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The combined usage of ground waste glass with an industrial by-product in manufacturing Portland cement mortar

A. Yilmaz* and N. Degirmenci†

Department of Civil Engineering, Balikesir University; Department of Architecture, Balikesir University, Turkey

The aim of the present study was to investigate the possibility of using a combination of ground waste glass and fly ash as a replacement for Portland cement in the manufacture of mortar. Ground waste glass with an average particle size of 100 μm was used as cement replacement with a class C fly ash. The influence of waste glass and fly ash combination on the physical properties of cement paste such as the initial and final setting time, volume expansion and water requirement for normal consistency were investigated. The compressive and flexural strength measurements were conducted on the mortar samples at ages of 2, 7, 28 and 56 days. The effect of high temperature at 300, 600 and 900°C on the mortar samples was also investigated. Results indicate that cement paste containing the combination of waste glass and fly ash showed longer setting times than the reference Portland cement. The mortars demanded slightly more water mainly due to the high fineness of the fly ash. It was found that the replacement of Portland cement by a combination of waste glass and fly ash had no remarkable effect on the volume expansion. The mortars containing 5% waste glass + 5% fly ash and 5% waste glass + 10% fly ash satisfy the requirement of strength class 42·5 of the related standard.

Introduction

The utilisation of waste glass in construction has attracted worldwide interest due to large quantity consumption in widespread construction sites. Recently, many studies have focused on the uses of waste glass as a partial replacement of natural aggregates or cement in concrete (Park *et al.*, 2004; Taha and Nounu, 2008; Topcu and Canbaz, 2004). A major concern associated with the use of waste glass in concrete is the alkali–silica reaction (ASR) that takes place between the alkalis in cement paste and reactive silica in glass. This reaction can be detrimental to the stability of concrete. Recent studies have shown that there are several approaches that can effectively control the ASR expansion due to glass aggregate. Many studies have reported that the use of by-products and waste such as fly ash, silica fume, metakaolin and granulated blast-furnace slag are very important to produce durable concrete (Yuksel *et al.*, 2006; Zhu and Byars, 2004).

Previous studies have also reported that finely ground glass produces a fast pozzolanic reaction inhibiting the ASR reaction (Karamberi and Moutsatsou, 2005; Shayan and Xu, 2006). The pozzolanic reactivity of ground glass is derived from its high silica (SiO_2) content. Finely ground glass, with its high surface area, participates in the relatively quick pozzolanic reactions that eliminate the danger of ASR at a later age (Dyer and Dhir, 2001). Recent studies have shown that ground glass with a particle size finer than 38 μm exhibited pozzolanic behaviour. It has also been indicated that concrete containing finely ground glass exhibited a higher strength at both early and late ages (Shao *et al.*, 2000). In another study, which compared the effects of waste glass and class F fly ash on pozzolanic activity and ASR expansion, finely ground glass powders exhibited pozzolanic activity. The pozzolanic activity increases with increasing fineness of waste glass. Moreover, an increase in curing temperature accelerates the activation of pozzolanic activity. The curing temperature has a greater influence on the pozzolanic activity of glass powder than that of fly ash. The

* Department of Civil Engineering, Balikesir University, Cagis Campus 10145, Balikesir, Turkey.
† Department of Architecture, Balikesir University, Cagis Campus 10145, Balikesir, Turkey.

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replacement of Portland cement (PC) with finely ground glass powder also reduces the ASR expansion, although it is not as effective as fly ash (Shi *et al.*, 2005). A previous study has demonstrated that no reaction was detected with particle sizes up to 100 μm, thus the waste glass can be used as fine aggregate in mortar and concrete (Corinaldesi *et al.*, 2005).

The addition of reinforcing fibres to mortar bars improved the reduction of expansion and strength caused by ASR between the alkali in the cement paste and the silica in the waste glass (Park and Lee, 2004). It has been reported that the combined use of waste glass and granulated blast-furnace slag or waste glass and fly ash could be more suitable than using waste glass alone in mortar (Ozkan and Yuksel, 2008). Replacement of cement by combining waste glass with by-products increased the resistance of mortars to sulfate attack. Fly ash and granulated blast-furnace slag also reduced the ASR expansion. Ternary blends containing glass powder and fly ash are very effective in reducing expansion due to ASR. The combination of glass powder and fly ash blends that made up a 20% cement replacement level was observed to be as efficient as 20% fly ash in reducing expansion (Schwarz *et al.*, 2008).

