EVALUATION OF ASR POTENTIAL IN WYOMING AGGREGATES USING MULTIPLE ACCELERATED TESTS

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Abstract

The purpose of this research was to evaluate the ASR potential of eight different aggregate sources throughout Wyoming and to compare the effectiveness of the various evaluation methods for the Wyoming Department of Transportation. Each aggregate was subjected to the Accelerated Mortar Bar Test (AMBT) and the Concrete Prism Test (CPT). In addition, an analytical method was applied which is referred to as the Kinetic Method. The CPT was used as the reference test, so the performances of the other accelerated methods were investigated with respect to their correlation with the CPT. The CPT identified a wide range of ASR potential among the eight aggregate sources, and the efficacy of the other accelerated tests was dependent on the type of aggregate that was being evaluated. Two of the aggregate sources were classified as non-reactive in the CPT while all aggregates sources were classified as reactive by the AMBT and the Kinetic Method.

Keywords: Alkali-aggregate reaction, Concrete Prism Test, CPT, Accelerated Mortar Bar Test, ABMT, Kinetic Method

1 INTRODUCTION

Alkali-silica reactivity (ASR) is a global concrete durability problem that has been identified in Wyoming. Over the past 10 years, the Wyoming Department of Transportation (WYDOT) has addressed this problem by subjecting aggregates to the Accelerated Mortar Bar Test (AMBT) before using them in new concrete. This test was used because of its relatively short duration (16 days) compared with other tests. When the AMBT showed an aggregate to be reactive, mitigation involved adding a Class F fly ash to the concrete mixture containing the reactive aggregate. Because fly ash was inexpensive, this mitigation technique added very little to the cost of a concrete project, and even though the AMBT is known to sometimes classify innocuous aggregates as reactive, the minimal cost of mitigation made these errant classifications irrelevant. Over time, the demand for fly ash has increased, and the material has become more expensive, which has made it more important for aggregates to be classified accurately.

After an initial study of existing ASR damage in Wyoming, eight aggregate sources, many concentrated in the Big Horn Basin, were selected for evaluation. The ASR potential of these eight sources was evaluated using a number of accelerated tests [1]. Although the AMBT is currently used as the screening test for WYDOT, it has known shortcomings such as false positive and false negative classifications. Consequently, in addition to the AMBT, the aggregates were also evaluated using the Concrete Prism Test (CPT) and an analytical technique referred to as the Kinetic Method which uses the expansion data from the AMBT. The CPT is regarded as the most reliable accelerated test, so the other tests were compared against it. The CPT was also used as the authoritative test in the case of differing reactivity classifications.

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In addition to the accelerated tests mentioned, these aggregates were also subjected to large scale field exposure, and those results will be presented in a future publication when the testing is complete.

2 MATERIALS AND METHODS

2.1 General

The names, locations, and abbreviations used for the eight different aggregate sources in this document are shown in Table 1, and their relative locations are identified on the map in Figure 1. The specific gravity and absorption of coarse and fine aggregate from each source was measured by the WYDOT Materials Lab and is reported in Table 2. Coarse aggregate unit weight, used to proportion the concrete mixture in the CPT, was measured at the University of Wyoming using ASTM C29 and is presented in Table 3.

Holcim Type I/II cement was used for all concrete mixtures in this research due to its resemblance to the type of cement that would be used in WYDOT construction projects. The cement was analyzed in accordance with ASTM C114, and its alkalinity was measured to be 0.706% as Na_2O equivalent. Technical grade NaOH pellets were used for the AMBT solution and to boost the alkalinity of the CPT prisms. Tap water was used for the CPT mixtures, and distilled water was used for the AMBT mixture. For the accelerated tests, a fixed length comparator was used to measure the length change of the specimens.

2.2 Test Procedures

Concrete Prism Test (ASTM C1293) - Modified

ASTM C1293 provides instructions for testing either a coarse aggregate or a fine aggregate for reactivity, and the standard outlines the gradation requirements for both types of aggregate, depending on which one is being tested for reactivity. To better represent the concrete mixtures that will be used in WYDOT construction projects fine and coarse aggregates were combined in this test. The individual specified gradations were used for fine and coarse aggregates as defined in ASTM C1293 and ASTM C33.

