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Synergistic effect of waste glass powder and fly ash on some properties of mortar and notably suppressing alkali-silica reaction

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Abstract: In this study the mitigation influence of incorporating waste glass powder (G) and class F fly ash (F) in mortar as partial cement replacement on the alkali-silica reaction (ASR) between reactive aggregate and alkali contents of cement were investigated. Waste G and F replaced cement separately and together on mass basis at 10%, 20%, and 30%. The unit weight (28 days), water absorption, porosity, compressive, and flexural strength tests were conducted at 28- and 90-day water curing time on 40×40×160 mm prismatic hardened samples and flow table test on fresh mortar. There was a slight reduction of the unit weight, an increased workability, and decreased water absorption and porosity; a little reduction of the compressive strength and flexural strength were seen after the tests. In addition, the expansions of mortar were measured up to 90 days. When 14 days expansions were considered according to ASTM C1260, addition of waste G and F separately reduced the expansion that occurred due to ASR. However, the mixture containing 15% waste G and 15% F together (GF-30) exhibited the lowest expansion in the order of 0.02% which was far lower than 0.10%. The higher replacement ratio of waste G and F together and separately caused lower expansion in mortar.

Keywords: Alkali silica reaction, glass powder, fly ash, expansion.

1. Introduction

The alkali–silica reaction (ASR), more commonly known as "concrete cancer", is a chemical deterioration process that occurs between the alkalis of cement paste and the reactive amorphous silica from the aggregates (Moser et al. 2010; Shafaatian et al. 2013; Shehata and Thomas 2000; Zheng 2016). Mitigation of ASR in concrete is essential for durable and sustainable constructions (Shi et al. 2018). The ASR is a complex reaction that takes place between the hydroxyl ions (OH^-) in the pore water of the concrete and the active silica contained in the aggregate (Swamy 1991). The chemical gel formed due to the ASR absorbing a high amount of water and causing internal stresses, deformations, and cracks in the concrete.

These cracks increase the permeability of the concrete; therefore, it causes corrosion on reinforcement steel. There are many factors that affect ASR: reactive silica form, a certain amount of alkaline material and humidity must be present in the environment for the ASR to occur (Comi, Kirchmayr, and Pignatelli 2012; Drolet, Duchesne, and Fournier 2017; Gautam and Panesar 2017; Shehata and Thomas 2006).

Many studies have been carried out to reduce the harmful effects of ASR. These effects are reduced by the use of fly ash (Shehata and Thomas 2000; Ye and Chen 2019), granulated blast furnace slag (Kandasamy and Shehata 2014), metakaolin (Moser et al. 2010), silica fume and different pozzolans in concrete. Apart from these commonly used supplementary cementitious material (SCM), improvements have been made with other materials such as glass powder (He et al. 2020), nano-SiO_2 (Cai, Xuan, and Poon 2019) and rice husk ash (Abbas, Kazmi, and Munir 2017). Generally, it has been possible to reduce the harmful effects of ASR to harmless levels specified in the standards with the replacement of 20-30% fly ash, 5-10% metakaolin and 50% slag with Portland cement.

Shehata and Thomas carried out a study on the alkali release characteristics of blended cements. As a result of their experimental study, they reported that using only fly ash with high content of calcium ions is not particularly effective in preventing ASR. However, they concluded that the using 5% silica fume with fly ash in mixture considerably contributed to the suppression of ASR (Shehata and Thomas 2006).

Bleszynski and Thomas (Bleszynski and Thomas 1998) examined microstructural studies of ASR in fly ash concrete immersed in alkaline solutions. They reported that using 40% or higher amount of fly ash in the mixture as cement replacement prevented ASR, thoroughly.

In their study, Kandasamy and Shehata (Kandasamy and Shehata 2014), prepared binary and ternary mixtures using cement, slag and high-calcium fly ash materials to control ASR expansion. They found out that fly ash is more effective than slag in reducing ASR expansion. Shehata and Thomas concluded that using more fly ash results in a higher reduction of ASR expansion. They observed that for a given fly ash replacement level, the expansion was found to increase as the calcium or alkali content of the ash increases or its silica content decreases. Therefore, the minimum level of fly ash required in the mixture to limit the expansion of ASR to an acceptable level increases as the calcium or alkali content of the ash increases or its silica content decreases.

