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Evaluation of three test methods for determining the alkali–silica reactivity of glass aggregate

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ABSTRACT

Consumption of natural raw materials and pollution have become significant problems due to technological developments and continual increase in demand. Accordingly, great efforts are being made in order to recover wastes including glass. One of the possible applications is utilizing waste glass in concrete; however, alkali–silica reaction (ASR) is of major concern. In this study, tests were conducted by applying three different procedures: ASTM C1293, RILEM AAR-2, and microbar test methods. In microbar testing, glass aggregate was used as coarse aggregate, whereas the other two methods dealt with investigating the reactivity of the finer fraction of the waste glass. The effects of chemical composition, particle size and amount of glass in the mixture were studied. According to the results, flint glass expanded to a greater extent than amber and green glass. Expansions, within the specified time periods dictated by the methods, remained low; however, extended durations resulted in very high length change values of the flint glass-including mixtures, particularly in the AAR-2 and microbar tests.

1. Introduction

Compared to other engineering materials, concrete is the most popular one owing to its availability, excellent resistance to water, its lower cost and the ease with which it can be formed into a variety of shapes and sizes [1]. Due to these primary and also many other advantages for different applications, concrete production figures have reached huge amounts and concrete has become the world's most consumed man-made material [2]. In 2009, approximately 66.4 million m^3 of ready-mixed concrete was used in the construction industry in Turkey. It appears that on a per capita basis, concrete consumption in Turkey has reached 0.93 m^3. 21 Member countries of the European Ready Mixed Concrete Organization including Turkey produced 377.4 million m^3 of concrete in 2009, which corresponds to 0.70 m^3 production per capita [3].

It is evident that the natural resources are rapidly consumed by the industrially advancing world to obtain raw materials for cement and concrete. Sustainable development in concrete production requires reducing the greenhouse gas emissions, energy consumption and raw material resource depletion. Utilizing by-products or wastes as alternative materials in concrete as aggregate or cementitious material will provide a more sustainable concrete technology through the creation of a balance between development and environment [4].

Another global concern about the environment is the increased amount of waste resulting from rapid urbanization and population growth in parallel with technological developments and industrialization. The world is trying to cope with this problem by converting the wastes generated as a result of production, marketing and consumption activities into economic assets. For this purpose, waste management strategies are developed and regulatory programs are established to reach the sustainable development objectives. In Turkey, waste management has been the subject of a number of legal arrangements since the 1930s [5]. In spite of the strict regulations on solid waste management and the efforts to change open waste disposal sites into modern recycling facilities, Turkey still has over 2000 open dumping areas. According to the Turkish State Institute of Statistics figures, in 2008, approximately 52% of the municipal solid waste collected in Turkey was sent to such open dumping areas [6].

It is well known that containers and packaging materials such as glass, metal, paper and plastic are the most common recyclable materials. Among these, glass can be recycled infinitely with no quality loss and glass recycling offers significant benefits from both economic and environmental points of view. By using waste glass cullet as a secondary raw material in the production of new bottles and jars; (i) raw materials are saved, (ii) the energy demand in manufacturing process is dropped, (iii) CO_2 emissions are reduced, and (iv) the furnace life is extended due to the reduced melting temperature [7].

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27 Members of the European Union reached an overall glass recycling rate of 67% in 2009 according to the European Container Glass Federation (FEVE). In Europe, glass recycling statistics varied from one country to another and Belgium was the leading one with a recycling rate of 96%. Austria, Netherlands, Sweden and Switzerland were the other countries that recycled at least 90% of their glass waste in 2009. On the other hand, Greece was the least successful since the glass recycling rate remained at 15% [8]. In Turkey, lack of a well-organized collection system for recoverable wastes, insufficient funding for recycling programs and low societal awareness of sorting recyclables are some reasons which led to glass recycling rate of only 25% in 2009 [6,8].

New glass can be produced from old glass only if the level of contamination from other categories and other colors of glass, as well as from non-glass materials (plastic, metal, ceramic, organic matter, etc.) is within the allowable limits. Otherwise, the recycling operation for glass, particularly in its broken form, may be too complex and costly [9]. This problem gave rise to recovery of glass for non-container uses (in secondary markets). The construction industry has made attempts to utilize waste glass in back-filling, roadway construction, pipe bedding, drainage applications, landfill gas venting layers and in many architectural and decorative applications such as glass tile, wall panels, etc. [9,10] In order to create another sustainable solution, extensive research has been conducted to understand the consequences of using waste glass as aggregate in concrete. These studies focused on determining the level of deleterious alkali–silica reaction (ASR) expansion arising from the reaction between cement alkalis and silica found in the amorphous structure of glass.

