ACCELERATED MORTAR BAR METHOD ASTM C9-P214

General considerations

This method, slightly modified from the South African NBRI method proposed by Oberholster & Davies (14), is becoming increasingly useful for rapid testing of aggregates for potentially alkali-reactivity in concrete, as more experimental data are gathered on different rock types and comparisons are made with standard methods and with field concretes containing them. The test is considered a powerful screening tool but cannot be used for rejecting aggregates. While it allows detection of most alkali-reactive aggregates (except the alkalicarbonate types and a limited number of alkali-silica/silicate varieties), it is overly severe for numerous innocuous aggregates (4). This method has also been used to assess the effectiveness of mineral admixtures against AAR (6, 7, 15, 16). In this study, the criterion proposed by ASTM C9-P214, expansion <0.1% at 14 days, was considered.

Experimental results

The results are shown in Figs. 5 to 10, and in Table 4. The observations are the following:

- Effect of CSF -- The minimum CSF content needed to limit expansion to 0.1% at 14 days for both reactive aggregates is 8% with the low-alkali CSF-A and 11% with the high-alkali CSF-B. On a preliminary basis, these results appear realistic and suggest that more CSF is needed with a higher alkali content and/or a lower amount of amorphous silica.
- Effect of PFA -- Even 40% of the very high-alkali PFA-C is not sufficient to meet the performance criteria. PFA-B, which contains much more calcium and silica than PFA-A (Table 1), looks the best PFA, despite a slightly higher alkali content. Indeed, 18-19% PFA-B is enough, while 22-24% is needed with PFA-A (Table 4). This does not indicate, however, that calcic PFAs are more efficient than others, in agreement with some studies (17) but not with others (18, 19), since the amount of amorphous silica (siliceous glass) is also a critical parameter to be consider.
- Effect of GBSF -- 34% and 39% GBFS are required to meet the performance criteria with the rhyolitic tuff and the siliceous limestone, respectively.
- Effect of alkali content -- When the accelerated mortar bar method is used to test aggregates for potential alkali-reactivity (with no mineral admixture), the alkali content of the mixture is not thought to be critical (3, 20) provided it remains between reasonable limits, say from 0.5 to 1.0% of the mass of cement (Na₂O eq.). This can be observed in Fig. 9 (0% graph). However, when NaOH is added to the mix water to reach 2% of the mass of cement, expansion was usually much greater. Moreover, even between practical limits (with respect to alkali content), the initial alkali content appears more critical with mineral admixtures (Fig. 9: see CSF-B, PFA-C). Note that alkali contents shown on Fig. 9 are relative to the mass of cement. For instance, when 50% GBSF (0.6% Na₂O eq.) is used with 50% of cement A whose Na₂O eq. has been increased to 2% (by adding NaOH), the global alkali supply is 1.3% ([0.5

x 0.6%] + [0.5 x 2.0%]) of the total mass of cementitious materials (cement + admixture) but the indicated value is 2.0%. In general, the higher the initial alkali content in the bars, the higher was the expansion after 14 days; an exception to this was found with the high-alkali PFA-C which behaved quite surprisingly; the highest expansion was obtained with the lowest alkali content. Chen & Suderman (5) also obtained peculiar results with a very high-alkali PFA, the only one among the six tested by the authors which satisfied the ASTM C441 test, while performing the worst in the presence of natural reactive aggregates (in ASTM C227 mortar bar tests).

- Effect of permeability -- The above results suggest that the alkali content of the bars should be controlled, say to 1.25% (Na₂O eq.) of the mass of cement, particularly when testing mineral admixtures. The higher expansion usually observed with a higher initial alkali content could be explained by the lower permeability of the specimens containing admixtures, as a longer time is required to achieve equilibrium between the pore solution and the NaOH 1N solution. However, as observed on Fig.9, immersion of mortar bars in water rather than NaOH 1N reduced the expansion to almost zero, with or without mineral admixtures (except again with PFA-C). This rather suggests very rapid Na⁺ and OH⁻ ion exchange between pore solution and water, which could be attributed to the lower viscosity of water compared to NaOH 1N, and to the greater concentration gradient involved when the bars are immersed in water.
- Long term behavior -- Figs. 5 to 8 demonstrate that, despite low expansion in the short term (up to 14 days), the bars made with mineral admixtures continue to expand significantly afterwards. With the siliceous limestone, the rate of expansion may even become greater than for control bars with no admixture (Figs. 7-8). In our opinion, the main effect of mineral admixtures against AAR is depletion of alkalies in the pore solution, with a consequent decrease in pH, as a result of pozzolanic reactions between portlandite and admixture particles, and formation of supplementary alkali-containing CSH (6). Using limits in the longer term (>14 days) is unrealistic because alkalies could re-build in the pore solution by exchange with the NaOH 1N test solution, and expansive AAR would then continue. External alkali supplies also explain why the standard ASTM C227 mortar bars made by Hobbs (21) with opal and CSF restarted to expand after ≈220 days when submitted to NaCl addition.
- Alkali recycling -- In the particular case of condensed silica fume, the supplementary CSH compounds produced early by pozzolanic reactions have a low CaO/SiO₂ ratio and a high alkali content (6). A number of authors who conducted experiments in the long term suggest that CSF merely retards expansion due to AAR (6). To explain this, the supplementary CSH compounds are thought to react further with any available calcium, becoming more calcic and likely more stable, while alkalies are recycled to the pore solution, therefore becoming available for AAR. Let us recall that the classic products of alkali-silica reaction, which are very similar in texture and composition to the CSH produced by reaction between silica fume and portlandite (22, 23), also tend to reorganize in the long term by trapping more and more calcium from the pore solution, and/or by contact with portlandite. Moreover, the CSH produced by pozzolanic reactions tend to fill the transition zone at the cement/aggregate interface (22); therefore the above transformation could be accelerated as a result of the close vicinity of limestone aggregates,