Afshinnia and Rangaraju (Afshinnia and Rangaraju 2015) worked on controlling ASR expansion in concrete mixture and they used C class fly ash, metakaolin, slag and glass powder alone and in different combinations. They concluded that when fly ash and metakaolin are used with glass powder, they are more effective in mitigating the harmful effects of ASR.

Zheng (Zheng 2016) investigated the pozzolanic properties of glass powder and its effects on ASR. In the study, under 50-micron glass powder and 125-200-micron granular glass powders obtained by grinding colored and colorless glasses were used. Expansion due to ASR was determined as 0.64% and 0.29% for control mortar after 14 days. In mixtures where glass powder is used as a cement replacement, it has been observed that the expansions from ASR have decreased to very low non-hazardous levels, 0.1%.

In their study, Kamali and Ghahremaninezhad (Kamali and Ghahremaninezhad 2015), determined 20% glass powder was more effective in reducing the expansions caused by ASR than 20% F class fly ash as cement replacement. In addition, they found that using glass powder outperformed fly ash in terms of compressive strength.

In another study examining the effect of particle size on ASR expansion that was carried out by Hongjian and Tan (Du and Tan 2013), it was concluded that glass pieces with particle size lower than 1 mm were found to be not harmful for ASR. However, it has been observed that glass particles with size larger than 1 mm cause ASR. The effect of the physical and chemical properties of the glass from which the glass powder is obtained on the ASR should not be ignored.

In the studies conducted, differences were observed in ASR, even between green, brown, and clear glasses; in some studies, mortar bars with green glass powder showed the lowest expansion (Park and Lee 2004; Topçu, Boğa, and Bilir 2008).

Adesina and Das carried out a laboratory study to evaluate the influence of glass powder on the durability properties of engineered cementitious composites. They observed that no detrimental ASR expansion (measure in comply with ASTM C1260) occurs in any of their specimens made with SCMs including glass powder and fly ash (Adesina and Das 2020).

Fanijo et all, studied on ASR mitigation using binary and ternary blends with waste glass powder. They used SCMs in their mixtures which were slag, silica fume and waste glass powder. They utilized ASTM C1260 testing procedure for ASR expansion measurement. They reported that all the SCMs used in their study reduce the ASR expansion, moreover, 30% replacement with glass powder with cement was the only mixtures to mitigate the ASR expansion of mixtures keeping the expansion under the specified limit of the respective test methods (Fanijo, Kassem, and Ibrahim 2021).

Schwarz et all, studied on influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash. They reported that glass powder and fly ash as a cement replacement material demonstrated the potential to reduce deleterious expansion due to ASR. Their study showed that fly ash replacement with cement gave larger reduction in ASR expansion contrary to glass powder. Moreover, they claimed that ternary blends containing glass powder and fly ash are very effective in reducing ASR expansion (Schwarz, Cam, and Neithalath 2008).

Bueno et all, made a review study on ground waste glass as a supplementary cementitious material particularly focusing ASR. After reviewing many studies, they summarized that waste glass used as a pozzolan decreases expansion caused by ASR. However, they commented that there was still a need for validation if waste glass can prevent ASR (Bueno et al. 2020).

Many studies have been conducted on mixtures in which pozzolans are used alone, binary or ternary to mitigate the harmful effects of ASR expansion. Studies show on the influence of using glass powder on the mechanical and durability related properties of concrete. However, based on the literature review, there are very few studies to evaluate the effect of using glass powder individually or in combination with fly ash in concrete. There is a discrepancy in the literature since some of these studies reported that fly ash performs better, while others stated that glass powder performs better. ASR expansion was generally measured over 14 days, and long-term measurements were not taken place in published literature (Afshinnia and Rangaraju 2015; Bleszynski and Thomas 1998; Schwarz et al. 2008)

This study investigated using fly ash and glass powder in mortar as cement replacements to reduce the harmful effects of ASR expansion. Mixtures were prepared by replacing class F fly ash and glass powder separately or together with cement. Accelerated mortar bar, unit weight, workability, flexural and compressive strength, porosity and water absorption tests were carried out on the mortar samples made with and without SCM in the mixtures. The results obtained from the experimental study are presented and evaluated.

