MANAGING ALKALI-AGGREGATE REACTIVITY: NORTH AMERICAN APPROACH

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Abstract

Over the past 25 years North America has developed a uniform and aggressive approach to managing the risk of alkali-aggregate reactivity in concrete. Currently, the Canadian Standards Associate –CSA (Canada), Federal Highway Administration – FHWA (USA), American Association of State Highway and Transportation Officials - AASHTO (USA) and ASTM International (USA) all now follow a nearly identical approach to the identification of reactive aggregates and the mitigation of potential reaction. The approach relies heavily on the use of the accelerated mortar bar test and the concrete prism test for assessing aggregate reactivity. Field history and petrography are also incorporated as options in identification of reactive aggregates. If an aggregate is found to be potentially alkali-carbonate reactive it is recommended to avoid using that aggregate in concrete construction. If an aggregate is found to be potentially alkali-silica reactive users can follow either a performance-based or a prescriptive-based approach for avoiding the reaction. This paper will cover an overview of the approach, highlight potential challenges for implementing the method and make recommendations for future modifications to improve the identification and mitigation of potential reactive aggregates for successful use in field concrete.

Keywords: alkali-aggregate reactivity, risk, risk management, performance-based, prescriptive approach

1 INTRODUCTION

After Stanton's discovery of alkali-silica reaction in the late 1930s, significant research efforts have focused on elucidating the mechanisms of the reaction as well as determining which preventative measures are the most efficacious in mitigating the reaction.[1] The ultimate goal has been to develop performance-based and prescriptive-based guidance to avoiding deleterious expansion. To do that it has taken many years of accelerated laboratory and field exposure testing to define the criteria that would allow such an approach to be implemented. Another goal as part of these research efforts has been to provide instruction as to the challenges with AAR related testing as the sample size, mixture proportions, cement alkalinity, temperature, length of exposure and exposing medium all play a significant role in the outcome of test methods. Central to these efforts has been the development of accelerated test methods to accurately predict field performance. Much of the early accelerated test methods used small mortar prisms (~ 25 x 25 x 285 mm) stored over water at 38ºC where expansion was measured up to one year with limits usually applied at 3, 6 or 12 months (depending on the level of expansion). These methods helped to identify the crucial role of cement alkalinity and enabled researchers to distinguish between different levels of expansion among aggregates.[1, 2] However, a challenge in these methods was identified early on, including that many slowly reacting aggregates were not detected in the test. It is clear that this was due to alkali leaching from the small prisms, thus rendering the test method highly ineffective across broad categories of aggregates, for testing job mixtures and for assessing the role of mitigation options.

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The accelerated mortar bar method developed by Oberholster and Davies [3] in the 1980s sought to overcome these alkali-leaching issues by submerging the same sized mortar prism in 1 N NaOH for a period of 14 days. This has become one of the most widely accepted accelerated test methods worldwide, mainly due to its very short duration. Despite this significant advantage the test method is known to have many issues: the high temperature solubilizes silica which would otherwise be non or lowly reactive at lower temperatures, it is known to have both false-positive and false-negative results, a pessimum effect and the overly aggressive soak solution will ultimately show expansion in any material that contains silica if the prisms are left in the soak solution for a long enough time period. Despite these many limitations it is still a highly favoured test method due to the short duration of the test. It should also be noted that when Oberholster and Davies developed this test method, the choice of a 1N NaOH solution showed the highest expansion with the set of aggregates they tested and it was thus chosen to use this as the most aggressive concentration (e.g. conservative approach). It is well known that many aggregates will produce a greater expansion at both lower and higher soak solution normalities (e.g. the pessimum effect).[4, 5] Owing to these discrepancies the test method must be used with caution and the recommendation is that it is always best to benchmark the test with the long-term concrete prism test or field exposure results so that the rapid 14 – day test can be relied on with confidence. In the absence of doing such benchmarking the user accepts a great deal of risk in relying on this test method alone.

