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Stories from the front: AAR testing gone awry

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Abstract

In the world of commercial/consulting materials testing, the vast majority of testing assignments that involve Alkali-Aggregate Reaction (AAR) evaluation of materials that are proposed for use as concrete aggregates are done in strict compliance with standardized test methods, such as those published by American Society for Testing and Materials (ASTM), Réunion Internationale des Laboratoires et Experts des Matériaux, systèmes de construction et ouvrages (RILEM), Canadian Standards Association (CSA), British Standards (BS) and others.

Due to legalities associated with undertaking tests on behalf of clients, or for specific project requirements, and in order to satisfy contractual obligations as well as certification and quality requirements demanded by industry, the primary focus of private consultancies is to conduct testing in conformance with those standards, using standard equipment and materials, and with a high degree of attention to record-keeping, detailed methods and making use of personnel who are, similarly, highly trained in these methods.

Periodically, however, requests are received from Clients to conduct tests that are out-of-compliance with these standards – in some cases, the deviations are minor such that the "technical intent" of the test is not compromised, while in other cases, the modifications are such that the tests may be of dubious relevance.

This paper examines a number of cases of these modified tests, and provides comments, discussion and insights that have been accumulated over several years.)

***Keywords**: accelerated mortar bar; alkali-aggregate reaction; concrete prism; job mixes; standards*

1. INTRODUCTION

The commercial consulting and testing of materials that are (or are proposed to be used as) aggregates in concrete makes use of standard test procedures that have been developed by a range of national and international standards organizations. The use of standard tests is essential as the basis for comparison of test results with accepted limits for those tests, and determination of acceptability or rejection of the material under test. Making use of tests that have parameters or design elements that deviate from the standards reduces the relevance of the data produced in them, and thereby results in lessened significance.

The primary 'predictive' and 'quality control' tests that are used worldwide for the evaluation and checking of reactivity potential of aggregates are as follows:

- Accelerated Mortar bar test ("AMBT") – based on the NBRI method developed in South Africa in the 1980s (Oberholster and Davies, look up year 1988?), this test involves preparation of a mortar mix made of crushed coarse aggregate or regraded fine aggregate, making of 1" x 1" x 11.25" bars and their subsequent storage in an 80°C oven in an alkaline-charged solution for a period of 14 days. Periodic length-change measurements are made of the bars, with the 14-day measure taken as the 'standard' time in solution. Various specifications provide a range of acceptance/rejection criteria, typically ranging from 0.10% to 0.20% length change.
- Determination of Potential Alkali-Carbonate Reactivity (ACR) of quarried carbonate rocks involves chemical analysis of the suspected carbonate rocks. This is based on the understanding that deleterious expansive alkali-carbonate reactive aggregates are dolomitic limestones with a high clay, or acid-insoluble residue content. Dolomitic limestone can be recognized by determining the CaO:MgO ratio and clay can be determined by measuring alumina (Al2O3) content (Rogers, 1986).
- Concrete Prism expansion test ("CPT") – is also based on the use of a cementitious mixture, in this case, utilizing both coarse and fine aggregate sizes, but formed into prisms that measure from 3"

x 3” to 4” x 4”, by 11.25” length or -- in some standards -- up to 16” in length. Samples are then stored in 38°C at 95% relative humidity for one year, again, with length-change measurements made at stated intervals. Test samples that average over 0.04% expansion at one year are considered “potentially reactive” in most standards.

This paper will focus on these three test procedures only, as well as standardized derivatives that are based on them. Although the companies that the authors are employed by are located in Canada, both have a global presence with clients and projects that have a global geographic footprint. Hence, the project work that is conducted in our laboratories supports projects from around the world; invariably, the standards and specifications to which our work is conducted are those that are used within those areas and countries. More often than not, it has been found that these national standards are very closely aligned with ASTM, CSA, and RILEM. For this reason, much of the testing cited below is consistent with one of these standards.

