SESSION 3

Test Method and Criteria for Alkali–Reactivity of Aggregate

Keynote Lecture

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TEST METHODS AND CRITERIA FOR EVALUATING THE POTENTIAL REACTIVITY OF AGGREGATES

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1. INTRODUCTION

Test methods such as the mortar bar method (ASTM C227 [1]) and the concrete prism test method (CSA A 23.2-14 [2]) which have traditionally been used to evaluate the potential reactivity of aggregates are no longer considered satisfactory as they take too long to complete. The chemical method, (ASTM C289 [3]) while it is rapid, it is not suitable for use with all types of aggregates and and furthermore because it does not give an estimate of the expansion potential of the aggregate, is not suitable as an acceptance test. In the evaluation of new rapid test methods it is essential that the results obtained are compared with those of reliable standard tests, or with field performance; the latter is often not available. Recent research [4] has shown that standard tests such as the mortar bar method ASTM C227, may seriously underestimate the expansiveness of an aggregate; there is thus a need to refine existing standard tests, and to the develop new methods. Both the above topics will be addressed in this paper.

Reliable criteria must be developed for the evaluation of the results of new rapid test methods; those for the evaluation of existing standard tests also need to be improved. The effect of varied exposure conditions on the expansion and deterioration of concrete in the field complicates the development of criteria for the evaluation of test results. For example, the author has observed that some greywackes can be used in concrete for high rise construction, without causing any apparent deterioration, despite the fact that the buildings are in an area frequently subject to fog, but the same aggregate used in concrete in highway bridges caused cracking after about 5 years. It would thus appear that there is a need for at least two sets of criteria, one for concrete exposed to severe conditions, the other for concrete which will exposed to mild conditions.

2. TRADITIONAL REFERENCE TEST METHODS

2.1. Mortar bar method ASTM C227.

The mortar bar method is the one most generally used for the evaluation of new test methods [5-9], however obtaining the optimum expansion with the mortar bar method is complicated by the large number of factors which effect expansion; a number of these will be discussed.

2.1.1. Proportion of reactive aggregate in mortar

It has been known since the earliest research on AAR [10] that with some aggregates, maximum expansion of mortar bars occurs when some relatively small percentage of reactive aggregate, typically 2-to 10% (known as the pessimum) is present in the mortar.(11,12).

2.1.2. Effect of alkali content of cement on expansion

The effect of the alkali content of the cement on the expansion of mortar bars varies with the type of reactive aggregate used. Mortar bars containing opal exhibit maximum expansion at some pessimum quantity of alkali in the cement, for the same reason that there is a pessimum quantity for opal [11] Hobbs [12] found that with one type of opal, maximum expansion in mortar bars occurs when the water soluble alkali content of the cement was about 0.6% Na_2O equivalent which corresponds to an acid soluble alkali content of about 0.8%. By contrast, with slowly expanding aggregates such as greywackes and hornfels expansion increases with the alkali content of the cement, at least up to an acid soluble alkali content of 1.2%

2.1.3. Effect of particle size on the expansion of mortar bars

Most of the investigations on the effect of particle size on the expansion of mortar bars were conducted with opal, [13], or opaline sandstone [14]. The effect of particle size on the expansion of mortar bars containing opal determined by Kawamura [15] is shown in figure 1. The pessimum size is about 0.2 mm. Other authors, [14,16,17] observed maximum expansions in mortar bars at about the same aggregate size range. In contrast to the above results, Diamond & Thaulow [18] observed maximum expansion when the size of opal particles was about 0.034 mm. The effect of particle size on expansion of mortar bars made with slowly expanding aggregates such as greywackes and argillites has not been documented.

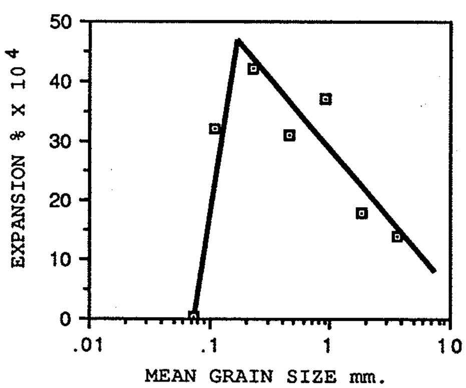

Figure 1. Effect of grain size of opal on expansion of mortar bars. After Kawamura [16].