In the concrete prism test a larger concrete prism (75 mm x 75 mm x 285 mm) is cast and stored above water at 38°C for a period of 1 year for aggregate reactivity testing and 2 years for evaluation of SCMs. The development of the concrete prism test was also met with challenges early on in that it failed to detect aggregate reactivity for slow/moderately reacting aggregates. The cement content in the test was increased ultimately to 420 kg/m^3 so that the total alkali loading in the concrete was 5.25 kg/m^3, which was enough to identify the reactivity of aggregates of the slow/moderate reacting variety. This test method is generally considered the most reliable for evaluating aggregate reactivity. However, the 1-year duration of the test has hindered its acceptance, especially in the USA. The 2-year testing duration for the evaluation of preventive measures is an even longer duration and is thus met with challenges. Further, recent research has showed that there is a disconnect between the results of the 2-year concrete prism test and outdoor field exposure blocks. More detail on that is outlined in the Discussion section of this paper.

2 MATERIALS AND METHODS

2.1 Overview of the Method

The Canadian Standards Association CSA A23.2-27A, ASTM C1778-14, AASHTO PP65 and FHWA-HIF-09-001 all follow the same general approach to assessing the reactivity of an aggregate and determining the appropriate approach for selecting the preventive measures[6-9]. For the purposes of this paper, the ASTM C1778-14 approach will be followed. FIGURE 1 is a flow chart giving an overview of the procedure for determining aggregate reactivity and selecting preventive measures in ASTM C1778. Specific sections within the ASTM C1778-14 standard are referred to give guidance to the user on making determinations. The flow chart is meant to give only an overview of the general approach. The standard provides the specific guidance on testing and materials selection. Solid lines indicate the preferred or "lower risk" approach whereas the dashed lines indicate a higher level of risk. For example, using only the results of petrography, in the absence of testing or field performance data results in a higher level of risk of developing AAR than if several (or all) of the steps are followed.[6]

Field History

The first steps involve determining if the aggregate has a known history of satisfactory field performance (e.g. no ASR or ACR) or if the combination of that aggregate with preventive measures (e.g. SCMs) has a history of satisfactory field performance. The standard provides very detailed information regarding how satisfactory field performance is established. Several key points include:

- the structure is at least 15 years old
- cement and any SCM content and composition is documented
- cores are taken for a petrographic examination
- any evidence of AAR is documented

If the results of the field survey indicate that the aggregate (and/or combination of aggregate and SCMs) is non-reactive, the standard then states "the aggregate may be used in new construction provided that the new concrete is not produced with a higher concrete alkali content, a lower SCM replacement level, or placed in a more aggressive exposure condition than the structures included in the survey."[6]

Petrograhic Examination

Petrographic examination according to ASTM C295 is the next step recommended. This step is particularly useful if a new source of aggregate is being explored for use in concrete construction or if a new ledge or section in an existing pit or quarry is being excavated. Additionally, petrographic examination is a very quick analytical tool that quickly aids in the determination of potential reactivity of an aggregate. While the AMBT is often cited for its aggressive nature, adding petrographic examination (ASTM C295) to the suite of testing for an aggregate source is an extremely time efficient method and does not add significant cost to the determination of aggregate reactivity. The additional information from petrographic examination is useful in determining the next steps for construction and the need for selection of preventive measures, if warranted. If the aggregate is identified as being potentially reactive, the petrographic examination will aid in classifying it as potentially alkali-carbonate or alkali-silica reactive. This is where the flow-chart branches.

Alkali-Carbonate Reactivity

If the aggregate is potentially alkali-carbonate reactive, additional steps should be taken to determine if it is truly alkali-carbonate reactive. The aggregate may be tested for its chemical composition according to CSA A23.2-26A [9] or it may be tested in ASTM C1105[10]. If the aggregate is tested in ASTM C1105, the alkali loading should be kept to 1.8 kg/m^3 to ensure that any expansion that occurs is a result of ACR and not ASR. If the aggregate is identified as alkali-carbonate reactive, it should not be used in concrete construction.