2. Materials and methods

2.1. *Materials*

CEM II / A-M 42.5R type cement with an equivalent high alkali content (Na_2O+0.658K_2O=1.1%) was used. Blaine's fineness of cement was 3650 cm^2/g and, the volume expansion of cement was less than 0.20% which complies with the ASTM C1260 (ASTM C1260 2014). The glass powder was produced by pulverizing ordinary window glass. The glass powder was sieved using a 45-micron sieve, and glass powder past 45-micron sieve was utilized in the mixture. F class fly ash used in this study was provided from Sugözü thermal power plants located in Turkey. The specific gravity of cement, waste glass powder (G) and fly ash (F) were 3.07, 2.50 and 2.27 g/cm^3, respectively.

The chemical oxide composition of cement, fly ash and waste glass powder was performed by using X-ray fluorescence analysis (XRF) and was given in Table 1. The reactive aggregate was obtained from the river Kelkit delta which was located in upper Kızılırmak in Turkey. The supplied reactive aggregate was graded according to ASTM C1260 (ASTM C1260 2014) standard.

The aggregate specific gravity was measured by Archimedes principle and it was 2.45 g/cm^3. Sieve analysis of aggregate was presented in Table 2. Pure water according to ASTM D 1193 (ASTM, 2017) specification was used in the production of the mortar samples.

Table 1. Chemical oxide components of binders.

(%)	Cement	Glass powder	Fly ash
SiO_2	17.72	67.52	58.93
Al_2O_3	5.36	0.83	21.44
Fe_2O_3	3.03	0.44	6.58
CaO	55.80	8.96	2.79
MgO	1.94	4.27	1.61
SO_3	3.30	0.21	0.24
Na_2O	0.53	16.78	1.53
K_2O	0.86	0.14	2.51
LOI	3.86	1.00	2.27
Insoluble residue	6.51	-	-

Table 2. Gradation of reactive aggregate.

Sieve size		Mass (%)
Passing	Retained on	
4.75 mm	2.36 mm	10
2.36 mm	1.18 mm	25
1.18 mm	600 µm	25
600 µm	300 µm	25
300 µm	150 µm	15

2.2. Mixture design and testing

The mortar samples were produced at a sand/binder ratio of 2.25 and a water/binder ratio of 0.47. The waste glass powder and fly ash were replaced separately and together at the ratios of 10%, 20% and 30% by cement mass and used for mixture production. The reactive aggregate according to ASTM C1260 (Abbas et al. 2017) was used for all mixtures. The fresh mortars were mixed and prepared in a Hobart mixer. Mix proportions are presented in Table 3.

Table 3. Mortar mixtures proportions.

Materials (g)					
Mixture	Cement	Glass Powder (G)	Fly Ash (F)	Water	Aggregate
Control	440	-	-	206.8	990
G-10	396	44	-	206.8	990
G-20	352	88	-	206.8	990
G-30	308	132	-	206.8	990
F-10	396	-	44	206.8	990
F-20	352	-	88	206.8	990
F-30	308	-	132	206.8	990
GF-10	396	22	22	206.8	990

GF-20	352	44	44	206.8	990
GF-30	308	66	66	206.8	990

The workability was measured with mini flow table while the mortar was fresh according to TS EN 1015-3 (EN 1015-3 1999). Density of mortars were measured after 28 days water curing at 23°C in compliance with ASTM C642 (ASTM C642-13 2013). The water absorption and porosity (voids) tests were performed at 28 and 90 days water curing time, using 40×40×160 mm sized prismatic samples according to ASTM C642 (ASTM C642-13 2013). The compressive and flexural strength tests were carried out in accordance with TS EN 1015-11 (EN 1015-11 2006) at 28 and 90 days. The three-point flexural strength test was carried out on a 40x40x160 mm sample. The compressive strength test was carried out using a 40x40 plate on end of six broken pieces of specimens obtained after the flexural strength test.

