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Role of Ground Glass Fiber as A SCM in Improving Selected Properties of Portland Cement Concrete

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Abstract

Millions of tons of fiber glass are produced annually for a variety of applications every year. Due to stringent quality requirements and due to operational characteristics of the manufacturing plants, a significant quantity of fiber glass that does not meet required specifications of the industry ends up as waste and is disposed in landfills. In this study the use of ground glass fiber (GGF), discarded from the plants as an off-spec product, as a supplementary cementitious material (SCM) was investigated at different replacement levels (10, 20 and 30% by mass) of portland cement in paste, mortar and concrete mixtures. Mechanical and durability properties of the mixtures were compared with two control mixtures: a mixture with 100% portland cement and a mixture having 25% class F fly ash as a cement replacement material. It was observed in these studies that even though replacement of portland cement with GGF does not lead to any significant changes in the mechanical behavior of hardened concrete, significant improvements in the durability properties were observed at replacement levels up to as high as 20%. Use of GGF was found to significantly improve the resistance of mortar mixtures against alkali-silica reaction and sulfate attack. In addition, the use of GGF as an SCM significantly reduced the chloride ion permeability of concrete. Results of this study showed that using GGF as an SCM can result in a better durability performance compared to a mixture having similar level of class F fly ash.

1 INTRODUCTION

Utilization of ground glass powder, typically obtained from processing of recycled glass containers made of soda-lime glass, as an SCM has been the subject of many studies (*1-4*). Due to the high amount of alkali present in these glass powders, susceptibility of concrete mixtures containing glass-derived pozzolans to Alkali-Silica Reaction (ASR) has been always a big concern. On the other hand, ground glass fiber (GGF), a pozzolan derived from finely grinding fiber glass (commonly referred to as E-glass) that has very low alkali content. Due to its chemical composition, GGF can potentially serve as a valuable pozzolan without the negative effects often associated with the use of high-alkali glass powders such as soda-lime glass, particularly in reducing the risk of ASR in the concrete mixtures.

Presence of reactive silica is essential for any supplementary cementitious material (SCM) to cause the pozzolanic reaction. Although like other SCMs, GGF has high enough combined silica, iron and aluminum oxide (S+A+F) content (i.e. > 50%) and can serve as a good pozzolan, unlike other SCMs such as fly ash, GGF is an engineered material which is produced in a controlled environment. This results in a uniform chemical composition of the material which lends itself to a consistent quality SCM for use in concrete.

Utilization of GGF as an SCM in concrete construction is a relatively new concept and unlike the conventional SCMs like fly ash, slag, meta-kaolin and silica fume, which are known to be used for several decades, the first use of this material as pozzolan was patented in 2004 by Hemmings et al (*5*). According to a report by the US Department of Energy in 2005, the total amount of waste glass fiber in United States that ends up in landfills was about 250,000 tons per year, which can be reclaimed for beneficial uses. This amount can be further increased to 500,000 tons/year if the waste streams from the users of glass fibers are also considered (*6*).

Past studies on the utilization of waste glass fiber as a SCM, have shown the advantages of using this material in improving some fresh and hardened properties of mortar and concrete mixtures. Chen et al. (*7*), investigated the utilization of E-glass particles in concrete mixtures. It was seen that the replacement of E-glass as cementitious material, up to 40% by mass of the cement showed pozzolanic reactivity. Furthermore, it was observed that the addition of E-glass as a cement replacement improved durability characteristics of concrete such as resistance against sulfate attack and chloride penetration. Hossein et al (*8*), studied the fresh and hardened properties of the concrete mixture containing glass fiber particles. It was reported that utilization of this material as a cement replacement increased the workability of the fresh concrete mixtures (higher slump), increased the plastic shrinkage and also reduced chloride ion permeability.

A few studies have been performed on the hydration mechanism of the mixtures having glass fiber as a cement replacement. A comprehensive study on the pozzolanic properties of milled glass fiber was performed by Neithalath et al. (*9*). It was reported that although the glass fiber powder did not show any cementitious properties, it had a significant pozzolanic effect. In addition, it was seen that addition of glass fiber (as cement a replacement) was very beneficial in reducing the calcium hydroxide level. In another study, Kamali and Gharemaninezhad (*10*) investigated the hydration and microstructure of cement pastes modified with glass fiber powder. It was found that addition of fiber-glass powder as cement replacement, improved the early hydration of the cement and also showed pozzolanic reactivity at later ages (i.e. 91 days). Furthermore, it was observed that the addition of fiber-glass reduced the porosity.