The concrete mixture was proportioned and cured according to ASTM C1293. The aggregates were oven dried before use in the concrete, and the w/c ratio was 0.42. A NaOH admixture was used to bring the alkalinity of the concrete mixture to 1.25% Na_2O equivalent as specified in ASTM C1293. Because the cement had an alkalinity of 0.706%, slightly lower than the 0.9 ± 0.1% specified, more NaOH was added to raise the concrete alkalinity to 1.25%. Cement with alkalinity in the specified range was not available in the region where the tests were conducted. Four 75 x 75 x 285 mm (3 x 3 x 11 ¼ inch) specimens were created with companion compressive strength tests, and the batch quantities for each aggregate can be found in Table 3.

The CPT specimens were measured at 1, 7, 28, and 56 days, and 3, 6, 9, and 12 months. In this research, the 1 day measurement was inadvertently taken at 23°C, and the subsequent measurements were taken at 38°C so there was expansion between the day 1 and day 7 measurements that was due to thermal changes. This was accounted for at the end of the testing process by allowing specimens to cool to 23°C and taking an additional measurement reading after the 38°C measurement, thereby allowing a direct comparison between the first and last measurement. Research indicates that the difference in one year expansion between CPT specimens that were measured at 38ºC and room temperature is negligible [2][3]. Therefore, the direct comparison of the day 1 and 12 month measurements at room temperature accurately represents the expansion of the CPT specimens.

At the end of one year, expansion values that exceed 0.04% indicate a potentially deleteriously reactive aggregate, while expansions less than 0.04% indicate a non-reactive aggregate.

Accelerated Mortar Bar Test (ASTM C1260) - Modfied

The AMBT specimens were proportioned and cured according to ASTM C1260, but to better characterize field concrete, each aggregate portion was composed of 60% crushed coarse aggregate and 40% natural fine aggregate by mass. First, the natural aggregate was sieved into coarse and fine size fractions. Then the coarse aggregate (#4 plus) was crushed and sieved into fine size fractions. To arrive at the appropriate amount of material, 40% of each size fraction was taken from the natural fine aggregate and 60% was taken from the applicable size fraction of the crushed aggregate. The overall aggregate gradation specified in the standard was adhered to, and the aggregate was washed and dried before use in the mortar mixture. The mixtures yielded three 25 x 25 x 285mm (1 x 1 x 11 ¼ inch) mortar bars.

Although, ASTM C1260 only requires the bars to be measured for 14 days, this research extended the duration of the test to allow for the use of a kinetic method of analysis. An aggregate is considered innocuous if the 14 day expansion is less than 0.10% and potentially deleteriously reactive if the expansion exceeds 0.20%. An area exists between 0.10% and 0.20% expansion where the aggregate cannot be classified. It should be noted that some agencies use different expansion limits. For example, the FHWA uses a limit of 0.08% and WYDOT uses a limit of 0.10% to indicate reactive aggregate.

Kinetic Method

This analysis method fitted a curve to the AMBT expansion data and used the points on the curve as input into a function for modeling ASR. Linear regression was performed to yield values that were used to delineate reactive and non-reactive aggregates.

The MMF equation, a sigmoidal growth curve developed by Morgan, Mercer, and Flodin [4] was fitted to the actual expansion data using a computer program called CurveExpert. The equation has the form:

$$\%Expansion = \frac{(a*b+c*t^d)}{(b*t^d)} \qquad \text{[Equation 1]}$$

where t is time and a, b, c, and d are variables used to fit the function to the data. The form of the Kolmogorov-Avrami-Mehl-Johnson (KAMJ) equation that is described in [5] and used to model ASR is:

$$\alpha = 1 + \alpha_0 - e^{-k(t-t_0)^M} \qquad \text{[Equation 2]}$$

where α is the expansion at time t, a_0 is the expansion at time t_0, k is the expansion rate constant, and M is the Avrami exponent. Linear regression was performed to obtain $ln(k)$ and M for a given value of t_0. Because the MMF equation was fitted to the expansion data, intermediate expansion values could be calculated. An algorithm was used to calculate $ln(k)$ and M for 100 values of t_0 (0.28 day intervals) and return the maximum value of $ln(k)$ along with the corresponding values of M and t_0. The value of t_0 refers to the time at which nucleation and growth reaction kinetics begin to dominate the reaction [6] and is intended to represent the time at which ASR begins. The value of M depends on the form and growth of the reaction products, and k is influenced by the effects of nucleation, multidimensional growth, the geometry of the reaction site, and diffusion. Further research on the use of the Kinetic Method may be found in [7] and [8]. An aggregate is classified as non-reactive if $ln(k) < -6$ and as potentially reactive if $ln(k) > -6$ [5].

3 RESULTS

3.1 Concrete Prism Test

The average expansions of the concrete prisms cast with each aggregate after one year are presented in Figure 2. Knife River, Labarge, and Goton exhibited the highest expansion and greatly exceeded the critical expansion limit that determines the reactivity classification. Harris and Devries Farm experienced the least expansion and were classified as non-reactive. The average expansion for the Blackrock specimens was less than 0.04%, but one of the four specimens greatly exceeded the reactivity limit. Therefore, the aggregate was conservatively classified as reactive. The research group is awaiting results of the field specimens to provide additional information on this behavior. Worland and Lamax proved to be moderately expansive in relation to the other aggregates but were still considered potentially deleteriously reactive. It should be noted that there is also a range of expansion rates among the aggregates. Knife River and Labarge, for example, take longer to begin their reaction but then have very high expansion rates for the remainder of the test. The other aggregates seem to start out with their highest expansion rates but slow down soon after.

3.2 Accelerated Mortar Bar Test

The average expansion for the aggregates in the AMBT is shown in Figure 3. All eight of the aggregates were classified as reactive in this test, with Devries Farm exhibiting the most expansion and Labarge exhibiting the least at 14 days. All the aggregates appear to begin their reactions almost immediately after the start of the test, but three of them have relatively shallow curves.

3.3 Kinetic Method

The values obtained using the Kinetic Method are presented in Figure 4. All aggregates are classified as reactive, with Worland expanding the most and Labarge expanding the least. Four of the t_0 values were very close to zero and represent a very short induction period. The other four values of t_0 are slightly larger, and with the exception of Blackrock, seem to correlate with lower levels of reactivity. The trend of increasing reactivity with decreasing induction period is evident.

4 DISCUSSION

4.1 General

The CPT is regarded as the most reliable accelerated test method so the other accelerated tests are compared to it in order to evaluate how effectively they evaluate ASR potential. The plot areas in the graphs comparing the accelerated tests are divided into four quadrants by the expansion limits of each test, shown as dashed lines. Data in the upper right and bottom left quadrants indicate agreement in the classification between tests. Data in the other two quadrants represent differing classifications by each test.

4.2 CPT Comparisons

Accelerated Mortar Bar Test

Average one year expansion in the CPT versus average 14 day expansion in the AMBT with error bars designating ± one standard deviation are plotted in Figure 5. Graphically, the tests agreed on the classification of five out of the eight aggregates, but with the reactive classification of Blackrock discussed earlier, there was agreement on six of the aggregates.

Although both tests agreed on the classification of many of the aggregates, the magnitude of expansion in the CPT was inversely related to expansion in the ABMT, with the exception of Harris. High expansion in one test was coupled with low expansion in the other test. Knife River and Labarge are very reactive in the CPT but their expansions were close to the upper limit of 0.2% expansion in the AMBT. The slowly reactive nature of these highly reactive aggregates may have played a role in the lower expansion values attained in the AMBT. The considerable expansion of Devries Farm in the AMBT while showing relatively little expansion in the CPT may indicate that the aggregate has a high sensitivity to concrete alkalinity.