In this study, the effects of a ground waste glass (WG) and class C fly ash (FA) combination when used as a PC replacement material on the properties of cement mortar were investigated through different combinations of WG and FA. Data reported in the literature show that if waste glass is finely ground to less than 100 μm, the ASR-induced damage is minimised. Also, the combination of glass powder and fly ash has been found to be effective in reducing ASR expansion. For this reason, ground waste glass with an average size of particle of 100 μm together with class C fly ash was used as cement replacement for preparing PC mortars in the present study. In the current authors' previous study waste glasses with different colours and contents were used as a replacement for limestone sand. In all mixtures, three different colours of waste glass (white, green and brown) were substituted in weight ratios of 0, 10, 30 and 100 of each limestone size fraction, respectively. The mixtures used in the study did not show any considerable ASR expansion (Yilmaz *et al.*, 2009). Thus, ASR expansion of the investigated mortars was not investigated in the present study. Setting times, water requirement for normal consistency, volume expansion of cement pastes and the strengths of cement mortars after 2, 7, 28 and 56 days were measured. The effect of high temperatures at 300, 600 and 900°C was also investigated for the mortar samples.

Reusing waste glass and fly ash in construction can reduce the demand for the sources of primary raw materials. Utilisation of waste glass with fly ash offers important benefits both environmentally and economically.

Experimental study

Materials and mix proportions

The cement used in the mortar mixture, an ordinary Portland cement (CEM I), had a strength class 42·5 N according to Turkish standard TS EN 197-1 (Turkish Standards Institution, 2002a). The specific gravity and specific surface area of PC was 3·15 and 3516 cm^2/g, respectively. The physical, chemical and mechanical properties of the cement are given in Table 1. Fly ash (FA) was obtained from Soma Seas thermal power plant in Manisa, Turkey. The Soma FA is produced from lignite coal. The chemical composition of Soma FA is given in Table 1. According to ASTM C 618 Soma FA can be classified as class C fly ash due to its chemical composition. In addition to having pozzolanic properties this fly ash also has some cementitious properties. The total amount of silica (SiO_2), aluminium oxide (Al_2O_3) and ferric oxide (Fe_2O_3) was 74·32% and the calcium oxide (CaO) content was 24·54%. The pozzolanic activity index of Soma FA is 88% at 28 days and the amount retained on a 45 μm sieve was 16%. CEN standard sand defined in TS EN 196-1 (Turkish Standards Institution, 2002b) was used as an aggregate in the manufacture of the mortars.

The waste glasses (WG) used in the experiments were soda lime bottles. After collection these bottles were kept in water to remove organic contaminants and

Table 1. Physical, chemical and mechanical properties of PC, FA and WG

Chemical composition: %	PC	FA	WG	Physical properties of PC	
SiO_2	20·04	46·26	57·41	Specific gravity	3·15
Al_2O_3	5·81	23·54	1·68	Initial setting time: min	150
Fe_2O_3	3·62	4·52	0·86	Final setting time: min	185
CaO	61·52	24·54	14·83	Volume expansion: mm	2·00
MgO	1·43	1·67	2·75	Specific surface: cm^2/g	3516
Na_2O	0·18	0·25	6·42	Compressive strength: MPa	
K_2O	0·94	1·17	0·60	2 days	23·02
SO_3	2·87	1·28	0·16	7 days	41·50
Free CaO(%)	1·41	–	–	28 days	50·37
Cl^-	0·013	–	–	Specific surface of FA: cm^2/g	3794
Loss on ignition	2·60	1·35	9·37	Specific gravity of FA	1·95

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were then crushed in the laboratory. Ground glass with an average size of particle of 100 μm was used as cement replacement. The chemical properties of the waste glasses are presented in Table 1. Mortar samples were produced according to the procedure described in TS EN 196-1 (Turkish Standards Institution, 2002b). Seven mortars were prepared, one of them being a reference PC mortar containing standard sand at a ratio of 3 : 1 with respect to the cement dosage. For the other six mortars, WG and FA were used as replacement by weight for PC and the sand and water quantities were kept constant. Three mortars were prepared by replacing PC with 5% WG plus 5, 10 and 15% FA and in the other three mortars, 10% WG was used with 5, 10 and 15% FA. The water-to-cement ratio of the mortars was 0·5 as specified in TS EN 196-1 (Turkish Standards Institution, 2002b). The mixture proportions for the mortar are reported in Table 2. The mortars containing the WG and FA combinations were designated as 5GF10, etc. with the number on the left representing the percentage of glass powder, and the number on the right representing the percentage of fly ash added.