2.1.4. Effect of storage temperature on expansion of mortar bars.

Cheng et al.[19] showed that expansion of mortar bars containing reactive siliceous limestone increased linearly, for temperatures between 5° and 55°C, however, in a second set of mortar bars, made with a different cement, expansion was found to level off at temperatures above 38°C, figure 2. Reduced expansion at higher temperatures has been observed by other authors,[20,21]; this may be due to desiccation of the bars at the higher temperature, or to changes in the properties of the reaction product. In the current version of the mortar bar test ASTM C227-86 a storage temperature of 38°C is specified.

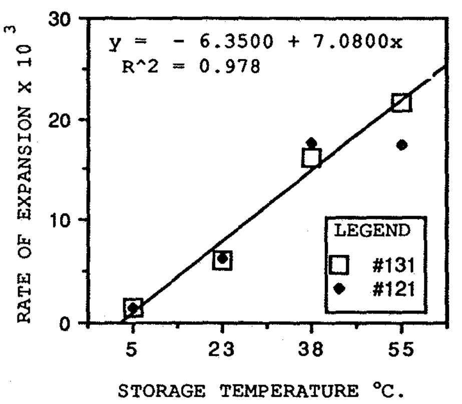

Figure 2. Effect of temperature on expansion of mortar bars made with two cements #131 and #121.

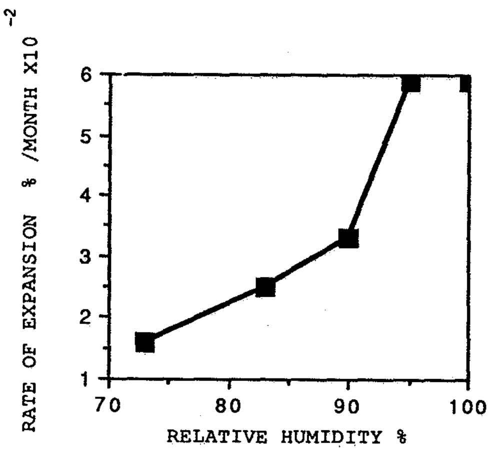

Figure 3. Effect of relative humidity on expansion of mortar bars containing reactive aggregate

2.1.5. <u>Effect of humidity in storage containers on expansion of mortar bars</u>.

It is generally recognized, that humidities greater than about 85% are necessary for damage due to AAR to occur in concrete [22]. Olaffson [23] showed that for humidities in the range of 70 to 90 %, the rate of expansion increased linearly with humidity, but that between 90 and 95% humidity the rate of expansion increased exponentially, figure 3. However, recent results reported elsewhere in this Proceedings by Hooton and Rogers showed that with some aggregates maximum expansion was obtained when the bars were stored above water in containers without wicks. The use of wicks up the sides of the mortar bar containers results in excessive moisture condensing on the bars, and leaching out alkalis resulting in reduced expansions.

2.1.6. <u>Effect of cross-sectional area of mortar bars on expansion</u>.

The size of mortar bars specified in ASTM C 490-86 [24] is 25 x 25 x 285 mm. This has been the standard size of mortar bars for many years but recently, Bakker [25] found that the rate of expansion increased with increasing cross-sectional dimensions up to at least 100 mm Locher [26] also reported greater expansions with RILEM bars (40 x 40 x mm) than with ASTM C490 bars. It would appear from the above discussion, that greater expansions are obtained when mortar bars with larger cross-sectional areas are used than the traditional 25 x 25 x 285 mm bars.

2.1.7 Effect of water:cement ratio on expansion of mortar bars

Changing the w/c ratio in mortar bars affects not only the alkali concentration of the pore solution but also the physical properties of the mortar; these changes effect the expansion of mortar bars made with alkali-reactive aggregates. Lenzner [27] observed maximum expansions of mortar bars containing opaline sandstone at a w/c of 0.6 with expansions at water:cement ratios of 0.7 <0.4 <0.5 <0.6. In contrast to the above results, Hobbs [13] found that in mortar bars containing opal, expansion was reduced when the w/c was greater than 0.5, however the relative proportions of reactive silica to alkali used by the two authors were different; this could account for the observed differences in expansion. The above results suggest that the optimum w/c ratio for expansion of mortar bars containing alkali-silica reactive aggregate is probably in the range of 0.4 to 0.6, the exact value depending on the physical and chemical properties of the aggregate.

