EFFECTIVENESS OF FLY ASH IN SUPPRESSING ASR EXPANSION IN THE UNIVERSAL ACCELERATED MORTAR-BAR TEST

Lu Duyou[1], Benoit Fournier[2], Paddy Grattan-Bellew[3], Xu Zhongzi[1],
Lu Yinong[1], Shen Xiaodong[1], Tang Mingshu[1],

[1] Nanjing University of Technology, Nanjing, 210009, China
[2] Laval University, QUEBEC, PQ, G1K 7P4, Canada
[3] National Research Council of Canada, OTTAWA, K1A 0E4, Canada

Abstract

The effectiveness of fly ash in suppressing ASR expansion in a newly proposed universal accelerated mortar-bar test (M-CAMBT) for both ASR and ACR was evaluated in comparison with results obtained in ASTM C1260, ASTM C1293 and long term field concrete blocks and slabs. Four kinds of alkali-silica reactive aggregates from the US and Canada, with various reactivity levels, three kinds of low calcium fly ashes were used in this study. Results show that for two moderate reactive aggregates and one highly reactive siliceious limestone, the new test generally gives the same outcome as those in other laboratory tests in term of the effectiveness of fly ash in controlling ASR expansion. For another highly reactive gravel aggregate composed of mixed acid volcanics, however, the M-CAMBT fails to give the real behaviour of fly ash in concrete. The incorporation of 20 and 30% of fly ash only slightly reduced or delayed the mortar bar expansion at early ages, while promoted their later age expansions, possibly by the formation of highly expansive ASR products.

KEYWORDS: concrete microbar test, fly ash, concrete prism test, accelerated mortar bar test.

1 INTRODUCTION

1.1 Accelerated test for evaluating the efficacy of SCMs in suppressing ASR

A quick evaluation of the long term efficacy of SCMs (Supplementary Cementitious Materials) is of paramount importance for the safe use of concrete incorporating alkali-silica reactive aggregates. Over the past decades, the Pyrex glass mortar bar test (ASTM C441) developed in 1940's has been widely used to assess the efficacy of SCMs in controlling ASR expansion. However, with the very highly reactive form of silica used, damaging expansion often takes place in the first few days in ASTM C441, which is usually faster than the pozzolanic reactions of fly ash and other SCMs. Furthermore, Pyrex glass contains a fair amount of soluble alkalis and is very sensitive to test conditions, whichraised concerns about the suitability/validity of such a quick test for judging the efficacy and determining the appropriate proportions of SCMs required to control deleterious expansion in concrete incorporating natural reactive aggregates in field conditions [1]. Based on extensive comparative field and laboratory studies [2-6], an accelerated test procedure, ASTM C1567 [7], which was developed from the accelerated mortar test (AMBT or ASTM C1260), was proposed to predict the long term efficacy of SCMs in controlling ASR expansion.

1.2 Development of accelerated test for ASR

As the most widely used accelerated test for alkali-silica reactivity of aggregates, ASTM C1260 possesses its limitations [8-12]. It fails to recognize the nonreactive character of several aggregates (based on field performance records), while failing to identify some other aggregates that were reactive in the concrete prism test (CPT) or in the field.

To try overcome the limitations in the AMBT, a universal accelerated test, which is modified from the Chinese Accelerated Mortar-Bar Test (M-CAMBT), was proposed for both alkali-silica and alkali-carbonate reactivity, based on extensive comparative study [13]. The main parameters in the M-CAMBT are as follows: 40mm*40mm*160mm bar size, 2.5-5.0mm single gradation of aggregate size, high alkali cement (0.9 ± 0.1% Na_2O) with cement-to-aggregate ratio of 1:1, storage and measuring procedures similar to those used in the ASTM C1260. For over 40 ASR aggregates from different countries, compared with AMBT, the results of the universal test generally show an improved correlation with those in the CPT using an expansion limit of 0.093% at 14 days; this suggests that the new method has a better predictive character of aggregate's reactivity levels in concrete. For alkali-carbonate reactive aggregates, the new method also gives the same outcome as using 5-10 mm particles based on the same criteria[13].

