively straightforward using microscopical and microchemical techniques. Assessing the importance, the severity, or the development stage of that reactivity is, however, a very much more difficult, and often impossible, process. For example, in one concrete from Leicestershire in England undergoing routine laboratory strength tests, small chert particles exhibiting both reaction rims and associated gel accumulations (Plate 4) were identified[21]. The concrete was not suffering any resultant distress at that time and the importance of this observation was impossible to gauge; the conflict of responsibilities mentioned in Section 2 was again in evidence. Similarly, several cases of alkali-aggregate reaction in *old* flint aggregate concretes have now been noted in the UK. Examples are in an early twentieth century structure in London (Plate 5) and in a pre-war jetty on the south coast, where seemingly minor alkali-reactivity has probably not contributed significantly to the concrete deterioration.

Finally, in stark contrast to the volume of information on reaction mechanisms that is now available, experience and knowledge of successful methods of repair are notably deficient. In cases where the affected structure is deemed presently safe, the decision has sometimes been taken to make local repairs or replacements and then to embark upon a continuous monitoring programme[2,3], presumably to terminate only when a predetermined safety threshold is reached and the structure becomes disused or is rebuilt. In other cases, attempts are made to prevent the ingress of external moisture into the concrete in order to bring the progress of the reaction down to acceptable levels, and also to avoid the onset of other deteriorative processes which may otherwise be facilitated by the initial damage caused by the alkali-reactivity. Little information is available on the success of such approaches in practice and, in the case of surface waterproofing treatments, arguments against the sealing of cracks have been put forward on the grounds that in some instances this may increase and not reduce the likelihood of further expansion[1]. Therefore, at present it is difficult to give any authoritative general guidance on the most appropriate remedial measures to apply in a given occurrence, and this would appear to be the aspect that is most worthy of urgent research at the present time.

6. SUMMARY

The results of standard tests for potential alkali-reactivity are too frequently regarded as definitive and the guidelines for interpretation often erroneously used as pass-fail criteria. The intended concept of using the test results to *assist* in making an overall judgement is insufficiently heeded. It is common for standard tests to be specified for inappropriate materials and sometimes competent findings have been rejected for being outside the scope of an ill-informed specification. Recurrent problems for the investigating materials engineer are insufficient time to complete reliable long-term tests, and insufficient sample to ensure representability and an adequate programme of tests.

Some form of petrographic examination should never be omitted, as it will identify the most pertinent sequence of tests required and help in the correct interpretation of the results. In particular, the confusion over the distinction between siliceous and carbonate rocks would be avoided. The commercial petrographer has to balance the two conflicting responsibilities of technical competence and the avoidance of unnecessary alarm. A compromise between these options can lead to apparently equivocal advice.

The ASTM C289–71 chemical test is attractive but rigorous, and can give misleadingly pessimistic results even when applied to seemingly appropriate materials. For English flint aggregates, for example, the gel pat test has been used as an alternative. It has been found that sulphates, as well as carbonates, can affect ASTM C289–71 test results, so that potentially reactive materials could be designated 'innocuous'.

In the ASTM C227–71 test, expansions below the guideline levels are not necessarily unimportant. Some materials, such as metamorphic quartz aggregates and some carbonate rocks, exhibit slow but progressive expansions, which are difficult to evaluate on practical engineering time scales. Anomalous mortar bar behaviour is not unusual, including unexplained contraction. The significance of a mortar bar result depends upon the combinations tested, and it seems more relevant to employ the cement type and aggregate blend actually proposed for use.

The ASTM C586–69 rock cylinder test works well for North American dolomites, but the results for Middle Eastern reactive carbonates are more difficult to interpret. It is common for these rock cylinders to contract initially, although after many months some exhibit a small but progressive expansion.

The use of low-alkali cement as a preventive measure is not always appropriate, and it is difficult to provide assurances about the effectiveness of mineral additives such as fly-ash and slag. It is not difficult to identify the presence of alkali-reactivity in a concrete, but the assessment of the importance and state of progress is almost impossible. Constant monitoring and surface waterproofing are common remedial measures, but there is little available information on the likelihood of success. Urgent research is needed to establish the most beneficial ways of dealing with an affected structure.

NOTE:

The above paper was completed before the 1980 Annual Book of ASTM Standards was available in the UK. The author would like to apologise for any small inaccuracies of quotation that may have resulted from use of the 1979 edition.

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DISCUSSION

Dr D Davis (PCI, Halfway House, South Africa) asked for more information about the gel pat test.

Dr I Sims, in replying, emphasised that the gel pat test was a very simple qualitative test which had been devised by the Building Research Station in England in the mid 1950's. It was used principally for monitoring, and enabled far more tests to be carried out than was possible with more sophisticated tests. It had some advantages because of its simplicity; for example it could be carried out by basically equipped site laboratories and it would therefore be possible to test almost every batch of material that came in. This had been done in England on some major construction sites where dredge materials had been used which were expected to be far more variable than pit material. Basically the test consisted of crushing the aggregate, taking representative portions and mounting them in a little cement pat, about 100 mm in diameter. This was immersed in a 1N NaOH solution and then observed to see whether a gel deposit built up on the surface, and which particular particles developed these. It could be important to note the way in which these developed and the morphology of the gel pile and one could note the earliest time that the gel began to develop and the rate at which it developed.

Dr A B Poole (Queen Mary College, London) gave it as his opinion that the low expansion in the case of the Bahrainian rocks was due to their low clay content (2 per cent palygorskite) whereas the Kingston limestone had of the order of 10 per cent clay, mainly illite.

Dr L Dolar-Mantuani (Toronto, Canada) explained that in the rock cylinder test for the Kingston rocks she had found first shrinkage and then expansion that went on for six to seven years, and hence the term *late expanding carbonate rocks.* This was typical of these rocks which were dolostones, i.e. containing 90 per cent dolomite and not limestone.

Prof S Diamond (Purdue University, Lafayette, USA) mentioned that the most common questions raised by Dr Sims demonstrated that the confusion in the whole field of alkali-aggregate reaction, was compounded when alkali-silica reactions and alkali-carbonate reactions were considered simultaneously. The difference in the mechanism of the response being considered was so great that he felt it would be better to arrange to treat these as independant problems rather than lumping them together as alkali-aggregate reactions.

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