1.1 Background

In common use, evaluation of the potential for AAR of materials proposed for use as concrete aggregates typically follows a route that includes the following items:

- Conducting a Petrographic Examination (using either CSA A23.2-15A or ASTM C295), in order to characterize the geological composition of the material under consideration and identify potentially reactive mineral phases or textures;
- Conducting an Accelerated Mortar Bar test (per CSA A23.2-25A or ASTM C1260) to rapidly (i.e., in about two weeks) identify whether a material has a potential for ASR or not; and if so, conduct the concrete prism test;
- Conducting chemical analysis (per CSA A23.2-26A) to determine whether quarried carbonate rock has potential for Alkali-Carbonate Reaction(ACR) or not, and if so;
- Conducting the Concrete Prism test (CSA A23.2-14A or ASTM C1293).

These test methods are also used for current production concrete aggregate materials, to verify that the products continue to satisfy applicable specifications. Many jurisdictions require this type of certification of their products to be conducted with some frequency. For AAR testing, such testing is often done on a minimum one-year frequency, and/or when changes in bedrock lithologies or bedrock quarry benches occur.

In some geographic areas, the regional aggregate supplies are known to include some materials that are classified as “potentially reactive”; these materials are required to undergo continual testing using various mitigative strategies, typically involving Supplementary Cementing Materials (“SCMs”) to reduce or limit the expansions due to AAR to an acceptable level.

In North America, these “mitigated tests” are conducted following methods given in ASTM as C1567 (for mortar bars only) or CSA A23.2-28A. ASTM C1293 (CSA A23.2-14A) can be utilized in a modified form to evaluate the effectiveness of various SCMs in preventing deleterious expansions due to AAR.

2. CASES

In the authors’ practices, in the running of thousands of these mortar bar, whole rock chemistry and concrete prism tests for a range of projects, cases have occurred wherein clients have requested modified test parameters.

The following sections describe some of the cases that have highlighted our respective practices.

2.1 Reduced or increased cement contents

A significant number of clients have requested that cement contents be adjusted to match intended mix design cement levels. While this is a simple matter in the CPT, some clients have requested that “job mixes” be used in the AMBT as well “to match the real-world concrete”.

In one case of “matching the job mix”, it was requested that testing be done to mimic a Roller-Compacted Concrete (RCC) mix, with and without fly ash, thus utilizing a low cement content as well as a low water/cementing materials (w/cm) ratio.

The cement content of the mix was roughly 50-60% of that required in the CPT, i.e., 200 – 230 kg/m^3. The requested w/cm ratio was to be about 0.25 – 0.30, which is significantly below that used in the CPT (i.e., about 0.45-0.50). Translating this mix into the parameters that are used in the AMBT, however, required significant modification of the mortar mixes.

2.2 Combined coarse and fine aggregates in mortar bar tests

With project schedules that push testing deadlines, we have often been asked to do “whatever testing can be done” in a shorter timeframe than that allowed in the Concrete Prism Test, which necessarily means using the Accelerated Mortar bar test.

Examples of these situations typically involve a project schedule that has concrete work being initiated within a timeframe that is far shorter than the 12 to 24 month-period required for CPTs, for instance, 3 months from the date of inquiry. The authors estimate that collectively, in their practices, such situations have been encountered dozens of times over the past decade. It is easy -- but nevertheless inappropriate -- to respond to such requests by declaring that the project planning should have allowed for sufficient time to undertake CPT testing, but the reality is that oftentimes projects do not proceed in that manner. It is in fact common that high-level planning for some projects may take place from five years to one year before construction, with finer details being added as necessary in the two-year to final months before initiation of construction.

Decisions about the concreting materials are often not undertaken in pre-feasibility or conceptual design stages; identification of potential aggregate sources and eventual selection of such sources often occurs, in our experience, within the final year runup to a project’s start date. Our experience has been that this is often the norm. Identification of aggregate sources for all types of infrastructure work is typically left to the last minute and frequently not given the level of attention that is required to adequately identify the suitability of materials for construction. This suggests that more effort should be associated with understanding material performance in order to be able to address these concerns in a timely manner, thereby providing the appropriate level of due diligence.

This underlines one of the construction engineering industry’s largest reservations with the CPT – its one year time line. Or, in the case of evaluating mitigation measures using the CPT, two years or more.

This leads to the somewhat common request from clients to undertake AAR evaluations using the AMBT, but to simply combine the fine and the coarse aggregate “just as they are in real concrete”.