The influence of using waste glass powder and fly ash on the expansion of the ASR of the mortar produced with reactive aggregate was investigated. For this purpose, mortar bars containing different amounts of waste glass powder and fly ash were produced, separately and together. ASR test was carried out on 25×25×285 mm sized prismatic samples in accordance with ASTM C1260 (ASTM C1260 2014). ASTM C1260 (ASTM C1260 2014) method specified that expansion at 14 days is lower than 0.10% represent harmless aggregate, aggregates with a expansion at 14 days greater than 0.20% represent potentially hazardous aggregate, expansion between 0.10% and 0.20% at 14 days represent suspicious aggregate. After casting mortar bars, samples were kept and cured in a cabin with 95% relative humidity at 23°C for 24 hours. They were demolded and placed in a water bath and cured in an oven at 80°C for 24 hours. Following this, the first reading for expansion measurement for specimens was made using a comparator with an accuracy of 0.002 after 80°C for 24 hours of curing as indicated in related standard. Then, specimens were put in a water bath prepared with 1 M NaOH solution and cured in an oven at 80ºC. The expansions of specimens were measured up to 90 days. The measurements were done at the day after the mortars were cast. The expansion of mortar bars was measured every day for up to 14 days. Then the measurement was continued until 90 days and expansion was recorded each week.

3. Experimental results and analysis

3.1. Unit weight and workability

The workability of fresh mortar and unit weight of mortars produced in the study at 28 days are presented in Table 4. The unit weight of the mortar mixture was reduced when waste glass powder or fly ash was replaced with cement. This is valid for separate or combined use of mineral admixtures. Moreover, fly ash inclusion reduced the unit weight of hardened mortar more than waste glass powder did. This is explained with the difference between specific gravity of mineral admixtures and cement. It should be noted that specific gravities of cement, waste glass powder and fly ash were 3.07, 2.50 and 2.27 g/cm^3, respectively.

A closer look at the workability values of mortar showed that inclusion of waste glass powder and fly ash in mortar mixture, separately, as cement replacement resulted in significant workability improvement. Moreover, the influence of fly ash on workability was more prominent than the influence of waste glass powder inclusion. When both mineral admixtures were used together, the workability values of GF mixtures were found to be between the workability of waste glass powder and fly ash mortar mixtures. An increase in workability was attributed to low water absorbing content and spherical shape of fly ash particles by causing ball bearing effect reducing internal friction of fresh mixture (Erdoğan 1997). However, it was attributed to only low water absorbing content for glass powder particles. The higher replacement of mineral admixtures results in better workability behavior and more unit weight reduction.

Table 4. Density and workability of mortars

Mix No.	Density (g/cm^3)	Workability (mm)
	28 days	Fresh
Control	2.06	153
G-10	2.05	155
G-20	2.03	157
G-30	2.01	159
F-10	2.03	165
F-20	2.00	171
F-30	1.99	178
GF-10	2.05	158
GF-20	2.03	162
GF-30	2.01	167

3.2. Water absorption and porosity

The water absorption and porosity of the mortar samples produced in the study were measured as an indicator of the durability of the mortar. The water absorption and porosity of the mortar samples produced in the study were measured as an indicator of the durability of the mortar. Water absorption and porosity experiments result are presented in Figure 1.

Although the 28-day water absorption and porosity values of the mortar samples containing waste glass powder decreased slightly compared to the control cement mortar, they were found to be comparable to the control mortar. On the other hand, after 90 days of curing, the mortar samples containing waste glass powder decreased water absorption and porosity values considerably compared to the control mortar. Water absorption and porosity values, measured at 28 days of the mortar samples containing fly ash slightly increased compared to the control cement mortar. However, it was found to be equivalent to the control mortar. Moreover, after 90 days of curing, the water absorption and porosity values of the mortar samples containing fly ash decreased slightly compared to the control mortar. Thus, in the long term, fly ash reduced water absorption and porosity due to pozzolanic reactions (Erdoğan 1997; P. Kumar Mehta and Monteiro 2014).

