EVALUATING COMBINATION OF AGGREGATES IN THE ACCELERATED MORTAR BAR TEST

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Abstract

The accelerated mortar bar test (AMBT) or ASTM C 1260 is one of the most common test methods for determining the potential for aggregate reactivity due to alkali-silica reaction (ASR). In this test method coarse and fine aggregates are tested separately to determine their reactivity. The AMBT is widely favored due to its rapidity (results in 16 days from time of casting). As a result this has led to many "non-standard" variations of the test. Over the past few years in North America, one of the modifications seeing use and acceptance by certain agencies is to test combinations of aggregates that reflect actual aggregates proposed for a concrete mixture design. The results presented herein demonstrate that this is dangerous approach to follow without proper bench-marking to actual concrete tests, outdoor exposure and long-term field experience. The combination of fine and coarse aggregates (both tested as a fine fraction) in the AMBT produces results that may not properly evaluate the potential reactivity of a concrete mixture.

Keywords: reactive aggregate, accelerated mortar bar test, test methods, combinations of aggregates, pessimum effect

1 INTRODUCTION

The accelerated mortar bar test (AMBT) is often considered to be a harsh test that tends to fail aggregates that would usually perform well in the field. However, due to its short duration, it has become one of the most popular test procedures for determining the potential for alkali-silica reactivity. It only takes 16 days to determine the reactivity of an aggregate compared to 1 year with the concrete prism test (CPT) and even longer for exposure block testing or field performance. While the AMBT was created to determine the reactivity of single aggregate, within the past few years the test method has been changed by some to encourage the use of evaluating "job" or actual concrete mixtures within the test method. Certain agencies have been specifying the use of the AMBT to determine if a concrete mixture would be reactive by using a mixture design that would be similar to that used in the field to be used in the AMBT. The modification to the standard involves testing both the coarse (crushed to a fine gradation) and the fine aggregate, graded to meet the AMBT requirements, combined together in the mortar bars. Aggregates are tested then at a relative ratio of their mass fraction that would be used in the actual concrete mixture.

It is well known that certain types of aggregates, especially the ones that contain rapidly reactive forms of silica (chert, opal, flint, among others), exhibit a 'pessimum' behavior with respect to the alkali-silica reaction in concrete. With these types of aggregates, expansion increases with increasing content of the

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reactive aggregate up to a certain point, which has been referred to as the 'pessimum' proportion. For aggregate contents greater than the 'pessimum', expansion decreases with increasing amounts of reactive silica. Over the years, several researchers have tried to obtain the 'pessimum' curve (expansion vs. quantity of reactive constituent) in the laboratory by combining known amounts of highly reactive forms of silica with innocuous aggregates.

Most of the research that was found on this subject used accelerated test methods to obtain the 'pessimum' curve. In a review paper on ASR, Fournier and Bérubé (2000) reported maximum expansion for mortar bars (ASTM C1260 test procedure) was obtained when incorporating 10% leached chert. Similar results were obtained when combining opal with non-reactive basalt by Shayan (1992) and combining chert with non-reactive aggregate by Hudec (1990). Bektas et al. (2004 and 2006) used the AMBT test method to test different combinations of chert and non-reactive limestone; the 'pessimum' expansion was found to be between 5% and 15%; the results were confirmed by measuring ultrasonic velocity and performing petrographic analyses of the cracked mortar bars. However, other investigations have not been able to detect the 'pessimum' behavior using accelerated test regimes. Larbi and Visser (2002) tried varying the percentage of chert up to 12.5%, but no clear 'pessimum' was observed in the AMBT. Grattan-Bellew et al. (2004) were unable to observe the 'pessimum' behavior of chert using the concrete microbar test.

After an extensive literature review, only a couple of investigations were found where a 'pessimum' behavior was detected using a non-accelerated test. The test used had similar conditions to those of ASTM C1293 (concrete prisms stored at 38°C and 100% relative humidity for 8 months). For a given alkali content, concretes containing fine and coarse reactive siliceous limestone aggregates expanded less than concretes made with reactive fine aggregates and non-reactive coarse aggregates (Garcia-Diaz et al., 2010). Thames Valley River gravel in the UK is another aggregate that shows the pessimum occurring in non-accelerated tests (Thomas et al, 1996). Roy and Morrison (2000) found similar behavior of decreased expansion with a combination of a coarse and fine aggregates from the same source versus the coarse with a non-reactive fine, or the fine aggregate with a non-reactive coarse aggregate.

