EVALUATION OF ALKALI-SILICA REACTION POTENTIAL OF MARGINAL AGGREGATES USING MINIATURE CONCRETE PRISM TEST (MCPT)

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Abstract

Existing test methods to evaluate aggregate alkali-silica reactivity such as the accelerated mortar bar test (AMBT) and the concrete prism test (CPT) have shown deficiencies. Manipulating aggregate size by crushing coarse aggregate to meet the required gradation and high test temperature in the AMBT test are primary causes for its unreliability in accurately assessing aggregate reactivity, while alkali leaching from test specimens and long test duration required in the CPT test makes it somewhat impractical from routine evaluation. However, in terms of reliability of performance prediction in field, CPT test results have shown more reliability compared to that of the AMBT test method. This paper reports on a study to investigate Alkali-Silica Reaction (ASR) in concrete containing 42 different aggregates with a wide range of reactivity using a newly-developed test method called the Miniature Concrete Prism Test (MCPT) that overcomes the shortcomings of CPT and AMBT methods. MCPT results were correlated with the CPT and AMBT test results. Based on the findings from this study, it can be concluded that for assessing coarse aggregate reactivity, MPCT method provides equally reliable aggregate reactivity characterization as the CPT method in a much shorter duration of 56 days, instead of the 1-year test duration that is needed in the CPT method. However, the MCPT and CPT methods showed lesser correlation when characterizing the fine aggregate reactivity. The lack of agreement between MCPT and CPT in case of certain fine aggregates needs further investigation, along with calibration of all the threshold expansion values for all test methods with true field performance of aggregates.

Key words: alkali-silica reaction, concrete expansion, miniature concrete prism test, concrete prism test, ASR gel

1 INTRODUCTION

Alkali-silica reaction (ASR) is a deleterious chemical reaction that can occur in concrete between aggregates containing reactive silica and the alkaline pore solution present within the matrix of concrete. The product of this chemical reaction is a hygroscopic gel, which in the presence of moisture, can absorb and swell, exerting pressure on the surrounding concrete causing significant expansion and cracking in the matrix. Stanton (1940) recognized ASR as a source of distress in concrete [1]. Over the years since the discovery of ASR in concrete, several strategies have been developed and used to prevent or minimize ASR-induced distress in concrete structures. Among them, the most effective solution to mitigate ASR distress in concrete has been the use of supplementary cementitious materials such as fly ash, meta-kaolin, slag, and silica fume [2-8].

Along with the strategies to mitigate ASR, several test methods have been developed to assess the potential reactivity of aggregates, among which the accelerated mortar bar test (AMBT, ASTM C1260) and the concrete prism test (CPT, ASTM C1293) have been widely used [9-14]. Due to the short duration of the AMBT test (i.e., 16 days), this test has been widely adopted by agencies to assess the ASR potential of coarse and fine aggregates using mortar mixtures. However, the crushing process used to achieve certain size fractions of gradation specified in the ASTM C1260 test, particularly with coarse aggregates, along with the harsh exposure conditions such as the high temperature (i.e., 80°C) and the alkaline soak solution (i.e., 1N NaOH) used in this test often produce test results that are false-positive and occasionally false-negative, limiting the reliability of results from this test. False-positive results demonstrate that the aggregates are reactive in the test method, while the field performance of the aggregate does not show any deleterious behavior.

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Conversely, false-negative results demonstrate the non-reactivity of the aggregate in the test method, while the aggregate shows evidence of sufficient reactivity in the field concrete to cause distress.

The CPT method has long been considered as a more reliable test method than the AMBT method, wherein the reactivity of both fine and coarse aggregates can be evaluated independently without any significant crushing of the coarse aggregate to fine sizes (except when the coarse aggregate size is greater than 20 mm) and without the need for highly elevated test temperatures or the need to use any soak solution. Also, better correlation between the field performance of the aggregates and the CPT results has been documented in previous research [15]. However, long test duration (i.e., one year to show results of aggregate reactivity and two years to show the results of ASR mitigation) along with the alkali leaching, due to the convective action of moisture movement within the storage container, are two concerns often raised about the CPT method [16]. A study by Thomas et al. (2006) was carried out to evaluate the various test methods available for testing the ASR reaction [16]. It was found that approximately 35% of the alkalis in the concrete prisms (i.e., the CPT specimens) leached out after one year, and around 20% of the alkalis leached out after just 90 days [15]. This level of alkali leaching is significant, particularly when an aggregate of low reactivity or when slowly reactive aggregates are tested [16].

In order to overcome the shortcomings of both the AMBT test and the CPT test methods, the Miniature Concrete Prism Test (MCPT-AASHTO TP110) was recently developed [17]. In this test method, concrete prisms are stored in a 1N NaOH solution at 60°C, which is a lower test temperature compared to 80°C used in the AMBT method and limits the potential alkali-leaching observed in CPT method. A study by Latifee and Rangaraju (2014) was carried out to compare the reactivity of a wide range of aggregates with different mineralogy in the AMBT, MCPT and CPT methods [17]. In this study, aggregates from 33 different sources ranging from "highly reactive" to "non-reactive", with known field performance were evaluated in each of the three test methods [17]. It was found that the results from MCPT and CPT method correlated very well in characterizing the aggregate reactivity (R^2=0.968), while a poor correlation was observed between the results of MCPT and AMBT methods (R^2=0.503) [17]. However, most of the aggregates used in the study by Latifee and Rangaraju were either non-reactive or moderate to highly reactive in nature. Very few aggregates were tested that showed either low or marginal reactivity (i.e., with expansion values of test specimens very close to the threshold limits in the AMBT or CPT methods) or slowly reactivity aggregates that take a long time to exhibit their potential to cause ASR distress in the field, and often are characterized as false-negatives in standard test methods.