2.1.8. Effect of cement fineness on expansion of mortar bars

If maximum expansion of mortar bars containing reactive aggregate is to be obtained within a few months, it is essential that most of the alkali in the cement goes into solution rapidly. The finer the cement, the more rapidly the alkalis would go into solution. Expansion of concrete prisms has been shown to increase with increasing fineness of cement,[28], the same effect probably occurs in mortar bars.

2.1.9. Effect of type of aggregate on expansion of mortar bars.

Results of mortar bar expansions presented by McConnell et al [29] indicate that opal is the most expansive form of silica or silicate, followed by some types of chert, rhyolite, pitchstone, andesite, novaculite and obsidian. Slowly expanding siliceous aggregates such as greywackes and quartz sandstones show much less expansion at 6 months but none-the-less cause deterioration of concrete after 5 to 10 years. The expansion potential of a particular type of aggregate may also vary with its source.

2.2. Criteria for the evaluation of the results of mortar bar tests.

Currently, most results from mortar bar expansion tests are evaluated following the criteria recommended in ASTM C33 [30]; despite the widespread use of these criteria, they have many short-comings. For example it is difficult to understand how fixed expansion limits of 0.05% at 3 months and 0.1% at 6 months can be specified when wide variation is permitted in the alkali content of the cement. ASTM C227 specifies that either the job cement with an alkali level in excess of 0.6% Na_2O equivalent or a reference cement with the highest available alkali can be used. The non-mandatory information given in ASTM C33 suggests that the alkali content of the cement should be substantially above 0.6% and preferable above 0.8%. The use of such loose specifications can in some instances lead to incorrect diagnosis of the potential reactivity of an aggregate; an example of this is shown in figure 4,[31]. It is evident from figure 4, that the aggregate which causes deterioration in concrete, would be classed as innocuous even if the alkali content of the cement was 1.1%; when evaluated according to the Bureau of Reclamation criteria,(>0.1% @ 1 year) [32]the aggregate would be classed as deleterious even it the alkali content of the cement was 0.82%. The above results suggest that the alkali content of the cement used in the mortar bar test should be about 1% Na_2O equivalent and the criteria for deleterious expansion should be expansion greater than 0.1% at one year, and possibly a proportional amount (0.05%) at 6 months.

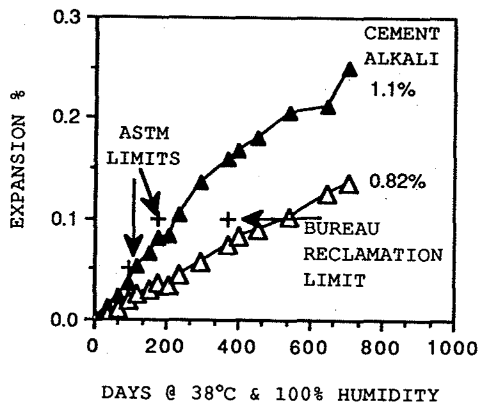

Figure 4. Effect of alkali content of cement on expansion of mortar bars made with slowly expanding Malmsbury aggregate. Data from Oberholster [31]

3. CONCRETE PRISM TEST

4.1. Concrete prism test method.

In the current version of the test [2], the alkali content of the cement used is specified as 1.0 ± 0.2% Na_2O equivalent, to be increased to 1.25% by the addition of NaOH to the mix water. The cement content of the mix is 310 kg/m^3. The alkali content of the cement is boosted to 1.25% to try and insure that concrete prisms made with all types of reactive siliceous aggregates would expand within about one year of storage at 38°C and 100% humidity. In tests for alkali-carbonate reactivity, the prisms are stored at 23°C and 100% humidity. The concrete prism test should work for all types of aggregates and therefore should be suitable as a referee test method, but unfortunately, concrete prisms made with a documented reactive gravel aggregate containing greywackes and argillites expand less than the 0.04% limit specified in CSA A23.1 Appendix B [2] When the cement content of the concrete prisms containing the above aggregate was increased to 420 kg./m^3 the aggregate would be classed as expansive according to the CSA A23 criteria. Excessive increases in the cement content of concrete prisms can however lead to satisfactory aggregates being classed as deleteriously expansive; for example, a well documented non-reactive limestone from Ireland [33] was diagnosed as being expansive using the Draft BS 812 method [34] in which the cement content of the concrete is 700 kg/m^3. The same aggregate evaluated in the very severe NBRI accelerated mortar bar test (5) expanded by only 0.075% in 14 days; aggregates giving rise to expansions of less than 0.1% in the NBRI test are considered innocuous. More research is needed to determine the optimum mix design for concrete test prisms.