In the presence of glass aggregate, expansion characteristics will be influenced by particle size, chemical composition, thermal history of the glass, and the amount of glass in the mixture; however, their exact effects have not been well understood yet. Results of experiments by many authors are often in disagreement. Some researchers [11,12] reported that among the soda-lime glasses, green glass was less reactive due to a suppressing effect of the Cr_2O_3 found in its composition. On the contrary, according to Dhir et al. [13], green glass produced the largest quantity of expansion when compared to flint and amber glasses. Therefore, authors reported that rather than chemical composition of different colored glasses, the thermal history of glass during manufacturing process may be an important parameter since this factor plays a role in the levels of internal stress generated and the rate of leaching and dissolution of the glass. The particle size distribution of the glass is another feature that influences its alkali reactivity. Jin et al. [14] indicated that the size of clear soda-lime glass leading to the greatest amount of expansion (pessimum size) was 1.18 mm. However, during some other research studies, no pessimum size was observed and the coarser glass particles reacted to a greater extent [11,15,16].

2. Research significance

The method used to measure the reactivity of glass aggregate is of great importance. Although the accelerated mortar bar test is the most widely used method due to its being a rapid indicator, for compositions with glass aggregate, reliable test results may not be achieved [11,17]. The aim of this experimental study is to evaluate the influence of the particle size, chemical composition and amount of the soda-lime glasses on ASR expansion. For assessing ASR reactivity, three test methods (RILEM AAR-2, ASTM C1293 and the microbar test) whose details will be explained in this paper were followed.

3. Experimental details

3.1. Materials

Test specimens were manufactured using (1) CEM I 42.5 R type Portland cement (EN 197-1) with an alkali content of 1.03% in terms of equivalent Na_2O, (2) a non-reactive crushed limestone (CL), (3) flint glass aggregate (F) from post-consumer window glass, (4) green glass aggregate (G) from soda bottle waste, (5) amber glass aggregate (A) from beer bottle waste. The chemical compositions of the cement and aggregates are given in Table 1.

All aggregates were used up to 12.5 mm particle size. No chemical or mineral admixture was used in the study.

3.2. Applied procedures

There exist some studies in the literature dealing with the influence of various test methods on the degree of observed reactivity of different natural aggregate types [18,19]. By using aggregates with a wide variety of mineralogies and geographical origins, Ideker et al. [18] found that, while assessing the reactivity of fine aggregates, the results obtained by keeping the specimens at 38 or 80 °C correlated well with the results of outdoor exposure testing. In the current experimental study, three test methods (RILEM AAR-2, ASTM C1293 and the microbar test) were selected. Among these, AAR-2 [20] was proposed by RILEM TC 106-AAR (Alkali-Aggregate Reaction) and by raising the temperature to 80 °C, it enables a rapid assessment of potential reactivity of fine aggregate in question. Such accelerated tests are apparently fast ways of screening expansions; however, due to less severe test conditions and testing concrete rather than mortar, ASTM C1293-08b, "Standard Test Method for Determination of Length Change of Concrete Due to Alkali–Silica Reaction" [21] seems to have a higher reliability. Finally, a concrete microbar test that was proposed by Grattan-Bellew et al. [22] has the advantage of detecting the reactivity of coarse aggregates. This test applies the same storage conditions as in the AAR-2 test and it is expected that the results give further information about the particle size effect.

3.2.1. Concrete Prism Test (CPT)

As per ASTM C1293, a cement content of 420 kg/m^3 and a water/cement ratio of 0.42–0.45 by mass were used. This method requires the production of concrete prisms measuring 75 mm × 75 mm × 285 mm, while boosting the alkali content of the cement to 1.25% Na_2O equivalent by the addition of NaOH. After demolding at 1 d, initial length was measured and three prisms from each mixture were placed vertically over water at 38 °C in a sealed container. The length change was monitored over a period of 3 years.

Table 1
Chemical composition of cement and aggregates (% by mass).

	Cement	Limestone	Flint glass	Green glass	Amber glass
SiO_2	18.98	1.33	71.38	70.30	71.31
Al_2O_3	5.22	0.40	1.30	1.83	1.80
Fe_2O_3	2.39	0.33	0.107	0.311	0.97
CaO	63.90	53.88	8.28	10.07	9.15
MgO	1.01	0.53	4.27	3.00	2.16
SO_3	2.99	0.08	0.23	0.15	0.21
Na_2O	0.48	–	14.29	13.44	14.10
K_2O	0.84	0.18	0.07	0.59	0.21
TiO_2	–	–	0.076	0.059	0.080
Cr_2O_3	–	–	–	0.25	0.01
Cl^-	0.0007	–	–	–	–
LOI	3.73	41.20	–	–	–
Sum	99.54	97.93	100.00	100.00	100.00

3.2.2. RILEM AAR-2, Ultra Accelerated Mortar Bar Test (UAMBT)

In accordance with this method, three mortar-bars, each 25 mm × 25 mm × 285 mm in size, were cast from mixtures. The water/cement ratio was maintained constant at 0.47 and the dry materials were proportioned using 1 part of cement to 2.25 parts of aggregate by mass. The test involved keeping the specimens in a moist curing room for the first 24 h, water-curing for 1 d at 80 °C, and then immersing them in a 1 M NaOH solution that was kept at 80 °C until the end of the test. Instead of the typical 14 d period, the duration is extended considerably and comparator readings of the specimens were made periodically up to 180 d.

