ASSESSMENT OF EXPANSION LEVELS OF VARIOUS MIXTURES WITH MULTIPLE EXPOSURE CONDITIONS (CONSECUTIVE FREEZE-THAW AND ASR CYCLES)

Cihat Yüksel, Özge Andiç-Çakır*, Kambiz Ramyar

Ege University, Civil Engineering Department, 35100 Bornova, Izmir, TURKEY

Abstract

There are many test methods offered in standards and specifications for determining the potential damage due to individual durability problems (including alkali-silica reaction – ASR) that may occur in concrete. However, in many cases, testing the exposure of concrete to only a single environmental exposure condition does not reflect the real conditions. Durability problems that act simultaneously or consecutively may lead to a greater damage than expected. In this study, a newly developed test method was adapted for determining the extent of expansion level due to consecutively acting freeze-thaw and ASR cycles. The specimens were subjected to frost action in accordance with the ASTM C666 standard and a total of 300 cycles were applied by using the rapid freezing in air and thawing in water (Procedure B) method. In order to promote the potential ASR in concrete prisms, RILEM AAR-4.1 method was followed at pre-specified time intervals and the total exposure time reached to 20 weeks. These multiple exposure conditions were investigated on four conventional mixtures including basalt and waste glass as aggregate. Besides, four mixtures of self-consolidating concrete with two different powder types and two different water/powder ratios were tested. According to the results, generally, expansion due to ASR occurred starting from the first weeks of exposure and frost action generated a triggering effect in the extent of expansion particularly in the late freeze-thaw cycles. The newly developed test method that simulates multiple durability problems for concrete seems to be promising.

Keywords: freeze-thaw, alkali-silica reaction, concrete, multiple exposure conditions

1 INTRODUCTION

Any performance test method to evaluate the durability of concrete should ensure a reliable correlation with field conditions while ensuring the conditions below;

- rapid, economical and easy to conduct,
- able to predict the performance of real-life structures for a practical period of service life,
- consider most of the exposure conditions the structure may meet during its service life.

Among many concrete durability tests developed today, it is possible to ensure the first two, but not always easy to simulate more than one exposure condition by conducting one methodology. Considering the alkali-aggregate reaction (AAR) performance tests, field vs lab correlation has always been a challenge and thus, necessitated several conditions to be fulfilled or optimized. Today, the influences of these parameters are widely studied and documented [1-3];

- prism size and use of wrapping,
- moisture and temperature conditions,
- alkali content
- drying/wetting effect during the test,
- alkali boosting
- type of cement (Na^+, K^+ ratios)
- mixture conditions (W/Cm, Agg/Cm ratios)
- permeability and water transport properties of concrete.

According to Thomas et al. an ideal AAR performance test should be capable of:

- evaluating the “critical” alkali contents,
- assessing the effects of SCMs, blended cements, lithium compounds and their combinations [4].

* Correspondence to: ozge.andic@ege.edu.tr

Today, RILEM TC 258-AAA is working on developing performance test methods that fulfill these requirements. For the first requirement it was focused on suppressing the alkali leaching problem with minimal alkali boosting, i.e. on-site alkali levels, and for the second requirement, the effect of different AAR inhibitors are studied.

Nevertheless, may a third requirement be considered as "the test should be able to assess the performance of concrete under multiple environmental conditions"?

As an attempt to assess this for pavement concretes, a cyclic performance test, the cyclic climate storage, was first developed at Finger-Institute (FIB). The test method was successful for considering the influence of externally supplied alkalis. The test is applied to 100x100x400 mm concrete prisms with embedded steel studs for expansion measurement. The cyclic storage of 21 days starts 7 days after casting. De-icer test solutions are applied on top of stored prisms. The cyclic period consists of, 4 days of drying at 60°C and <10% RH, 14 days of wetting at 45°C and 100% RH and 3 days of freeze thaw cycling between ±20°C. The ASR potential is assessed after 8 cycles (6 months) through microscopic examination. After 12 cycles, thin section analysis was carried out for pavements, while longer testing periods are suggested for longer service life structures as well as concretes incorporating SCMs. The test method correlates well with the field performance of pavements [5].

This study presents the data obtained from a part of the PhD study of the first author. The main objectives of this paper are to suggest a newly developed testing procedure for investigating multiple environmental effects and summarize the results obtained by subjecting eight different mixtures to consecutive freeze-thaw and alkali-silica reaction (ASR) cycles.