This paper presents selected findings from a comprehensive study conducted to evaluate the material characteristics of a ground glass fiber produced from E-glass and its role in affecting a range of fresh and hardened properties of pastes, mortars and concrete. Findings from the material characterization of GGF and its effects on fundamental material and selected mechanical properties of cementitious matrices are published elsewhere *(11)*. The focus of this paper is to report findings from studies conducted to evaluate the impact of a specific GGF of defined fineness on selected mechanical and durability properties of mortars and concrete mixtures. To evaluate the mechanical properties, concrete specimens were tested for their compressive strength, splitting tensile strength, and modulus of elasticity. In addition, durability properties of the mixtures containing GGF were evaluated by conducting alkali-silica reaction, sulfate attack and, rapid chloride penetration test (RCPT). Furthermore, to assess the pozzolanic behavior of the GGF, strength activity index (SAI), and thermo gravimetric analysis (TGA) were performed on mixtures containing various level of GGF.

2 EXPRIMENTAL PROGRAM

2.1 Materials:

Following materials were used in this study:

2.1.1 Cement

In this study, a Type I/II (ASTM C 150) ordinary portland cement (OPC) with a specific gravity of 3.15 and an average particle size of 17 microns was used. The chemical composition of the portland cement and its selected physical properties are presented in Table 1.

2.1.2 Ground Glass Fiber

The Ground Glass Fiber (GGF) used in this study was a fine white powder that was prepared by milling the off-spec glass fiber in a ball mill to a fine powder with an average particle size of 4 microns. The scanning electron microscope (SEM) observation showed that the GGF particles were angular with a smooth surface texture. The chemical composition of the GGF and its selected physical properties are presented in Table 1.

2.1.3 Fly Ash

A class F fly ash (ASTM C618) with a specific gravity of 2.25 and an average particle size of 28 microns was used as an SCM. The chemical composition of the fly ash and its selected physical properties are presented in Table 1.

2.1.4 Fine Aggregate (Siliceous Sand)

A non-reactive siliceous river sand meeting ASTM C33 gradation requirements with a fineness modulus of 2.60, absorption of 0.30% with an oven-dry specific gravity of 2.67 was used in this study.

TABLE 1. Chemical Composition and Physical Properties of the Cementitious Materials

Chemical composition/Physical properties		Cement (%)	GGF (%)	Fly ash (%)
Chemical composition	SiO_2	19.9	47.7	50.7
	CaO	62.3	19.6	3.3
	Al_2O_3	4.8	10.4	25.1
	Fe_2O_3	3.1	0.3	12.5
	MgO	2.7	2.3	1.1
	Na_2O_{eq}	0.38	0.70	2.0
	SO_3	3.23	0.02	0.70
Physical properties	Specific Gravity	3.15	2.60	2.25
	Amount Passing #325 Sieve (%)	98%	96%	76%
	Blaine's fineness (cm^2/g)	4720	10200	6040
	Loss On Ignition (LOI)	2.6%	1.0%	2.3%

2.1.5 Coarse Aggregate:

In concrete mixtures, a #57 (ASTM C33) granitic aggregate with the specific gravity of 2.65 and absorption of 1% was used.

2.1.6 Crushed reactive aggregates:

To study the ASR-related expansion of the mortar mixtures (using standard ASTM C1260 and ASTM C1567 tests), a highly reactive rhyolitic crushed gravel aggregate from Las Placitas gravel pit from New Mexico (NM) was used. The NM aggregate had an absorption of 1.10% and an oven-dry specific gravity of 2.60.

2.2 Mixture Properties

In this study, GGF was employed in the mortar and concrete mixtures as a partial substitute for cement by mass at selected dosage levels of 10, 20 and 30%. In addition, two control mixtures were tested for comparative purposes. The first control mixture (CTRL-1) consisted of 100% plain Type I portland cement as the binder, while the second control mixture (CTRL-2) consisted of a binary blend of 75% Type I Portland cement with 25% Class F fly ash, by mass, as the binder. Table 2 shows the mixture ID and the composition of the cementitious portion of the above-mentioned mixtures. Specified mixture proportions from the relevant test methods were used for designing mortar mixtures.

In the case of concrete mixtures, water-to-cementitious materials ratio was maintained at 0.45 and a total cementitious materials content of 355 kg/m^3 was employed. A #57 coarse aggregate (ASTM C33) was used in combination with siliceous river sand at 60:40 proportions by mass.