3.2.3. Concrete Microbar Test (CMT)

This method involves the production of no-fines concrete mixtures having a length of 160 mm and a larger cross-section (40 mm × 40 mm) than that required in the UAMBT. Three concrete microbars were prepared from each mixture by employing an aggregate/cement ratio of 1 and a water/cement ratio of 0.33. In order to ultra-accelerate the reaction, as in the UAMBT, the temperature level was raised to 80 °C and the same storage procedure was applied. While the UAMBT specifies a 14-d soaking period, in the CMT, a duration of 30 d is suggested, but again, the test was extended to 90 d in the present study.

The gradation requirements in these test methods are summarized in Table 2. Among the tests, ASTM C1293 allows the available sand-sized particles to be used without any sieving operation; however as Table 2 indicates, gradation guideline for coarse aggregate exists in this test. Fig. 1 shows the gradation curves of glass sand and limestone sand that were used in the ASTM C 1293 test. In order to comply with the grading requirement in each method, following the washing and drying processes, the collected waste glass particles were sized by crushing in a hammer crusher which employs impact and shear. Non-reactive aggregate was also sieved to obtain the required particle size distributions given in Table 2.

3.3. Mixture proportions

The experimental program began with producing the prismatic specimens that will be subjected to the ASTM C1293 test. In the control mixture, only non-reactive limestone was used as aggregate; fine aggregate and coarse aggregate contents were 726 and 1043 kg/m^3, respectively. This part of the study focused on determining the effect of flint and green glass as replacement of fine aggregate on ASR expansion. Replacement ratios were selected as 10%, 20%, 40%, and 50% by mass of fine aggregate. These mixtures were designated as 10F, 20F, 40F and 50F for flint glass aggregate and 10G, 20G, 40G and 50G for green glass aggregate.

One-year testing at 38 °C showed that the expansion values of glass-including mixes remained low, consequently higher replacement ratios were tried in RILEM AAR-2 and microbar tests. In the UAMBT, specimens were prepared by partial (25%, 50%, 75%) and full (100%) replacement of fine aggregate by flint, green and amber glass. In these mixtures, the gradations of crushed limestone and glass aggregates were the same. In this part of the investigation, in addition to the color and content of the waste glass, the particle size effect was also studied. In order to achieve this goal, additional mixtures were prepared by replacing five different single-size fractions of glass (2–4 mm, 1–2 mm, 0.5–1 mm, 0.25–0.5 mm and 0.125–0.25 mm) in three different colors with the corresponding particle size of non-reactive crushed limestone. For instance, the 1-2F mixture contained 10% limestone between 2 and 4 mm, 25% flint glass between 1 and 2 mm, 25% limestone between 0.5 and 1 mm, 25% limestone between 0.25 and 0.5 mm and 15% limestone between 0.125 and 0.25 mm. Table 3 gives the amounts of crushed limestone (CL) and flint glass (F) aggregates that are required to obtain three 25 mm × 25 mm × 285 mm specimens for each mortar mixture subjected to the UAMBT. In addition to the mortar bars in Table 3, amber and green glass-including mixtures having the same mixture proportions were prepared. In the designations of these specimens, the words "A" and "G" were used to represent amber and green glass-including mixtures, respectively.

Microbar samples were prepared in a similar manner as the UAMBT samples. Replacement levels of flint, green and amber glass as coarse aggregate in concrete mixtures were 25%, 50%, 75% and 100%. Additionally, presence of glass in the 4.75–9.5 mm and 9.5–12.5 mm size fractions was tested separately. For preparation of three specimens from each flint glass-including microbar mixture, the amounts of aggregates that are shown in Table 4 were used. The same mixture proportions were applied in amber and green glass-including mixtures exposed to conditions dictated in the microbar test.

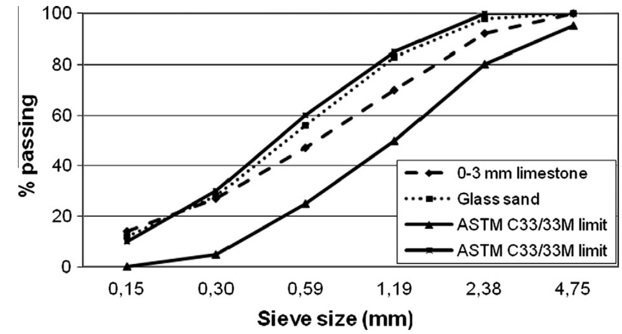

Fig. 1. The gradation curves of aggregates used as fine aggregate in the ASTM C 1293 test.

Table 2
Grading requirements in each test method.