2 MATERIALS AND METHODS

2.1 Materials

A high alkali (HA – 1.04% Na_2O equivalent) and a low alkali (LA – 0.63% Na_2O equivalent) Portland cement were used for preparing concrete mixtures. Both cements are CEM I 42.5R type in accordance with TS EN 197-1 [6]. Besides, in two of the self-compacting mixtures, a type of fly ash obtained from Çayırhan thermal power plant - Turkey was used to increase the powder content of the mixtures for providing high consistency and cohesiveness. The chemical compositions of the binders are given in Table 1.

Two types of reactive aggregates were selected for the experimental study. The first one was an andesitic basalt from Aliağa, Aegean Region, Turkey. It was used in three size fractions (0/4, 4/16 and 11.2/22.4 mm). Previous experience [7] had shown that this aggregate caused deleterious alkali silica reaction in accelerated mortar bar and concrete prism tests. In addition to expansion measurements, microstructural observations were conducted in another study and it was revealed that glassy phase of the basalt matrix having approximately 70% of SiO_2 was the main source of expansion [8].

The other aggregate type used in the study was waste soda-lime glass. In glass-including mixtures glass was used in only 0/3 mm or 0.063/3 mm size fractions while basalt was again used as the coarse aggregate particles. 0.063/3 mm size fraction was obtained by wet-sieving the crushed glass from 0.063 mm sieve. This was done for searching the influence of a possible pozzolanic activity of very fine glass particles which in turn may lead to reduction in the expansion. It is worthwhile to note that 8% of the particles in 0/3 mm glass can pass from 0.063 mm sieve after wet-sieving.

2.2 Mix designs

Mixtures were prepared in two series. The first group (Table 2) included four traditionally-vibrated mixtures in which cement dosage and water/cement ratio were kept constant at 440 kg/m^3 and 0.50, respectively. Among these mixtures, control mixture was prepared using LA cement and only basalt as aggregate with a total alkali load of 5.50 kg/m^3 Na_2O eq. as required per AAR-4.1 [9]. In order to assess the influence of alkalinity, control+ mixture was also prepared by using the same ingredients but with a higher amount of NaOH used for boosting and thus an excess (6.60 kg/m^3 Na_2O eq.) alkali level. Meanwhile, two waste glass-including mixtures were designed by using HA cement. Boosting was not applied in these series and in the calculation of alkali level, only the cement alkalis were taken into account. In the abbreviations of the mixture codes (0/3HA and 0.063/3HA) the numbers show the size fraction of glass in the mixture.

In the second group, four self-consolidating mixtures (SCC) were cast by using HA cement, 0.125/4 mm and 4/16 mm basalt aggregate. These mixtures had two powder types, i.e. the filler portion of reactive basalt and fly ash (FA) and two water/powder ratios, i.e. 0.34 and 0.31 (Table 3), respectively. The basalt powder (BP) came from the same source as the reactive fine and coarse basalt aggregates used in the study and it was obtained by dry sieving fine basalt aggregate from 125 μm sieve. For obtaining mixtures with adequate flow and stability, the required fresh concrete characteristics, i.e. slump flow, T_{50} cm flow time, V-funnel flow time, L-box flow time tests (T_{20} and T_{40}) and L-box blocking ratio (h_2/h_1) were tested in accordance with EFNARC Guidelines [10]. It became necessary to make some modifications in mix design criteria provided by AAR-4.1. For instance, the cement content was raised to 470 kg/m^3 and instead of the recommended coarse aggregate to fine aggregate ratio (by weight) of 60:40, a different and fixed gradation was employed. Cement content and water/cement ratio were kept constant. Besides, slump flow values remained approximately constant at 73±2 cm by adjusting the amount of a polycarboxylate ether-based superplasticizer. In the abbreviations of the SCC mixtures (BP-34, BP-31, FA-34 and FA-31), the letters and the numbers represent the powder type and water/powder ratio, respectively.