TABLE 2. Mixture ID and Composition of the Binder Portion of Concrete and Mortar

Mix ID	Paste Composition
CTRL-1	100% Cement
CTRL-2	75% Cement+ 25% Fly ash
GGF-10	90% Type I Cement+ 10% GGF
GGF-20	80% Type I Cement + 20% GGF
GGF-30	70% Type I Cement + 30% GGF

2.3 Experimental Test Methods

2.3.1 Mechanical Properties:

In this study, 100 mm by 200 mm (4 in. by 8 in.) concrete cylinders were cast to test the mechanical properties of the concrete mixtures. The tested properties are compressive strength (ASTM C39), split-tensile strength test (ASTM C496) and modulus of elasticity (ASTM C469). The compressive strength test and split-tensile strength tests were conducted on 7, 28 and 56-days old samples and modulus of elasticity test was performed only on 28-days old specimens.

2.3.2 Pozzolanic Activity

The pozzolanic reactivity of the mixtures was evaluated by conducting strength activity index on the mortar and thermogravimetric analysis (TGA) of paste specimens.

Strength activity index: The pozzolanic reactivity of GGF was examined by evaluating the strength activity index of mixtures containing GGF as a cement replacement material using the ASTM C311 test procedure. In this test, 50 mm x 50 mm x 50 mm (2 in. x 2 in. x 2 in.) mortar cubes were cast for each mix design (0, 10, 20 and 30% GGF and 25% fly ash as the cement replacement) and the compressive strength of each mixture was evaluated at 7 and 28 days of curing.

Thermogravimetric analysis: Effectiveness of GGF in consumption of calcium hydroxide, was evaluated by performing TGA on the paste specimens containing different dosage levels of the GGF as SCM. In this test method, crushed paste samples were gradually heated from ambient temperature to 800^{o}C and the change in their mass was monitored and recorded. Decomposition of calcium hydroxide occurs in the temperature range between 440 to 520^{o}C, causing a significant mass loss in the sample. The mass loss in this temperature range can be used to calculate the amount of calcium hydroxide in the sample.

In the present study, the TGA test was performed on the paste samples containing 10, 20 and 30% GGF as SCM and two control samples (one with plain cement and the other with 25% fly ash as cement replacement) at 28 and 56-day of ages. In addition, TGA test was performed on 200-day old mortar bars that were used in the sulfate attack test.

2.3.3 *Resistance Against Alkali-Silica Reaction*

Effectiveness of GGF in mitigation of ASR related expansion was evaluated by performing the accelerated mortar bar test (ASTM C1260 and ASTM C1567) using reactive crushed NM aggregate. The test method of ASTM C1260 was used for the CTRL-1 mixture, which had no pozzolan. For all the other mixtures, which had pozzolan in their mix design, ASTM C1567 test method was used.

2.3.4 *Sulfate Attack Resistance*

Following ASTM C1012 test method, 25 mm x 25 mm x 285 mm (1 in. x 1 in. x 11.25 in.) mortar bars and sufficient numbers of 50 mm x 50 mm x 50 mm (2 in. x 2 in. x 2 in.) mortar cubes were cast for each mix design. The samples were removed from their molds after 24 hours and were placed in a saturated lime water bath until they reach the required compressive strength of 3000 psi. At this point, zero-day reading for length-change measurement was taken on the mortar bar specimens. They were then placed in a 5% sodium-sulfate solution at ambient temperature. Further length-change readings were taken on days specified by ASTM C1012 test method. After each reading, the old solution would be replaced with a fresh one.

2.3.5 *Rapid Chloride Penetration Test*

Rapid Chloride penetration test (RCPT) was performed on all the concrete mixtures (as presented in Table 2). For the purpose of this test, 100 mm by 200 mm (4 in. x 8 in.) concrete cylinders were cast and tested at 7, 28 and 56 days. According to the ASTM C1202, RCPT samples were cut in 50 mm (2 in.) thick discs and prepared before placing them in the RCPT cell containing 3% sodium chloride solution on one end and 0.3N sodium hydroxide solution on the other end. Each cell was subjected to 60 V DC potential difference and the charge passing through the specimens was monitored for 6 hours.