Test	Size range	Mass (%)	Description
RILEM AAR-2 (UAMBT)	2–4 mm	10	–
	1–2 mm	25	
	500 μm–1 mm	25	
	250–500 μm	25	
	125–250 μm	15	
ASTM C 1293	12.5–19 mm	33	+ Fine fraction
	9.5–12.5 mm	33	
	4.75–9.5 mm	33	
Microbar	4.75–12.5 mm	100	–

4. Results and discussion

4.1. Concrete prism test

Expansion values of flint and green glass including mixtures as a function of time up to 3 years are reported in Figs. 2 and 3, respectively.

Although the length change values of all mixtures are well below the limit of 0.04% at 1 year as specified by ASTM C1293, F series mixtures did not stop expanding beyond this time. On the other hand, after 1 year, further increase in the expansion values of mixtures belonging to the G series was comparatively low. It was found that as the amount of glass in the mixture was increased, ASR expansion of the specimens increased. When the values at 1 year are considered, the green glass was slightly more reactive (Fig. 4), however 3 year expansion values indicate that the flint glass had reacted to a greater extent. Among all mixtures, at 3 years, only 40F and 50F exceeded the 0.04% standard limit (proposed for 1 year expansion).

Table 3
Aggregate contents of flint glass-including mixtures subjected to the UAMBT.

	Mass retained between sieves (g)									
	2–4 mm		1–2 mm		0.5–1 mm		0.25–0.5 mm		0.125–0.25 mm	
	CL	F	CL	F	CL	F	CL	F	CL	F
Control	90	–	225	–	225	–	225	–	135	–
25F	67.5	22.5	168.8	56.3	168.8	56.3	168.8	56.3	101.3	33.8
50F	45	45	112.5	112.5	112.5	112.5	112.5	112.5	67.5	67.5
75F	22.5	67.5	56.3	168.8	56.3	168.8	56.3	168.8	33.8	101.3
100F	–	90	–	225	–	225	–	225	–	135
2–4F	–	90	225	–	225	–	225	–	135	–
1–2F	90	–	–	225	225	–	225	–	135	–
0.5–1F	90	–	225	–	–	225	225	–	135	–
0.25–0.5F	90	–	225	–	225	–	–	225	135	–
0.125–0.25F	90	–	225	–	225	–	225	–	–	135

Table 4
Aggregate contents of flint glass-including mixtures subjected to microbar test.

	Mass retained between sieves (g)			
	4.75–9.5 mm		9.5–12.5 mm	
	CL	F	CL	F
Control	450	–	450	–
25F	337.5	112.5	337.5	112.5
50F	225	225	225	225
75F	112.5	337.5	112.5	337.5
100F	–	450	–	450
4.75–9.5F	–	450	450	–
9.5–12.5F	450	–	–	450

When green, amber and flint glass were used as 100% replacement for fine aggregate, Dhir et al. [13] observed expansion levels of approximately 0.60%, 0.35% and 0.06%, respectively at the end of 60 weeks. Thereafter, unlike flint glass, expansion ceased for amber and green glass. This test was carried out according to BS 812-123 which specifies a similar testing program to ASTM C1293. The authors also replaced 50% fine aggregate with green, amber and flint glass; the expansion curves of these three mixtures followed a close trend. Although Dhir et al. found somewhat higher expansion values than those obtained in the current study for 50% substitution level; at the end of 52 weeks, the expansion values of the mixtures in both studies did not exceed the limit proposed for expansive concrete mixtures.

4.2. RILEM AAR-2

According to the results obtained within the typical 14-d soaking period, none of the glass-including mixtures exhibited potentially deleterious expansion (Figs. 5–7). However, the extended testing duration led to a great amount of expansion, particularly in the mixtures containing flint glass. The color of the glass had an impact on both magnitude and rate of expansion. In mixtures containing monosize glass, the initiation of the reaction was earlier for flint glass. At 35 d the expansion value of the 2-4F mixture was recorded as 0.125% whereas expansions of the 2-4A and 2-4G mixtures were 0.005% and 0.008%, respectively. At 180 days, among all mixtures, the 100F mixture had the highest expansion value (1.158%), which is around three times as high as the length change of the 100A mixture. Green glass caused considerably less ASR expansion to occur compared to flint and amber glass, which is thought to be a consequence of the Cr_2O_3 present in green glass. As cited by Park and Lee [12], Prezzi et al. [23] hypothesized that the valence of the ions in the reaction products determines the double-layer thickness and the repulsion forces. Smaller expansive forces are generated by gels containing ions having higher ionic valence such as Cr^{3+}.

As it is clear in Figs. 5–7, there is an apparent time-lag behavior in all glass-including mixtures. This finding is consistent with the results of the study conducted by Zhu et al. [11], who attributed this delay to the pozzolanic reaction that finer glass particles undergo. The authors indicated that the reactivity of coarser glass particles is mitigated in the short term by this accelerated pozzolanic reaction. However, regardless of the color, mixtures including glass with a particle size of only 2–4 mm or 1–2 mm (2–4F, 1–2F, 2–4G, 1–2G, 2–4A and 1–2A mixtures) had a similar time-lag behavior. 2–4F and 1–2F mixes started to expand after roughly a 14-d soaking period and the delay periods for the 2–4G, 1–2G, 2–4A and 1–2A mixtures were even longer. Since these mixtures did not contain any fine glass that could undergo a pozzolanic reaction, there is a need for further investigation in order to explain the cause of the delay in the mesaured ASR expansion of monosize glass-including mixtures.