Experimental methods

The cement, glass powder, fly ash and sand were initially dry-mixed in a Hobart mixer and then water was added. The mixtures were cast in two layers into three-gang moulds and compacted for 60 s by a vibration table. After casting, all samples were stored in a moisture room for 24 h at relative humidity of 90–95% at 20 ± 3°C. After demoulding, the samples were cured in water at 20 ± 3°C until the time of testing.

The standard consistency of cement paste containing different WG and FA combinations was measured by the Vicat apparatus using a 10 mm diameter plunger. The water content was expressed as a percentage by weight of cement mixtures. Cement pastes having standard consistency were used to determine the initial and final setting times. The setting times of the cement pastes were measured using a Vicat needle at room temperature in accordance with TS EN 196-3 (Turkish Standards Institution, 2002c). The soundness test was conducted by using Le Chatelier apparatus as described in the related Turkish standard. The test results are given in Table 3.

The flexural and compressive strength tests were performed at 2, 7, 28 and 56 days in conformance with TS EN 196-1 (Turkish Standards Institution, 2002b). For the flexural strength test, three samples from each mix were prepared and tested by a one-point loading configuration with a span of 10 cm. The flexural strength test was performed in an ELE model testing machine with a capacity of 10 kN. The results indicated are the average results of the three samples. Compressive strength tests were conducted using six broken pieces of test prisms obtained after the flexural strength test as per TS EN 196-1 (Turkish Standards Institution, 2002b). The compressive strength measurements were carried out using an ELE International ADR 3000 hydraulic press with a capacity of 3000 kN, the loading rate was 2·5 kgf/cm^2 per s. The test results represent the average of the six samples. The results of compressive and flexural strength tests are presented in Table 4 and Figures 3 and 4 below, respectively.

Table 2. Mix proportions of reference PC mortar and the mortars containing WG and FA

Designation	Mix proportion	PC	WG	FA
Reference PC	100% PC	100	0	0
5GF5	90%PC + 5%WG + 5%FA	90	5	5
5GF10	85%PC + 5%WG + 10%FA	85	5	10
5GF15	80%PC + 5%WG + 15%FA	80	5	15
10GF5	85%PC + 10%WG + 5%FA	85	10	5
10GF10	80%PC + 10%WG + 10%FA	80	10	10
10GF15	75%PC + 10%WG + 15%FA	75	10	15

Table 3. Normal consistency water, setting times and volume expansion of the mortar mixtures

Designation	Normal consistency water: %	Setting time: min (Vicat)		Volume expansion: mm (Le Chatelier)
		Initial	Final	
Reference PC	27·6	164	227	1
5GF5	31·4	260	340	1
5GF10	33·8	310	370	1
5GF15	34·0	270	370	1
10GF5	30·2	260	350	1
10GF10	32·4	240	320	1
10GF15	33·0	270	370	1

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Table 4. Mechanical properties of the reference PC mortar and the mortars containing WG and FA

Mix	Compressive strength: MPa				Flexural strength: MPa			
	2 days	7 days	28 days	56 days	2 days	7 days	28 days	56 days
Reference PC	23·02	41·50	50·37	59·54	3·98	6·94	7·84	8·50
5GF5	23·35	37·55	48·52	49·83	4·68	6·20	7·64	7·96
5GF10	23·01	33·21	43·29	48·76	4·02	5·23	6·94	7·96
5GF15	19·45	29·88	38·83	47·15	3·12	4·64	6·40	7·41
10GF5	21·26	33·30	40·98	50·05	4·10	5·30	7·41	8·15
10GF10	19·43	26·32	33·77	44·45	3·67	4·33	5·93	6·75
10GF15	17·26	24·82	33·59	42·69	3·00	3·86	5·85	7·49