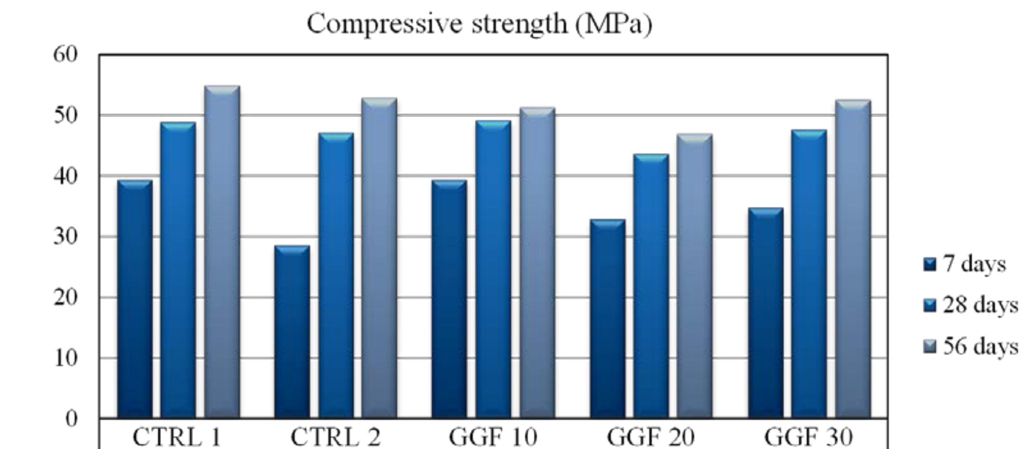
3 RESULTS AND DISCUSSION

3.1 Mechanical Properties:

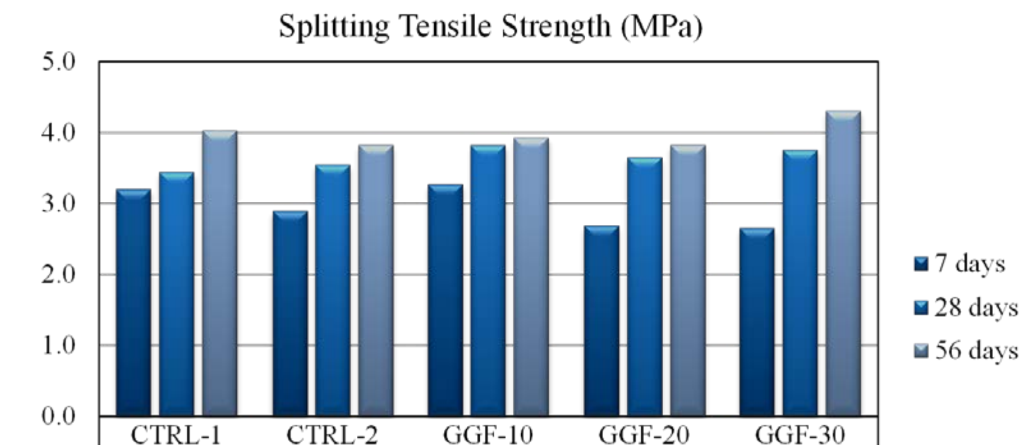
Results of the compressive strength and split-tensile strength are presented in Figure 1. As it can be observed from Figure 1, the compressive strength of CTRL-2 samples (with 25% fly ash) was lower at early ages (7 days), however by 56 days reached to a similar level as CTRL-1. However, in the case of mixtures containing GGF, at dosage levels of 10% and 30% the compressive strength of the mixtures were similar to that of CTRL-1 samples at all ages. However, at 20% dosage of GGF the observed compressive strength was lower than that of the control mixtures. The precise reason for the observed trend in the GGF samples, i.e. lower strength at 20% dosage level compared to that at 10% and 30% is not entirely evident at this time. It is hypothesized that perhaps the competing influences of micro-filler effect and the pozzolanic reactivity effect of GGF may be different at different dosage levels. Further investigation is needed to ascertain the underlying reasons for this unexpected trend in the results.

In the case of split-tensile strength test, while lower strength at 7 days were observed in mixtures containing 20% and 30% GGF, the 28-day and 56-day values of all the mixtures containing GGF were similar to that of CTRL-1 samples. As a general observation, it appears that the use of GGF as a cement replacement material does not affect the split-tensile strength at the dosage levels evaluated, particularly at 28 days and beyond.

Modulus of elasticity of all the specimens was measured at 28 days. The results of this test were 33.1, 32.5, 33.2, 31.2 and 32.6 GPa for CTRL-1, CTRL-2, GGF-10, GGF-20 and GGF-30 mixtures respectively [1 GPa is equal to 145 ksi]. From these results it can be concluded that the modulus of elasticity of all mixtures containing pozzolans were very similar to the value obtained for CTRL-1 mixture.