Kinetic Method

Figure 6 compares aggregate expansion in the CPT with values of *ln(k)* obtained from the Kinetic Method. As in the case of the AMBT, the Kinetic Method classifies all aggregates as reactive while the CPT yields two non-reactive aggregates (Blackrock is considered reactive). There doesn't seem to be a definitive relationship between aggregate performance in the CPT and the Kinetic Method, but the results are less inversely correlated than was the case with the AMBT. Also, the Kinetic Method may be useful in identifying the timing of aggregate's reaction. Based on the CPT testing, the slowest reacting aggregates were Labarge and Knife River; these aggregates also showed elevated t_0 values in the Kinetic Method. Quantifying the induction period of an aggregate's reaction, a potential source of misclassification in the AMBT, could aid in improving the reliability of the AMBT. Additional comparisons of CPT and AMBT results are needed to better understand the capabilities of this method.

5 CONCLUSIONS

Several conclusions can be drawn about the reactivity of the aggregates and the effectiveness of the accelerated test methods. Reactivity classifications should be regarded as preliminary until the results are verified by large scale field exposure testing, which is currently underway.

- Six of the eight aggregates tested were classified as reactive by all the accelerated tests. Harris and Devries Farm were classified as non-reactive by the CPT.
- Although many of the aggregates were classified the same in all the tests, there was an inverse correlation between the CPT and the AMBT.
- The Kinetic Method has the advantage of quantifying the induction period, but ultimately there was not a clear correlation with the CPT. However, the method may be a useful supplement to the AMBT with respect to the timing of the aggregate reaction.
- This research confirms the assertion that the AMBT tests are too severe to accurately characterize field performance and must simply be used as a screening test.

6 REFERENCES

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Table 1: Aggregate abbreviations and locations

Aggregate Name	***Abbreviation***	***Location***
Devries Farm	DFP	Thermopolis, WY
Harris	HPC	Cody, WY
Lamax	LX	Basin, WY
Goton	GP	Greybull, WY
Knife River	KR	Cheyenne, WY
Worland	WOR	Worland, WY
Labarge	LBG	Rock Springs, WY
Blackrock	BR	Powell, WY

Table 2: Aggregate properties

	COARSE AGGREGATE			**FINE AGGREGATE**	
Aggregate Name	***Specific Gravity (SSD)***	***Absorption***	***Unit Weight (pcf)***	***Specific Gravity (SSD)***	***Absorption***
Devries Farm	2.518	2.19%	96.6	2.614	1.56%
Harris	2.601	1.83%	97.2	2.621	2.25%
Lamax	2.540	2.02%	97.7	2.603	1.81%
Goton	2.579	1.07%	99.0	2.627	1.01%
Knife River	2.662	0.67%	98.8	2.629	0.91%
Worland	2.549	1.45%	99.0	2.614	1.56%
Labarge	2.600	0.67%	98.8	2.622	1.05%
Blackrock	2.591	1.80%	97.7	2.600	2.15%

Table 3: Batch quantities for all aggregates used in the CPT

Aggregate Name	*Cement (lb)*	*Water (lb)*	*CA (lb)*	*FA (lb)*	*NaOH (lb)*
Lamax	19.89	9.90	51.87	27.82	0.14
Harris	19.89	9.96	51.58	29.53	0.14
Goton	19.89	9.21	52.54	28.93	0.14
Devries Farm	19.89	9.83	51.28	28.11	0.14
Worland	19.89	9.55	52.58	27.77	0.14
Knife River	19.89	8.98	52.43	30.97	0.14
Blackrock	19.89	9.90	51.89	28.84	0.14
Labarge	19.89	9.01	52.48	29.57	0.14