1.3 Scope of the paper

Fly ash is one of the most commonly used supplementary cementitious materials (SCMs) to control expansion due to alkali-silica reaction (ASR). Huge amounts of published data on the efficacy of fly ash and other SCMs against ASR refers to modified versions of the conventional laboratory testing methods for alkali-aggregate reactivity, such as mortar bar tests, AMBT and CPT. In order to evaluate the suitability of the newly proposed test in assessing the efficacy of SCMs in controlling ASR expansion, expansion results in the test with various fly ashes and aggregates were compared with published results in the AMBT, CPT, as well as concrete blocks and slabs exposed outdoors [14]. For easy reading and comparison purposes, the abbreviations of aggregates and fly ashes used in this paper are the same as those in published reference [14].

2 MATERIALS AND METHODS

2.1 Materials used

Table 1 gives the petrography and the physical properties of the four reactive coarse aggregates used in this study, i.e. two highly-reactive (Sp and NM) and two moderately (Su and Al) aggregates from Canada and the USA. A control high-alkali CSA Type 10 normal Portland cement from Canada was used, along with three ASTM Class F fly ashes from Canada (FA2, FA3) and the USA (FA5). The chemical composition of the above materials is given in Table 2.

2.2 Specimen preparation and testing

All the mixtures were made using the same proportioning, i.e. 900g of 2.5-5.0mm aggregates, 900g of cementitious materials and a fixed water-to-cementitious materials ratio of 0.32. Control mixtures were made with the high-alkali cement without fly ash. Fly ash mortars were made, where the ash was used at 20 and 30% replacement, by mass, of the high-alkali cement (Table 2). All mixtures were made without superplasticizer.

Three short-fat bars, 40 by 40 by 160-mm in size, were cast from each one of the mortar mixtures. After 24 hours in their moulds, the bars were demolded and placed in a plastic container filled with tap water at room temperature, and the containers placed in an oven at 80 ± 2°C for a period of 24 hours. The mortar bars were then measured (L0), and transferred to a plastic container filled with a 1N NaOH solution at 80°C. The containers were then returned to the oven at 80°C for a period of 28 days during which their length changes and the mass changes were monitored regularly. The expansion and the mass change results are the average of that obtained on three bars.

3. RESULTS AND DISCUSSION

3.1 Expansion in various laboratories and field testing

Table 3 summarizes the expansion data of the various types of specimens tested in this and previous studies [14], i.e.:

- 14-day expansion in the M-CAMBT (conventional for controls and modified to incorporate SCM);
- 14-day expansion in the accelerated mortar bar test (conventional for controls and modified ASTM C1260 to incorporate SCM – i.e. ASTM C 1567);
- 104-week expansion in the concrete prism test modified to allow incorporation of SCM (CSA A23.2-14A, A23.2-28A [15,16]);
- Six to ten-year expansion of concrete blocks and slabs exposed outdoors.
- Thirteen to fifteen-year expansion of concrete blocks and slabs exposed outdoors.

A previous study has shown that, for a broad range of aggregates with various reactivity levels, comparing the results from two-year CPT with added alkalis and six to ten-year concrete blocks made from companion mixtures without added alkalis, i.e. real-world conditions, could provide a fairly reliable assessment of the efficacy of supplementary cementing materials in controlling deleterious expansion in concrete due to AAR [14]. It should noted, however, that the correlation between the two-year CPT expansions and the concrete block expansions tends sometimes to decrease with time (i.e. from 7-10 to 13-15 years), because of the limited expansion in the CPT due to the leaching of alkalis during the test and because of the severity of the exposure in outdoor conditions (action of the freezing and thawing in cracked concrete).