	CTRL 1	CTRL 2	GGF 10	GGF 20	GGF 30
7 days	39	29	39	33	35
28 days	49	47	49	44	48
56 days	55	53	51	47	53



	CTRL-1	CTRL-2	GGF-10	GGF-20	GGF-30
7 days	3.2	2.9	3.3	2.7	2.7
28 days	3.4	3.5	3.8	3.7	3.8
56 days	4.0	3.8	3.9	3.8	4.3

FIGURE 1. Compressive strength (top) and splitting tensile strength (bottom) of concrete samples [1 MPa is equal to 145 psi].

3.2 Pozzolanic Reactivity

3.2.1 Strength Activity Index

The results from testing compressive strength of mortar cube specimens and the resultant strength activity index (SAI) values are presented in Table 3. As it can be seen in this table, the GGF-20 mixture showed the SAI values of 104% and 110% after 7 and 28 days, respectively. Since these values are higher than 75%, the GGF is considered as a pozzolanic material (ASTM C618). Moreover, as the results revealed, the SAI value of all GGF containing mixtures showed higher values than CTRL-2 mixture at both 7 and 28 days.

The better performance of mixtures containing GGF in comparison with CTRL-2 mixture (having 25% fly ash) can be explained by the smaller size of the GGF particles that are much finer ($4\mu m$) than the size of fly ash ($28\mu m$) particles which can refine the porosity, and can be engaged in the pozzolanic reaction faster. Furthermore, the results of XRD test revealed that the structure of GGF powder is very amorphous. This amorphous structure accelerates the pozzolanic reaction by allowing silica to react and form C-S-H gel. As a result of the pozzolanic reaction all the GGF containing mixtures have surpassed the compressive strength of the CTRL-1 mixture after 28 days (see Table 3). It should be noted that the strength activity index is not necessarily a complete reflection of the pozzolanic reactivity of the pozzolan such as GGF rather it also includes any micro-filler effect imparted by the pozzolan in the test mixtures. Further, with materials such as GGF, due to the particle size and the surface texture characteristics of the GGF grains, to ensure a constant flow, the w/c ratio of mixtures containing GGF at different dosage levels is significantly lower than that of the control mixture, which can also influence the SAI.

TABLE 3. Compressive Strength and Strength Activity Index of Mortar Cubes for 7 and 28 Days

Age (days)		CTRL-1	CTRL-2	GGF-10	GGF-20	GGF-30
7	Compressive strength (MPa)	42	34	38	44	41
	SAI (%)	100	81	89	104	97
28	Compressive strength (MPa)	54	48	56	60	58
	SAI (%)	100	89	103	110	106

3.2.2 TGA Results

The TGA results from crushed paste powder with different dosage of GGF replacement are presented in Figure 2 for the ages of 28 and 56 days. As it can be seen, the amount of calcium hydroxide significantly decreases with the increase in GGF dosage. The reduction occurs as a result of a combination of both dilution effects of GGF, which reduces the total amount of calcium hydroxide in the systems and the pozzolanic reaction, which consumes the calcium hydroxide to form C-S-H gel. It is evident from Figure 2 that the pozzolanic effect increases with the increase in the replacement dosage and time of curing. The results of 28-days samples showed the values of 1%, 2% and 7% for GGF-10, GGF-20 and GGF-30 for the amount of calcium hydroxide that was consumed through the pozzolanic reaction respectively. In the case of 56-days old samples, the pozzolanic effect caused 3%, 4% and 17% reduction in the calcium hydroxide for GGF-10, GGF-20 and GGF-30 respectively.