Expansions obtained with the concrete prism test are affected by a number of parameters in addition to the mix design:
(i). The temperature and humidity of the storage containers have a major impact on the observed expansion. When evaluating the potential expansivity of slowly

expanding siliceous aggregates such as greywackes, it is essential to store the prisms at 38°C. The author has observed that in the concrete prism test, contrary to what was found in the mortar bar test, expansion was reduced considerably when the wicks were removed from the storage containers. (ii) The water:cement ratio effects expansion but results obtained by the author using two siliceous limestones, are not conclusive. (iii). It has been shown that the fineness of the cement has a major impact on the the expansiveness of concrete prisms, figure 5 [28]. (iv) Research by the author has indicated that the expansion of concrete prisms is affected by the particle size of the aggregate, but conclusive results are not yet available. It will be evident from the above discussion that if optimum expansions are to be obtained in the concrete prism test, conditions must be optimized.

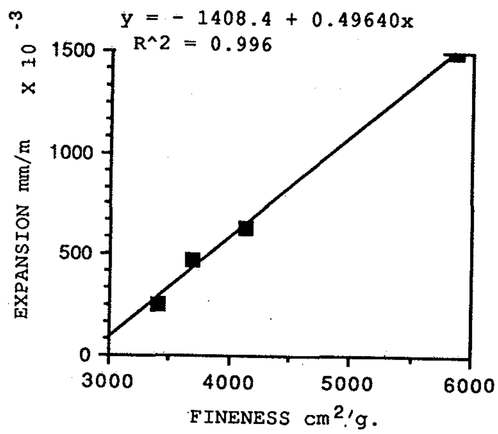

Figure 5. Effect of fineness of cement on expansion of concrete prisms. After Krell [28]

3.2. Criteria for evaluation of results of concrete prism test

Cracking in concrete is usually observed when expansion reaches about 0.04%, the limit specified in CSA A23.1 Appendix B.[2]. In the Cement and Concrete Association test, the concrete is considered to be deleteriously expansive if expansion exceeds 0.05% at 6 months if thin section examination indicates that alkali reactivity is the probable cause of deterioration.

4. CHEMICAL METHODS

4.1. Introduction

A number of methods which may loosely be classed as chemical have been proposed:
ASTM C289-86 chemical method [3]
German (Vorbeugende Masnahmen) weight loss method [35]
Danish chemical shrinkage method, [36]
Osmotic cell test (USA) [37]
Gel Pat test (UK) [38]

Each of the above methods is suitable for use with certain types of aggregates but with the possible exception of the osmotic cell test none are universally applicable. The chemical methods were devised to give rapid test results in instances when there was not sufficient time to carry out conventional concrete prism or mortar bar tests; the chemical methods have now been largely superseded by the newly developed accelerated mortar bar methods The chemical methods have recently been reviewed by Hobbs [38]. Only the Danish Chemical Shrinkage test will be reviewed here.

4.1.2. Danish chemical shrinkage method

The continuous quick chemical method for characterization of ASR of aggregates was described by Knudsen [36]. The method is based on measurement of the chemical shrinkage that occurs when reactive silica (flint) reacts with alkali. The method is designed to evaluate the potential reactivity of Danish sands containing potentially reactive flint. In the test 25 g sand is put in the reaction flask along with 50 ml of 10 M NaOH, air is removed, a layer of oil is added and a 0.2 ml pipette is sealed into the top of the flask. The flask containing the sample is put in a water bath at 50°C and as the silica reacts with the alkali, the meniscus in the pipette starts to drop due to shrinkage of the sample. The method is relatively simple and an automatic apparatus, the Konometer [36] has been developed. The high cost of the Konometer will likely limit its use. Good correlation has been reported by Knudsen (ibid) between the results of chemical shrinkage test and the expansion of mortar bars made with the same aggregate, using the Danish accelerated mortar bar test TI-B51, but no use of this method outside Denmark has been reported.

5. PETROGRAPHIC EVALUATION OF AGGREGATES

5.1. Introduction

Petrographic examination alone cannot provide information on the expansiveness of a particular cement-aggregate combination, however, experienced petrographers can predict the likely behavior of aggregates with which they are familiar. A petrographer can identify potentially reactive materials e.g.chert,flint,chalcedony,opal,agate,cristobalite,tridymite,volcanic or artificial glass and microcrystalline quartz in aggregates, by optical microscopy of thin sections, aided, when necessary, by use of x-ray diffraction, infra-red spectroscopy and other instrumental techniques. A broad outline of the procedure to be followed in making a petrographic examination is given in ASTM C295.[39] Recently, a number of new petrographic techniques have been proposed to aid in the identification of potentially reactive siliceous aggregates.