In this study, a larger suite of aggregates than that was used in the previous investigation conducted by Latifee and Rangaraju was considered, particularly aggregates that are considered as being of low or marginal reactivity. In this study, the alkali-silica reactivity of 42 aggregates (coarse and fine aggregates) of widely different mineralogy using MCPT, CPT and AMBT test methods was evaluated. Among the 42 aggregates, 30 aggregates were selected that showed a marginal level of reactivity as indicated by the AMBT method, i.e., the 14-day expansion of mortar bars was between 0.10% and 0.20%. The 56-day expansion values from MCPT method were correlated with 1-year expansion values from CPT method and the 14-day expansion values from AMBT method to assess the reliability of MCPT method to characterize aggregate reactivity as compared with CPT method.

2 EXPERIMENTAL WORK

2.1 Materials

Portland Cement

In this study, the ASTM C150 Type I portland cement with high-alkali content (Na_2O_{eq}=0.88%) was used. The chemical composition of the portland cement is given in Table 1.

Reactive coarse aggregate

In this study, 26 coarse aggregates of different lithologies, including 10 slow/low-reactive aggregates, 13 moderate-reactive aggregates and 3 high/very high-reactive aggregates were selected. The basic properties, along with their 14-day mortar bar expansion values obtained from the AMBT test, 56-day mini concrete prism expansion at 56-days and the 1-year concrete prism expansion values obtained from the CPT test, are shown in Table 2.

Reactive fine aggregate

In this study, 16 fine aggregates including 4 slow/low-reactive aggregates, 11 moderate-reactive aggregates and 1 high/very high-reactive aggregate were selected. The rock type, physical properties, along with their 14-day mortar bar expansion values obtained from the AMBT test and the 1-year concrete prism expansion values obtained from the CPT test, are shown in Table 3.

Non-reactive coarse aggregate (used with reactive fine aggregate)

A non-reactive limestone coarse aggregate with an oven-dry specific gravity of 2.83 and an absorption value of 0.35%, from Adairsville Quarry in Adairsville, Georgia, USA was used in this study. The non-reactive coarse aggregate was used when evaluating the reactivity of a fine aggregate in the concrete mixture.

Non-reactive fine aggregate (used with reactive coarse aggregate)

A siliceous non-reactive fine aggregate from Glasscock, SC with an oven-dry specific gravity of 2.62 and an absorption value of 0.30% was used in this study. The non-reactive fine aggregate was used when evaluating the reactivity of a coarse aggregate in the concrete mixture.

Sodium hydroxide pellets

Reagent grade sodium hydroxide from Fisher Chemicals was used to boost alkali level of concrete to 1.25% Na_2O_{eq} by weight of cement.

2.2 Test Procedure

MCPT (Miniature Concrete Prism Test) – AASHTO TP110

In this test method, concrete prisms with dimensions of 50 mm x 50 mm x 285 mm were prepared with a high-alkali cement content of 420 kg/m^3 and a water-to-cement ratio of 0.45. In order to accelerate the ASR reaction in concrete prisms, the alkali content of the concrete mixture was boosted up to 1.25% Na_2O_{eq}. by weight of portland cement by adding reagent grade NaOH pellets into the mix water. Also, to avoid alkali leaching from concrete specimens, concrete prisms were immersed in 1N NaOH soak solution. The concrete prisms were stored in curing room at 23°C for 24 hours before demolding to allow for setting and hardening. The concrete specimens were then immersed in water at 60°C for an additional 24 hours to allow for sufficient gain in their mechanical strength. After 24 hours, the zero-day readings of the concrete prisms were recorded and the test specimens were immediately transferred into a 1N NaOH soak solution at 60°C. Thereafter, periodic length change measurements were taken on the test specimens up to 84 days.

Based on the guidance given in the MCPT method, concrete prisms that show expansion values less than 0.030% at 56 days are considered to indicate non-reactivity of the aggregate in question [17]. Concrete prisms that show expansion values between 0.030% and 0.040% at 56 days represent aggregates that show either non-reactive or slowly-reactive aggregates, depending on their averaged 2-week rate of expansion between 56 days and 84 days. The averaged 2-week rate of expansion of concrete prisms of 0.01% or more, between 56 and 84 days in the MCPT, is considered to represent aggregates that are of low or slow-reactive nature. Concrete prisms that show expansion values between 0.040% and 0.120% at 56 days are considered to represent moderately-reactive aggregates, while concrete prisms that show expansion values between 0.120% and 0.240% at 56 days are considered to represent highly-reactive aggregates. Concrete prisms that show expansion values more than 0.240% at 56 days are considered to represent very highly-reactive aggregates.