The effect of high temperature at 300, 600 and 900°C was investigated using 5 cm cube mortar samples. Three mortar samples were prepared from each group. The samples were demoulded after 24 h and then cured in water for 28 days. After curing the samples were kept at 105°C for 24 h for drying. The samples were put into a furnace and the temperature of the furnace was then raised to the desired temperature. The rate of heating of the furnace was 9°C/min. When the inner temperature of the furnace had reached the desired temperature, the samples were kept for 2 h in the the furnace. At the end of the heating process, the furnace was turned off and left to cool to room temperature. After the cooling process was completed the samples were weighed and the compressive strength tests were conducted on the cooled samples. The compressive strength of the heated samples was measured. Weight and compressive strength loss were determined by dividing the values after the heating process by values before heating. The weight and compressive strength losses of the PC reference mortar and the other mortar samples at various temperatures (300, 600 and 900°C) are presented in Table 5 and Figures 6 and 7 later.

Test results

The water consistency, setting times and volume expansion of the reference PC and the cement pastes containing WG and FA combinations are given in Table 3. Figure 1 also illustrates the effect of WG and FA combination as cement replacement on the initial and final setting time of the cement pastes. Both initial and final setting times exhibited an increase for the mortars containing the WG and FA combinations. The observed retardation in the initial and final setting times may be attributed to the rate of the pozzolanic contribution of fly ash. The test results showed that the initial setting time of the PC was 164 min and the final setting time was 227 min. The initial setting times of cement pastes containing the WG and FA combinations were in the range 240–310 min and the final setting times were from 320 to 370 min. The maximum difference in initial setting times between the PC and cement pastes containing WG and FA combinations was 146 min and this value was 143 min for the final setting times. According to TS EN 196-3 (Turkish Standards Institution, 2002c), the initial setting time of PC should

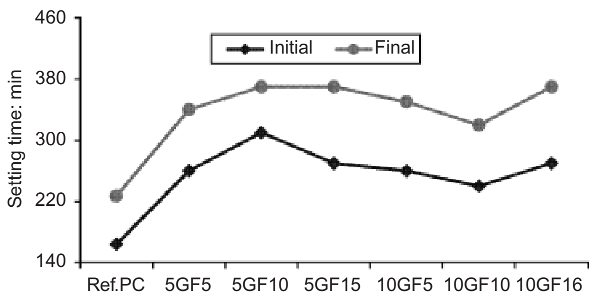

Figure 1. Setting times of cement pastes containing WG + FA

Table 5. Weight and compressive strength loss of the samples under elevated temperatures (300, 600 and 900°C)

Designation	Weight loss: %			Compressive strength loss: %		
	300°C	600°C	900°C	300°C	600°C	900°C
Reference PC	6·05	7·80	8·78	11·73	61·96	89·48
5GF5	6·19	7·60	9·44	9·50	61·42	80·44
5GF10	6·64	7·75	9·55	6·17	57·66	72·65
5GF15	6·43	7·45	9·11	6·43	52·02	73·55
10GF5	5·55	6·88	9·00	13·25	35·36	74·21
10GF10	5·19	6·94	8·38	1·42	45·42	74·74
10GF15	5·16	6·77	8·34	1·58	40·73	61·83

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not be shorter than 60 min and its final setting time should not be longer than 600 min. All setting time results obtained in the present study were within these limits.

Table 3 and Figure 2 indicate that the water requirement of the cement paste increased with the increased quantity of WG and FA combination. The water demand of the cement pastes containing the WG and FA combinations varied from 30·2 to 34·0% whereas the reference PC had a water demand of 27·6%. The slight increase in water demand should be attributed mainly to the high fineness of the FA. The specific surface area of the FA was higher than that of the PC and so the FA needed more water. The Le Chatelier test results of volume expansion are given in Table 3, which remained within the limits of the corresponding standards. The volume expansion of the mortars measured according to the Le Chatelier process was 1·0 mm whereas the limit according to TS EN 196-3 (Turkish Standards Institution, 2002c) was 10·0 mm.