Increasing the alkali content in the fly ash mixtures is recommended in the CPT [15], but it generally resulted in only a slight increase in concrete prism expansion for the combinations tested(Table 3); alkali additions did not result in any significant increase in concrete prism expansion with the moderately (Su, Al) and high reactive aggregates (Sp) selected, provided the proportion of fly ash in the mix was already important (Table 3).

On the other hand, the increase in the alkali content of the fly ash concrete mix does seem to result in increased expansions in the long term for some outdoor exposure specimens (see 30 versus 30+ fly ash mixes in Table 3 with the aggregate Sp, Su and Al). A reasonable time limit for correlation between CPT and field blocks, i.e. a time after which the field exposure data will no longer represent what we measure in the CPT in the laboratory, is currently being established.

Table 4 presents the diagnostic characteristics (Pass or Fail, in accordance with the limit criteria) of the different tools available in the laboratory (AMBT, CPT) and in the field (exposure blocks) for evaluating the efficacy of SCMs to control ASR expansion. For all tested aggregates, the use of 20 and 30% of the ASTM Class F fly ashes selected resulted in significant reduction of expansion compared to the control concretes. The use of 20% (and 30%) fly ash was sufficient to control the two-year concrete prism expansion of mixes incorporating the moderately-reactive aggregates Su and Al below the 0.04% expansion level (Tables 3 & 4); however, expansions > 0.04% were obtained for exposure blocks/slabs incorporating 20% fly ash FA2 (Su) and FA3 (Al) after 15-years.

In the case of the highly-reactive Sp aggregate, the use of 20% fly ash FA2 in the concrete mixtures resulted in block/slab expansions higher than 0.04%; unfortunately, no concrete prism expansion data (mix with added alkalis) are available for that mixture. The 30% fly ash concrete was found to pass the test (expansion < 0.040%) in laboratory (added alkalis) and field (no added alkalis) specimens (Tables 3 & 4).

The use of 20 and 30% fly ash FA5 was found to be insufficient to control deleterious expansion in concrete incorporating the highly reactive NM aggregate, both in laboratory and field exposure testing (Tables 3 & 4).

With the 0.10% expansion criteria at 14 day, the AMBT results are generally consistent with the two-year CPT, while some discrepancies are noticed with longer term (15 years) field exposure test data (Table 4).

3.2 Expansion in the M-CAMBT

Figure 1 shows the expansion curves of the four aggregates selected, with and without fly ashes, in the M-CAMBT. For the Sp, Su and Al aggregates, as expected, the use of 20 and 30% of the ASTM Class F fly ashes selected resulted in significant reduction of expansion compared to the control mixtures. Considering that for most reactive aggregates, the expansions values in the new test were between those obtained in the AMBT and the CPT, i.e. smaller than that in the AMBT but larger than that in the CPT, an expansion limit of 0.050% at 14 day is proposed for the new test. The use of 20% (and 30%) fly ash was sufficient to control the 14-day expansion of mortar bars incorporating the moderately-reactive aggregates Su, Al and the highly-reactive aggregates Sp below the 0.05% expansion level (Table 3).

Regarding the highly-reactive aggregates NM (Figure 1d), the use of 20% of fly ash FA5 only reduced slightly the expansion at early age (before 5 days); the mortar bar then expanded significantly more than the control over the rest of the testing period. When the fly ash content was increased to 30%, a delay in the mortar bar expansion was observed up to 3 days; the expansion of mortar bars then developed with a similar pattern to that of the 20% fly ash mix, resulting in a higher expansion than the control after 14 days. In the M-CAMBT, the use of 20 even 30% of fly ash FA5 is thus insufficient to control expansion of the NM gravel, which is consistent with the AMBT, two-year CPT and field tests data.

3.3 Mass change of mortar bars in the M-CAMBT

Figure 2 gives the mass change pattern of the test bars for the various aggregates in the M-CAMBT, with and without fly ash. The results show that the specimens started by uniformly gaining some weight during the first day of immersion in the alkaline solution, but the mass change pattern changed from one aggregate to another afterwards.