2.3 Test procedure

It is stated in AAR-4.1 that the total duration for expansion measurements of concrete prisms last for 20 weeks. On the other hand, ASTM C666/C666M-03 [11] requires subjecting the specimens to a total of 300 rapid freeze-thaw cycles. In the newly developed performance testing procedure in this study, after demolding the specimens, it is recommended to start testing by storing the 75x75x285 mm concrete prisms as required by AAR-4.1 (60°C, in a reactor) for the first 4 weeks. After that, the containers are removed from the reactor, stored at 20±2°C for 24 h and then the specimens are subjected to 60 freeze-thaw cycles according to ASTM C666. Consequently, they were kept at 20±2°C for 24 h again. This single consecutive ASR and freeze-thaw test process is repeated five times in total as plotted in Figure 1 and thus, the total required test durations are completed. Length change measurements were obtained at each time while the specimens were at 20±2°C as shown in Figure 1. Also additional 100 mm cubes were prepared for determining weight change and ultrasound pulse velocity (UPV) values of the mixtures. In ASTM C666 two different test procedures exist: rapid freezing and thawing in water (Procedure A) and rapid freezing in air and thawing in water (Procedure B). Among these, Procedure B was selected and as stated in this method, the temperature was alternately lowered from 4 to -18°C and raised from -18 to 4°C in 2-5 hours.

3 RESULTS AND DISCUSSION

Test results for control, control+, 0/3HA and 0.063/3HA mixtures are presented in Figure 2a, 2b, 3a and 3b. While Figure 2a shows the expansion values obtained after subjecting the four mixtures to consecutive ASR and freeze-thaw tests, expansions at 60°C resulting from only ASR are given in Figure 2b. In addition, Figure 2c was plotted in order to compare the theoretical sum of the ultimate (20-week) expansion in AAR-4 test and the expansion due to only frost cycles in consecutively applied tests with the actual value obtained at the end of the consecutively applied tests. Meanwhile, Figure 3a and 3b shows the change in weight and ultrasound pulse velocity of these mixtures, respectively. In the graphs, ASR and FT abbreviations stand for the periods at which AAR-4 test and freeze-thaw test was applied, respectively.

The results shown in Figure 2 and 3 indicate that the increase in expansion in the early stages of the testing results mainly from alkali-silica reaction. Initial frost cycles created substantial changes in weight and UPV of the mixtures; however, their effect on expansion values was rather minimal. This behaviour can be attributed to the fact that concrete undergoes linear contraction down to -20°C and strain-temperature behaviour is characterized by a hysteresis [12]. Thus, in freeze-thaw tests, non-recoverable deformations are expected to occur due to progressive damage in the structure of concrete at later cycles. Expansions originating from frost damage appear in particularly waste glass including mixtures at later frost cycles. Due to the highly reactive behaviour of glass aggregate, ASR damage proceeds in a rapid manner and causes a triggering effect on frost damage. This behaviour is apparent in Figure 2c since the expansion due to frost is considerably higher in waste glass including mixtures than those obtained in control and control+ mixtures. It can be understood by comparing Figure 2a and 2b that for all mixtures, cyclic ASR and freeze-thaw exposure lead to higher expansion levels than the corresponding expansions obtained at AAR-4.1 test.

In most of the conventional alkali-reactive aggregates, ASR originates at the surface of the aggregate and the cracks formed in the interfacial zone and in some cases inside the aggregate particles extend into the hardened cement paste. Besides, the damage may manifest itself as map cracking. On the other hand, in the case of frost damage, progressive cycles may cause damage ranging from weight loss from the surface which is limited to cement paste and fine aggregate to more serious spalling. Alkali-silica gel and cracks uptake water upon exposure to ASR and the weight of the specimens increase. According to Figure 3a, cyclic tests show that glass-including mixtures undergo weight increase at each ASR testing interval. However, control and control+ mixtures had much lower reactivity and the reaction rate dropped after the 10th week. Therefore, significant increments in the weight values of these mixtures were obtained during only the early ASR exposures. Frost cycles caused some material loss from the surface of glass-including mixtures. Due to the high alkali reactivity of these mixtures, pre-existing ASR damage played role towards increasing also frost damage. Since the deterioration resulting from ASR in control and control+ mixtures was not that high, the resistance of these mixtures to freeze-thaw effect remained comparatively high and significant surface damage and weight loss did not occur.