This paper provides results of 10 reactive aggregates combined with either a non-reactive aggregate or with other reactive aggregates (based on accelerated and long-term performance at the author's laboratories) to provide initial results for testing combinations of reactive and reactive/non-reactive aggregate blends. Where possible the results were compared to the performance in longer-term testing (e.g. concrete prism testing, outdoor exposure block testing).

2 MATERIALS AND METHODS

2.1 General

A total of 15 aggregate sources with varying reactivity levels were chosen from across North America for this study. Nine of the aggregates were coarse aggregates and 6 of the aggregates were fine aggregates. Table 1 shows the list of aggregates along with a designation "C" for coarse aggregates and "F" for fine aggregates. Ordinary ASTM C150 Type I high alkali cements were chosen for all AMBT testing. A variety of aggregate reactivity was chosen to provide a broad range of results. Aggregate reactivity was chosen based on both prior AMBT and CPT testing. Aggregates C8, F2, F3, and F5 are all considered to be non-reactive and were used in the majority of the replacements.

2.2 Methods for assessment and analysis

2.2.1 ASTM C1260 Expansion Testing Accelerated mortar bar testing (AMBT) followed ASTM C 1260. A detailed explanation of the test method can be found in the standard. Overall, fine aggregates were sieved and washed to meet gradation specifications found in the standard. Coarse aggregates were crushed, sieved, and washed to meet the same gradation specification. Five different sieve sizes were used in the test method , 10% retained on a 2.36mm sieve, 25% retained on a 1.18mm sieve, 25% retained on a 600μm, 25% retained on 300μm, and 15% retained on 150μm). These aggregates were mixed at a 0.47 w/cm and a fixed sand/cement of 2.25. The test involves casting 25 x 25 x 285mm mortar prisms followed by wet curing the prisms in their molds for 24 hours. The prisms are then immersed in tap water at 80 °C for 24 hours prior to initial measurement and subsequent storage at 80 °C in 1 N NaOH. Length change measurements were made periodically at 80 °C throughout the testing duration. A value of less than or equal to 0.10% at 14 days for mortar bar was used to indicate aggregate considered to be innocuous. Mortar bars containing aggregates which expanded over 0.10% were considered to be potentially reactive.

In order to determine the reactivity of mixtures resembling concrete mixture designs, combinations of aggregates at various ratios were investigated. The majority of testing involved replacement of 30 and 40% of reactive aggregate with a non-reactive aggregate. The amount replaced was replaced from each sieve size outlined above. This was the only modification to the test method, which is similar to what agencies are doing to test the potential reactivity of concrete mixture designs in the AMBT. Table 2 provides the mixtures tested in the study. In a limited number of tests, reactive aggregates were mixed with different reactive aggregates to determine the impact on behavior, specifically a pessimum proportion.

2.2.2 ASTM C1293 Testing

Concrete prism testing (CPT) was followed according to ASTM C1293. A detailed explanation of the test method can be found in the standard. In this test the coarse and fine aggregates are tested separately to determine their reactivity. In order to determine the reactivity of a coarse aggregate, the coarse aggregates were sieved to acquire three fractions, 33% by mass retained on 12.5mm, 33% by mass retained on 9.5 mm, and 33% by mass retained to 4.75mm sieve. This coarse aggregate was tested along with a non-reactive fine aggregate to solely obtain the reactivity of the coarse aggregate. In order to determine the reactivity of fine aggregates, it was tested in combination with a non-reactive coarse aggregate. A high alkali cement was required, to which sodium hydroxide was added to obtain a sodium equivalent (Na2Oeq) of 1.25%. A cement content of 425 kg/m^3 and was mixed at a 0.42 w/cm. The concrete was cast into four 75 X 75 X 285mm prisms and cured for 24 hours. The prisms were then demolded and initial length measurements were taken. Length measurements were periodically taken during the test duration. A value of less than or equal to 0.040% at 1 year considers the aggregate to be non-reactive. Expansion values greater than 0.040% were considered the aggregate to be reactive.