3 RESULTS

The results of this study are presented in different graphs for coarse and fine aggregates and each of these aggregates are presented in three categories based on their level of reactivity: 1) high/very high reactive aggregates; 2) moderate reactive aggregates; 3) low/slow reactive aggregates.

3.1 ASR evaluation of coarse aggregates

Figure 1 shows the ASR expansion behavior of three aggregates which are high/very high-reactive coarse aggregates. As shown in Figure 1, the 56-day expansion values of the concrete prisms containing SS, VV and UU aggregates were 0.147%, 0.147% and 0.184%, respectively. Based on the ASR expansion criterion proposed in the MCPT test, the aggregates with 56-day expansion values between 0.121% and 0.240% are considered as high reactive aggregates. Therefore, all the three aggregates shown in Figure 1 are characterized as high reactive aggregates. As presented in Table 2, the 1-year CPT expansion values of SS, VV and UU were 0.181%, 0.0.192% and 0.251%, respectively, and the 14-day AMBT expansion values of SS, VV and UU were 0.35%, 0.53% and 0.90%, respectively. Therefore, based on both the CPT and the AMBT test methods, all the three aggregates are characterized as reactive aggregates.

Figure 2 shows the ASR expansion behavior in the MCPT of thirteen coarse aggregates, which are considered as moderately-reactive. As shown in Figure 2, the 56-day expansion values of the all aggregates shown in this figure were between 0.04% and 0.12%. The highest and lowest 56-day expansion values in MCPT for concrete prisms containing Dell Rapids and PP aggregate were 0.970% and 0.043%, respectively. As shown in Figure 2, the expansion behavior of concrete prisms containing these aggregates increased gradually, even after 56 days. Among all thirteen aggregates shown in Figure 2, five aggregates (PP, EE, NN, GG and TT) showed similar behavior in both the CPT and the AMBT test. Of these, two aggregates (PP and EE) are considered as non-reactive aggregates in both the CPT and the AMBT test, and three aggregates (NN, GG and TT) are considered as reactive aggregates in both the CPT test and the AMBT test. Aggregates AA, LL, JJ, MM, QQ and XX are aggregates which showed less than 0.10% expansion in AMBT, while their 1-year expansion in CPT was more than 0.04% (false negative test results). Aggregates II and KK are aggregates where CPT expansions were less than 0.04 % (considered as non-reactive aggregates), but their AMBT expansion were more than 0.1% (false-positive test results).

Considering the MCPT test results for these thirteen (moderately reactive) aggregates, only three aggregates (GG, NN and TT) showed similar behavior in AMBT, MCPT and CPT tests. For instance, the AMBT, MCPT and CPT expansion values for the GG aggregate were 0.15%, 0.061% and 0.047%, respectively, and the AMBT, MCPT and CPT expansion values for the NN aggregate were 0.16%, 0.081% and 0.074%, respectively. As presented in Table 2, the rock type of both NN and GG aggregates is characterized as gneiss. Aggregates AA, LL, JJ, MM, QQ and XX showed ASR reactivity in both the MCPT and the CPT test results, while aggregates II and KK showed reactivity in both the MCPT and the AMBT test results.

Figure 3 shows the expansion behavior of concrete prisms containing coarse aggregates, which are considered as non- reactive aggregates and low/slow reactive aggregate (i.e., YY). As shown in Figure 3, the 56-day expansion values of all aggregates shown in this figure were between 0% and 0.040%. The highest and lowest 56-day expansion values were for concrete prisms containing RR and HH aggregate with 0.040% and 0.00%, respectively. As presented in Table 2 and Figure 3, all aggregates were characterized as non-reactive aggregate based on the MCPT results, with the exception of YY, which based on its 2-week rate of expansion of 0.011% between 56 and 84 days, is characterized as low/slow reactive aggregate. Also, all of these aggregates were also characterized as non-reactive aggregates in the CPT test. Among all the aggregates that were characterized as non-reactive in the MCPT, the AMBT results correlated well, with the exception of aggregate DD. For instance, while the 56-day MCPT expansion value of concrete prisms containing DD aggregate was 0.018% and the 1-year CPT expansion value of the concrete prisms containing DD aggregate was 0.024%, the 14-day AMBT result of mortar bars containing this aggregate was 0.15%.

Results from evaluation of coarse aggregates used in this study suggested that all the coarse aggregates that were characterized as either high-, moderate- or non-reactive aggregates in MCPT, showed similar reactivity behavior in the CPT. However, aggregates which were characterized as being low/slow reactivity aggregates in the MCPT method were characterized as being non-reactive aggregates in the CPT method.

3.2 ASR evaluation of fine aggregates

Figure 4 shows the expansion behavior of concrete prisms containing aggregate N in the MPCT test, indicating the very-high reactive nature of the fine aggregate. As shown in Figure 4 and Table 3, the N aggregate is also characterized as a highly reactive aggregate in AMBT and CPT tests.