Considering that the individual reactive particles are only 2–4 mm and 1–2 mm in size, theoretically, it may be expected that, in the presence of sufficient alkalies, the expansion level of the 100F mixture should be roughly equal to the sum of expansion

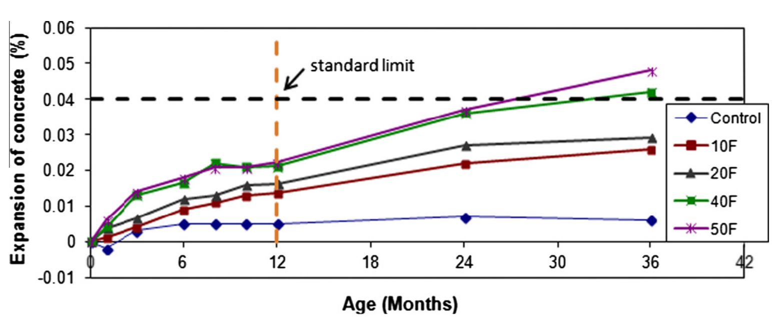

Fig. 2. Expansion of concrete prisms containing flint glass.

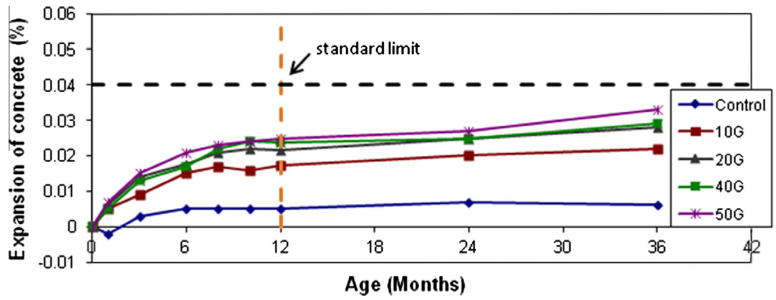

Fig. 3. Expansion of concrete prisms containing green glass.

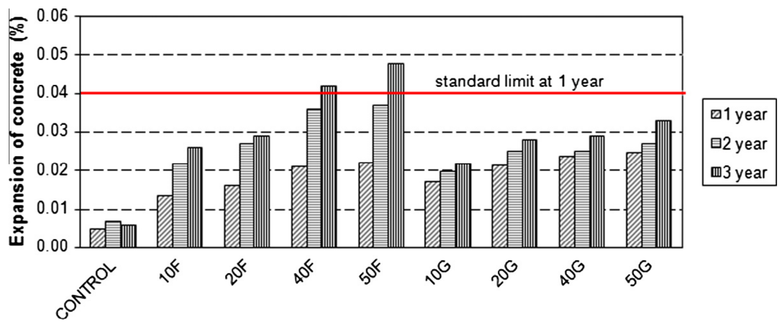

Fig. 4. The expansion values of concrete prisms observed at 1, 2, and 3 years.

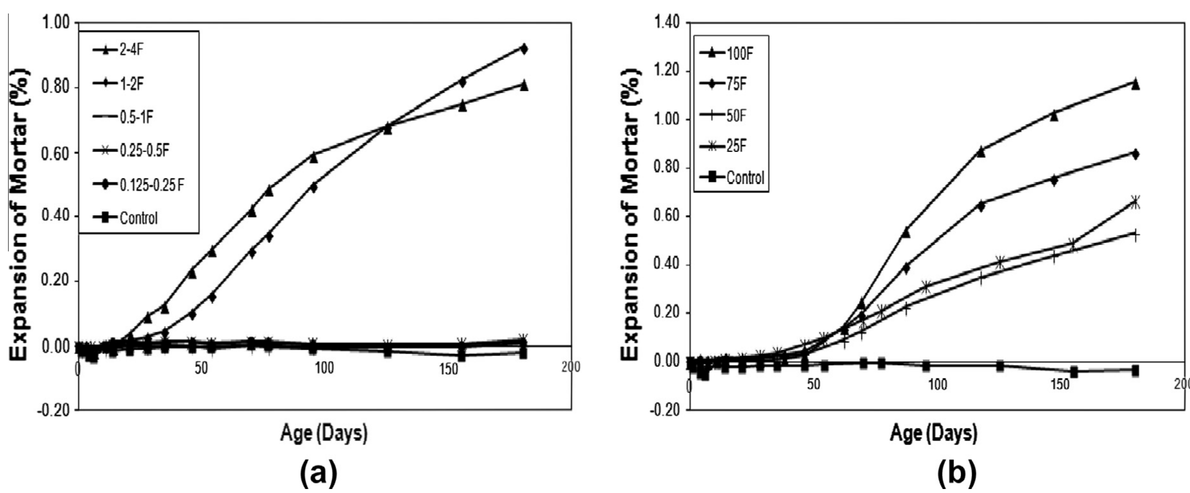

Fig. 5. Expansions of mortar bars including (a) monosize flint glass, (b) flint glass with varying percentages.

levels of 2–4F and 1–2F mixes. However, regardless of the color of the glass, this is not the case. When the replacement level is 100%, most of the glass present in the mixture may show pozzolanic behavior which in turn, may contribute to the reduction in the gel production [11,13].