The compressive strength test results of reference PC mortar and the investigated mortars are presented in Table 4 and also in Figure 3. According to the test results, a 28-day compressive strength value of 50·37 MPa was obtained for the reference PC mortar. The mortars containing WG and FA combinations achieved 28-day compressive strengths in the range 48·52–33·59 MPa. The compressive strength of the mortar containing 5%WG + 5%FA was 48·52 MPa, which was close to the strength of PC reference mortar at 28 days. Based on the 28-day strength results, the mortars

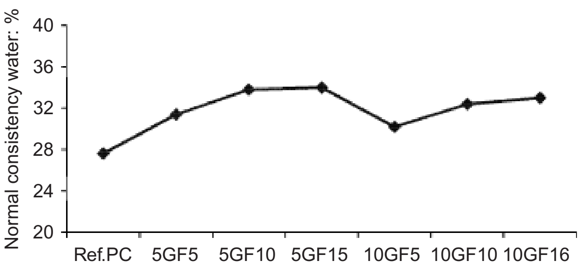

Figure 2. Normal consistency water of cement pastes containing WG + FA

containing 5%WG + 5%FA and 5%WG + 10%FA met the compressive strength requirement of 42·5 MPa in the Turkish standards. The mortar mixtures containing WG and FA combinations had lower strength than the PC reference mortar at the ages of 2, 7, 28 and 56 days. For the combination 5%WG + 5%FA, there was a decrease of 3·67% in the 28-day compressive strength, whereas there was a decrease of 22·91% in the compressive strength of mortar with 5%WG + 15%FA. When the proportion of WG was 10%, a decrease of 33·61% in 28-day compressive strength was determined for the 10%WG + 15%FA combination This decrease may be attributed to the change in the nature of the hydration products. The maximum strength losses observed in 7 days were 40·19% for 10%WG + 15%FA. In comparison with the PC reference mortar, the mortar containing 5%WG + 5%FA had a higher early strength. The reference PC mortar had a compressive strength of 23·02 MPa at 2 days and the 2-day compressive strength of mortar containing 5%WG + 5%FA was 23·35 MPa. For the 5%WG+10%FA combination the compressive strength was 23·01 MPa, which was very close to the compressive strength value of the PC reference mortar at 2 days. The high early strength could be attributed to the high alkali content in soda lime glass. The presence of fly ash in mortar mixtures decreased the early strength. Comparison of strength results at ages of 2, 7, 28 and 56 days generally showed moderate increases in the strength with age.

Figure 4 shows the influence of WG and FA combinations on the flexural strength with time. The results showed that the flexural strength decreased with the increasing WG and FA combinations at all ages. Flexural strength was observed to change consistently between 7·64 and 5·85 MPa at 28 days. The PC reference mortar reached 7·84 MPa at 28 days. Flexural strength of the mortar containing 5%WG + 5%FA was close to the flexural strength of the reference PC mortar at 28 days.

To observe the high-temperature resistance of the mortars, samples were exposed to different high temperatures (300, 600 and 900°C). Figure 5 shows the mortar samples after exposure at elevated temperatures.