from which calcium is readily available. This could explain why the expansion rate increased considerably in the long term for mortar bars made with reactive limestones and mineral admixtures, while expansion flattened out for bars made with rhyolitic tuffs (Figs. 7-8 vs 5-6).

Discussion

The results from the accelerated mortar bar method also confirm that the effectiveness of mineral admixtures against ASR depends on their chemical composition, particularly on the alkali content, even though the bars are immersed in NaOH 1N. So, with a given reactive aggregate, a higher alkali content (as well as a lower amount of amorphous silica) should call for a higher amount of admixture to satisfy the proposed limit of 0.1% after 14 days. Also, in addition to the other specifications detailed in ASTM C9-P214, it is recommended that the alkali content of the bars be increased to 1.25% (Na₂O eq.) of the mass of cement. Under such conditions, the test appears capable of distinguishing good from bad admixtures, and could be used to determine the minimum content needed to prevent excessive expansion due to ASR.

COMPARISON BETWEEN TESTING METHODS

The minimum admixture contents needed to meet the performance criteria described above are given in Table 4 for each admixture and for each aggregate tested. The values were obtained from Figs. 2 (concrete), 4 (pyrex) and 10 (accelerated mortar). They apply strictly to the very reactive aggregates tested, and different contents may be needed with other reactive aggregates.

When testing concrete, the more severe criterion which calls for expansion similar to a low alkali control (<0.01% after 1 year), seems more appropriate than the CSA proposed limit (<0.04% after 1 year). This is particularly so when considering the results with GBFS, for which the CSA limit leads to quite low minimum contents (27-33%) compared with results reported elsewhere (5: $\geq 60-65\%$).

The minimum contents suggested by the accelerated mortar bar tests and tests on concrete prisms are in very good agreement (Table 4; Fig. 12: $R \ge 0.96$). With the rhyolitic tuff, a better agreement is observed between both tests when using the less severe criterion (concrete expansion <0.04% at 1 year; Fig. 12: the corresponding regression curve exhibits a closer fit to the 1:1 diagonal line). With the siliceous limestone, the more severe criterion (expansion <0.01% at 1 year) leads to the best agreement. In fact, only four combinations (on a total of 26) did not satisfy the ASTM C9-P214 criterion (e.g. exhibited expansion >0.1% at 14 days) while expanding less than 0.04% after 1 year in concrete (Fig. 11). However, 25 mixtures (on 26) satisfying the other criterion (expansion <0.01% at 1 year in concrete) also satisfied ASTM C9-P214 (Fig. 11). Again, this supports the above recommendation concerning the use of a more severe criterion when conducting expansion tests on concrete.

Tests with Pyrex indicated that 25% PFA-A or B is not sufficient to satisfy even the less severe criterion (expansion reduction by 75%). As all other tests suggest lower minimum contents for PFA can be used safely (Table 4), this test may appear too severe for this type of admixture. The reverse is observed with CSF, however; according to the less severe criterion, 4-5% CSF is considered

enough, while all other tests and many other studies have established that this is not enough (6). In other words, the ASTM C441 method seems too severe for PFA, but not severe enough for CSF, for which a more severe criterion (expansion <0.02% at 14 days or <0.05% at 3 months) is necessary (Table 4). Moreover, the long-term limit (e.g. at 3 months) is more highly recommended (lower risk of experimental error). Finally, the 25% content specified in the standard is unrealistic for CSF (too high) and GBFS (too low); the results obtained in this study clearly call for practical contents.