The weight of the control bars incorporating the siliceous limestone Sp (Figure 2a), increased rapidly during the first 3 days in the alkaline solution, then increased at a lower but steady rate throughout the rest of the testing period, reaching 0.7% of the initial weight (1 day in water at 80°C) after 21 days. The bars incorporating fly ash gained more weight than the control after 1 day of immersion in the alkaline solution, continued with a fairly sharp weight increase up to 5 days and then continued gaining weight at a similar rate as the control for the balance of the test. Generally speaking, the addition of fly ash has no obvious effect of the mass change pattern of the Sp aggregate in the M-CAMBT.

Similar to Sp, the addition of fly ash has no obvious effect on the weight change pattern of the Su aggregate over the testing period (Figure 2b).

However, for the Al and NM aggregates (Figures 2c and 2d), the addition of fly ash had a significant impact on the weight change pattern of the mortar bars. All mortar bars incorporating the Al aggregate showed a sharp increase in weight during the first 5 days. The weight of the fly ash bars then levelled off, while the control bars started to lose weight at a sharp and steady rate till the end of the testing period.

The mass change pattern of the mortar bars incorporating the NM aggregate, which gave extremely high expansion in the M-CAMBT, was different from that of the other aggregates The control bars increased in weight by about 0.4% by 1 day of immersion, remained stable up to 10 days and then suffered a slow mass reduction rate till the end of the testing period. On the other hand, the weight gain of the NM bars with fly ash was lower than that of the control bars after 1 day, but increased steadily throughout the rest of testing, reaching 1.01% for NM FA5 20 and 0.73% for NM FA5 30 after 21 days, which is much higher than the control (0.27% after 21 days). Compared to the bars incorporating the other aggregates, the NM bar with 20% fly ash had the highest weight gains throughout the testing period amongst all of the selected aggregates, with and without fly ashes.

Measuring the change in mass of the bars over the course of testing is helpful in interpreting the expansion behaviour of the aggregates. Since the mass gain of the bars with pure cement paste was found to stabilize at about 0.25% throughout the test (after picking up the weight during the first 3 days of immersion [13]), the various weight change patterns of the bars incorporating aggregates and fly ashes are mainly due to the nature and the reaction type of the aggregates and the fly ashes with alkalis in the bars and the solution. Since the rock type, the mineral compositions of the aggregates and the chemical composition of fly ashes selected for this study are significantly different and, considering that the reactions of minerals other than quartz in each of the aggregates, with the alkalis in the soak solution at 80°C, may also contribute to the mass change of the mortar bars, there is no direct comparative ground for evaluating the mass change patterns among these mortar bars with the different aggregates and fly ashes. However, comparing the above patterns may still provide some clues in interpreting the "abnormal" expansion behaviour, or orient further investigations.

For instance, the high expansions observed for the bars incorporating the NM aggregate when the fly ash FA5 was used was not uncommon. For some highly-reactive aggregates, such as opaline silica, especially Beltane opal, when the fly ash or slag content in the mortar bar was insufficient to control ASR expansion, larger expansions than that of the control specimens (without fly ash or slag) were also reported [1]. It may due to the formation of reaction/expansive products with suitable composition and viscosity to result in high expansive behaviors. The reactive components in the extremely-reactive NM gravel correspond to acidic mixed volcanic rocks. In the modified accelerated mortar bar test (M-CAMBT), the control bars showed a rapid weight gain during the first day (over 0.4%), suggesting the rapid reaction of the volcanic material in the NM gravel aggregate. With the progress of reaction and the expansion/cracking in the bar, the dissolution of the reactive siliceous particles results in the leaching of siliceous species and gel into the alkaline solution, thus inducing a progressive weight loss of the control specimens at later ages. On the other hand, bars incorporating 20 and 30% fly ash show a steadily increasing weight gain, reaching 0.73% and 1.01% after 21 d, respectively. The above behavior is possibly due to the formation of expansive reaction products with different (higher) viscosity than that produced in control bars, and thus less leached into the soak solution. A somewhat similar behavior was observed with the Alberta aggregate. The latter includes sandstones, quartzite and mixed volcanics as reactive materials, which also tend to dissolve and release gel in the soak solution, thus resulting in weight loss of the control bars. The bars incorporating the Al aggregate and the fly ash FA3 showed an increase in weight, which levelled off after about 3 days of immersion; the Alberta gravel is significantly less reactive than the NM aggregate and the fly ash FA3 was effective in controlling mortar bar expansions at low levels.