2.3 Differing aggregate proportions

For some aggregate products, certain size fractions that are required in the CPT are not present. For example, a “birdseye” concrete aggregate – typically consisting of fine coarse aggregate of about 2.5 to 8 mm or 10 mm nominal size – simply does not contain the required coarser fraction specified for the Concrete Prism Test, i.e., the 10 – 20 mm size fractions.

In such cases, there is no alternative but to use 100% of the available aggregate to formulate the concrete mix used to manufacture the prism specimens.

Other examples include the testing of significantly large-size concrete aggregates such as 28 mm or 40 mm nominal aggregates. In these cases, two primary options seem to be appropriate: (1) reduce the size of the aggregate by crushing to a 20 mm minus grading or (2) increase the size of the prism specimens, for example, to 4” x 4” cross-section by perhaps 16” length. Alternatively, the use of 6” x 12” cylinders might be another possibility.

Still other examples include different sands that are used in cementitious mixtures, such as mortar sand or blend sands. Some producers, for examples, prefer to blend their primary sand with a finer blend sand in order to adjust properties of their concrete mixes as needed. Some periods may see them blending their sands at ratios of 90:10, while in other periods, adjustment of the blends may range, for example, to 60:40. When the sands originate from deposits that have distinct geological composition, with differing AAR characteristics, individual testing of the products is often requested or recommended. Neither sand individually meets the gradation requirements given in ASTM C1260 / CSA A23.2-25A, but yet they are tested separately.

Do these variations from the “standard test grading” invalidate the test? In our opinion, they do not.

All other aspects of the testing are per the standard procedure, using standard equipment, specimen sizing, and standard materials. Furthermore, they provide data that is the direct result of the sample under test. The question that remains is “will the expansion data from non-standard gradation sands / coarse aggregates be mathematically predictable when the actual proportions of these materials are adjusted in field / project concrete mixes? That is a question that we have not evaluated but presume that it could be answered by testing mixtures that utilize the actual aggregate proportions.

2.4 Chemical analysis of multi-lithic gravels for ACR potential

A limited but persistently recurring request in both Project Specifications as well as during pre-cast concrete plant certifications is for the chemical analysis of multi-lithic gravel coarse aggregate to determine the potential for ACR.

Chemical analysis (whole rock chemistry) is a standard analytical approach used in the geological identification and classification of bedrock lithologies. This quick, relatively inexpensive and reproducible analytical methodology identifies distinct chemical signatures of individual bedrock units, thereby allowing for the proper geological classification into rock type. In CSA, the test method is A23.2-26A, "*Determination of Potential Alkali-Carbonate Reactivity of Quarried Carbonate Rocks by Chemical Composition*". This test method is intended to provide a screening test that is applicable to sample of rock that are quarried in carbonate bedrock formations, and is not intended to be used to evaluate the potential reactivity of mixed-lithology gravels.

Based on a comparison of the ratio of calcium oxide to magnesium oxide with the amount of aluminum oxide, this test does not work when applied to a mixture of multiple rock types, particularly if the rocks include minerals that bear aluminum, such as feldspars, micas or clay minerals.

In one test series, the test sample included some proportion – ranging from 25 to 40% -- of carbonate rocks, consisting of limestone and dolomite. Granitic rocks, gneiss, with minor sandstone and quartzite made up the rest of the sample. When the CaO:MgO ratios were plotted against Al_2O_3, the samples plotted into the "potentially reactive" portion of the graph.

As a check on the testing work, we submitted a separate test sample in which we had sequestered the carbonate rocks, removing the siliceous and granitic and other crystalline rocks. In this test analysis, the sample plotted within the "non-reactive" portion of the graph (see Figure 2.1).