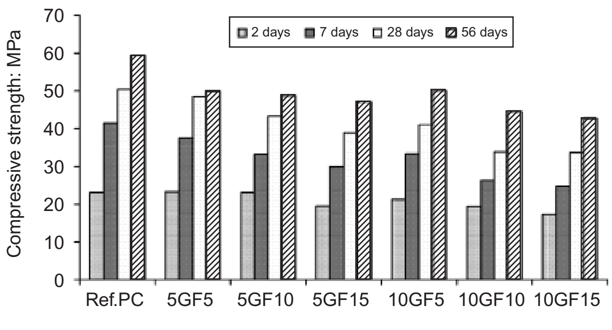

Figure 3. Compressive strength of the mortars containing WG + FA

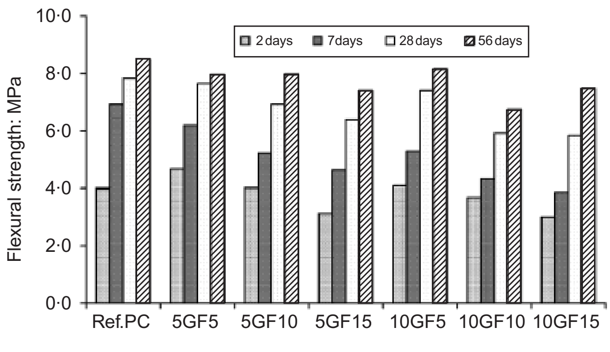

Figure 4. Flexural strength of the mortars containing WG + FA

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The compressive strength loss and weight loss of the mortar samples after elevated temperature exposure are given in Table 5 and Figures 6 and 7, respectively. From 20 to 300°C, the mortars showed decreases in strength. The maximum strength loss was shown by the reference PC mortar which was 11·73% of the original strength. The compressive strength loss varied between 1·42 and 13·25% for the mortars containing WG and FA at 300°C. No visible cracking or spalling of the specimens was observed in this temperature range. Compressive strength losses were rapid for temperatures over 300°C. From 300 to 600°C, a significant strength loss was observed in the mortars. The strength loss was 61·96% for the reference PC mortar. At 600°C the compressive strength loss ranged between 40·73 and 61·42% for the mortars containing WG and FA. Hairline cracking was observed in the mortars and no spalling occurred in any specimens. A severe strength loss was observed in the 600–900°C temperature range. The average loss was 89·48% in the reference PC mortar. The compressive strength loss ranged between 61·83 and 80·44% for the mortars containing WG and FA at 900°C. For each temperature, the mortars containing WG and FA performed better and showed no spalling or cracking except for a few hairline cracks.