As a general rule, while ASR exposure causes weight values to increase, frost action has an opposite effect. On the other hand, both durability effects reduce ultrasound pulse velocity which is related with the concrete density and the level of damage within the specimen. While weight loss values did not exceed 2.5% in any mixture, cyclic loading caused great UPV loss in glass-including mixtures reaching up to even 15-20%. This arises from the combined effect of serious ASR damage itself and also the triggering effect of this damage on frost behaviour. An additional cause for the rapid drop in UPV in glass-including mixtures may be the poor bond behaviour between the glass aggregate particles and the hardened cement paste. Glass particles initially have smooth surface textures and although crushing operation causes change in surface texture to some extent, waste glass does not seem to be an ideal aggregate type particularly to be used at 100% replacement for fine aggregate.

Test results for BP-34, BP-31, FA-34 and FA-31 mixtures are presented in Figure 4a, 4b, 5a and 5b. Figure 4a shows the expansion values obtained after subjecting these four SCC mixtures to consecutive ASR and freeze-thaw tests. Expansions at 60°C resulting from only ASR are given in Figure 4b for comparison. Figure 4c was plotted in order to compare the theoretical sum of the ultimate (20-week) expansion in AAR-4 test and the expansion due to only frost cycles in consecutively applied tests with the actual value obtained at the end of the consecutively applied tests. Figure 5a and 5b show the influence of cyclic testing on weight and UPV change, respectively.

Before the interpretation of the results, it is worthwhile to note that the scales of the y-axes of Figure 4 and 5 are different from those of the Figures 2 and 3. It is possible to compare the results given in Figure 2 and Figure 4; however, attention should be paid for the numerical values by the reader. Expansion, weight change and UPV alteration trends for SCC mixtures were similar with those for traditionally-vibrated mixtures. For instance, subjecting the mixtures to cyclic testing resulted in higher expansion levels compared with the expansion levels arising from ASR exposure only. The two SCC mixtures which showed the maximum ultimate expansion (BP-31 and FA-31) in AAR-4.1 test according to Figure 4b underwent the highest ultimate expansion and the greatest UPV reduction at the end of the cyclic loading procedure. Figure 5a indicates that frost action resulted in increments in the weights of the specimens at some intervals. This may be attributed to the uptake of water by the specimens through the ASR cracks formed.

For six out of eight mixtures, the expansion value obtained at the end of the consecutively applied tests exceeded the theoretical sum of the ultimate (20-week) expansion in AAR-4 test and the expansion due to only frost cycles in consecutively applied tests. This may be considered as an indication of the fact that the multiple exposure conditions create a more deteriorative effect than the effect of the individual durability problems.

Due to the high powder content and dense matrix structure, SCC mixtures are expected to have low permeability against water ingress and due to this reduction in saturation level; a higher frost resistance is also expected. However, it should be remembered that frost cycles in our testing program are applied after subjecting the mixtures to 60°C and a very high relative humidity. This high temperature level causes a substantial increase in relative diffusion coefficient which in turn makes the ingress of water into concrete easier resulting in a high relative humidity [13]. It can be indicated by comparing Figure 3b and 5b that in some cases, the UPV change of SCC mixtures exceeded the values belonging to control and control+ mixtures. This fact can be attributed to the increased volume of paste and reduced porosity in SCC mixtures. In concretes with high binder content and high strength, hydraulic pressure cannot be relieved since the distance from any point to a void is great [14].

In addition to the behaviour of the mixtures under cyclic loading, some comments should also be made regarding the validity of the newly developed testing procedure. At the beginning of the tests, a serious concern arose from the possible leaching of alkalis due to the running action of thawing water used in frost tests. In the PhD study alkali leaching measurements were made in AAR-3 and AAR-4.1 tests using atomic absorption spectrometry however during cyclic loading it was practically impossible to make such analysis. Since the expansion levels continued to rise even in the last stages of ASR exposure according to Figure 2a and 4a, it seems that a significant extent of alkali leaching did not take place. Before starting the experimental study, minimum thawing duration was determined by using thermocouples and special attention was paid in order not to apply excess water on to concrete surface. In accelerated concrete prism tests, the general expectation is a higher rate of reaction at early ages followed by a drop in reaction rate at later ages. However, this was not the case when exposing particularly more reactive mixtures to cyclic loading. These mixtures had high slope in expansion-time graphs in cyclic loading at both early and late ASR exposures. This may be attributed to the easier penetration of water due to the increased damage after frost test application.