Alkali-Silica Reactivity

If the results of the petrographic examination indicate that the aggregate is not a quarried carbonate, then the potential for alkali-silica reactivity should be determined. The potential for deleterious alkali-silica reaction can be determined following either ASTM C1260 (AMBT) or ASTM C1293 (CPT). If the aggregate falls below the 0.10% expansion limit at 14 days in the AMBT, the aggregate is considered to be innocuous in most cases. If the aggregate expands by 0.10% or more in the AMBT it is considered to be potentially deleteriously reactive. The standard then recommends testing the aggregate in the CPT. However, preventive measures may be selected based on the results of the AMBT following either the prescriptive or performance-based approach in ASTM C1778. It is still recommended that the CPT be done to compare the results of the AMBT and the CPT. This is to ensure that both tests produce the same result (e.g. fail/fail) and that the AMBT does not produce a false negative result that would indicate no mitigation is necessary, when in fact the CPT would predict the aggregate to be potentially reactive. Caution is given that the AMBT can also produce false positive results and, for aggregates that are known to give such results, the CPT is recommended to assess aggregate reactivity and preventive measures. This ensures that a proper amount of SCM is chosen, if the aggregate produces reactivity in the CPT. In some cases, aggregates are known to produce high levels of expansion in the AMBT due to the 80ºC temperature, which solubilizes silica that would otherwise remain stable at normal in-service temperatures.[4] The user is also cautioned that the test method should not be used for evaluating combinations of aggregate. This is because no thorough and systematic study has been done to show a correlation to the CPT and, more importantly, field exposure (blocks or real structures). Some initial work has been done that shows that a pessimum proportion can exist when two reactive aggregates are tested in the accelerated mortar bar test. Therefore, an improved test method or significant benchmarking to the field should be done to ensure that the proportions in the test method and the cement content (and alkali loading) are representative of the concrete used in construction, so that an accurate assessment of the potential for deleterious expansion can be determined.[11]

Preventive Measures

As previously stated, if the aggregate is determined to be alkali-carbonate reactive it should not be used in concrete construction. If the aggregate is shown to be alkali-silica reactive, the aggregate can be used, provided it is used in combination with SCM (s) following either a 1) Performance -based or 2) Prescriptive-based approach.

In the performance-based approach either the AMBT (ASTM C 1567 in ASTM for assessing efficacy of SCMs to mitigate ASR) or the CPT are used. The duration of the AMBT is 14 days using the desired SCM and the expansion limit is 0.01%. Generally it is best to run 3 or more AMBT where the level of SCM that is thought to control the reaction is selected, as well as higher and lower dosage rates so that the testing is as expedient as possible. If the CPT is used to determine the efficacy of SCMs the duration is carried out to 2 years and the expansion limit is kept at 0.04%. The user is cautioned that the AMBT for the reactive aggregate be compared to the CPT for the same aggregate to ensure that the two tests are in agreement (e.g. pass-pass or fail-fail). If that criteria is not met then the AMBT may either under predict or over predict the amount of SCM needed to control the reaction. Certainly an under predication represents the more concerning case, as deleterious ASR may develop.

In the prescriptive approach a number of factors about the concrete mixture and the structure must be known:

- expansion of the aggregate in either the AMBT or the CPT
- structure size, type and exposure conditions
- alkali loading of the concrete (e.g. alkali content of the cement and cement content)
- composition of the SCMs under consideration for mitigation.

First the reactivity of the aggregate is determined and assigned as an **R0** (non reactive), **R1** (moderately reactive), **R2** (highly reactive) or **R3** (very highly reactive). Exact values are given for the different categories based on their expansion in either the AMBT or the CPT. After the reactivity of the aggregate is known, the level of risk of ASR developing is determined using a table that relates the size and exposure condition of the structure to the aggregate reactivity class. The lowest level of risk, **Level 1,** is for a non-massive concrete in a dry environment, where dry is defined as having an average relative humidity less than 60% (usually only found in buildings) and where the aggregate reactivity is either **R0** or **R1**. The highest level of risk is **Level 6** for concrete exposed to alkalis in service where the aggregate reactivity is **R3**. The next step is to determine the structural classification that ranges from an SC 1 to an SC 4. SC1 structures are generally structures where the safeties, economic or environmental consequences of ASR developing are very low. These may also be temporary structures and structures with an expected service-life of 5 years or less. An SC 4 structure on the other hand is one where no level of ASR can be tolerated at all. This would include as examples: dams, nuclear power plants, major bridges, critical elements where inspection may not be possible, tunnels, waste water treatment facilities, etc. Often these types of structures also have design lives of 75 years or more.