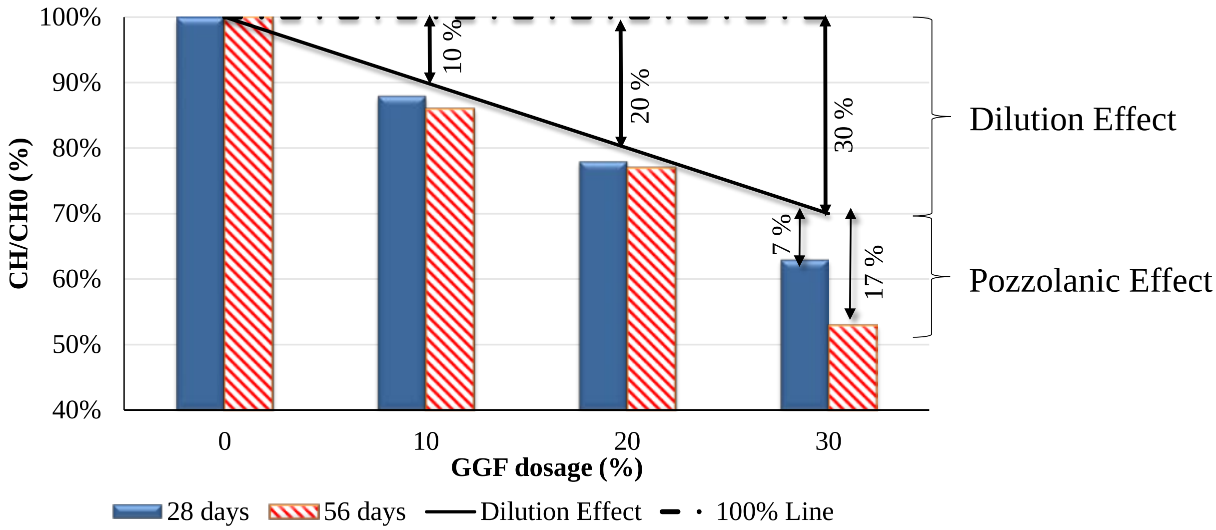


FIGURE 2. Effect of GGF dosage on the TGA result [where CH is calcium hydroxide content of the sample and CHo is the calcium hydroxide content of the CTRL-1 (100% Cement)]

3.3 Alkali-Silica Reaction:

The effect of GGF in the mitigating ASR related expansion was studied by conducting the accelerated mortar bar test (ASTM C1260 and ASTM C1567). Figure 3, shows the expansion of the mortar bars up to 28 days. It is evident from Figure 3 that the addition of GGF as an SCM significantly reduced the ASR-related expansion, while the CTRL-1 mixture, which has no pozzolan, showed a significant expansion. At 14 days, the expansion of CTRL-1 mortar bars reached 0.90%, which is significantly higher than the 0.10% threshold limit as identified in ASTM C33 to identify reactive aggregates. Beyond 14 days, the expansion of CTRL-1 samples continued further and reached 1.40% at 28 days. In the case of GGF-10 mixture, although a considerable reduction in expansion was observed in comparison to CTRL-1 mixture, the 14-day expansion of this mixture was still far above the 0.10% limit.

At the higher dosage of GGF, i.e. GGF-20 and GGF-30, the expansion results showed a significant reduction in comparison to the CTRL-1 mixture. Replacement levels of 20% and 30%, successfully mitigated the expansion of the mortar bars and kept it below the 0.10% limit at 14 days. At this age, the expansion of GGF-20 and GGF-30 mixtures reached 0.04% and 0.03% respectively. The CTRL-2 mixture was also able to mitigate the expansion of the mortar bars and showed an expansion of 0.10% at 14 days. However, the expansion of this mixture was higher than GGF-20 and GGF-30 mixtures. The results from this investigation also indicated that among all the mixtures, the GGF-30 mixture had the best performance in terms of expansion mitigation. It can be observed from Figure 3 that even after 28 days of testing, the expansion of GGF-30 mortar specimens was only 0.06%, which is significantly lower than the 0.10% limit.