4 CONCLUSIONS

The main conclusions drawn from this study are as follows:

- Exposing the mixtures to consecutive ASR and freeze-thaw cycles showed that the increase in expansion in the early stages of the testing results mainly from alkali-silica reaction. The influence of frost action on expansion values appeared rather at the later ages.
- For all mixtures, cyclic ASR and freeze-thaw exposure lead to higher ultimate expansion levels than the corresponding expansions obtained at AAR-4.1 test.
- Among all mixtures, glass-including mixtures had the highest alkali reactivity. Frost cycles caused some material loss from the surface of glass-including mixtures. This type of frost damage was not evident in the other mixture types that had lower reactivity.
- SCC mixtures suffered a higher degree of UPV loss upon exposure to frost cycles compared to control and control+ mixtures due to their denser structure.
- The newly developed test method that simulates multiple exposure conditions for concrete seems to be promising. Care should be taken to avoid the excess contact of thawing water with concrete surfaces.

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TABLE 1: Chemical compositions of the binders used in the study (% by mass).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	LOI[a]	Cl^-	Na_2O eq[b]
High alkali CEM I (HA)	19.72	5.31	3.37	62.33	2.33	3.33	0.53	0.77	2.09	0.0136	1.04
Low alkali CEM I (LA)	19.54	4.80	5.71	62.65	1.89	3.12	0.37	0.40	1.53	0.0087	0.63
Fly ash	47.07	11.56	7.22	15.94	7.77	2.78	1.59	3.04	0.42	-	1.25[c]

[a] Loss on ignition
[b] Na_2O equivalent = Na_2O + 0.656 K_2O
[c] Available alkali content according to ASTM C311

TABLE 2: Amounts of ingredients (kg/m^3) in the first series.

	Control	Control+	0/3HA	0.063/3HA
Low alkali (LA) cement	440	440	-	-
High alkali (HA) cement	-	-	440	440
Water	220	220	220	220
0/4 basalt	696	696	-	-
4/16 basalt	522	522	501	501
11.2/22.4 basalt	522	522	501	501
0/3 glass	-	-	667	-
0/3 glass (screened from 63 μm sieve)	-	-	-	667
Added NaOH	3.57	5.02	-	-
Total	2404	2405	2329	2329
ALKALI CONTENT (kg/m^3)	5.50	6.60	4.60	4.60
ALKALI CONTENT (% OF CEMENT)	1.25	1.50	1.04	1.04

TABLE 3: Mix proportions of SCC mixtures (second series).

	BP-34	BP-31	FA-34	FA-31
Cement, kg/m^3	470	470	470	470
Water, kg/m^3	235	235	235	235
0.125/4 mm basalt, kg/m^3	780	753	769	739
4/16 mm basalt, kg/m^3	651	628	640	617
Basalt powder, kg/m^3	230	280	-	-
Fly ash, kg/m^3	-	-	230	280
NaOH, kg/m^3	1.30	1.30	1.30	1.30
Superplasticizer, kg/m^3	13.8	12.8	13.8	12.1
Total, kg/m^3	2381	2380	2359	2354
ALKALI CONTENT (kg/m^3)	5.50	5.50	5.50	5.50
ALKALI CONTENT (% OF CEMENT)	1.25	1.25	1.25	1.25
w/c, by weight	0.50	0.50	0.50	0.50
w/p**, by weight	0.34	0.31	0.34	0.31
w/p, by volume	1.00	0.93	0.97	0.90

*w/c: water/cement ratio, **w/p: water/powder ratio

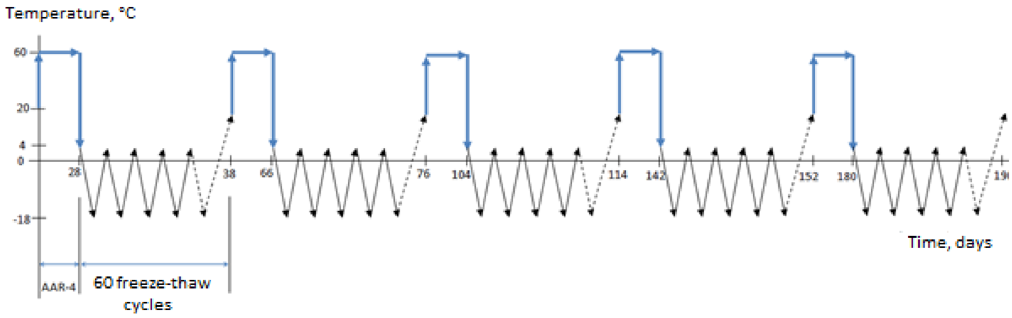


FIGURE 1: Schematic representation of the cyclic testing procedure followed in the study.