After the risk level is known (Level 1-6) and the structural classification has been identified (SC1-SC4), the prevention level (V-ZZ) can be determined using a table relating these two items. The prevention level of V is the lowest whereas prevention **Level ZZ** is the highest (e.g. most SCMs). Alkali loading criteria are also given for the various prevention levels. These range from no limit (**Level V**) to 1.8 kg/m^3 for **Level Y**. For **Level Z** and **ZZ**, the user is given a further table to determine the highest levels of prevention needed that combine alkali-loading criteria with SCM criteria. The prevention levels correspond to a table that gives the chemical composition of fly ash (two ranges), slag and silica fume replacement levels, corresponding to the given prevention Level. The table on prevention selection is shown in TABLE 1. For example, if the user was in prevention **Level Y**, one of the following options to mitigate ASR could be selected:

- 25% fly ash (alkalis < 3.0 %)
- 25% fly ash (CaO </= 18% and alkalis between 3.0 – 4.0%)
- 30% slag cement
- 3.0 x KGA silica fume

Where KGA is calculated by multiplying the cement content of the concrete in kg/m^3 by the alkali content of the cement divided by 100. If the fly ash has a CaO content higher than 18% and the alkalis are greater than 4.0%, then performance testing using the AMBT or CPT is the only recommended approach. Additionally, combinations of SCMs may be used; this can lower the amount of a particular SCM and in turn would impact constructability or local building codes/standards. For instance, if a highly reactive aggregate calls for a 40% replacement of fly ash, silica fume could be used in conjunction with the fly ash and the total amount of SCM can be reduced due to the synergistic effects of the two combinations. The standard guide states that if two or more

SCMs are used together, then the minimum replacement levels shown in TABLE 1 can be reduced, providing that the sum of proportions of both SCMs is greater than or equal to one. [6]

2.2 Rationale for Approach

The rationale for the development of this unified approach to dealing with AAR in North America is based on decades of research in Canada and the United States, and is most recently given in an AASHTO report.[12] While the CSA standard was developed many years before the FHWA, AASHTO and ASTM standards, some important modifications were made to the AASHTO and ASTM standards, which are now also reflected in the CSA standards. Much of the work to develop the CSA standards was based on the well-known Spratt aggregate, a highly reactive siliceous limestone. However, additional work in the United States since the late 1990s showed even higher categories of reactive aggregates, thus a fourth category was created for "very highly reactive" aggregates. [13-15] The rationale notes that the structural classification system was based on RILEM TC 191-ARP, "Alkali-Reactivity and Prevention – Assessment, Specification, and Diagnosis of Alkali-Reactivity".[16] The rationale covers the assumptions made when setting for the prescriptive approach. Several key assumptions follow: [12]

- The level of ASR risk increases as the reactivity of the aggregate, the size of the structure, or the availability of moisture in service increases and if the structure is exposed to alkalis during service.
- Some concrete structures can tolerate a higher level of risk than other structures (i.e., a concrete sidewalk), either because the consequences of ASR are less severe or because the required service life is less (or both). In such cases, a lower level of prevention may be warranted.
- Deleterious ASR can be prevented solely by limiting the alkali content of the concrete.
- The maximum alkali content that can be tolerated without the occurrence of deleterious ASR will depend mainly on the reactivity of the aggregate and whether the concrete is exposed to alkali compounds in service.
- Deleterious ASR can be prevented by using supplementary cementing material (SCM), or combination of SCMs.
- The amount of SCM required to prevent deleterious ASR depends upon a number of factors including (but not limited to) the following:
  - The reactivity of the aggregate
  - The composition of the SCM (particularly CaO, SiO_2, and Na_2O_{eq})
  - The alkali provided to the system by the portland cement
  - The presence of alkali compounds in service

The selection of prevention measures was based on many different studies, especially those in Canada and the United States, as they were the most representative of the types of aggregates and SCMs available regionally. The studies ranged from AMBT to CPT to exposure blocks. However, the strongest weighting for selection of the prevention levels for a specific SCM type and composition was based on studies where the accelerated laboratory testing was benchmarked to exposure blocks or field structures.[12]

The rationale provides useful information regarding the ambient relative temperature conditions and discusses that while the approach does not take into account differences in temperature, warmer wetter conditions will accelerate the reaction over cooler drier climates or even cooler wetter climates. Additionally, the role of other forms of deterioration is not taken into account (e.g. freeze-thaw, corrosion or sulfate attack). It is known from many surveys of field structures that often ASR will initiate cracking and deterioration and then another one or more deterioration mechanisms will become the dominate deterioration feature and/or along with ASR will lead to long term damage in the structure. Further detailed information on the rationale can be found in reference [12].