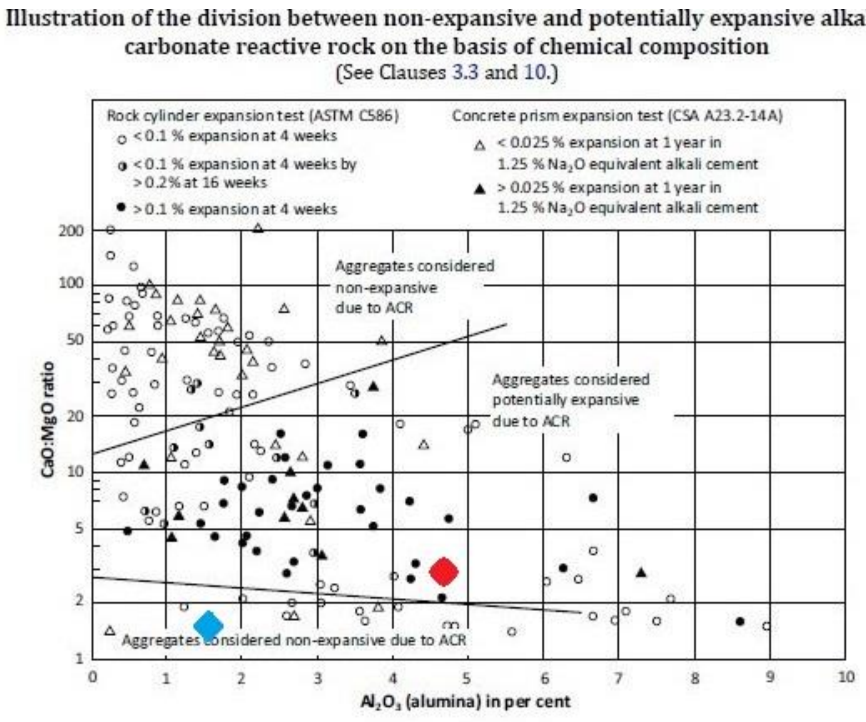

Figure 2.1: Graph showing plotted results obtained from ACR testing by chemical composition of natural gravel containing carbonates. Red diamond is as-received gravel; blue diamond is carbonate fraction only.

This indicated that, as anticipated, the alumina values were likely the result of the presence of aluminum-bearing minerals contained in the granitic rocks, gneisses and not the result of clay minerals in the carbonates.

Petrographic examination of the samples, done as part of the testing program, confirmed the mineralogical assessment of the nature of the rocks comprising the sample.

3. PROBLEMATIC RESULTS

3.1 “So what do these results mean?”

The objective of laboratory testing and evaluation of aggregates is to determine the suitability of concrete aggregates for use in Portland cement concrete applications either because the aggregate has not previously been used in concrete or because the aggregate is derived from a different location in the pit or quarry than that used previously. Under these circumstances, or when the alkali content of the new concrete or the exposure condition is more severe than those of the existing concrete structure, a laboratory investigation is undertaken to determine the potential reactivity of the aggregate (for example, as outlined in CSA A23.1-19, Annex B “Alkali-aggregate reaction”).

Typically, national and international standards state the need for caution in interpreting the results of laboratory experiments because with many types of aggregate, a correlation between the results of laboratory tests and field performance has not been adequately documented.

Consequently, from time to time, commercial laboratories are faced with the task of conducting laboratory testing such as accelerated mortar bar expansion or concrete prism expansion testing using *non-standard* mixture designs, aggregate proportions, cementitious material combinations or addition of chemical admixtures that have been requested by the client. In these situations, regardless of whether the commercial laboratory has made every effort to stress to the client that making these adjustment to the test methods completely invalidates the validity of the testing, they are asked, “So what do these results mean?”

Following are examples that represent some of the cases that have come through our laboratories over the years.

3.2 Accelerated mortar bar mix proportions

Some mortar bar tests (following ASTM C1260 or CSA A23.2-25A) have been requested, with modifications or design criteria as follows:

- Combinations of crushed natural gravel with natural sand
- Gravel and stone combined in specific proportions found in various mix designs
- Ratios of fine/ coarse aggregate that range from 0.30 - 0.85
- Total cementitious contents that ranged from 220 - 380 g/ mix
- Total water contents that range from 88 to 128 ml/ mix
- Total aggregate mass of 990 g
- w/cm - 0.30 - 0.40

In some cases, Clients have instructed our laboratories to prepare the mixes using Superplasticizer, water reducing admixture, slump retention admixture, or accelerating admixtures.

Expansions for a series of modified test mixes are shown in table 2.1.