Figure 5 shows the expansion behavior of concrete prisms containing moderately reactive fine aggregates in the MCPT method. As shown in Figure 5, the 56-day expansion values of the all aggregates in this figure were between 0.04% and 0.12%. The highest and lowest 56-day expansion values were for concrete prisms containing P and M aggregates with 0.115% and 0.046%, respectively. Aggregates M, O, and P are considered as moderately reactive in MCPT test and reactive in the CPT test, while A, B, D, F, G, H, I and J are considered as moderately reactive aggregates in MCPT test but non-reactive in the CPT test. Also, A, F, H, I, O, M and P are considered as moderately reactive in MCPT tests and reactive in AMBT tests, while B, D, G and J are characterized as moderately reactive in the MCPT test but non-reactive in AMBT tests. Among all the moderately reactive fine aggregates tested in this study, the M, O and P aggregates, which have chert, were characterized as reactive aggregate in all test methods.

Figure 6 shows the ASR expansion behavior of the non-reactive fine aggregates. As shown in Figure 6 and Table 3, all of these aggregates were characterized as non-reactive aggregates in AMBT, MCPT and CPT tests. Although the 56-day expansion values of C, K and L were between 0.030% and 0.040%, their two-week average rates of expansion were less than 0.01%. Therefore, these aggregates are characterized as non-reactive.

Results from evaluation of the reactivity of fine aggregates suggested that among all the fine aggregates tested in this study, the best correlation between all the various test methods (AMBT, CPT and MCPT) was observed within the slow/low reactive aggregates. Also, better correlation was observed between the AMBT and the MCPT results, when the moderately reactive aggregate was used.

3.3 Correlation of MCPT data with CPT data

Figure 7a and Figure 7b show the correlation between the 56-day MCPT expansion results with 1-year CPT expansion results for coarse and fine aggregates, respectively. In these Figures, four zones – I, II, III and IV are identified, wherein zones I and III represent conformity of aggregate reactivity as characterized in the MCPT, CPT and AMBT methods. Zones II and IV represent non-conformity of aggregate reactivity between the three test methods.

As shown in Figure 7a, the 56-day MCPT expansion values of concrete prisms containing low/slow, moderate and high/very-highly reactive aggregates correlate well with the 1-year CPT expansion values, as indicated by the presence of the vast majority of data points in zones I and III. As shown in Figure 7b, the CPT and MCPT results of non-reactive fine aggregates showed good correlation. However, several aggregates that were characterized as moderately reactive in the MPCT method (A, B, D, F, G, H, I and J) were characterized as non-reactive in the CPT method, as indicated by the data points shown in zone IV of Figure 7b. Also, several of the aggregates that were characterized as reactive in both MCPT and CPT method showed substantially different levels of expansions (M, O and P) in the concrete prisms in the two tests.

The reason for the poor correlation of aggregate reactivity as characterized in the MCPT and CPT methods for certain fine aggregates may be related to the sensitivity of the rate of reactivity of fine aggregates to higher temperature and the ready availability of alkalis from the pore solution as well as the soak solution due to the higher surface area of the aggregate, as well as the ready availability of alkalis from the surroundings (i.e., pore solution and soak solution). Also, Figures 7a and 7b suggest that a vast majority of the expansion values are greater in the MCPT method than in the CPT method. Higher test temperatures along with a more sustained presence of high alkali level in the pore solution MCPT test specimens may enhance the rate of alkali-silica reaction in the aggregate and cause greater expansion in concrete compared to test specimens subjected to CPT method, wherein alkali leaching may have a significant negative effect in reducing the severity of ASR and hence expansion of test specimens.

3.4 Correlation of MCPT data with AMBT data

Figure 8a and Figure 8b show the correlation between the 56-day MCPT expansion results with 14-day AMBT expansion results for coarse and fine aggregates, respectively. As shown in Figure 8a, it is evident that for coarse aggregates, a poor correlation exists between the MCPT results and the AMBT results. However, for fine aggregates, a better correlation was observed between the MCPT results and the AMBT results. It is likely that the similarity of the performance of test specimens containing fine aggregates in the MCPT and the AMBT is due to the fact that the reacting component of the concrete in both tests is the mortar, with similarly sized aggregate particles and the similarity in the access to level of alkalis from the soak solution in both specimens and absence of any leaching of alkalis from test specimens in both methods.

4 CONCLUSION

This study presented the test results from evaluation of the alkali-silica reactivity of 42 aggregates (coarse and fine aggregates) of widely different mineralogy using MCPT, CPT and AMBT test methods, and compared the reactivity of the aggregates as characterized by these three test methods. Among the 42 aggregates evaluated in this study, 30 aggregates were selected that showed a marginal level of reactivity as indicated by the AMBT method, i.e., 14-day expansion of mortar bars is between 0.10% and 0.20%. The 56-day expansion values from MCPT method were correlated with 1-year expansion values from CPT method and the 14-day expansion values from AMBT method.

Based on the results of this study, it can be concluded that MCPT and CPT methods showed a much better correlation in characterizing the coarse aggregate reactivity, regardless of the level of reactivity of the aggregate. However, the MCPT and AMBT methods showed a better correlation when characterizing the fine aggregate reactivity. While CPT characterized all of the fine aggregates as non-reactive, the MPCT method was more discriminating in its assessment. Based on the findings from this study, it can be concluded that the MPCT method provides equally reliable aggregate reactivity characterization as the CPT method, in a much shorter duration of 56 days instead of the 1-year test duration that is needed in the CPT method, particularly for assessing the coarse aggregate reactivity. Additional work is needed to discern the influence of alkali leaching in CPT on the assessment of fine aggregate reactivity.