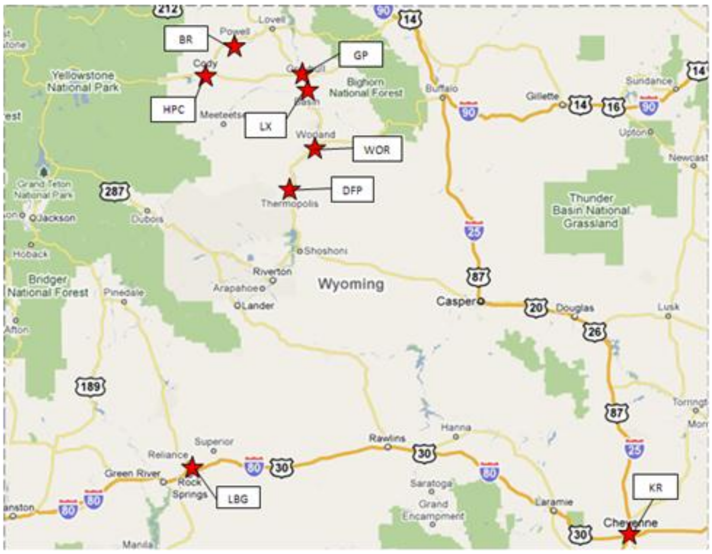

Figure 1: Wyoming map showing the location of each aggregate source

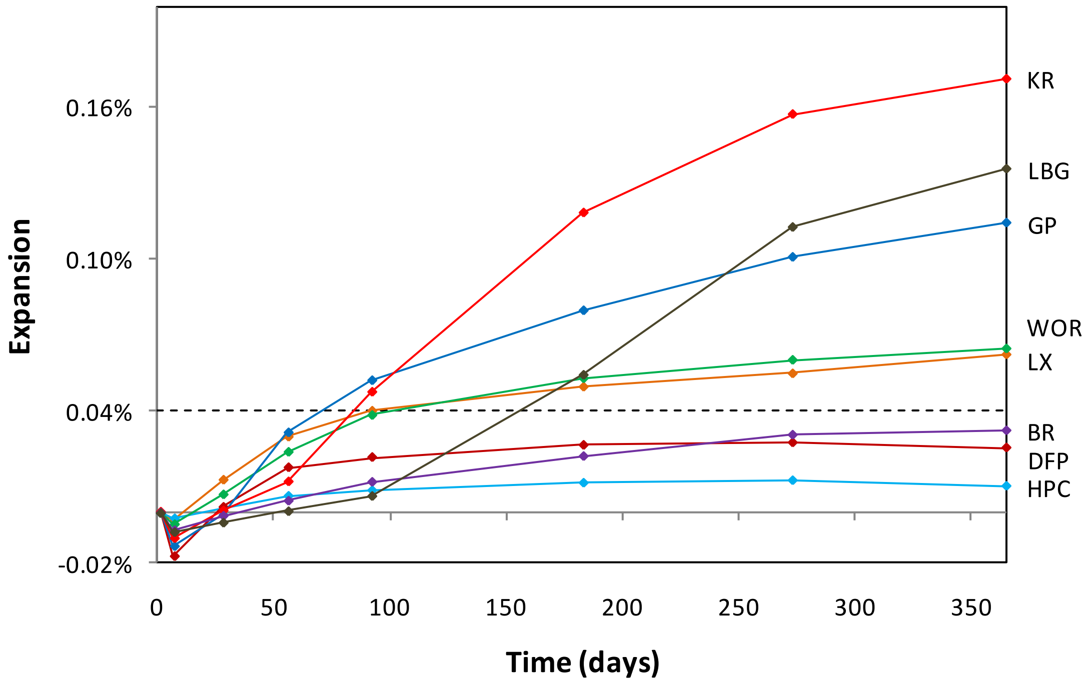

Figure 2: Average expansion for eight aggregates subjected to the CPT