2.2.3 ASTM C289 Testing

Aggregates were tested according to ASTM C289 to determine the amount of available silica contributed from the aggregates. Fine aggregates were sieved to obtain sand particles on the #100 sieve (i.e. 150 to 300 μm in size), and coarse aggregates were crushed and sieved to obtain enough material collected on the same sieve size. The aggregate was then washed and allowed to dry. Ten gram samples were placed into enclosed reactive chambers along with 25ml of 1 N NaOH and placed in a waterbath at 80 °C for 24 hours. The chambers were then cooled with running tap water over the chambers for 15 minutes. The samples were then filtered and diluted where they were analysed by ICP to measure silica to calculate the amount of dissolved silica. The filtrate was also used to measure reduction in alkalinity.

3 Results

3.1 Aggregate Reactivity

Table 1 shows the ASTM C1260 expansion results at 14 days after immersion in 1N NaOH for the aggregates tested in this study. These results are shown for only single aggregate testing. For the AMBT expansions equal to or less than 0.10% are considered to be non-reactive and those above (shown in bold) are considered to be reactive. Four coarse aggregates are shown to be reactive and four coarse aggregates are shown to be non-reactive. Aggregate C2 provided the highest 14 day expansion of the coarse aggregates. Table 1 also provides ASTM C1293 expansion results. For the CPT, expansions equal to or less than 0.040% are considered to be non-reactive and those above (shown in bold) are considered to be reactive. Eight of the aggregates tested are above the 0.040%. Three of these aggregates (C1, C6, and C9) fail the CPT, but pass AMBT. Two of the three fine aggregates tested in the study were shown to be non-reactive, and the majority of the mixture designs used these two non-reactive aggregates as replacements for the other reactive aggregates studied.

3.2 Combined Aggregate Expansions

The mixture matrix, including the 14-day expansion values, showing the combination of aggregates evaluated in ASTM C1260, is shown in Table 2. Each mixture listed shows the percentage of each type of aggregate that was tested. The 100% of each aggregate (singular aggregate testing) is shown in Table 1, which is the standard AMBT. The values in bold show the mixtures which the failed the 0.10% expansion criteria.

Two of the four coarse aggregates (C2 and C3) that fail the AMBT at 14 days showed decreased expansion when replaced with F1 aggregate. In both cases, as more reactive coarse aggregate was replaced with the non-reactive fine aggregate F1, expansion was reduced. Figures 1 and 2 show this trend of reduced expansion with an increase in non-reactive materials. All three of these aggregates still do not fall below the 0.10% expansion criteria with 40% of the reactive aggregate removed. Figure 3 shows the behaviour of replacing a reactive aggregate with a non-reactive manufactured lightweight fine aggregate. The lightweight non-reactive aggregate decreased the expansion of the mixture when combined with a highly reactive fine aggregate. For these aggregates the overall trend that a reduction in expansion is seen as the reactive aggregate portion is replaced with increasing amounts of non-reactive aggregate.

Four coarse aggregates, (C4, C5, C6 and C9) all showed an increase in expansion as the non-reactive portion of the aggregate material was increased. In the standard AMBT test, C5 failed the test with an expansion of 0.12%. The removal of 40% of this aggregate and replacement with F1 aggregate increased the expansion to 0.19%. Aggregates C4, C6, and C9, which all passed the AMBT test with an expansion below 0.10%, showed an increase in expansion when replaced with non-reactive fine aggregate. Figures 4 and 5 show the increase in expansion. At a replacement of 50% of C4 aggregate, the mixture fails at 14 days, and the expansion increases as 75% of C4 is replaced with non-reactive sand. Figure 5 shows similar results for the C6 aggregate. At 40% replacement, the mixture passes the test, but at 50% and higher replacements the mixtures fail the AMBT. These aggregates all show a pessimum effect where a higher expansion is observed with less reactive material present. This may be due to the availability of reactive silica in these aggregates. Further testing was thus undertaken on a limited set of samples in the ASTM C 289 test to provide more information to understand this trend.

3.3 ASTM C289 Results

The results of the quick chemical test (ASTM C289) are shown in Table 1. These results provide information on the silica solubility for selected aggregates as part of this study. The values that are in bold suggest that the aggregate may be ASR susceptible according to the standard. The coarse aggregates (C1, C4, and C7) are considered to be non-reactive according to the test and coarse aggregates (C5, C6, and C9) are considered to be reactive.