5.1.1. Undulatory extinction angle (UE angle) as an indicator of potential reactivity of quartz particles

Gogte [40] studying a series of quartz bearing Indian aggregates observed high UE angles in quartz grains in aggregates found to be expansive in the mortar bar test run at 50°C. Mather [41], found that in concrete cores exhibiting ASR, the aggregate was a highly deformed quartzite. Subsequently, other authors [42-44] discussed the possible relationship of UE angles in quartz to the reactivity of aggregates. The author [45] suggested that the apparent correlation between high UE angles in quartz and the expansivity of quartz bearing aggregates, might be coincidental and that the reactivity might be due to the presence of microcrystalline quartz, a known reactive material in the aggregates. Mullick et al [46] attempted to correlate undulatory extinction in quartz with expansion of mortar bars containing quartz bearing aggregates. The expansion of all his samples is plotted against the percentage of quartz grains in the aggregate showing strain in figure 6a, and against the average UE angle in figure 6b. It is evident from both the above figures,that there is little correlation between the expansivity of the aggregates and either the percentage of quartz grains with strain or those with high UE angles. However despite the lack of formal correlation, aggregates in which about 90 percent of the quartz grains are strained or in which the UE angle is larger than 35 degrees show greater expansions in mortar bars than other aggregates. The above conclusions are in agreement with those of the author. Microcrystalline quartz is invariably present in aggregates containing strained quartz and probably accounts for the expansivity of those aggregates.

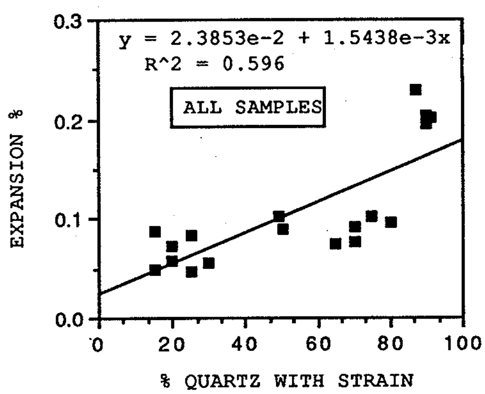

Figure 6a Influence of percentage of strained quartz in aggregate on the expansion of mortar bars. After Mullick [46]

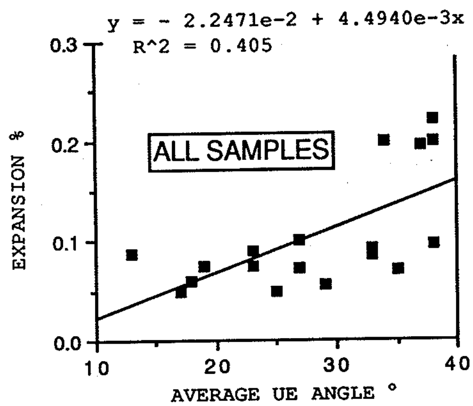

Figure 6b. Influence of UE angle in quartz grains in aggregates on the expansion of mortar bars After Mullick [46]

5.1.2. <u>Infrared method of determining the potential reactivity of siliceous aggregates</u>

Reaction between alkalis in cement and siliceous aggregates occurs when metastable silica is present in the aggregates. Some forms of metastable silica such as cristobalite and tridymite are readily detectable by x-ray diffraction but poorly crystalline silica or glassy silicates are not, however, in theory, at least, it should be possible to detect differences in the degree of crystallinity of silica minerals using infrared spectroscopy. Baronio et al [47] have proposed an infrared method for determining the potential reactivity of siliceous aggregates. A factor termed the coefficient of disorder (Cd) of the silica lattice is calculated from the heights of the n_1 and n_3 peaks which occur at about 800 and 1,100 cm^{-1} respectively, and width of the then n_1 peak at 1/3 of its height. The use of the KBr disk method of sample preparation creates a potential problem because in this procedure the sample is ground to <45 μm before mixing with KBr and pressing into disks. It has been shown [48],that grinding crystalline quartz, to sizes less than 100 μm causes it to become soluble in alkali in the chemical test ASTM C289. It would thus appear that, to some extent, at least, the disorder which is being evaluated is being introduced into the silica lattice by the sample preparation technique. In an attempt to overcome this problem the author tried to measure Cd in reactive chert samples, using an infrared microscope in the reflectance mode but this proved to be impossible, because the n_1 peak in the spectra was not well enough defined. More research is needed to try and develop this method.