The increase in the replacement level of glass increased the tendency for ASR to occur. The only exception was the 25F mixture that showed slightly higher expansion than the 50F mixture at all ages. It is well known that the particle size of glass found in the mixture is a critical factor influencing the reactivity. It can be seen in Fig. 4a, Figs. 5a and 6a that when the particle size is less than 1 mm, regardless of the color, no excessive expansion was observed in the specimens. This may be an indication of no reaction between glass and alkalies in the pore solution. According to the results of their study, Rajabipour et al. [16] reported that in the presence of glass, unlike most reactive natural aggregates, ASR does not occur at the aggregate-paste interface; rather it takes place in the pre-existing cracks in the interior of glass particles. It seems that as the particle size of glass is lowered, the accessibility (and perhaps the number) of cracks reduces and the penetration of pore fluid becomes more difficult.

Despite the delay of the expansion in the first weeks, particularly the 1–2F, 2–4F, 75F and 100F mixtures suffered great damage due to ASR manifested through map-cracks and formation of an arch-like shape due to their high amount of expansion after 180 d exposure to the NaOH solution. Fig 8a and b shows examples of cracked and uncracked specimens, respectively, while the surface views of 100F, 100G and 100A are compared in Fig. 8c. As it can be seen in Fig. 8c, although specimens belonging to the 100G and 100A mixtures expanded, their expansion levels were lower than that of 100F and any type of deterioration was not observed on the surface of these specimens. Photographs in Fig. 8 were captured at the end of the exposure to NaOH solution (180 d).

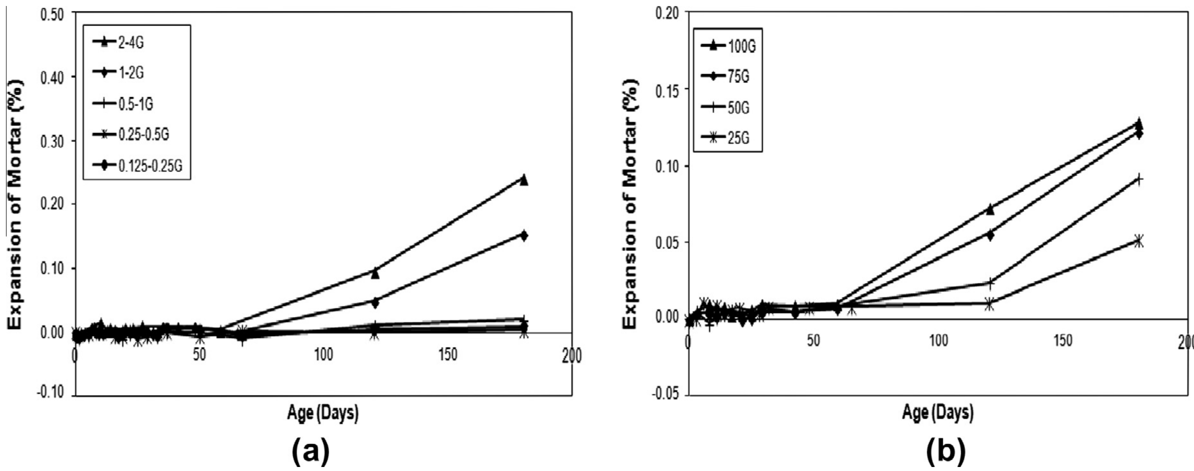

Fig. 6. Expansions of mortar bars including (a) monosize green glass, (b) green glass with varying percentages.