4 DISCUSSION

4.1 Dilutional effects on mixtures

Overall, the mixing of aggregates in the AMBT test tends to change the level of expansion. In most cases, if a nonreactive aggregate replaced a known reactive aggregate, the mixture tended to decrease in expansion. This is likely a result of diluting the reactive aggregate fraction and thus lowering expansion. For three reactive aggregates (C2, C3 and C7), the use of a nonreactive aggregate as a replacement in the mixture decreased the expansion level. The reactive aggregates consisted of various mineralogies and were mixed with a non-reactive manufactured limestone. The level did not drop below the 0.1% expansion criteria, but did result in lower expansion values. The overall expansion of these aggregates in the standard AMBT are well above the 0.10% limit, which may suggest that there was not enough of the reactive material removed to reduce the expansions below the 0.10% criteria. Mixture 16 shows that the C7 aggregate falls below 0.10% at 14 days when 40% of that aggregate was replaced with non-reactive aggregate. Since this value fell below the 0.10% expansion criteria, an agency may use this mixture design in a concrete mixture since it passes the AMBT. In the concrete prism test, however, the C7 aggregate fails at an expansion value of 0.08% (twice the expansion limit). The CPT mixture design is similar to the mixture that passed the AMBT, in term's of relative aggregate fractions. This provides an example of how testing combined aggregates in the AMBT produces conflicting results with the more reliable concrete prism testing.

The use of a lightweight non-reactive aggregate (expanded shale) behaved similar to that of a natural non-reactive aggregate. Figure 3 shows the decrease in expansion of F4 as it is replaced with non-reactive lightweight aggregate (F5). This behaviour could be due to the reduction of reactive silica (dilution effect), but the use of lightweight aggregates could be beneficial to provide some accommodation for gel growth (in their high porosity) depending on time of gel growth. Other studies have shown a refinement of the interfacial transition zone in mixtures incorporating LWFA which may reduce permeability and help in turn to reduce the potential for deleterious ASR. Further studies are being conducted to determine the use of lightweight aggregates as mitigation techniques.

4.2 Pesimum Mixtures

Mixtures containing aggregates C4, C5, C6, and C9 all showed an increase in expansion when combined with a non-reactive aggregate. In all cases with these aggregates, the expansion increased when increasing amounts of non-reactive aggregate were combined into the mixture. Mixtures 11 and 12 shown in Table 2 show an increase in expansion for increasing replacement levels of a nonreactive aggregate in combination with C5. While in the standard CPT, C5 failed the test (0.09% expansion), use of a non-reactive aggregate in combination with this reactive aggregate further exacerbated expansion observed in the AMBT. This is likely indicative of a pessimum proportion for this aggregate. Even further concerning were the results with aggregates C4, C6, and C9. Figures 4 and 5 show the dramatic increase in expansion when higher amounts of non-reactive material were substitued in these mixture. These aggregates pass the AMBT, however the use of nonreactive material increased the expansion closer to the failure criteria of 0.10%. Increasing the replacement levels to 50 and 75% results in mixtures that fail the AMBT by surpassing 0.10%. Figures 4 and 5 show aggregates C4 and C6 surpassing the expansion level of 0.10%. The mineralogy of these aggregates are a mixture of quartz and chert. This may suggest that a pesimum effect occurred with these aggregates. Furthermore, these same aggregates fail the CPT, which suggests that the AMBT is not an adequate test method for testing these aggregates.. Interestingly, the quick chemical test shows the highest levels of soluble silica from these two aggregates. This may suggest that a pesimum effect occurred with these aggregates. Furthermore, these same aggregates fail the CPT, which suggests that the AMBT is not an adequate test method for testing these aggregates.