6. RAPID MORTAR BAR EXPANSION TESTS

6.1 Danish accelerated mortar bar method TI-B51

The Danish method was the first of the accelerated methods [48]. The size of the mortar bars is 40 x 40 x 160 mm. After demoulding the bars are moist cured for 28 days before the initial lengths are measured. The bars are then transferred to a saturated NaCl solution which is maintained at 50°C. The bars are cooled to 20°C at weekly intervals and the changes in length are recorded. The total time required for the test is about 6 weeks which is an improvement over the 6 months required for ASTM C227. The Danish method does not appear to have been used much outside of Denmark, and has, in the author's opinion been superseded by the NBRI,and the Chinese and Japanese autoclave methods.

6.2. NBRI Quick mortar prism test

The mortar bars are prepared following the ASTM C227 procedure. After the bars are demoulded they are put in a container with water at 23°C and placed in an oven at 80°C.[5] After 24 hours,the bars are removed, one at a time, from the hot water, and the lengths are recorded within 20 seconds, to prevent excess shrinkage due to cooling; the bars are then put in 1 M NaOH solution at 80°C and returned to the oven. Length change of the bars is monitored for two weeks. The mean expansion of a set of bars after 12 days in NaOH solution is used for evaluating the potential expansivity of the aggregate. No firm criteria have yet been established for the evaluation of the reactivity of aggregates but Davies and Oberholster [50] suggested the following:

Expansion ≤ 0.10%	aggregate innocuous.
Expansion ≥ 0.10 ≤ 0.25%	potentially reactive, slowly expanding.
Expansion ≥ 0.25%	potentially reactive, rapidly expanding.

As with the mortar bar test C227, expansion of the mortar bars is influenced by a number of factors: Both temperature and the concentration of alkali in the solution affect the expansion; immersion of bars in 1 M NaOH solution at 80°C was found to give the maximum expansion. Expansion increases with increasing water:cement ratio at least up to 0.55, the highest practical value. The author found that expansions of bars made with a cement with an alkali content of 1.08% were identical with those of bars made with a cement having an alkali content of 0.66%, indicating that the alkali content of the cement has little effect on expansion. Preliminary inter-laboratory testing reported by Davies and Oberholster[ibid] showed that the average difference in expansion for tests with reactive aggregates between the two laboratories was about 25%. In the NBRI laboratory, the within laboratory variation on the 12th day was found to be 8%. A limited evaluation of test results in the author's laboratory gave a coefficient of variation of 6.5%, i.e. about the same order of magnitude as the NBRI result. Expansion data for mortar bars made with a reactive siliceous limestone aggregate have been obtained, independently by a number of laboratories, including the author's; the results are shown in figure 7. The coefficient of variation between the results is 22%.. The wide variation in the above results is probably due, in part at least, to variations in the test procedure used in different laboratories.

The correlation between expansions of mortar bars in the NBRI test and expansions in standard concrete test prism or mortar bars tests from three of the laboratories referred to in figure 7, is shown in figure 8. Although there is a general trend of increasing expansion of mortar bars, in the NBRI test, with increasing expansion in standard tests, the correlation is very poor;

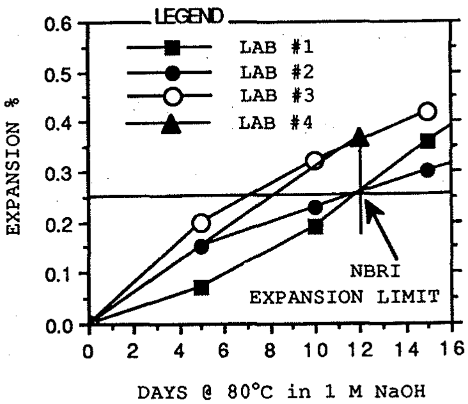

Figure 7 Expansions of mortar bars made with siliceous limestone aggregate in the NBRI test by four laboratories: #1 [51], #2 [52], #3 the author's and #4 [53]