Globally, good correlations were obtained between the three series of experiments, except perhaps when testing PFA with Pyrex (higher minimum contents are suggested - see Table 4). When testing admixtures, Davies & Oberholster (15) also obtained good correlations between results from ASTM C227 mortar bars tests, accelerated mortar bar tests, and expansion tests on concrete; they also concluded that the accelerated mortar bar method is a little more severe than the other tests. The minimum contents needed to prevent excessive expansion which are suggested here from accelerated mortar bar tests and expansion tests on concrete agree with some values found in the literature (24: CSF, PFA & GBFS; 25: PFA; 26: GBFS), but appear a little low compared to other results. For instance, using a severe criterion (expansion <0.01% at one year), the minimum contents suggested by concrete tests are $\geq 10\%$ for CSFs, 18-20% for good PFAs, and 34-47% for GBFS, depending on the reactive aggregate, while the study by Chen & Suderman (5) established that $\geq 15\%$ CSF, \geq 30-40% good PFAs, and \geq 60-65 GBFS was required for ASTM C227 mortar bars made with a reactive argillite to expand no more than control bars made with a low alkali cement.

CONCLUSION

With a given alkali-reactive aggregate, one cannot use just any mineral admixture in any proportion to suppress expansion of concrete due to AAR. Most aggregates behave differently, so laboratory testing is called for.

The Pyrex Mortar Bar Method ASTM C441 is not appropriate for many reasons, and particularly because Pyrex does not behave as a natural aggregate. At best, the test could be used to reveal the general effectiveness of a given mineral admixture against alkali-<u>silica</u> reactivity. Moreover, if it is used despite its limitations, a number of modifications should be made (6): 1) practical admixture contents should be tested; 2) the alkali content should be controlled with respect to the mass of cement, let us say 1.25% (Na₂O eq.), the content specified by CSA; 3) the water/cement ratio should be fixed to about 0.5; 4) the container should always contain wicking (which promotes expansion with Pyrex), and 5) the performance should be evaluated in the long term, for instance at three months, to reduce the risk of experimental error (which is high in the short term). For CSF, the limit of expansion proposed in the long term is 0.05% (at three months); for PFA, a reduction in expansion by 75% seems sufficient.

The Concrete Prism Method CAN/CSA-A23.2-14A is the procedure most recommended for evaluating the effectiveness of mineral admixtures against AAR. The alkali content of the mix must always be increased to 1.25% of the mass of cement (Na₂O eq.), otherwise the test is not sufficiently accelerated and low expansion could result irrespective of the admixture content. It is recommended the water/cement ratio be controlled between 0.50 and 0.55. The effectiveness in

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the long term of mineral admixtures in suppressing expansion due to AAR is presently questioned by a number of workers. Some experiments also suggest that mineral admixtures do not provide sufficient protection for concrete containing reactive aggregates when it is exposed to external sources of alkalies (sea water, deicing salt,...). Therefore, it is firmly recommended that conservative limits be used when testing laboratory concretes, and the tests be extended up to at least 2 years. The recommended performance criterion is to achieve expansion similar to a control made with a low-alkali cement (<0.6% Na₂O equiv.). Let us recall that the concrete specimens tested in this study contained 350 kg/m³ of cement rather than the amount (310 kg/m³) specified in the CSA standard, which contributes to a greater factor of safety.

The Accelerated Mortar Bar Method ASTM C9-P214, for evaluating the effectiveness of pozzolans in counteracting expansion due to AAR, yields results in good agreement with those of the CSA Concrete Prism Method, when expansion limits of 0.1% at 14 days and 0.01% at 1 year are used for the ASTM and CSA tests, respectively. The results suggest that if there is not sufficient time to conduct a concrete prism test, the accelerated mortar bar method may give a good indication of the effectiveness of pozzolans to counteract expansion in concrete due to AAR.

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OXIDE (%)	PFA			CSF		GBFS	CEMENT		
	Α	В	С	Α	В	-	Α	В	С
SiO2 Al2O3 Fe2O3 TiO2 MnO MgO CaO Na2O K2O P2O5 Cr2O3 SO3 LOI	42.20 21.60 27.60 - - 0.92 1.87 0.66 2.55 - - 1.10 1.85	53.90 20.90 3.52 - - 1.11 12.00 2.74 0.57	32.59 17.93 5.94 1.17 0.03 4.12 20.70 8.08 0.72 0.59 0.01 1.48 0.96	94.17 0.21 0.00 0.07 0.47 0.50 0.00 1.17 0.04 0.00 0.12 2.77	74.60 0.59 6.54 0.00 0.38 1.56 0.40 1.68 2.97 0.00 0.03 0.81 7.34	36.60 8.00 0.67 	20.53 5.46 2.50 0.25 0.05 2.79 63.33 0.25 1.14 0.15 0.00 2.84 0.90	20.66 4.62 3.11 0.28 0.05 2.31 61.76 0.20 0.82 0.26 0.01 2.98 2.82	20.05 4.78 3.38 0.26 0.04 2.32 62.94 0.26 0.42 0.06 0.07 2.75 3.00
Total	100.35	95.33	94.32	99.84	96.90	100.89	100.19	99.88	100.33
Alk.(eq.Na2O)	2.34	3.07	8.55	0.77	3.63	0.60	1.00	0.74	0.54