Table 3.1: Accelerated Mortar bar test expansion data for eight mixes

Mix	Standard	A	B	C	D	E	F	G	H
14-days	0.26	0.012	0.014	0.013	0.035	0.018	0.030	0.037	0.052
28-days	0.37	0.022	0.022	0.019	0.037	0.033	0.062	0.072	0.088

A	Combined crushed stone with natural sand, with low-alkali cement	**E**	All sand mix, w/cm 0.35, fly ash 20%
B	Coarse agg 70% sand 30%, with air entrainment and fly ash	**F**	Gravel / sand of 0.60, fly ash 20%, slag 20%
C	Cement content 220 g, 40% fly ash replacement, w/cm 0.30	**G**	Crushed rock 75%, sand 25%, low alkali cement, 35% slag
D	Cement content 325 g, 8% silica fume	**H**	50% slag, w/cm 0.40

All the results indicate expansions that are below the typical expansion limits. However, due to the modified nature of the test mixes, interpretation of these results is highly speculative.

3.3 Concrete prism

For the concrete prism testing portion of these programs, similar aggregates were used as in the accelerated mortar bar tests. Partly crushed natural gravel and natural sand as used in 25A tests, with parameters as noted below.

- Gravel and stone combined in proportions to mirror those used in various mix designs
- ratio coarse/ fine aggregate – 60/ 40
- total cementitious – 420-660 kg/m^3
- w/cm – 0.30 – 0.45

As with the accelerated mortar bar mixes, the concrete prism mixes made use of Superplasticizer, water reducing admixture, slump retention admixture, and accelerating admixtures.

Expansions for these mixes are given below.

Table 3.2: Concrete Prism test data for six mixes, measured at one- and two-years

Mix	A	B	C	D	E	F
52 weeks	0.015	0.002	0.001	0.000	-0.006	0.008
104 weeks	0.011	0.013	0.007	0.007	0.002	0.017

A	Coarse:Fine 0.65; high alkali cement, fly ash @25%	**D**	Coarse:Fine 0.55; moderate alkali cement, slag @ 40%
B	Coarse:Fine 0.50; low alkali cement, fly ash 25%	**E**	Coarse:Fine 0.55; low alkali cement, slag @ 50%, w/cm 0.38
C	Coarse:Fine 0.45; low alkali cement, slag @ 50%, AEA@ 6%	**F**	Coarse:Fine 0.55; low alkali cement, fly ash 50%

3.3.1 Comment

Data obtained from the accelerated mortar bar expansion test and the concrete prism expansion test involves following clearly prescribed procedures for sample preparation, batching volumes and mix proportions in order to develop information that can be compared with testing data from other materials to serve as a basis for comparison. If the methods, materials and proportions are changed, and/or if additional materials are introduced, then the basis for comparison with other test results loses meaning.

At some (poorly-defined) point, the test may no longer have meaning at all – this is likely when the essential elements of the test are abandoned.

3.4 More modifications

One client required AAR testing as input for mix designs for concrete used in interior applications, such as precast stair treads, decorative elements, and countertops. With well-placed intentions and high-end design cues in place as objectives, the client wished to assess the potential for AAR of concrete mixes that utilized recycled bottle glass. This approach not only benefitted the environment through the use of recycled material that would otherwise end up as waste, it also provided an attractive material (see Figure 3.1) when the surfaces were ground to reveal the aggregate in the paste, after which a polished surface finish would be applied.

The choice of glass as aggregate was identified early on as a potential concern for longevity of the concrete elements due to the likelihood of AAR potential associated with the glass, since it is a non-crystalline form of silica and a known reactive participant in AAR. To evaluate this potential and possible mitigation strategies, a program of testing, consisting of a series of Accelerated Mortar Bar tests and Concrete Prism tests was conducted.

Initial testing was done using AMBTs, to provide an indication of whether there were certain mitigative designs that appeared to hold more promise than others. After these initial AMBT “indicator” tests were completed, CPT mixes were prepared to guide the mix designs that were selected as likely candidates for production.

Figure 3.1: A polished disc sample cut from a concrete cylinder made using recycled crushed glass as aggregate. Disc is 100 mm in diameter.

Test mixes were prepared with the following designs:

- Standard tests – high alkali GU cement
- Mitigated tests
  - "Job" cement (low alkali [0.49% Na_2O-eq.])
  - Job cement with (a) LiNO3, (b) metakaolin and (c) an unspecified admixture
  - Fly ash at varying proportions
  - Silica fume at 8% replacement of cement

[1]. The results from this program are depicted in Figure 3.2.