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TABLE 1: Chemical compositions of portland cement used in this study.

Chemical composition (%)	High-alkali cement
SiO_2	19.45
Al_2O_3	4.85
Fe_2O_3	3.79
CaO	61.37
MgO	2.92
Na_2O_{eq}	0.88

TABLE 2: Properties and expansion values of coarse aggregate used in this study.

No.	Aggregates	Specific Gravity	Abs (%)	CPT-365 days	AMBT-14 days	MCPT-56 days	Aggregate Lithology	Reactivity*
1	AA	2.83	0.40	0.049	0.08	0.056	Dolomite	Moderate Reactive
2	BB	2.64	0.90	0.028	0.06	0.007	Serpentine	Non Reactive
3	CC	2.93	0.77	0.023	0.06	0.020	Diabase	Non Reactive
4	DD	2.70	0.85	0.024	0.15	0.018	Argillite	Non Reactive
5	EE	2.69	0.65	0.036	0.07	0.049	Limestone	Moderate Reactive
6	FF	2.99	0.57	0.026	0.05	0.027	Diabase	Non Reactive
7	GG	2.69	0.87	0.047	0.15	0.061	Gneiss	Moderate Reactive
8	HH	2.67	1.88	0.021	0.01	0.001	Dolomite	Non Reactive
9	II	2.81	0.52	0.033	0.11	0.042	Dolomite	Moderate Reactive
10	JJ	2.69	0.87	0.046	0.07	0.055	Limestone	Moderate Reactive
11	KK	2.69	0.87	0.033	0.12	0.083	Argillite	Moderate Reactive
12	LL	2.73	0.27	0.065	0.05	0.054	Limestone	Moderate Reactive
13	MM	2.70	0.87	0.054	0.09	0.058	Limestone	Moderate Reactive

No.	Aggregates	Specific Gravity	Abs (%)	CPT-365 days	AMBT-14 days	MCPT-56 days	Aggregate Lithology	Reactivity*
14	NN	2.78	0.34	0.074	0.16	0.081	Gneiss	Moderate Reactive
15	OO	2.79	0.40	0.025	0.01	0.004	Marble	Non Reactive
16	PP	2.77	0.87	0.027	0.09	0.043	Schist	Moderate Reactive
17	QQ	2.63	0.77	0.041	0.02	0.046	Argillite	Moderate Reactive
18	RR	2.72	0.70	0.033	0.03	0.040	Argillite	Non Reactive
19	SS	2.69	0.46	0.181	0.35	0.149	Limestone	High Reactive
20	TT	2.51	0.42	0.109	0.22	0.097	Quartzite	Moderate Reactive
21	UU	2.60	1.09	0.251	0.90	0.185	Rhyolite	High Reactive
22	VV	2.75	0.34	0.192	0.53	0.149	Argillite	High Reactive
23	WW	2.71	0.72	0.032	0.04	0.018	Dolomite	Non Reactive
24	XX	2.75	0.92	0.070	0.08	0.070	Limestone	Moderate Reactive
25	YY	2.64	1.03	0.030	0.19	0.039	Alluvial Gravel	Slow/Low Reactive
26	ZZ	2.67	0.62	0.030	0.10	0.023	Granite	Non Reactive

*Reactivity based on the AASHTO TP 110 Method (MCPT)

TABLE 3: Properties and expansion values of fine aggregate used in this study.

No.	Aggregates	Specific Gravity	Abs (%)	CPT-365 days	AMBT-14 days	MCPT-56 days	Aggregate lithology	Reactivity*
1	A	2.64	0.21	0.026	0.14	0.086	Quartz	Moderate Reactive
2	B	2.63	0.28	0.021	0.1	0.048	Quartz	Moderate Reactive
3	C	2.65	0.32	0.026	0.05	0.032	Quartz	Non Reactive
4	D	2.65	0.40	0.028	0.08	0.051	Quartz	Moderate Reactive
5	E	2.63	0.28	0.02	0.07	0.026	Quartz	Non Reactive
6	F	2.61	1.21	0.021	0.12	0.051	Gravel	Moderate Reactive
7	G	2.64	0.23	0.022	0.09	0.047	Quartz	Moderate Reactive
8	H	2.69	0.72	0.016	0.24	0.099	Gravel	Moderate Reactive
9	I	2.64	0.18	0.025	0.12	0.094	Quartz	Moderate Reactive
10	J	2.63	0.27	0.022	0.1	0.059	Quartz+Chert	Moderate Reactive
11	K	2.64	0.28	0.019	0.07	0.032	Quartz	Non Reactive
12	L	2.64	0.37	0.017	0.07	0.036	Quartz	Non Reactive
13	M	2.65	0.52	0.050	0.24	0.046	Chert	Moderate Reactive
14	N	2.58	1.50	0.590	0.64	0.435	Chert/Volcanic	Very Highly Reactive
15	O			0.090	0.26	0.091	Chert	Moderate Reactive
16	P			0.150	0.46	0.115	Chert	Moderate Reactive