3.4 Efficacy of the M-CAMBT for evaluating the effectiveness of FA in controlling ASR expansion

Based on the comparative studies carried out on various tests to establish the effectiveness of fly ash in controlling expansion due to ASR, the newly proposed universal accelerated test, M-CAMBT, generally gives the same outcome as those in other laboratory tests in terms of the P/F diagnostic characteristics (Table 4), except for the Sp with 20% of FA2 (Sp FA2 20). With 20% of FA2, Sp gave a 0.040% 14-d expansion in the M-CAMBT, but a 0.103% 14-d expansion in AMBT (Table 3).

When considering the real expansion behaviour of mixtures with fly ashes, however, the M-CAMBT gave an abnormal expansion for the highly reactiveNM gravel incorporating mixed acid volcanics. The incorporation of 20 and 30% of fly ash only slightly reduced or delayed the mortar bar expansion at very early ages, but promoted larger expansions at later age, which does not mimic the real situation observed in concrete prisms, as well as in the other laboratory and field tests. Based on previous discussions regarding the mass change patterns of mortar bars (section 3.3), it is believed that the abnormal expansion of NM with FA5 is possibly due to the formation of highly expansive but less soluble (more viscous ?) ASR gels. Further petrographic work of the mortar bars under the scanning electron microscope will be necessary to support the above hypothesis.

4 CONCLUSION

For three of the four moderately and highly reactive aggregates used in this study, the newly proposed universal accelerated mortar-bar test (M-CAMBT) for both ASR and ACR, was generally effective in properly evaluating the effectiveness of fly ash in suppressing ASR expansion in comparison with results obtained in ASTM C1567, ASTM C1293 and long term field concrete blocks and slabs. It generally gives the same outcome as those in other laboratory tests. There is one exception, however, for one highly-reactive gravel aggregate composed of mixed acid volcanic. For the above NM aggregate, the M-CAMBT fails to mimic the real behaviour of fly ash in concrete. The incorporation of 20 and 30% of fly ash only slightly reduced or delayed the mortar bar expansion at early ages, while promoting their later age expansions. It is believed that the above behaviour is possibly related to the formation of highly expansive ASR products; however, further microstructural work is required to support the above hypothesis.

5 ACKNOWLEDGEMENTS

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Table 1: Reactive aggregates used in the study

Aggregate	Location	Rock Type	AMBT 14d exp,%	CPT 1-year exp,%	Reactivity level
Sp	Spratt, Ottawa (Canada)	Crushed siliceous limestone	0.391	0.184	High
Su	Sudbury (Canada)	Gravel (sandstone, quartzwacke, arkose, greywacke and argillite)	0.278	0.075	Moderate
Al	Calgary (Canada)	Gravel (sandstone, limestone, quartzite and mixed volcanics)	0.360	0.090	Moderate
NM	New Mexico (USA)	Gravel (mixed volcanics)	0.854	0.212	Very high