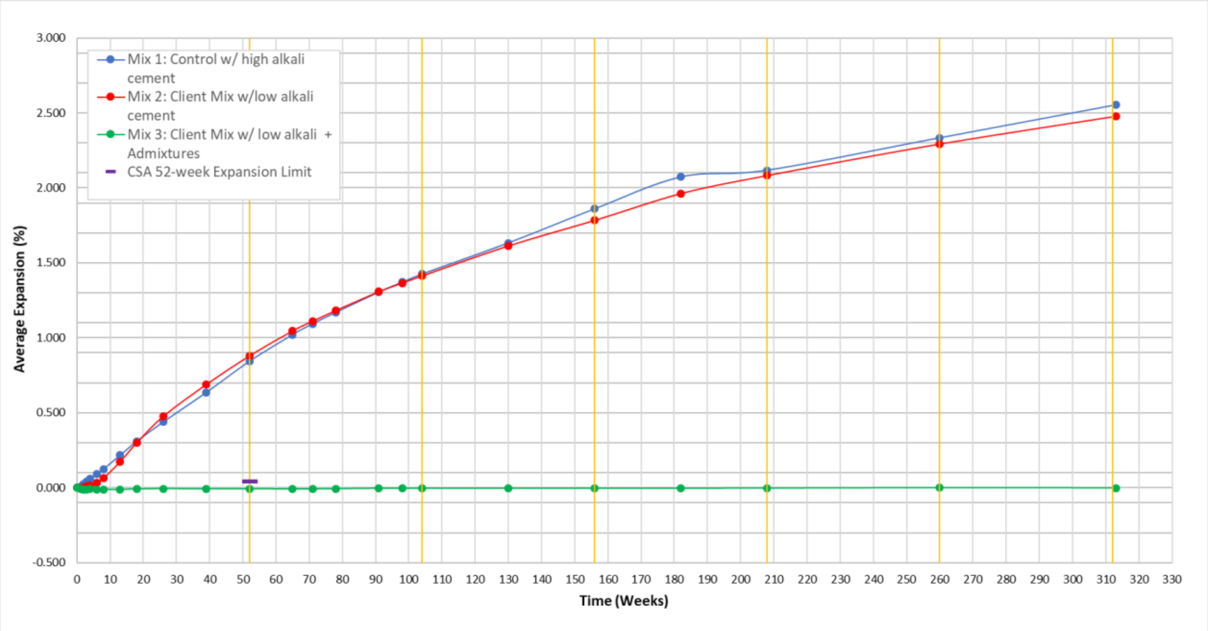

Figure 3.2: Expansions of three Concrete Prism tests using recycled glass as aggregate

The results of the test programs showed the following:

- the job cement with low alkalis developed similar expansion in the CPT to that of the high alkali laboratory stock cement (alkali content of 0.97% Na_2O-eq.)
- the job mix with low alkali cement and a combination of three mitigative measures showed no expansion after two years.
- Readings taken to six years indicated that the unmitigated mixes exhibited continued expansion of the prisms on the order of an additional 67%, over the two-year expansions

3.5 Low water-cementitious ratios, cement contents with variable SCMs

In another case, a client requested a test program -- using mortar bars only – to evaluate various sources of crushed rock to be used in the construction of a Roller-Compacted Concrete (RCC) dam project. The rock was a slightly metamorphosed igneous plutonic rock in which some quartz crystals exhibited some strain.

No “standard” AMBTs were run on any of the samples in order to quantify the potential reactivity level of the rock as a baseline for comparison. Instead, the client instructed that AMB tests were required that would mimic the job mixes:

- Water/cementitious ratios that ranged from 0.3 to 0.45 to 0.67;
- Cement contents that were between 17% and 71% of the amounts specified in C1260;
- Cement replacement with SCMs that were either 35% or 45%;

Figure 3.3: RCC mixture placement at project site.

Due to the low cement contents, the samples were left in the molds for three days in order to enable them to gain strength such that they would be less likely to break upon demolding.

The samples that were cast with low w/cm ratio were characterized by a high number of voids, since the mortar was not readily compactable in the molds. This was similar for samples that were cast from mixes with the low (17% of normal) cement content.