5 CONCLUSIONS

AMBT is a rapid test that is used to predict aggregate reactivity, and, in recent years, it has been modified to test mixtures that resemble concrete mixtures by substituting the reactive aggregate. This paper has shown combining aggregates in the AMBT can provide misleading results. This test method was developed to test a single aggregate, and testing a combination of aggregates further complicates the interpretation of the results. Depending on the nature of the reactive material/aggregate, dilution with non-reactive aggregate can result in pessimum effects with maximum expansion being observed at specific replacement levels. Further testing needs to occur that tests a wider range of reactive aggregates in combination with non-reactive and other reactive aggregates to understand how many other aggregates behave in this similar matter. Rather than using a non-reactive aggregate, future testing may include the use of an inert quartz filler. All of this work and future testing would need to be compared to exposure blocks to see how these AMBT mixtures would compare to actual concrete mixtures in outdoor environments.

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Table 1: Aggregate Properties

Aggregate ID	Mineralogy	ASTM C1260 (%)	ASTM C1293 (%)	Silica Solubility (mmol/L)	Reduction in Alkalinity
C1	Granitic gneiss, metarhyolite	0.07	**0.05**	12.3	17.5
C2	Rhyolite/Mixed Quartz	**0.34**	**0.16**	-	-
C3	**Limestone**	**0.17**	0.02	-	-
C4	Chert with Quartz and Limestone	0.04	0.00*	64.9	97.5
C5	Mixed Quartz/Chert	**0.12**	**0.09**	**74.6**	**46.3**
C6	Chert and Quartzite	0.04	**0.13**	**488.3**	**192.5**
C7	Mixtures of granodiorite and metadacite	**0.12**	**0.08**	16.7	15.0
C8	Limestone	0.02	0.00	-	-
C9	Mixed Quartz and Chert	0.03	**0.11**	**562.9**	**205**
F1	limestone	0.02	0.00	-	-
F2	Manufactured Limestone	0.03	0.00	-	-
F3	Mixed Quartz and Chert	**0.29**	**0.21**	-	-
F4	**Silicious**	**0.66**	-	-	-
F5	Expanded Shale	0.04	-	-	-

***0.89 Na2Oeq**

Table 2: Mixture Matrix

Mix ID:	Aggregate	% of Mixture	Aggregate	% of Mixture	14 Day %
1	C1	70	F1	30	0.07
2	C1	60	F1	40	0.05
3	C2	70	F1	30	**0.27**
4	C2	60	F1	40	**0.26**
5	C3	70	F1	30	**0.12**

6	C3	60	F1	40	**0.11**
7	C4	70	F1	30	0.05
8	C4	60	F1	40	0.07
9	C4	50	F2	50	0.17
10	C4	30	F2	70	0.21
11	C5	70	F1	30	**0.16**
12	C5	60	F1	40	**0.19**
13	C6	70	F1	30	0.05
14	C6	60	F1	40	0.05
15	C7	70	F1	30	**0.10**
16	C7	60	F1	40	0.09
17	C1	70	F3	30	**0.18**
18	C1	60	F3	40	**0.23**
19	C4	70	F3	30	**0.24**
20	C4	60	F3	40	**0.27**
21	C8	70	F1	30	0.04
22	C8	60	F1	40	0.01
23	F4	75	F5	25	**0.52**
24	F4	50	F5	50	**0.26**
25	C6	50	F2	50	**0.12**
26	C6	25	F2	75	**0.23**
27	C9	50	F2	50	**0.11**
28	C9	25	F2	75	**0.20**