TABLE 1--CHEMICAL COMPOSITION OF CEMENTS AND MINERAL ADMIXTURES

TABLE 2--MIX CHARACTERISTICS OF SAMPLES TESTED

PARAMETER MORTAR BA ASTM C441		ACCELERATED MORTAR BAR ASTM C9-P214	CONCRETE PRISM CSA A23.2-14A
w/c	0.5	0.5	0.5
(<u>Cement + min. adm.</u>) aggregate	1:2.25	1 : 2.25	-
Cement content	-	-	350 kg/m ³
Mineral admixture (% cement repl.)	CSF: 0,5,10,25% PFA,GBFS: 0,25% (% vol.)	CSF: 0,5,10,15% PFA: 10,20,30,40% GBFS: 35,50,65% (% weight)	CSF: 0,5,10% PFA: 20,40% GBFS: 35,50% (% weight)
Aggregate	Pyrex	Spratt limestone Rhyolitic tuff	Spratt limestone Rhyolitic tuff
Grading	According to C227	According to C227	1/3 : +14-20 mm 1/3: +10-14 mm
Cement alkali content (Na2O eq.)	A: 1.0%	A: 1.0% C: 0.54% A+NaOH: 2%	B+NaOH: 1.25% C: 0.54%
Storage conditions	38°C, 100% RH	Immersion 80°C NaOH 1N, H2O	38℃, 100% RH

ALKALI CONTENT	PYREX	ACC. M	IORTAR	CONCRETE PRISM		
CEMENT	BAR	Rhyolitic tuff	Spratt limestone	Rhyolitic tuff	Spratt limestone	
% CSF - A, B						
- 1% (cement A) - 0.54% (cement C) - 2% (cement A+NaOH) - 1% (cement A/H2O) - 1.25% (cement B+NaOH) % GBFS	0,5,10,25 - - - -	0,5,10,15 0,10 0,10 0,10 -	0,5,10,15 0,10 0,10 0,10 -	0	0 - - 0,5,10	
- 1% (cement A) - 0.54% (cement C) - 2% (cement A+NaOH) - 1% (cement A/H2O) - 1.25% (cement B+NaOH)	25 - - -	0,10,20,30,40 0,40 0,40 0,40 -	0,10,20,30,40 0,40 0,40 0,40 -	0 - 0,20,40	0 - - 0,20,40	
%PFA - A, B, C - 1% (cement A) - 0.54% (cement C) - 2% (cement A+NaOH) - 1% (cement A/H2O) - 1.25% (cement B+NaOH)	0, 25 - - - -	0,35,50,65 0,50 0,50 0,50 -	0,35,50,65 0,50 0,50 0,50 -	- 0 - 0,35,50	0 - 0,35,50	

TABLE 3--MINERAL ADMIXTURES AND ALKALI CONTENTS OF SAMPLES

TABLE 4--MINIMUM ADMIXTURE CONTENTS REQUIRED TO MEET EACH PERFORMANCE CRITERION USED IN EACH TESTING METHOD

METHOD	PYREX MORTAR BAR				ACC. MORTAR		CONCRETE PRISM			
	14 days 3 months			14 days		1 year				
CRITERION	Exp.red. >75%	Exp.< 0.02%	Exp.red. >75%	Exp.< 0.05%	Exp. < 0.1%		Exp. < 0.04%		Exp. < 0.01% (LA control)	
MATERIAL		Py	rex		Spratt Tuff		Spratt	Tuff	Spratt	Tuff
CSF-A CSF-B	4 5	7 10	4 5	6 9	8 11	8 11	9 10	10 >10	10 >10	10 >10
PFA-A PFA-B PFA-C GBFS	>25 >25 >25 >25	>25 >25 >25 >25	>25 >25 >25 >25	>25 >25 >25 >25	24 19 >40 39	22 18 >40 34	16 15 >40 27	16 15 >40 33	20 18 >40 34	20 19 >40 47



Fig. 1--Expansion of concrete prisms (CSA A23.2-14A) made with two reactive aggregates and various amounts of two CSFs, three PFAs and one GBFS. Two 0% controls were made with high-alkali and low-alkali (LA) cements