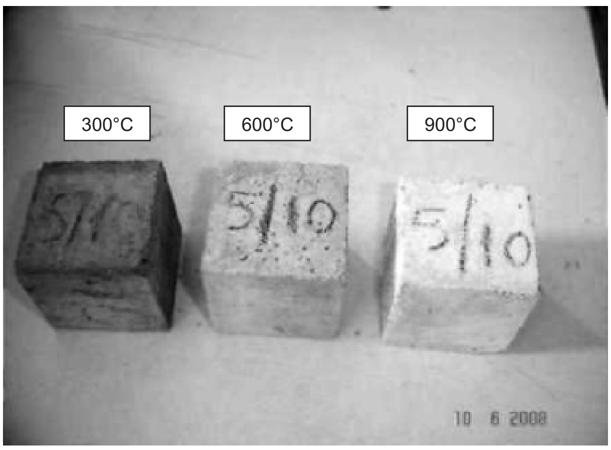

Figure 5. Exposure of the samples to elevated temperatures, 300, 600 and 900°C

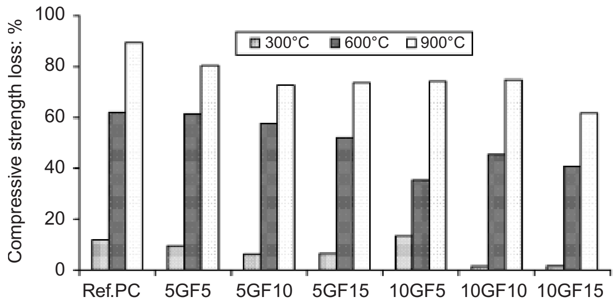

Figure 6. Compressive stength loss of the mortars at elevated temperatures

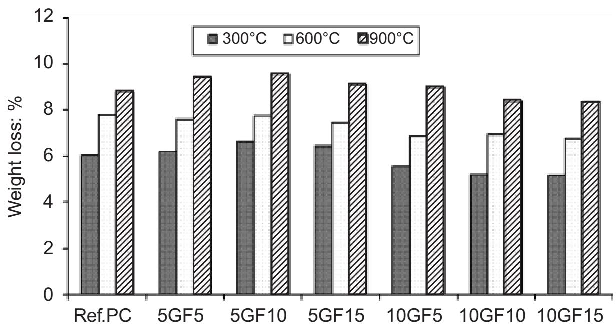

Figure 7. Weight loss of the mortars at elevated temperatures

The basic factor of the compressive strength in the reference PC mortar is related to matrix structural properties when exposed to elevated temperatures. For the mortars containing WG and FA combinations this factor was related to the properties of the FA and WG. It was found that FA improved the performance of the mortar at elevated temperatures in comparison with the reference PC mortar. FA also reduced the surface cracking of the mortar at elevated temperatures after post-cooling in air. The reduced calcium hydroxide in the cement pastes containing FA, which is due to pozzolanic reaction, could lead to reduced cracking. Sarshar and Khoury (1993) also reported that the benefical effect of the presence of FA was good for exposure to temperatures above 300°C. As supported by previous literature, the addition of FA enhanced the residual properties of the concretes at elevated temperatures (Poon *et al.*, 2001). Xu *et al.* (2001) studied the effects of pulverised FA replacement and the residual properties of concrete at elevated temperatures. They indicated that pulverised FA concrete specimens showed better performance up to 650°C than ordinary PC specimens. It was also found that high-volume FA concrete exhibited a much better fire resistance for maximum exposure temperatures of 450–600°C. The beneficial effect of FA diminished when the exposure temperature was raised to 800°C. Grainger (1980) carried out research on the cement FA paste subjected to high temperatures and found that the addition of FA could improve the residual compressive strength of cement paste, especially above 300°C. Previous studies have shown that WG also had a positive effect on the high-temperature resistance of mortar and concrete. Terro (2006) investigated the effect of the replacement of fine and coarse aggregates with recycled glass on the fresh and hardened properties of concrete at ambient and elevated temperatures. He indicated that the concretes made with waste fine glass aggregates had higher compressive strengths than those made with coarse glass aggregates at ambient and elevated temperatures. Concretes made with 10% aggregate replacement with waste glass possessed higher compressive strength than normal concrete at temperatures above 150°C. He ex-

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plained that the free water retained in the mix was dissipated at elevated temperatures much more readily in mixes containing glass than in the control concrete as glass does not absorb water. Thus concrete that was made with waste glass was more compact after the evaporation of free water at around 150°C. Alhumoud *et al.* (2008) indicated that with the use of between 10 and 25% crushed glass in concrete, the compressive strength exhibited higher values than those of normal concrete at ambient and elevated temperatures. Higher residual strength values were obtained for mortars that contained granulated blast furnace slag (GBFS)–glass and FA–glass than those of the mortars that were not exposed to high temperature. FA showed better behaviour than GBFS for high-temperature resistance (Ozkan and Yuksel, 2008).

In the present study, mortars that included combinations of WG and FA exhibited higher compressive strength than that of the reference mortar at elevated temperatures. However, further studies on the long-term strength and durability of the mortar should be undertaken.

Conclusions

In the present study, the effects on the properties of cement mortar of ground waste glass (WG) and class C fly ash (FA) combinations used as PC replacement material were investigated and, based on the experimental results, the following conclusions were made.

(*a*) The cement paste containing WG and FA combinations showed longer setting times than the reference PC. Setting times remained within the limits defined in the related standards. The observed retardation in the initial and final setting times may be attributed to the rate of pozzolanic reaction of FA.

(*b*) To reach the same workability, mortar with WG and FA would require a higher content of water than the reference PC mortar, mainly due to higher fineness of FA.

(*c*) It was found that the use of the replacement WG and FA combination instead of PC had no remarkable effect on the volume expansion. These values were within the permissible limits of the corresponding standards.

(*d*) The mortars containing 5%WG + 5%FA and 5%WG + 10%FA satisfied the requirements of the strength class 42·5 of TS EN 197-1 (Turkish Standards Institution, 2002a).

(*e*) Mortars made with WG and FA combination increased the compressive strength at elevated temperatures. The compressive strength loss decreased with WG and FA combination. The maximum loss in compressive strength was 89·48% at 900°C for the reference PC mortar. This value was 80·44% for the 5%WG + 5%FA and 61·83% for the 10%WG + 15%FA mortars at 900°C.

The mortars containing WG and FA combination had higher setting times and lower strength at ambient temperatures but they presented certain advantages such as higher resistance to elevated temperatures, lower energy cost and environmentally friendly building materials for concrete and pavement applications. The recycling of WG poses a major problem for municipalities everywhere and FA also poses a major waste disposal problem throughout the world. These problems can be reduced or eliminated by reusing WG and FA in the construction industry. The reuse of WG and FA in construction can also reduce the demand on the sources of primary raw materials. Utilisation of WG and FA offers important benefits both environmentally and economically.

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