*Reactivity based on the AASHTO TP 110 (MCPT)

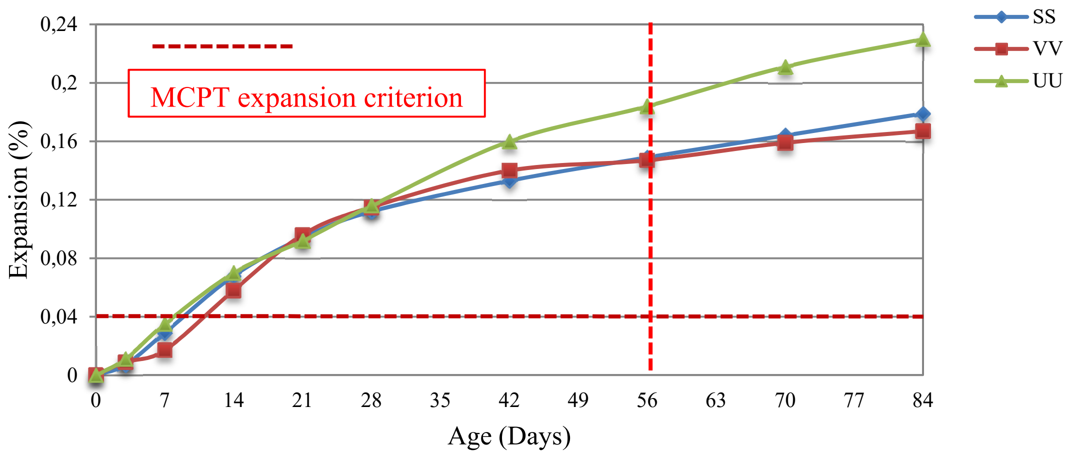


FIGURE 1: Expansion behavior of the high/very highly reactive coarse aggregates (MCPT).

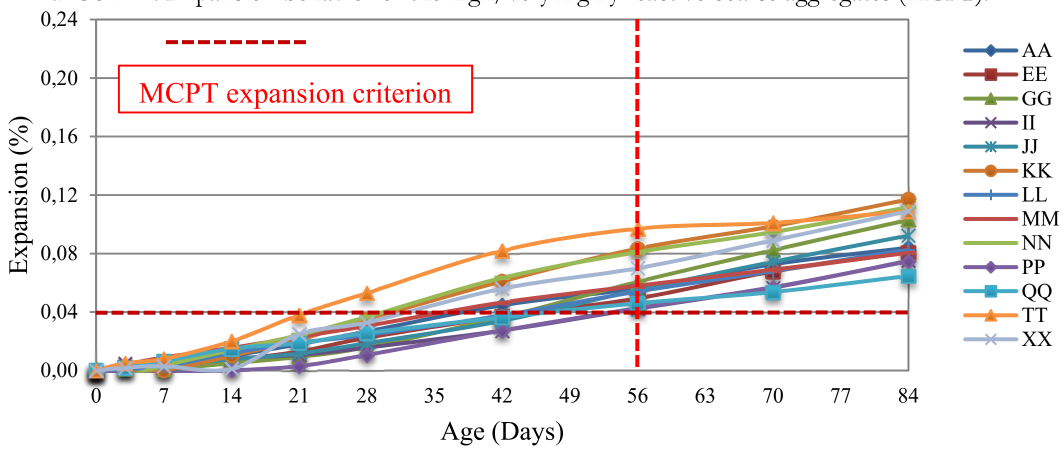


FIGURE 2: Expansion behavior of the moderately reactive coarse aggregates (MCPT).

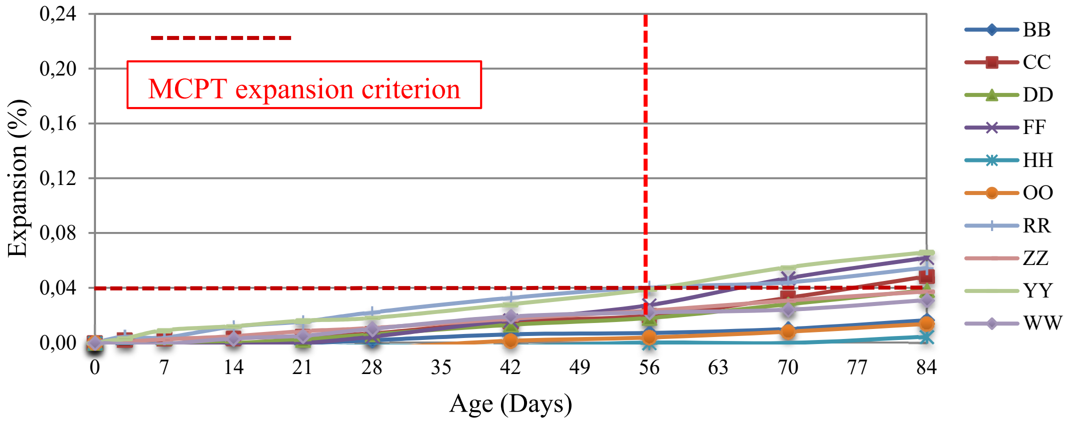


FIGURE 3: Expansion behavior of the slow/low reactive and non-reactive coarse aggregates (MCPT).