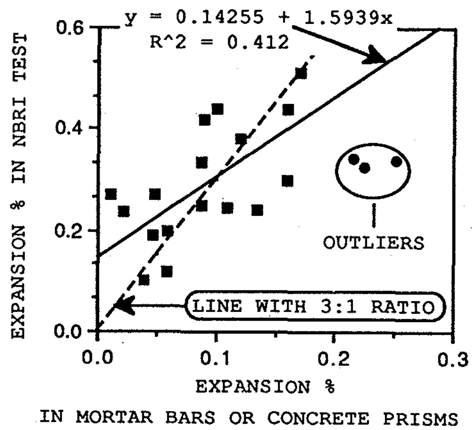

Figure 8. Comparison of expansions of mortar bars in the NBRI test, with results obtained using ASTM C227 or the concrete prism method by 3 laboratories. The outliers (circled) were excluded when the solid line was fitted to the points in the graph. The dashed line indicates the 3:1 ratio of expansion in the NBRI test : expansions in other methods.

better correlations were found when expansions from individual laboratories were evaluated independently. The mean value of the ratio of expansion in the standard tests to expansion in the NBRI test for the 21 aggregates shown in figure 8 is 4.68 with a standard deviation of 5.1, but when outliers, circled in figure 8, are removed, the mean ratio becomes 2.86 with a standard deviation of 1.19 which indicates that for most aggregates, the NBRI test gives about three times the expansion obtained in either the mortar bar or concrete prism tests.

An extensive inter-laboratory evaluation of this test method is in progress in Canada at the time of writing; results should be available later this year.

6.3. Japanese accelerated mortar bar method

6.3.1. Test protocol

A method of accelerating the expansion of mortar bars which also involves storage of the bars in 1 M NaOH at 80°C was proposed by Yoshioka et al [9] The procedure follows ASTM C227 until the bars have been demoulded and the initial lengths recorded. The bars are then placed in 1 M NaOH and heated to 80°C for 24 hours, cooled to 20°C and the second length measurement is recorded. The samples are then stored at 80°C and 100% humidity for 72 hours, cooled to 20 °C and the final length recorded. The test takes 7 days to complete. The correlation coefficient between the expansion of mortar bars containing reactive andesite aggregate in the accelerated test and in ASTM C227 is 0.95.

Only limited testing with this accelerated method has been reported; more evaluation of the method will have to be done before it can be recommended for general use. The expansion of mortar bars in the accelerated test corresponding to the ASTM C33 limit of 0.1% is 0.168%; expansions greater than this are considered to be deleterious.

6.4. Autoclave methods for accelerating mortar bar expansion

6.4.1. Introduction

Three autoclave methods have been proposed [6-8], A variation of the Chinese method in which a different sized sample is used has been reported [55]. The procedure to be used in the autoclave test methods is summarized in table 1.

Table 1. Summary of autoclave methods for accelerating mortar bar test.

METHOD & AUTHOR	SIZE OF BARS cm	w/c	c/a	CEMENT ALKALI Na2O eqv.	DEMOULD @ 24 hrs. MEASURE	PRE-TREATMENT	MEASURE	AUTOCLAVE	COMMENTS
CHINESE, TANG [6]	1 x 1 x 4	0.3	10:01	-	X	STEAM 4 hr @ 100°C, COOL TO 20°C	X	6 hr in 10% KOH @ 150°C	MEASURE
JAPANESE NAKANO [54]	2.54 X 2.54 X 28	0.3	10:01	-	DEMOULD @ 24 hr MEASURE	STEAM 4 hr @ 100°C,COOL TO 20°C	X	6 hr in 10% KOH @ 150°C	MEASURE
JAPANESE NISHIBAYASHI [7]	4 x 4 x 16	0.45	1:2.25	0.5% + NaOH TO GIVE 1.5%	DEMOULD @ 24 hr MEASURE	-	-	4-5 hr @ 0.15 MPa (120°C)	MEASURE
JAPANESE GBRC TAMURA [8]	4 x 4 x 16	-	1:01	OPC ADJUSTED TO 2.5% BY ADDING NAOH	DEMOULD @ 24 hr MEASURE	IN WATER @ 20°C 24 hr	X	2 hr @ 1.5 kg/cm2 (111°C)	MEASURE PULSE VEL. or OBSERVE CRACKS