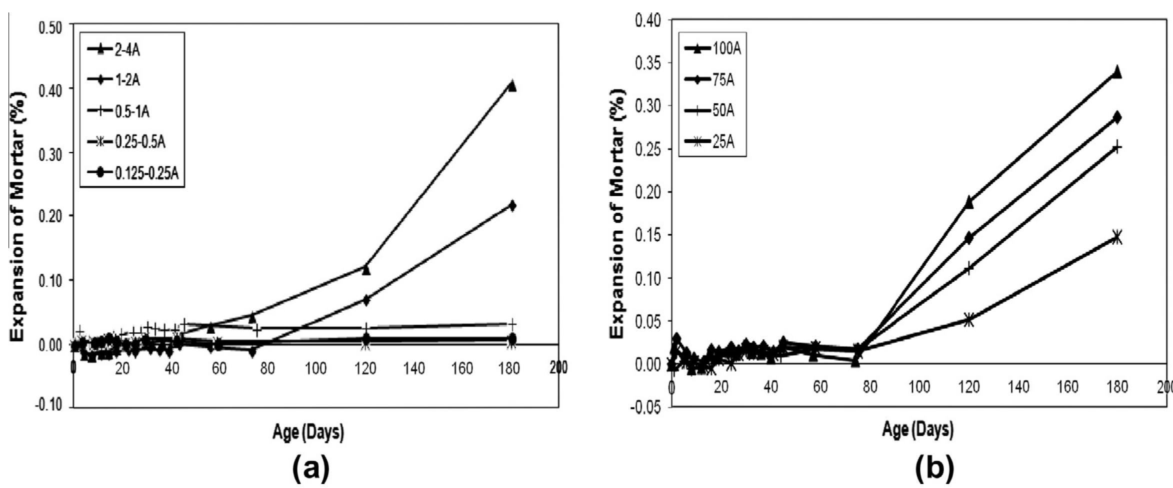

Fig. 7. Expansions of mortar bars including (a) monosize amber glass, (b) amber glass with varying percentages.

Previous studies which were conducted in order to examine ASR performance of glass aggregate by an accelerated mortar bar test led to a wide range of expansion values at the end of their 14-d soaking period. The current study and Zhu et al. [11] observed a time-lag behavior; in spite of applying a replacement level of 100%, for flint, amber and green glass, 14-d expansion values were all approximately zero. However, such a delay in expansion was not evident in other studies. For instance, Kou and Poon [24] prepared mortar bars containing different amounts of mixed-color glass aggregate up to 45% and reported a continuous increase in expansion at all replacement levels. Nevertheless, within 14 d, all expansion values remained below 0.1%. Similar results were obtained in another study conducted by Limbachiya [25] with a maximum replacement level of 20% for mixed-color glass. On the other hand, there also exist other studies in which glass aggregate caused higher expansion rates. At 100% replacement level, for amber and green glass, Park and Lee [12] observed approximately 0.7% and 0.25% expansion, respectively, while expansion values of the mixed-color glass including mixture reached 0.4% in the study conducted by Rajabipour et al. [16]. The discrepancy in the results may be attributed to the possible differences in the chemical composition, thermal history and degree of microcracking within the glass particles used by different researchers.

4.3. Concrete microbar test

Fig. 9a and b shows the microbar test results in terms of content and particle size of flint glass.

Grattan-Bellew et al. [22] found a linear trend in expansion for most tested aggregates up to 30 d. As can be seen in Fig. 8a, linear lines can indeed be plotted in order to present the expansion behaviors of flint glass-including mixtures tested up to 30 d in this study. Only the 75F and 100F mixtures exceeded the suggested expansion limit of 0.04% at 30 d. However, beyond this time, the rate of expansion increased sharply for all mixtures containing uncolored glass. Thus, it is apparent in Fig. 8b that the linearity in expansion behavior does not continue after 30 d. The highest expansion value again belongs to the 100F mixture which is followed by the 75F mixture.

It should be noted that the 9.5–12.5F mixture expanded to a higher degree than the 4.75–9.5F mixture, confirming the particle size effect observed in UAMBT results. Increasing the size of the glass aggregate in the mixture led to a higher expansion. Among the mixtures, 4.75–9.5F had the least amount of expansion at 90 d, which equals to nearly half of the expansion value of 25F. It seems that the effect of replacement of limestone with reactive glass aggregate (25F, 50F, 75F and 100F) on the ASR expansion is

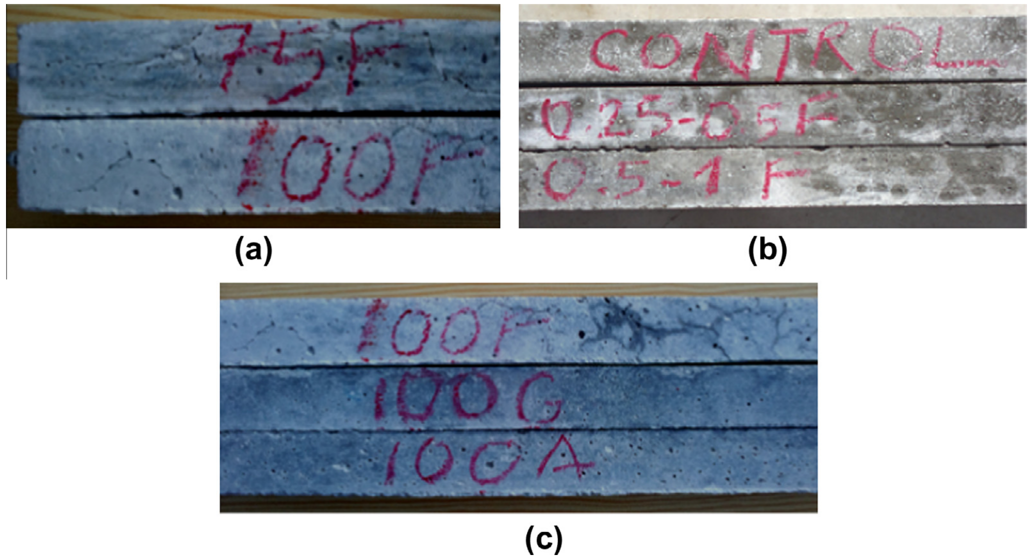

Fig. 8. Photographs showing the (a) crack formation – 180 d old 75F and 100F, (b) specimens without cracking – 180 d old Control, 0.25–0.5F and 0.5–1F, (c) comparison of surface views of 180 d old 100F, 100G and 100A.