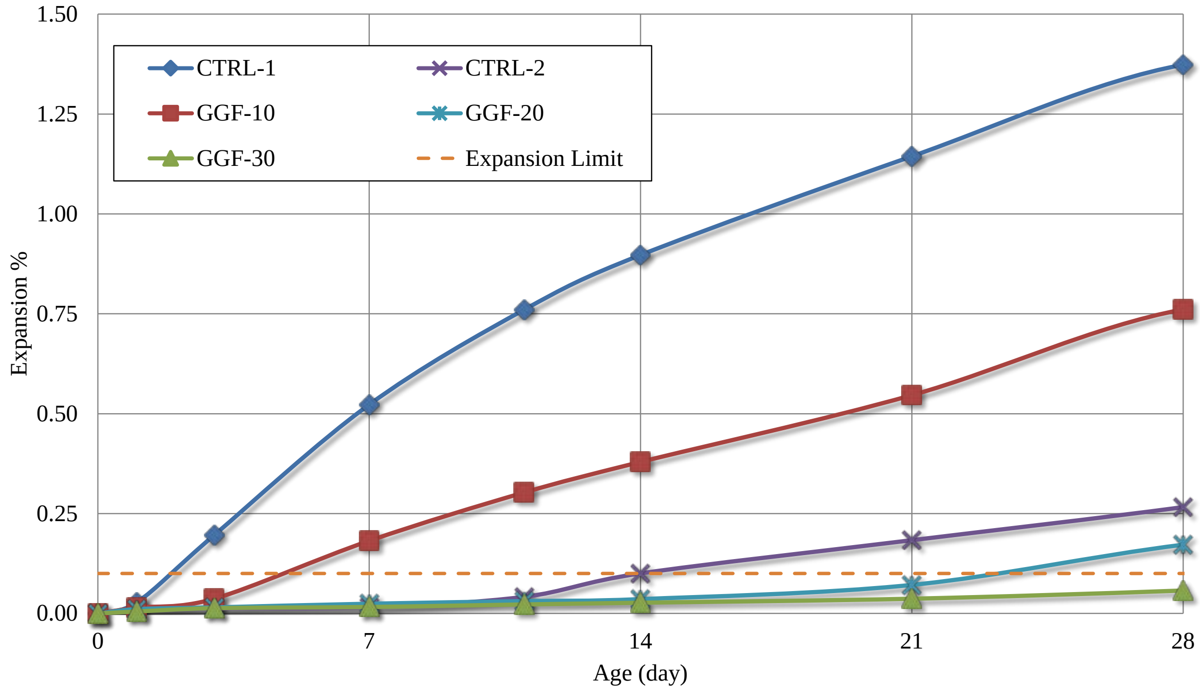


FIGURE 3. Expansion of the mortar bar versus time

The mitigation mechanism of the GGF containing mixtures in terms of ASR-related expansion has been discussed in detail elsewhere (*11*). However, the main mechanisms for the mitigation can be summarized as follow:

Reduction *in available calcium for newly formed ASR gel*. As it was presented in the TGA results, GGF containing mixtures have a lower level of calcium hydroxide, which is essential for triggering ASR-associated expansion and damage. It has been shown that calcium hydroxide reacts with freshly produced low-viscosity ASR gels (by exchanging calcium ions with alkalis) forming a more viscous ASR gel, that can induce significant tensile stress on the mortar matrix upon absorption of moisture and expansion (*12*). As result, addition of fine and highly reactive silica glass in the form of GGF or fly ash will reduce the risk of ASR damage as the level of calcium hydroxide will be lowered through the dilution and pozzolanic reaction effects.

Reduction in Ca/Si ratio. Addition of glassy silica in the form of GGF or fly ash, leads to the formation of a C-S-H gel with a lower Ca/Si ratio. Past studies have shown that the C-S-H gels with lower Ca/Si ratio will retain a higher amount of alkalis in comparison to the gels with greater Ca/Si ratio (*13-14*). As a result, the C-S-H gel in the GGF containing samples is likely to retain more alkalis in its structure. The EDX analysis of the paste portion of GGF samples showed that Ca/Si ratio was 22% lower than the Ca/Si ratio in the CTRL-1 samples (For more information see the reference (*11*)).

Effect of alumina in reducing ASR. It is known that the presence of Al in SCMs increases their effectiveness against the ASR (*15-16*). Two suggested mechanisms for the role of Al are: 1) better performance of C-A-S-H gel in binding alkali in comparison to C-S-H gel (*17*). And 2) reduction in the rate of solubility of Si from the reactive aggregates (*18*). Regardless of the responsible mechanism for reducing ASR, a higher amount of aluminum was observed in GGF-30 samples compared to other samples. The EDX results performed on at least three points of the paste portion of each sample showed a higher aluminum content of the GGF-30 in comparison to the CTRL-1 sample. According to the EDX results, the aluminum atomic percent in the GGF-30 and CTRL-1 samples were 7.25% and 3.09% respectively *(11)*.

Reduction in paste permeability. Addition of pozzolans in terms of cement replacement, introduces a large amount of reactive silica into the system. In the presence of reactive silica, the pozzolanic reaction takes place by consuming CH and producing C-S-H gel, thus refining the paste structure and reducing the permeability. In addition, small particles of GGF are thought to refine the pore structure of the paste and hence reduce the permeability. Although no specific test was conducted in this study to test the effectiveness of addition of GGF on reducing the permeability of the samples, other studies have reported that using glass fiber in a powder form (as a pozzolan) caused a reduction in the permeability of mortar mixtures (*8*).