GF-30 mortar samples containing 15% waste glass powder and 15% fly ash together gave lower water absorption and porosity values than not only control mortar sample but also mortar samples containing only glass powder or fly ash. Notably, after a 90-day curing period, these decreases in water absorption and porosity were more marked. This may be explained that by using G and F together in the mixture results in these particles of varied sizes filling each other's spaces and forming a more compact structure

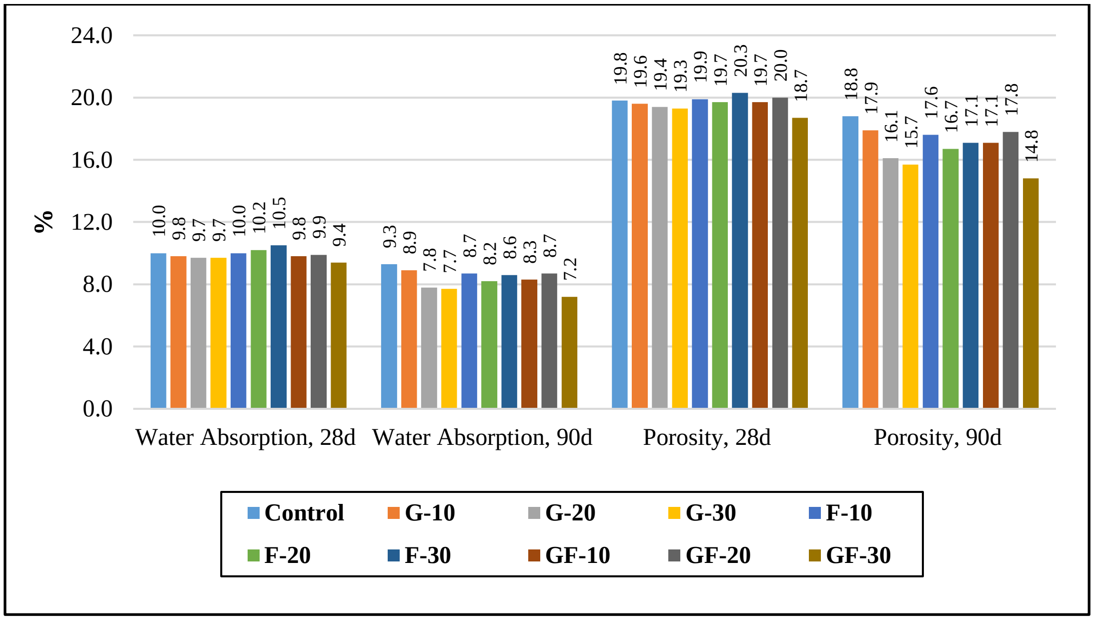

Figure 1. Water absorption and porosity results for 28 and 90 days.

3.3. Compressive strength and flexural tensile strengths

Compressive and flexural tensile strengths are presented in Figure 2 and 3. Evaluation of Figure 2 and 3 showed that mortars containing 10% fly ash or glass powder developed equivalent compressive strength, at 28 days, to mortar made with only cement. However, mortar 20% or higher waste glass powder or fly ash (G-20, G-30, F-20, and F-30) represented lower compressive strength than that of control mortar at 28 days. Nevertheless, the reduction in compressive strength rate was lower than the rate of replacement ratio of mineral admixtures. For instance, the F-30 mortar developed such compressive strength that 16% lower than the control mortar's compressive strength at 28 days. A similar observation of the influence of waste glass powder on compressive strength can be made. However, reduction in compressive strength for mortar containing waste glass powder was found to be lower 8% (for G-30), when it was compared to control mortar at 28 days.

When the compressive strength of mortar was evaluated at 90 days curing time, G-10, G-20 and F-10 mortars showed higher compressive strength than that of control cement mortar. This is attributed to the pozzolanic reaction between pozzolanic material and portlandite in the presence of water. The combined use of waste glass powder and fly ash together generally developed intermediate or higher compressive strength than mortar containing only waste glass powder or fly ash separately regardless of curing time.

Similar conclusions and discussions made for compressive strengths were valid for flexural strength. Replacing waste glass powder and fly ash reduced the flexural tensile strength of mortar at 28 days. The flexural tensile strength of control mortar was 10.9 MPa while flexural tensile strengths of G-10, G-20, G-30, F-10, F-20, F-30, GF-10, GF-20, and GF-30 were 10.8, 10.7, 10.2, 10.0, 9.9, 9.8, 10.3, 10.6, and 10.2 MPa, respectively at 28 days. However, due to the pozzolanic reaction, the replacement of waste glass powder and fly ash developed higher or comparable flexural tensile strength to control cement mortar at 90 days. The values of flexural tensile strengths of these mixtures can be seen in Figure 3 on top of bars. The flexural tensile strength of mortar produced in the study developed high flexural tensile strength in 10 MPa.