Table 2: Chemical analysis of the cements and SCM

Materials Characteristics	High-Alkali Cement	Fly Ash FA2	Fly Ash FA3	Fly Ash FA5
Chemical Analysis				
$SiO_2 + Al_2O_3 + Fe_2O_3$, %	28.9	89.8	80.0	83.6
Calcium oxide (CaO), %	62.39	2.39	9.07	7.45
Magnesium oxide (MgO), %	2.55	0.89	0.94	2.47
Sulphur oxide (SO_3), %	3.11	0.78	3.43	0.18
Loss on ignition, %	2.50	2.80	0.50	0.18
Total alkalis, (Na_2Oeq), %	0.90	1.73	5.44	3.20
Used with aggregate(s):	All	Sp, Su	Al	NM

Table 3 : Results of laboratory and field expansion testing for the selected aggregates. The alkali content in the mix corresponds to the alkalis provided by the cement and the NaOH, and excludes the alkalis in the fly ash.

Agg.	Concrete mix design	Alkali content in the mix, kg/m³	M-CAMBT Exp% at 14 days	AMBT Exp% at 14 days	CPT (38°C) Exp% at 2 years	Field exposure specimens **(A)** Exp % Blocks/slabs 7-10 years	Field exposure specimens **(B)** Exp % Blocks/slabs 13-15 years
Sp	Control	3.78	0.195	0.391	0.171	0.163/0.164	0.205/0.211
	FA2 20	3.02	0.040	0.103	0.019	0.025/0.053	0.062/0.110
	FA2 30	2.65	0.021	0.032	-0.001	0.014/0.017	0.015/0.018
	FA2 30+	3.68			0.005	0.016/0.025	0.036/0.065
Su	Control	3.78	0.136	0.278	0.100	0.104/0.102	---/0.159
	FA2 20	3.02	0.027	0.048	0.003	0.014/0.039	0.023/0.050
	FA2 20+	4.20			0.008	0.025/0.044	0.034/0.063
	FA2 30	2.65	0.023	0.021	-0.007	0.011/0.008	0.011/0.007
	FA2 30+	3.68			-0.007	0.009/0.017	0.016/0.024
Al	Control	3.78	0.153	0.360	0.032	0.091/0.119	0.150/0.130
	Control+	5.25			0.092	0.135/0.141	0.245/0.195
	FA3 20	3.02	0.044	0.037	0.007	0.012/0.032	0.051/0.087
	FA3 20+	4.20			0.016	0.016/0.048	0.059/0.105
	FA3 30	2.65	0.024	0.026	0.004	0.013/0.014	0.032/0.033
	FA3 30+	3.68			0.011	0.014/0.019	0.042/0.049
NM	Control	3.78	0.411	0.854	0.231	0.386/0.400	0.599/0.604
	FA5 20	3.02	0.519	0.395			
	FA5 20+	4.20			0.085	0.234/0.247	0.380/0.427
	FA5 30	2.65	0.376	0.088			
	FA5 30+	3.68			0.050	0.148/0.128	0.302/0.291

The expansion data for the concrete blocks exposed outdoors are given above for the following periods:

(A) Su aggregate: 10 years; Al aggregate: 9 years; Sp aggregate: 10 years; NM aggregate: 7 years

(B) Su aggregate: 15 years; Al aggregate: 15 years; Sp aggregate: 15 years; NM aggregate: 13 years

\+ concrete mixture with added alkalis; reagent grade NaOH was added to raise the total alkali content corresponding to the cement part of the system to 1.25% (Na_2Oeq).

Table 4: Diagnostic characteristics of the different tools in the laboratory (AMBT, CPT) and in the field (exposure blocks) for evaluating the efficacy of SCMs to control ASR expansion.