6.4.2. Chinese method.

The procedure to be followed in the Chinese autoclave test is outlined in table 1. Good reproducibility has been reported with this method. In a variation of the Chinese method, Nakano [55] using 2.54 x 2.54 x 285 cm mortar bars found that expansion was reduced by 50% compared to that obtained using the smaller bars specified in the Chinese method. Nakano [ibid] found a coefficient of variation of 11.9% for tests on 21 sets of mortar bars made with reactive aggregates. Tang ibid. and Nakano ibid.,report good results with a wide variety of reactive and non-reactive aggregates. Four Canadian aggregates, two reactive and two non-reactive were evaluated by Tang, personal communication, and by the author using the Chinese autoclave method, the results obtained are plotted in figure 9. For comparison, the results of tests of the four Canadian aggregates using ASTM C227 and the NBRI method are also shown in figure 9. The reproducibility of the autoclave test between the two laboratories is good except with the greywacke for which the author obtained a much lower expansion. The Chinese autoclave method gave slightly higher expansions than ASTM C227 with non-reactive aggregates, but somewhat lower expansions with reactive aggregates.

Tang [ibid] proposed an expansion limit of between 0.11 and 0.12% to differentiate between potentially reactive and non-reactive aggregates. Testing with a greater variety of aggregates will be needed to confirm the proposed expansion criteria.

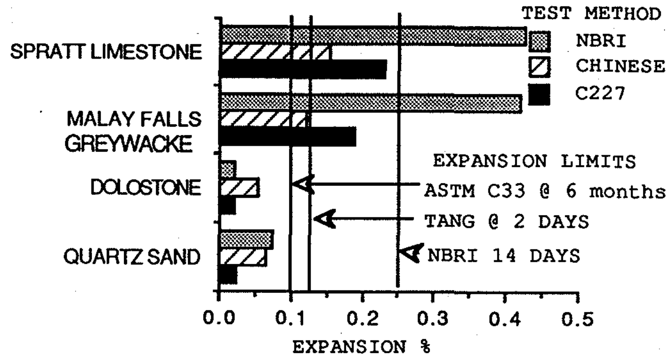

Figure 9. Comparison of expansions obtained with 2 reactive and 2 non-reactive aggregates using ASTM C227, the NBRI quick test and the Chinese autoclave method.

6.4.3. Japanese autoclave method

In this method, the bars are 4 x 4 x 16 cm; they are demoulded after 24 hours and autoclaved for 4 to 5 hours under a pressure of 0.15 to 0.2 MPa.. Nishibayashi et al.[7] reported that the optimum alkali content of the cement was 1.5% Na_2O equivalent; this was achieved by the addition of NaOH to the mix water. The expansions reported using Nishibayashi's method are about the same as those obtained with ASTM C227; therefore, presumably, expansions greater than 0.1% would be considered deleterious. More evaluation of this method would be required to establish firm expansion limits.

6.4.4. GBRC autoclave method

In this method 4 x 4 x 16 cm bars or mortar pats may be used. The alkali content of the cement is increased to 2.5% Na_2O equivalent by the addition of NaOH. The bars are cured in the moulds for one day and then in water for another day before autoclaving under a pressure of 0.15 MPa for 2 hours. A possible advantage of this method is that the potential reactivity of a cement-aggregate combination can be evaluated by simply observing if the mortar bars have cracked or not, however, measurement of the crack widths is needed to give some estimate of the expansivity of the aggregate. Tamura et al [8] also measured changes in the dynamic Young's modulus of the bars. A reduction ratio in Young's modulus of 10 or less was observed in mortar bars made with innocuous aggregates but in bars containing reactive aggregates the reduction ratio was between 30 and 45. Tamura ibid reported that the results of the GBRC method correlate well with those of ASTM C289, but only limited testing has been reported.

6.5. Conclusions

All the rapid test methods appear to give satisfactory results, at least with the limited range of aggregates which have been tested. All the methods are sensitive to minor changes in mix design, size of mortar bars and experimental procedure. The autoclave methods give expansions close to those obtained using ASTM method C227, but much greater expansions are obtained with the NBRI method. The larger expansions obtained with the NBRI method creates a danger that aggregates, with a satisfactory field performance, might be classified as deleteriously expansive. Extensive evaluation of all the proposed accelerated methods, in round robin tests, would be required to evaluate the various parameters affecting expansion and to establish firm criteria for the evaluation of aggregates. It is possible that due to the effect of exposure conditions on the deterioration of concrete, two sets of criteria may need to be established, one for mild exposure where the concrete would mostly be exposed to low humidity and one for severe conditions where the concrete would be exposed to high humidity and or the application of deicing salts.

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