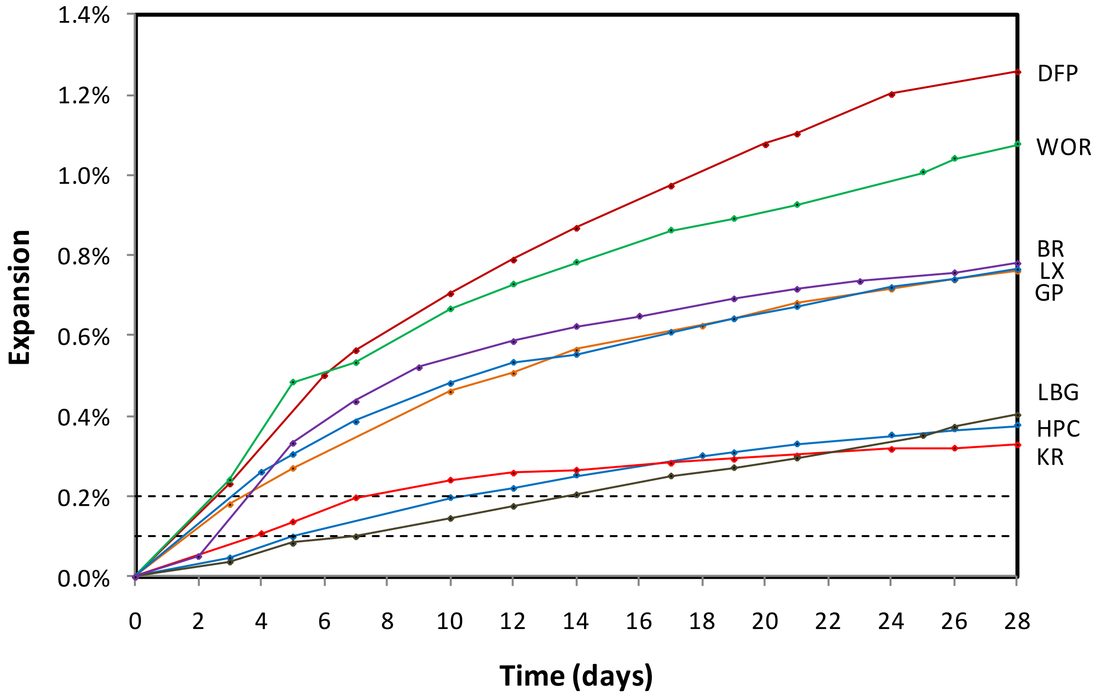

Figure 3: Average expansions for eight aggregates subjected to the AMBT

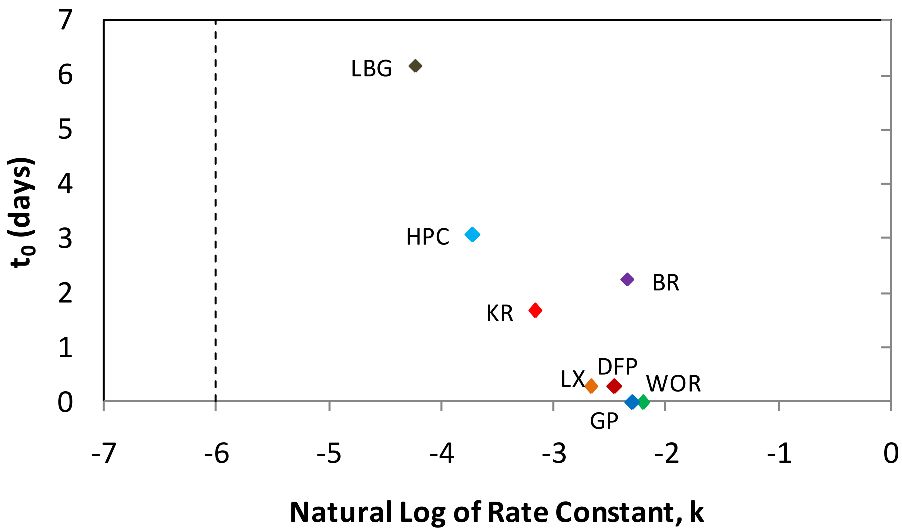

Figure 4: t_o vs. *ln(k)* for eight aggregates analyzed using the Kinetic Method