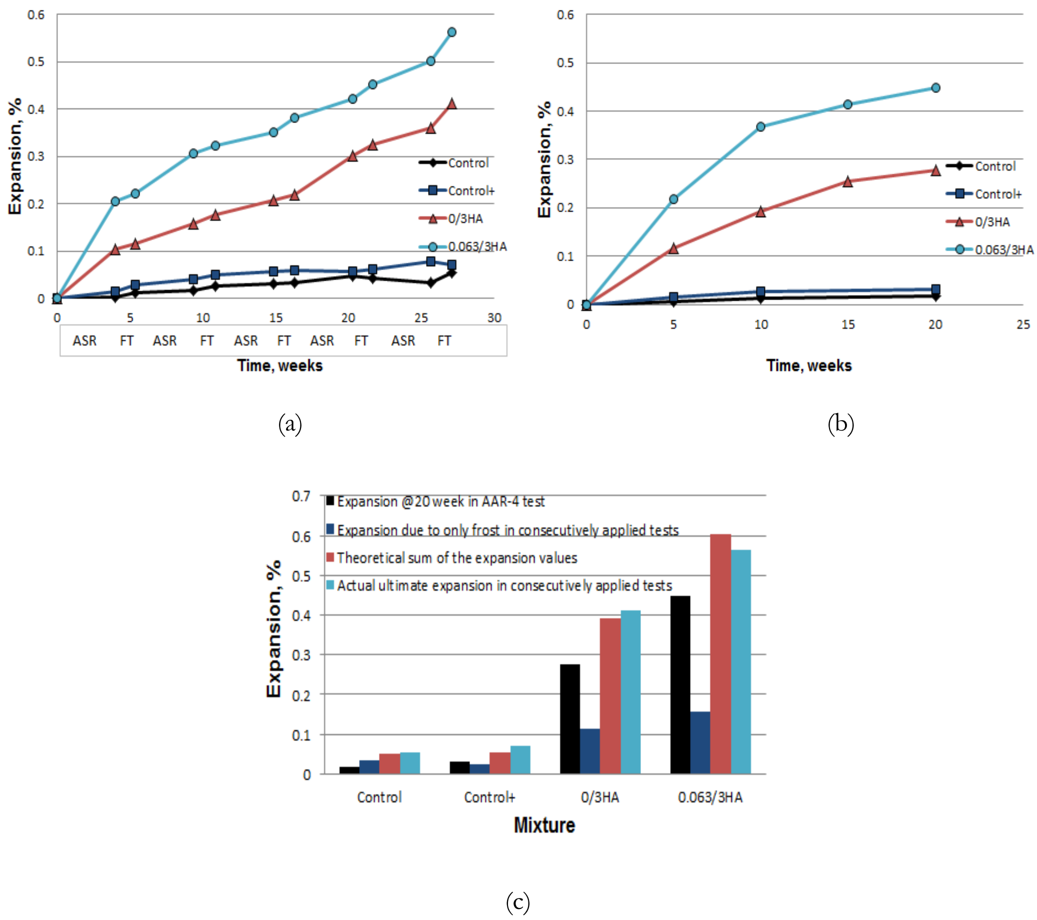
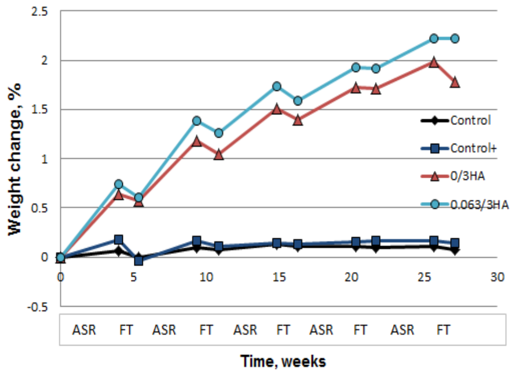


FIGURE 2: Expansion behaviors of Control, Control+, 0/3HA and 0.063/3HA mixtures when subjected to (a) consecutive ASR and frost cycles, (b) AAR-4.1 test.