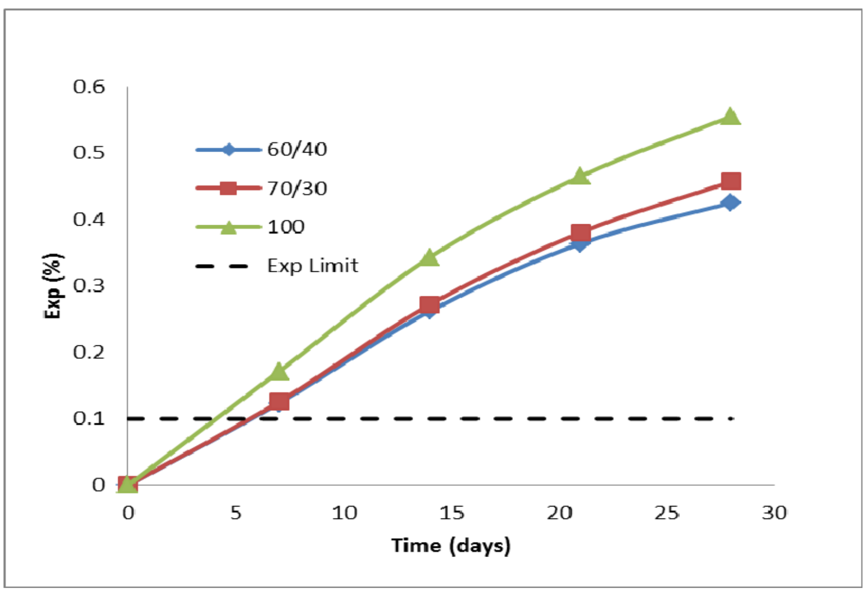

Figure 1: C2 aggregate replaced with 30 and 40% of non-reactive sand

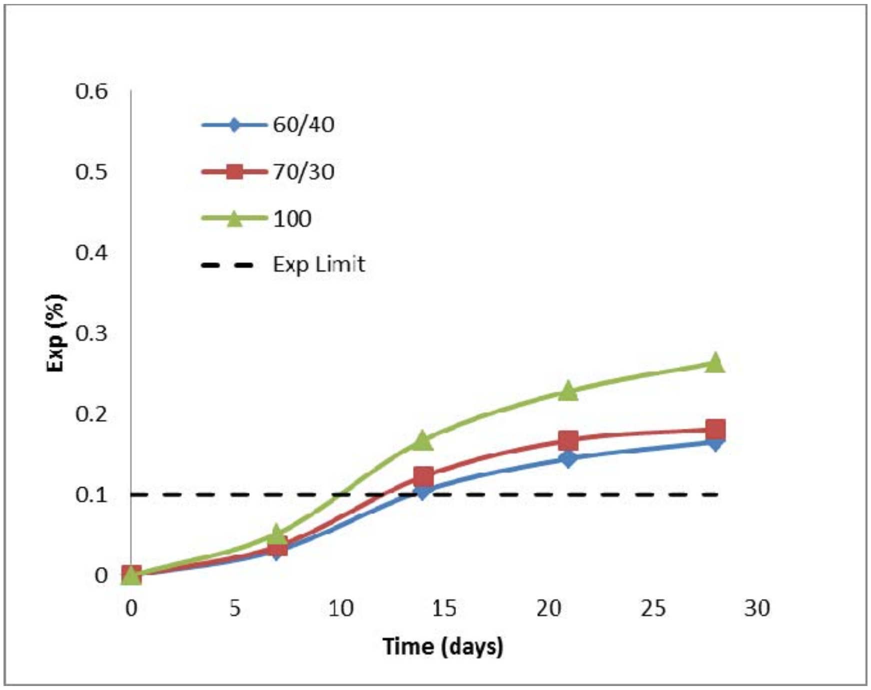

Figure 2: C3 aggregate replaced with 30 and 40% of non-reactive sand

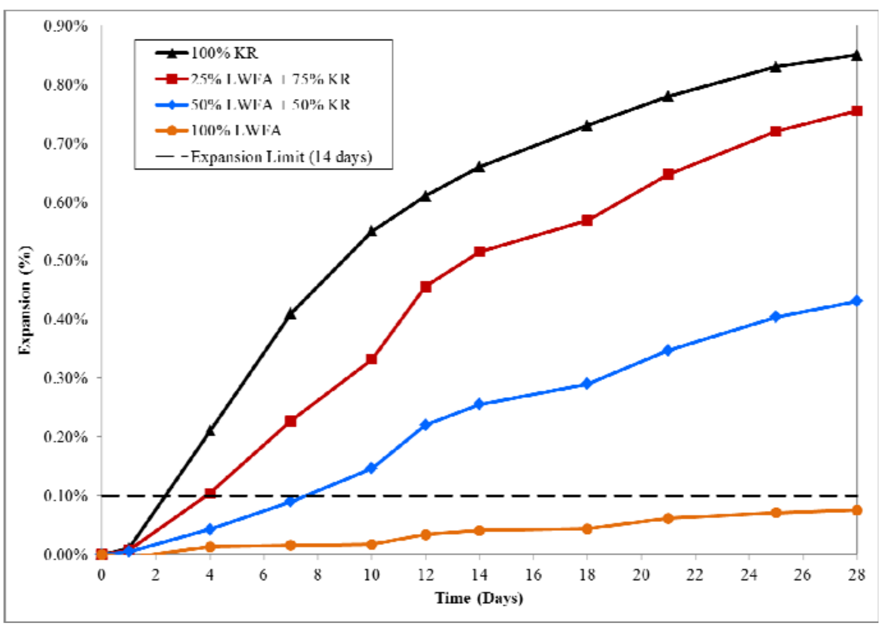