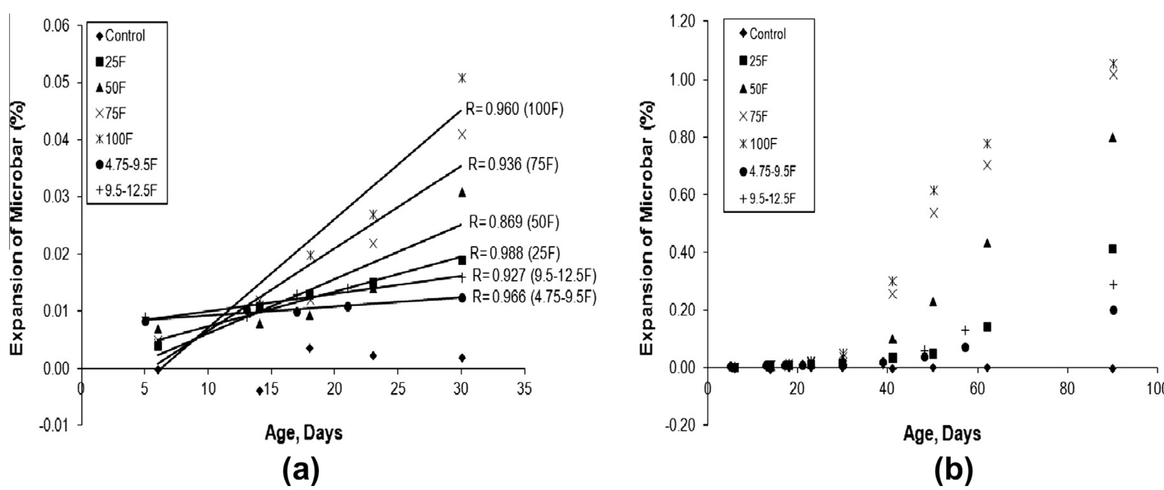

Fig. 9. Expansion of microbars containing flint glass up to (a) 30 d of exposure (b) 90 d of exposure.

Fig. 10. Cracking in (a) 25F and (b) 100F specimens.

more pronounced than the effect of a change in the grading of the reactive aggregate (4.75–9.5F, 9.5–12.5F).

At the end of the 90-d exposure period, all flint glass-including specimens in this test cracked heavily. In Fig. 10, photographs of two specimens belonging to the 25F and 100F mixtures are shown. When the results of the ultra accelerated mortar bar and microbar tests are compared, it is apparent that, glass as a coarse aggregate reacted more rapidly and the resulting deterioration showed that both the width and amount of developed cracks were higher.

On the other hand, microbars containing amber and green glass did not expand within the exposure time of 90 d. The inclusion of amber or green glass particles into the mixture prevented the dimensional instability of the mixtures in this period. Up to 90 d, the expansion values of these mixtures remained even below

0.005%. The only exception was the 100G mixture, which reached 0.022% and 0.065% length change values at 48 d and 90 d, respectively.

5. Conclusions

For the materials used and test methods applied, the following conclusions may be drawn:

1. Due to its amorphous nature and high SiO_2 and Na_2O content, the major concern in the utilization of soda-lime glass as aggregate is deleterious ASR. According to the results, testing environment, color, amount and particle size are all major factors affecting the rate and magnitude of expansion.
2. ASTM C1293 test results showed that flint and green glasses as fine aggregate seemed not to be reactive up to a 50% replacement level at 1 year, since expansion values did not exceed 0.04%. However, extending the test duration to 3 years led to a continual increase in expansion values of the flint glass-including mixtures.
3. Significantly, higher expansion values are observed when mortar bars are made with flint glass. Among the tested glasses, green glass was the least reactive according to the UAMBT results.
4. Microbar specimens prepared with amber or green glasses did not undergo expansion up to 90 d of exposure. However, length change values and visual observations showed that flint glass-including mixtures were highly reactive.
5. No pessimum size was observed in the experiments. As the particle size increased, the reactivity of the mixtures became greater. Probably due to their accelerated pozzolanic property, none of the glasses produced expansion when their particle size is reduced below 1 mm.
6. As mentioned before, due to the considerably long time-lag period, the proposed test duration in UAMBT was clearly not sufficient for all tested glass-including specimens. Similarly, in the microbar test, although the test was extended to 90 d, no expansion was observed in the amber and green glass-including specimens. It may be indicated that these tests are not as suitable as ASTM C1293 for assessing the reactivity of glass aggregate.

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