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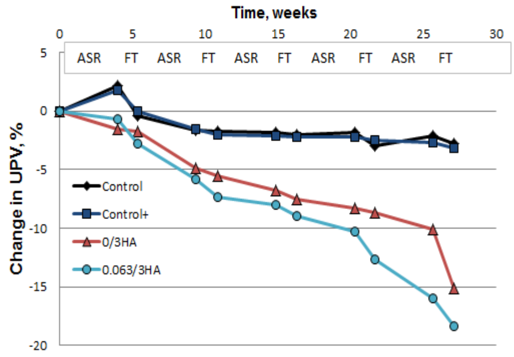
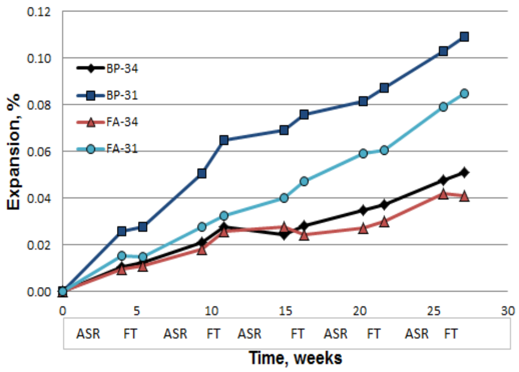


(b)

FIGURE 3: Changes in (a) weight (b) UPV of Control, Control+, 0/3HA and 0.063/3HA mixtures when subjected to consecutive ASR and frost cycles.



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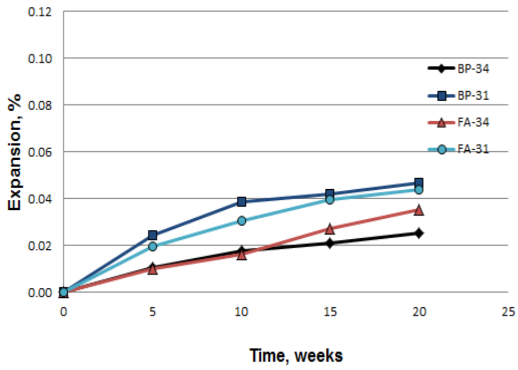

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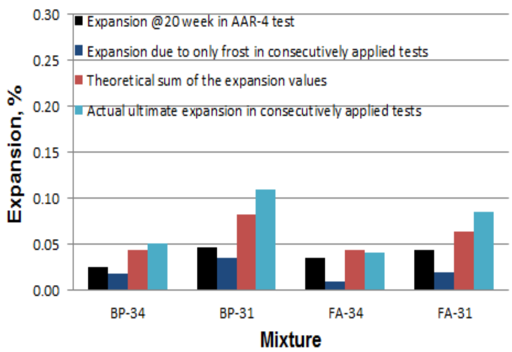
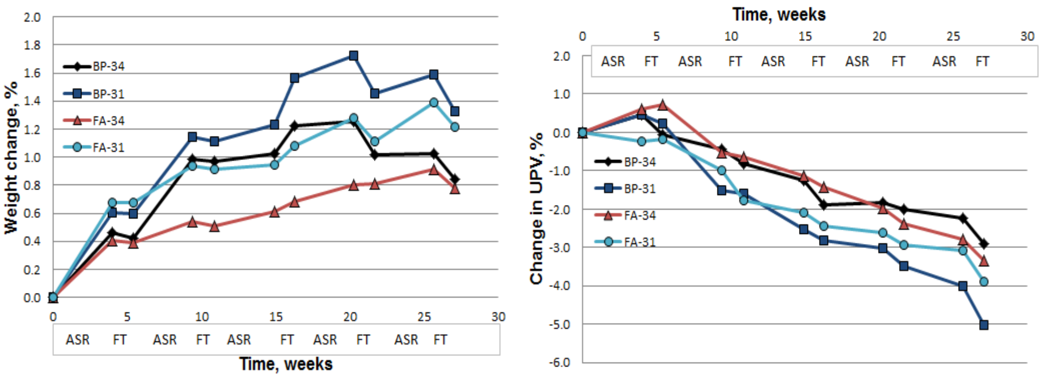


(c)

FIGURE 4: Expansion behaviors of BP-34, BP-31, FA-34 and FA-31 mixtures when subjected to (a) consecutive ASR and frost cycles, (b) AAR-4.1 test.



(a) (b)

FIGURE 5: Changes in (a) weight (b) UPV of BP-34, BP-31, FA-34 and FA-31 mixtures when subjected to consecutive ASR and frost cycles.