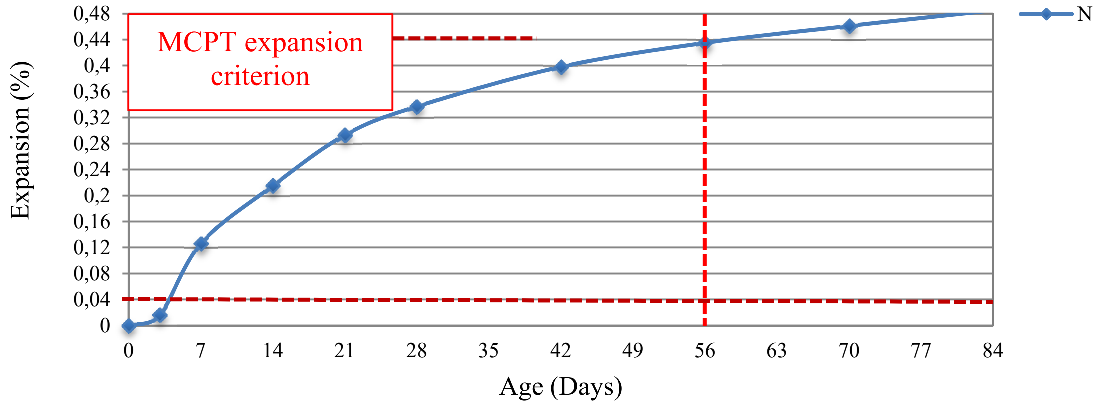


FIGURE 4: Expansion behavior of the high/very highly reactive fine aggregates (MCPT).

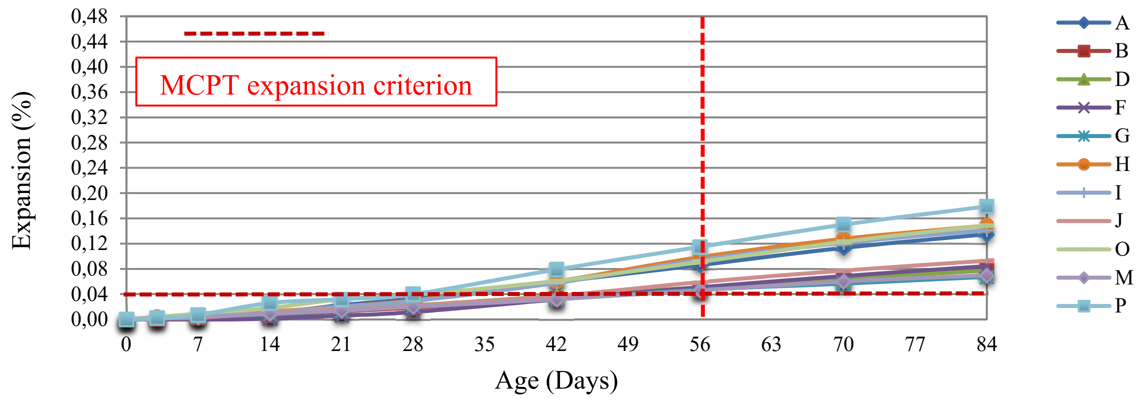


FIGURE 5: Expansion behavior of the moderately reactive fine aggregates (MCPT).