All samples included a 35% or a 45% SCM replacement of cement; the SCMs were Class C and F fly ashes.

The expansion results that were obtained for the samples are presented in table 2.2.

Table 3.3: Accelerated Mortar bar mix descriptions and expansions at 14- and 28-days.

TEST MIX DESCRIPTION				EXPANSION (%)	
w/cm	**Cement content (% std)**	**Fly ash (%)**	**Fly ash type**	**14 d**	**28 d**
0.44	71	35	C	0.041	0.078
0.67	17	45	C	0.024	0.028
0.44	71	35	F	0.039	0.077
0.30	17	45	F	0.020	0.030
0.44	71	35	C	0.044	0.083
0.67	17	45	C	0.019	0.028
0.30	40	35	F	0.016	0.022
0.44	71	35	F	0.035	0.080
0.67	17	45	F	0.019	0.034
0.44	71	35	C	0.038	0.070
0.67	17	45	C	0.022	0.026

Observations

The following observations were made during this test program:

- Some mixes were very harsh, likely owing to the low cementitious contents coupled with low w/cm ratios. These mixes did not compact well and – when hardened – were observed to have a higher proportion of voids within the sample than is typical
- Some test specimens were quite weak. This was anticipated, thus we extended the curing period by a few extra days to enable the low cement content samples to gain strength for an additional time period
- A few of the weaker specimens broke in handling
- None of the 14-day or 28-day expansions exceeded the 0.10% expansion limit cited in ASTM C1778-16
- The highest expansion measured for any of the samples at the age of 28 days was 0.83%
- The lowest expansion measured at 28 days was 0.022%

Whether the tests were meaningful was a primary consideration upon their conclusion. The low cement contents, high voids ratios in the “drier” mixes with low w/cm ratios, and the high fly ash replacement levels are elements that suggest the tests would be of little meaning in terms of input to project mix designs. In particular, given that no “standard tests” had been conducted on the rock to provide a sense of the potential for AAR, the mitigated “job mixes” were considered to be largely without merit.

4. DISCUSSION

The foregoing examples of projects that included modified versions of standard tests provide a considerable amount of food for thought.

In our experience, often it is a lack of familiarity with testing requirements and the nuances of AAR specifications and how these apply to concrete construction that lead to clients perhaps not having the information at hand that results in requests that do not make sense.

Sometimes the requests arise from an administrative staff person who refers to a set of specifications that is listed in a document and decides that “all the tests must be done”. Hence, requests for testing of chemical composition for ACR of quarried carbonate rocks is requested for non-carbonate gravels, or gravels that contain a small amount of carbonates.

In the world of physical testing of aggregates, a corollary would be requests to conduct Los Angeles Abrasion tests on samples of sand.

Although laboratory test methods have been used to predict field performance, they do not have a good practical correlation to requirements of majority of construction projects where this type of evaluation is left until just matter of few months or weeks before construction begins. This is increasingly common in a world where planning and design timelines are reduced from several years to a few years, and where final specifics (such as selection of aggregate sources where none have been previously used) are left to months before the construction start dates.

However, there are numerous cases where aggregate producers have been in operation for many years and have never elected to have their aggregates tested for the longer-term AAR tests, and may in fact have no AAR testing data available whatsoever. This may simply be because they were unaware that these requirements exist in national standards, or that data has never been requested previously.

In such cases, we have seen examples where a project is about to start (e.g., construction of a new bridge, or a bridge redecking job) in a few months, and the sole local commercial concrete supplier has no AAR testing data, but the Owner requires it to be done in three months. If the AMBT “fails” the specified expansion limit, they will need to begin a CPT and that will require at least a year prior to developing data useful for the project. Should it be assumed that the aggregates are truly reactive on the basis of the AMBT alone? If so, then mitigative measures should be checked immediately. Alternatively, a method such as ASTM C1778-16 or CSA A23.2-27A may be used to identify “failsafe” mitigative strategies, based on conservative engineering designs. Yet, the point remains that the concrete aggregate supplier should have had historic testing data available. It seems in these cases that dissemination of the required information about AAR is required.

More research is needed to develop a better understanding of the mechanism of ASR distress so that long term tests not required. Still, the ability to identify which aggregates are reactive and which ones are not continues to be the challenge.

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