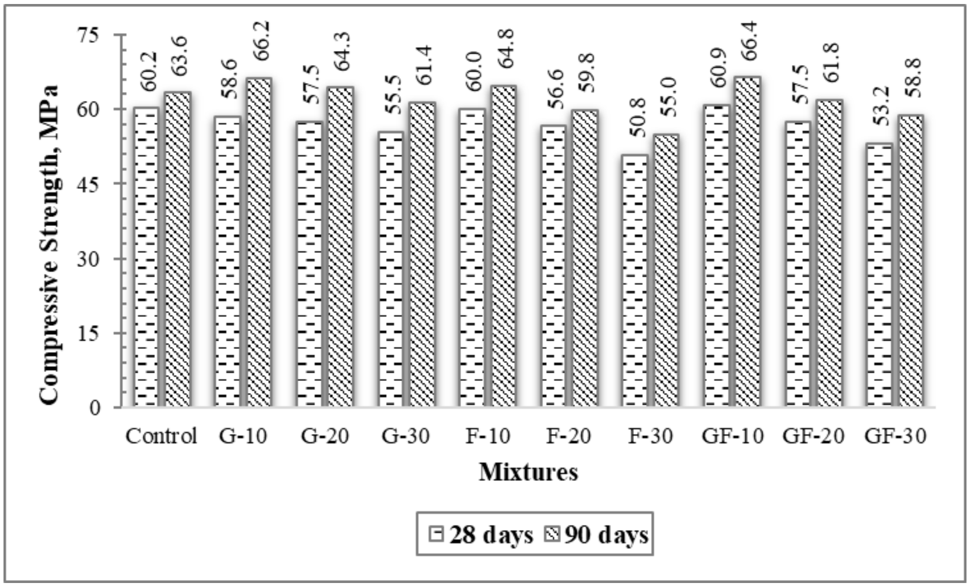

Figure 2. Compressive strength results for 28 and 90 days.

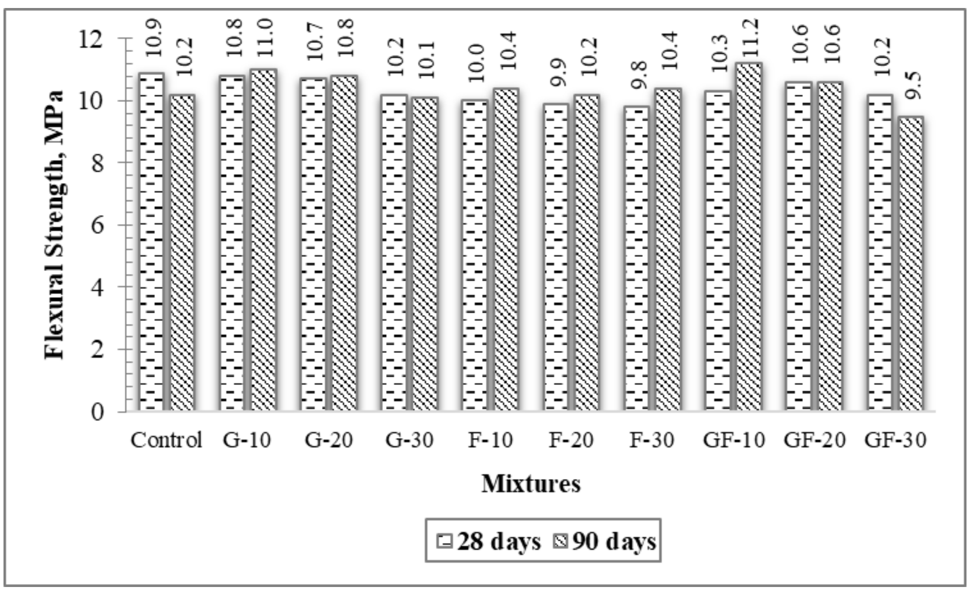

Figure 2. Flexural strength results for 28 and 90 days.

3.4. Accelerated mortar bars test (ASR test)

The expansions of mortar bars containing only Portland cement and binary and ternary blends of waste glass powder and fly ash are presented in Figures 4 and 5. The expansions of mortars up to 14 days are shown in Figures 4. It can be seen from Figure 4 that the 14-day expansion for control cement mortar was 0.32%. This value is found to be greater than 0.20% (that is specified by ASTM C1260 standard (ASTM C1260 2014)); therefore, the aggregate used in control cement mortar is considered harmful for ASR.