Figure 3: F4 aggregate replaced with non-reactive lightweight aggregate

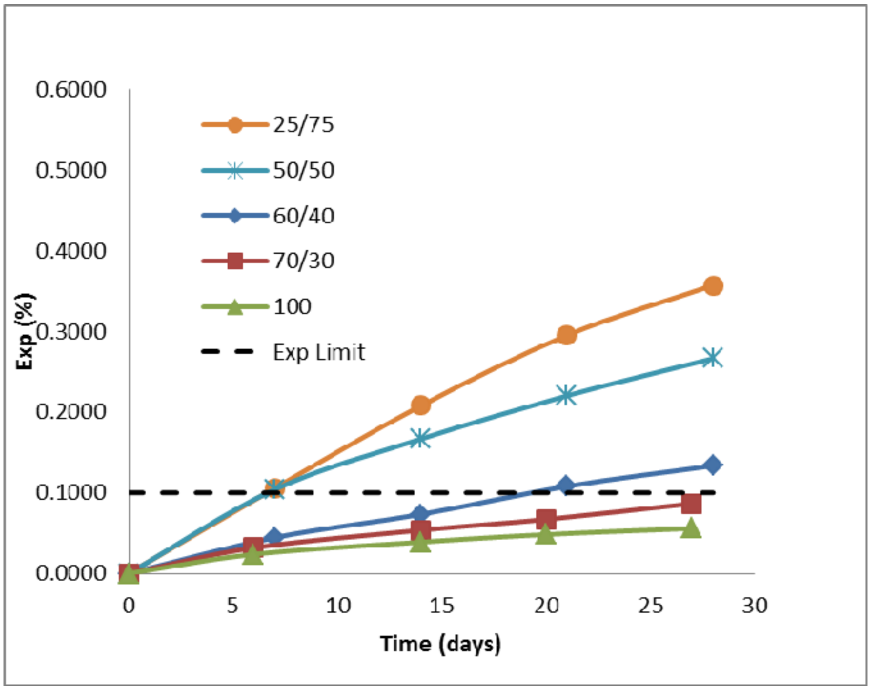

Figure 4: C4 aggregate replaced with different percentages of non-reactive sand

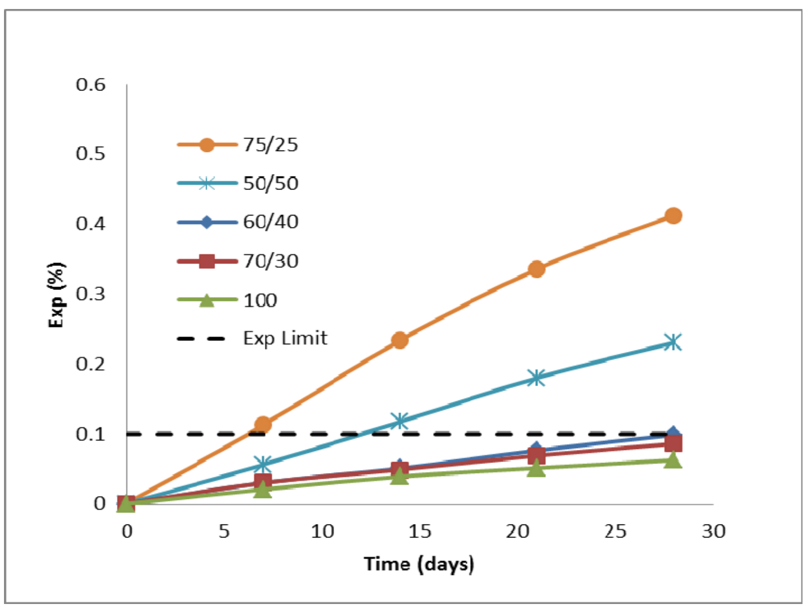

Figure 5: C6 aggregate replaced with different percentages of non-reactive sand