3 DISCUSSION

This unified approach presents a significant step forward in the way that North America addresses AAR. However some challenges still exist and there is work to be done to refine the procedure and to improve the test methods on which it is based. One of the current challenges that ASTM, CSA and AASHTO are working on is that in the prescriptive version of the test, levels of prevention vary with structural class, exposure condition and aggregate reactivity. Whereas in the, performance-based approach, there are no defined levels of "performance". Either the combination of materials passes the AMBT and/or CPT and it is suitable for use in concrete construction, or it does not pass and an increased replacement level is needed for testing or a new combination of materials is investigated. In the ASTM version of the AMBT a caveat states that a lower expansion limit may be used for critical structures such as hydraulic dams where absolutely no expansion can be tolerated. Using a lower expansion limit may be a way to include a varying level of "performance" within this methodology. It may also be possible to recommend increased replacement levels of SCMs and/or ternary systems where a greater level of efficacy over a sole SCM may be realized. However, more research and analysis of existing data sets is needed to determine an exact recommendation for such an approach.

Another challenge comes from our most recent data relating the 2-year concrete prism test to outdoor exposure block testing. As the age of outdoor exposure blocks is increasing into the 10-25 year mark (e.g., sites in Texas and Canada), we are learning that the predicted levels of SCM needed to control a reactive aggregate below the 0.04% expansion limit in the CPT may not be enough to prevent deleterious expansion in the field. FIGURE 2 shows a plot of a selected set of mixtures that were evaluated in the CPT up to 2 years versus the same mixtures placed on an outdoor exposure site in Austin, Texas. The same trend is observed for the 14-day AMBT compared to exposure blocks but that data is not shown for brevity. The exposure blocks are between 11.5 to 14 years of age and all mixtures have a 1.25% Na_2O_{eq}. It is of great concern that the majority of these mixtures passed the 2-year concrete prism test but have expanded beyond the 0.04% limit in outdoor field exposure; in many cases the expansion is significant. These expansions are below the companion control blocks (e.g. higher expansion in the control blocks), but the expansions observed are moderate to high and the blocks are cracking in the field and showing signs of deleterious ASR. The research team will be taking cores from these blocks to learn more about the progression of the reaction and why the SCMs appear to work in the short term but not in the longer term.

This points to an important research needed for the AAR community – how do we predict service-life based on our accelerated laboratory tests? Many criticize the exposure blocks as still being aggressive owing to the high cement and alkali content and lack of reinforcement. To fully elucidate the data we are getting from our field exposure sites, we need to significantly increase the link to actual field structures where the concrete mixture proportions are known and the structures are monitored on a regular long-term (e.g. 40-50 years and beyond) basis.

4 CONCLUSIONS

In North America a unified approach exists to assess the potential for alkali-silica and alkali-carbonate reaction and to determine appropriate mitigation strategies. Where ACR is identified the recommendation is to avoid the use of that aggregate in concrete construction. If ASR is identified the user is then guided to follow either a prescriptive of performance-based approach for avoiding deleterious ASR. This is a significant step forward for risk management of AAR and allows North America to address this issue in a well-defined and concerted effort among researchers, government agencies and industry. Challenges do still exist in that there are not defined levels of performance within the performance-based approach. Recent research results from outdoor field exposure sites also suggested that the 2-year concrete prism test and the 14-day AMBT might not produce sufficiently conservative levels of SCM replacement to fully mitigate AAR. Several significant research needs have emerged for the community to address:

- Determine why the AMBT (14 days) and CPT (2 years) under predict the amount of SCM needed to mitigate deleterious ASR
- Develop accelerated laboratory test methods that accurately predict true field performance
- Develop service-life predictions based on sound accelerated laboratory testing (see above) that allow an owner and designer to make decisions about mixture design that will provide appropriate length service-life for their structure type.