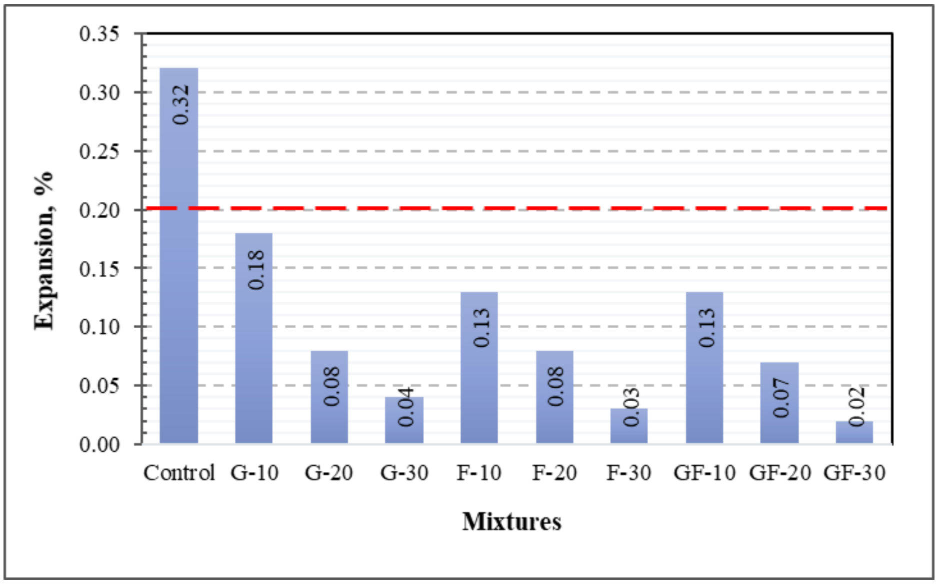

Figure 4. Expansion results for mortar bars for 14 days.

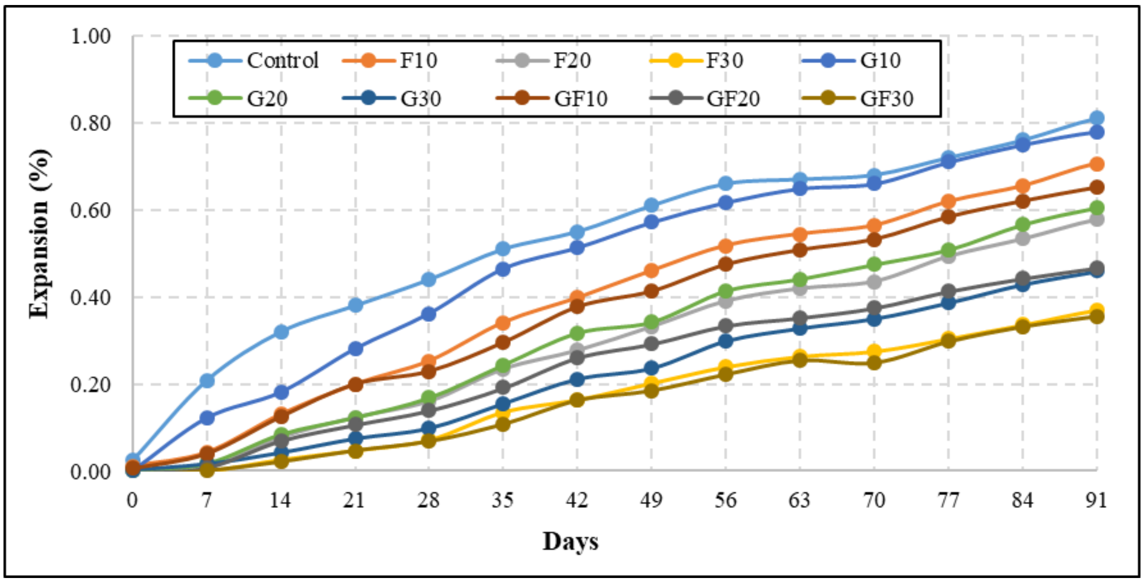

Figure 5. Expansion results for mortar bars for 90 days.