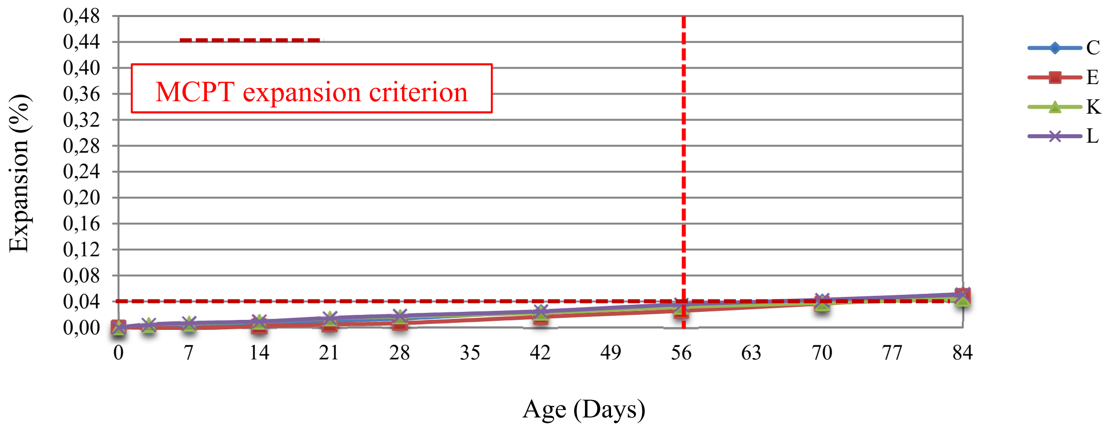
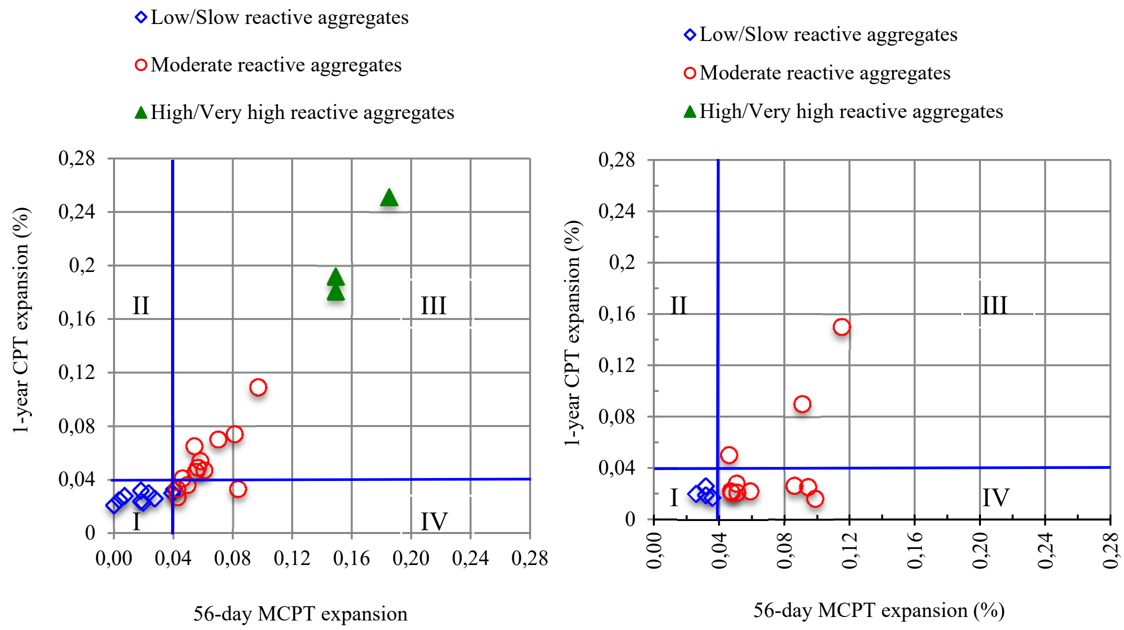


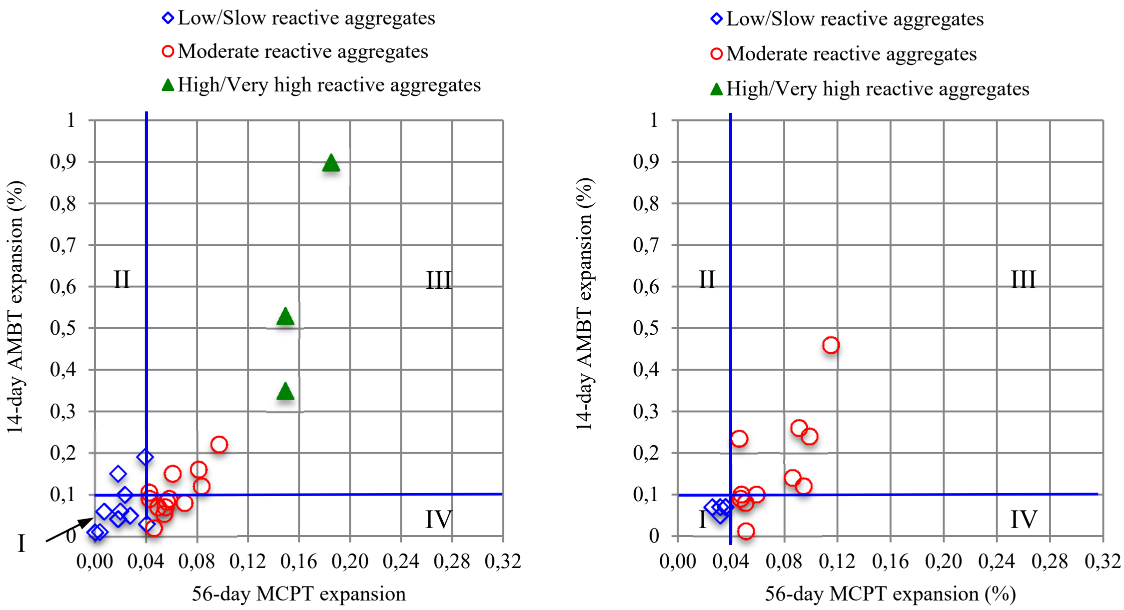
FIGURE 6: Expansion behavior of the non-reactive fine aggregates (MCPT).



a) Coarse aggregates b) Fine aggregates

FIGURE 7: Correlation between CPT and MCPT results: a) Coarse aggregates; b) Fine aggregates.

Note: Triangle, Circle and Rhombus-shaped symbols identify highly-reactive, moderately reactive and non-reactive aggregates, based on the MCPT method



a) Coarse aggregates b) Fine aggregates

FIGURE 8: Correlation between AMBT and MCPT results: a) Coarse aggregates; b) Fine aggregates.

Note: Triangle, Circle and Rhombus-shaped symbols identify highly-reactive, moderately reactive and non-reactive aggregates based on the MCPT method