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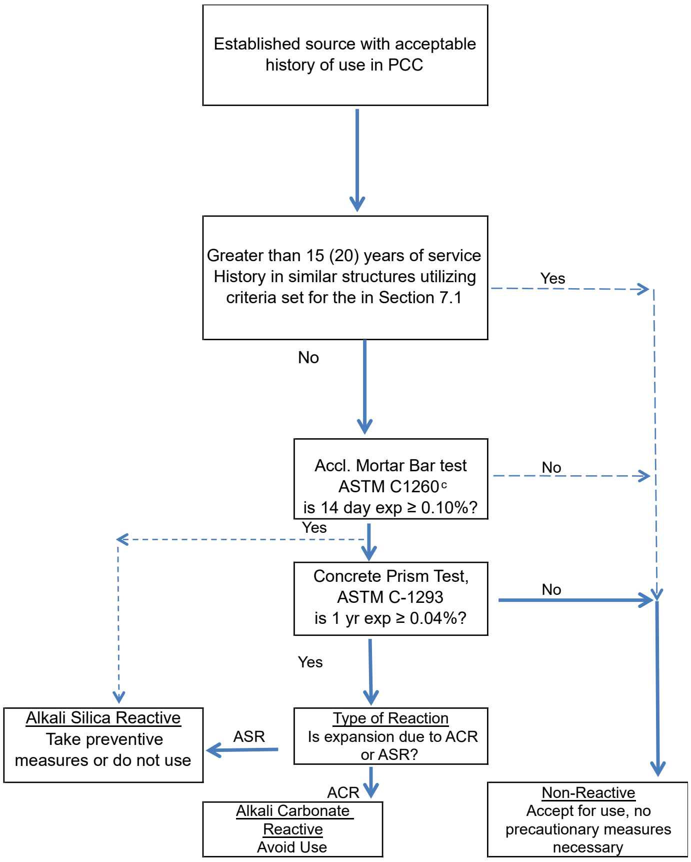

FIGURE 1: General approach for determining the type of alkali-aggregate reactivity and preventive measures.

TABLE 1: Prevention options following the ASTM C1778 prescriptive approach (after ASTM C1778, [6]).

Type of SCM	Alkali Level of SCM (%Na_2O_e)	Minimum Replacement Level ** (% by mass)				
		Level W	Level X	Level Y	Level Z	Level ZZ
Fly ash (CaO ≤ 18%)	< 3.0	15	20	25	35	Table 7
	3.0 - 4.5	20	25	30	40	
Slag Cement	< 1.0	25	35	50	65	
Silica Fume* (SiO_2 > 85%)	< 1.0	2.0 x KGA or 1.2 x LBA	2.5 x KGA or 1.5 x LBA	3.0 x KGA or 1.8 x LBA	4.0 x KGA or 2.5 x LBA	

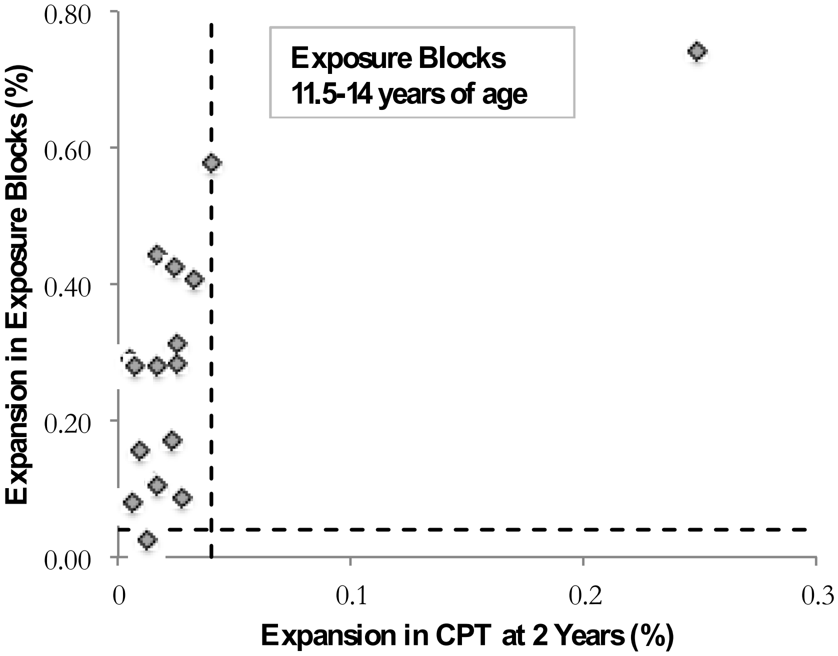

FIGURE 2: Comparison of expansion of exposure blocks at 11.5 to 14 years of age and concrete prism test results at 2 years.