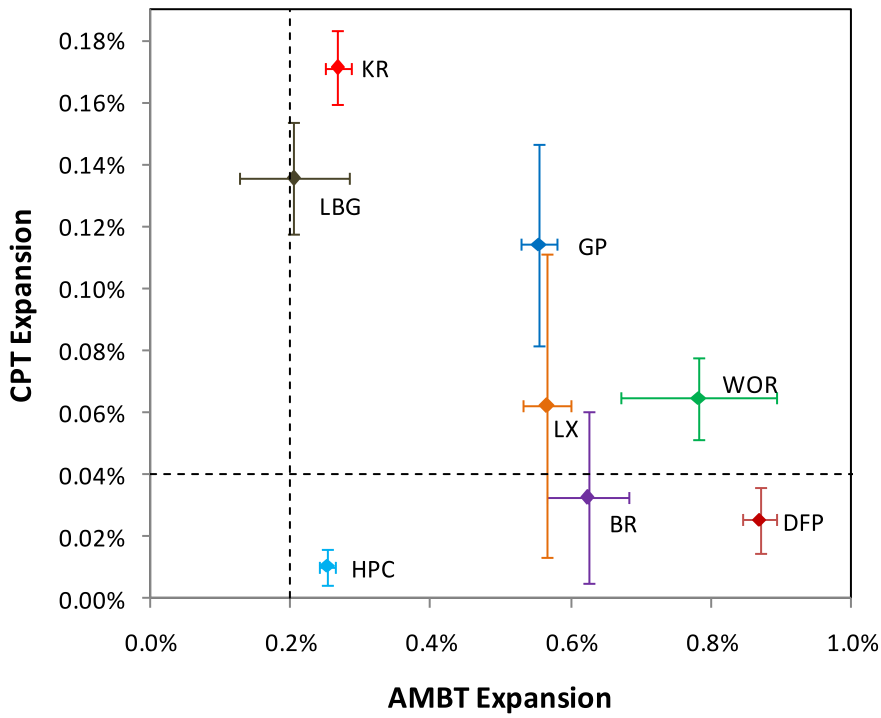

Figure 5: Comparison of expansions in the CPT and the AMBT with error bars showing standard deviation

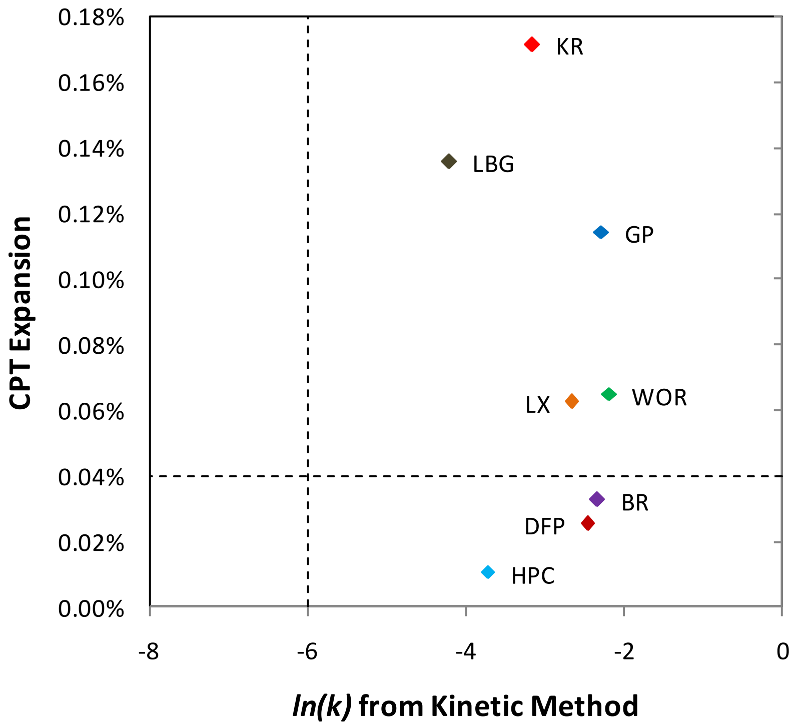

Figure 6: Comparison of critical limits in the CPT and the Kinetic Method