Figures 4 and 5 show that the expansion value of the control mortar made with Portland cement was found to be higher than that of mortars containing waste glass powder and fly ash. This is valid for all curing days. The expansion values of the mortars containing 20% and 30% binary and ternary blends of waste glass powder and fly ash (F-20, F-30, G-20, G-30, G-30, GF-20 and GF-30) did not cause any expansion for 1-day and 3-days. Moreover, the expansions of the G-10, F-10 and GF-10 mortar samples were 0.18%, 0.13% and 0.13% at 14 days, respectively. These values remained somewhat higher than the 0.10% stated in ASTM C33 (ASTM Standard C33 2003). These values dropped between 0.10% and 0.20% and were considered suspicious. However, the expansion values of F-20, F-30, G-20, G-30, GF-20, and GF-30 mixtures remained lower than 0.10%. Therefore, it is concluded that when the waste glass powder and fly ash substitution rate with cement is higher than 10%, the harmful effects of ASR expansion can be mitigated.

Based on the evaluation of the results at 14-days waste glass powder and fly ash substitution have been shown to reduce expansions. When the replacement ratio of SCM with cement was 10% (i.e. G-10, F-10 and GF-10), the reduction in ASR expansion became lower. Besides, with increased glass powder and fly ash content in mortar as cement replacement, the expansion caused due to ASR remarkably decreased. Expansions in G-10, G-20, and G-30 mixtures decreased compared to the control cement mortar mixture by 44%, 75%, and 87%, respectively. Expansions of F-10, F-20, and F-30 mixtures decreased by 60%, 75% and 90%, respectively, in comparison to the control cement mortar mixture. Similar results for glass powder and fly ash usage to suppress ASR expansion were seen in the literature (Adesina and Das 2020; Bueno et al. 2020; Fanijo et al. 2021; Schwarz et al. 2008; Zheng 2016). When fly ash and glass powder are used together, the expansions decreased by 59%, 78%, and 94% for GF-10, GF-20, and GF-30 mixtures in comparison to the cement mortar mixture, respectively.

The results obtained by measuring the expansions of the mortar samples containing waste glass powder and fly ash up to 90 days reduced ASR expansions. In addition, when the waste glass powder and fly ash are used both separately and together, the tendency to reduce expansions has been observed at all curing times (Schwarz et al. 2008). Evaluation of the expansion results showed that, the lowest expansions were measured from the mortar mixture made with waste glass powder and fly ash together (GF-30). It was concluded that the use of waste glass powder and fly ash together created a synergistic effect and developed better results than using them separately.

4. Conclusions and comments

The influence of the inclusion of waste glass powder and fly ash in cement-based mortar for suppressing the expansion of ASR was investigated. The following conclusions were made from the current study.

- The addition of waste glass powder and fly ash in cement-based mortar caused a slight reduction in the unit weight of samples. The reduction was attributed to the lower unit weight of waste glass powder and fly ash with respect to the unit weight of Portland cement.
- Utilization of waste glass powder and fly ash in mixture, separately or together, result with a marked increase in the workability of fresh mortar. The influence of fly ash on workability was better than that of waste glass powder.
- Water absorption and porosity of mortar samples were reduced due to the replacement of waste glass powder and fly ash with cement in the long term. This was due to the pozzolanic reaction of amorphous content of waste glass powder and fly ash.
- Using waste glass powder and fly ash result with a small reduction in compressive strength. However, the compressive strengths of mortar made with waste glass powder and fly ash were found to be comparable or equivalent to control mortar at 28 days. Moreover, it was higher in comparison to the control mortar at 90 days due to the pozzolanic reaction. For instance; compressive strength of GF10 was 4.4% higher than that of control cement mortar. The influence of using waste glass powder and fly ash as cement replacement on flexural strength was found to be similar to compressive strength.
- Expansion of mortar samples due to ASR increased during curing time. Using waste glass powder and fly ash reduced this expansion at all ages. The higher replacement ratio caused the lower expansion of ASR at all ages. Regarding expansion values, using waste glass powder and fly ash together creates a synergistic effect and gives better results than using them separately. For instance; expansion value of GF30 mixture containing 15% waste glass powder and 15% fly ash was 0.02% which was quite lower than that of limit of specification (0.2%).

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