Agg.	Concrete mixture designs	M-CAMBT Exp% 14d	AMBT Exp% 14d	CPT, Exp% 38C 104w	Field Exp% Blocks/slabs 7-10 years	Field Exp% Blocks/slabs 13-15 years
Sp	Control	F	F	F	F	F
	FA2 20	P	F	---	P/F	F/F
	FA2 30	P	P	P	P/P	P/P
Su	Control	F	F	F	F/F	---/F
	FA2 20	P	P	P	P/P	P/F
	FA2 30	P	P	P	P/P	P/P
Al	Control	F	F	F	F/F	F/F
	FA3 20	P	P	P	P/P	F/F
	FA3 30	P	P	P	P/P	P/P
NM	Control	F	F	F	F/F	F/F
	FA5 20	F	F	F	F/F	F/F
	FA5 30	F	F	F	F/F	F/F

A B

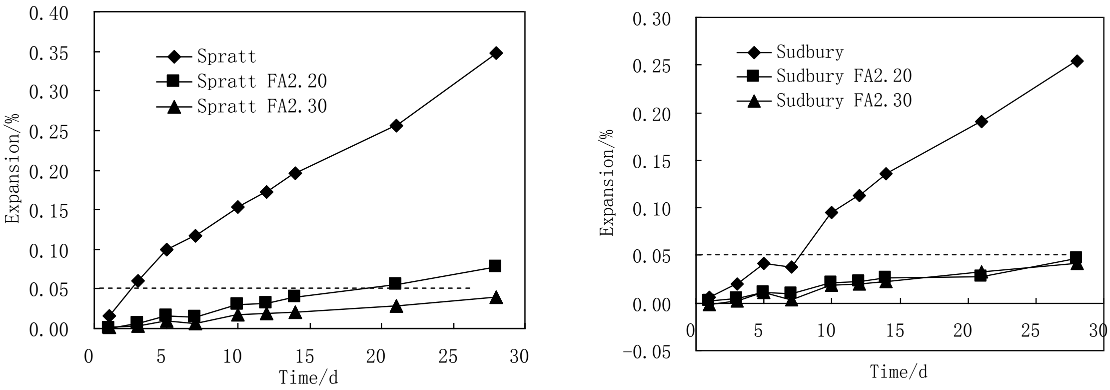

Figure 1 Expansion of aggregates in the M-CAMBT, with and without fly ashes

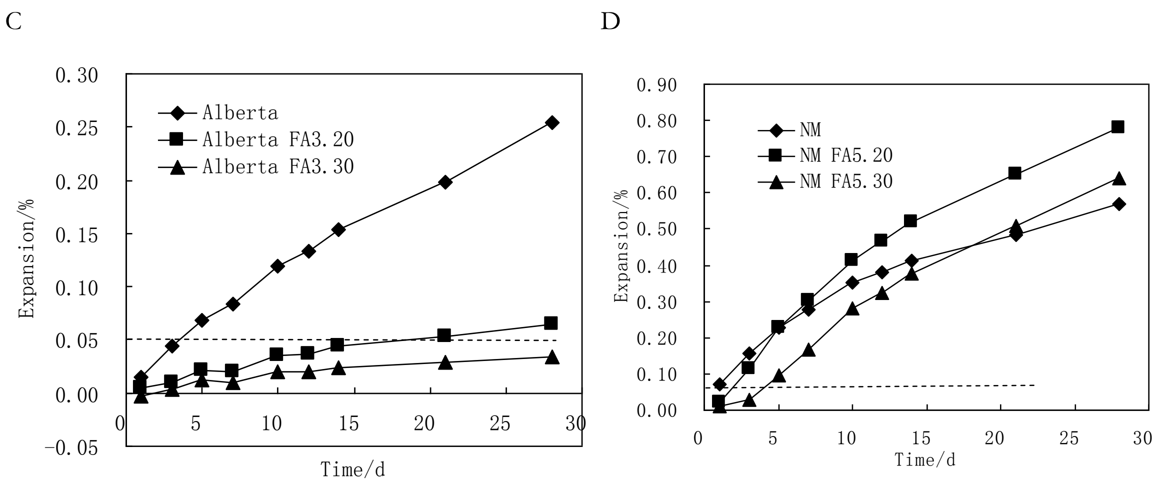

Figure 1 Expansion of aggregates in the M-CAMBT, with and without fly ashes

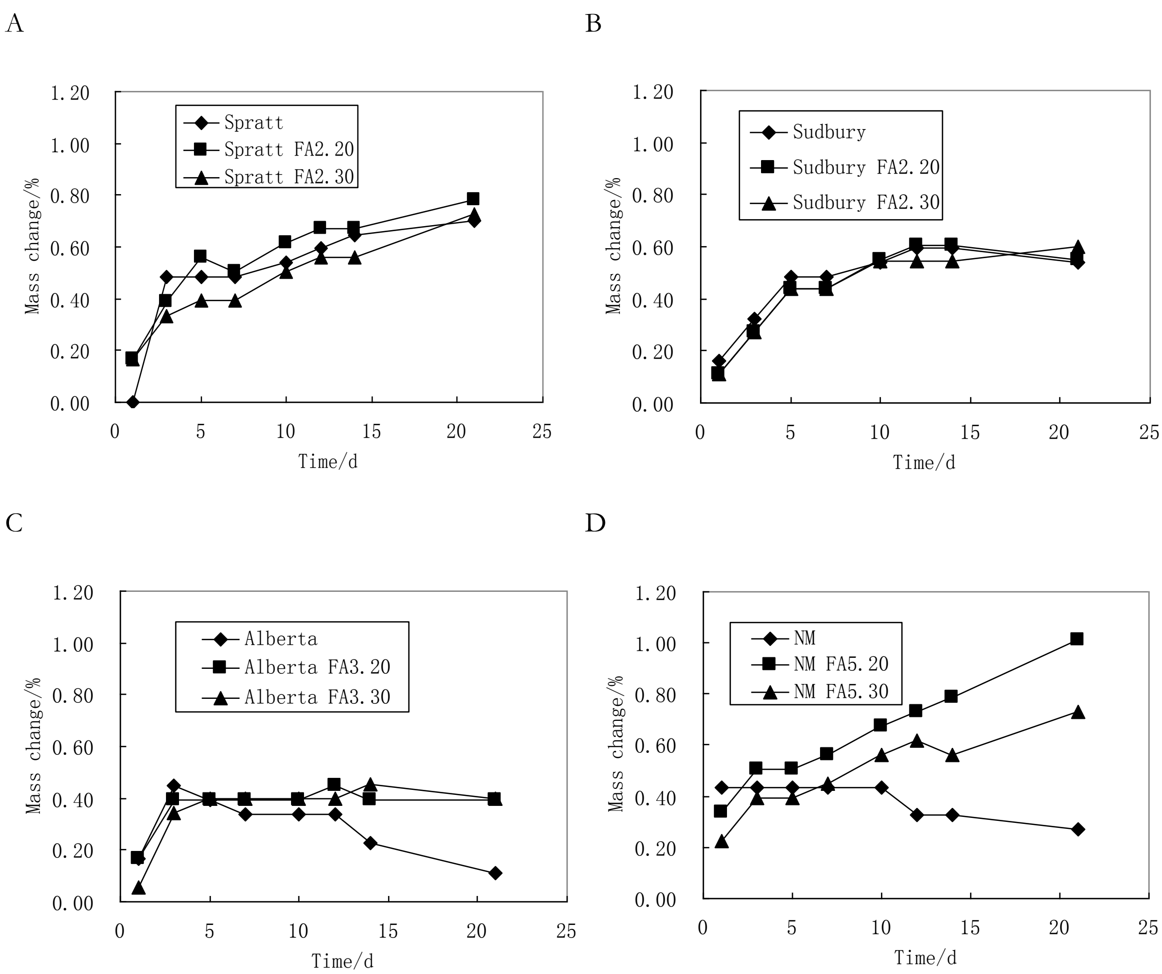

Figure 2 Mass change patterns of the bars in the M-CAMBT