3.4 Sulfate Attack:

Resistance of mortar bar specimens containing GGF replacement to sulfate attack was evaluated by studying their length change when submerged in a 5% sodium-sulfate solution at ambient temperature. From Figure 4 it is evident that the addition of GGF was seen to effectively reduce the rate of expansion, especially at later ages (i.e. after 28 days). As it can be seen, higher levels of replacement resulted in a lower expansion, as GGF-20 and GGF-30 samples showed the lowest level of expansion after 180 days.

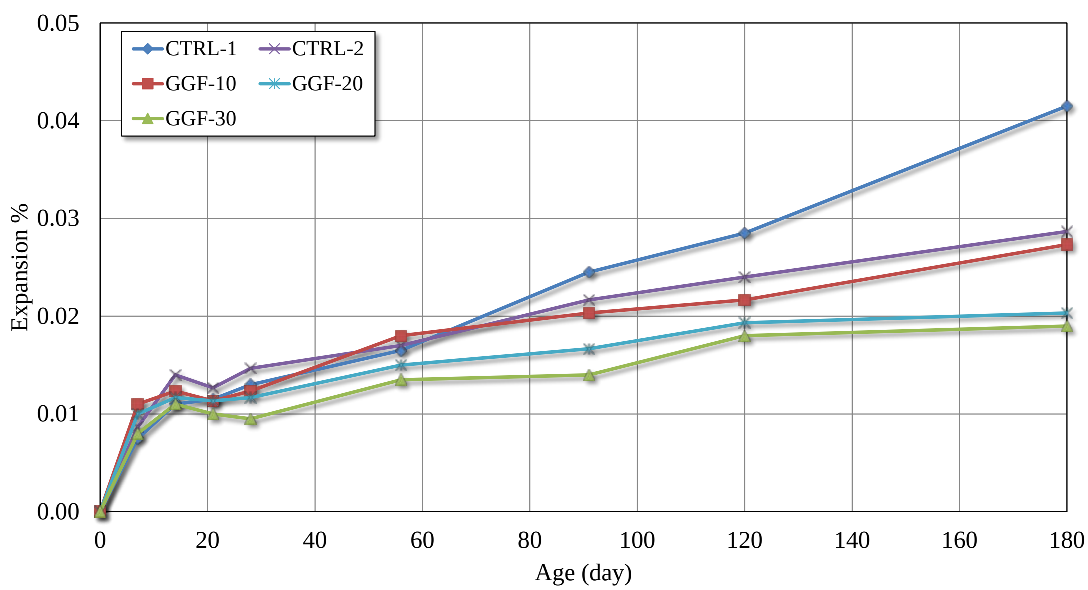


FIGURE 4. Expansion results of mortar bars subjected to 5% sodium sulfate solution.

The lower expansion of samples with GGF as the cement replacement can be attributed to their pozzolanic reactivity resulting in lower calcium hydroxide content of mixtures in comparison to CTRL-1 mixture (TGA results). Presence of CH is known to have a deleterious effect on the sulfate attack-related expansion. Calcium hydroxide is known to react with the sulfate and form the expansive gypsum, which, in the presence of a sufficient amount of alumina can form Ettringite. Formation of Ettringite is an expensive process and can lead to cracking and resultant strength-loss of the samples. In addition, other factors that reduce the expansion of GGF containing samples are the smaller particle size of GGF (in comparison to portland cement and fly ash), as well as its pozzolanic reactivity, that can refine the microstructure of the paste. Refinement of the paste structure reduces the permeability of the matrix and hence reduces the penetration of the sulfate ions into the samples.

Results from TGA tests conducted on mortar samples after 200 days of submersion in the 5% sodium-sulfate solution for CTRL-1 (a), CTRL-2 and GGF-30 samples are presented in Figure 5(a) through 5(c), respectively. Two distinct peaks in the differential analysis of the TGA curve can be identified in each of the graphs after 100^{o}C. The first peak which is located between 120^{o}C to 150^{o}C is thought to be as a result of decomposition of gypsum, which ideally occurs between 110^{o}C to 150^{o}C (19). The second peak which is located between 420^{o}C to 500^{o}C is known to be as a result of the decomposition of calcium hydroxide crystals from the cement hydration. Decomposition of calcium hydroxide has been reported to occur between 440^{o}C to 520^{o}C (20). The percent weight loss for the gypsum decomposition (first peak) and CH decomposition (second peak) for CTRL-1, CTRL-2 and GGF-30 curves progressively decreases from CTRL-1, CTRL-2 to GGF-30 curves as seen in Figure 5. The smallest peaks were seen in the case of GGF-30 samples, indicating that the lowest amount of gypsum and calcium hydroxide are present in this sample after 200 days of testing.

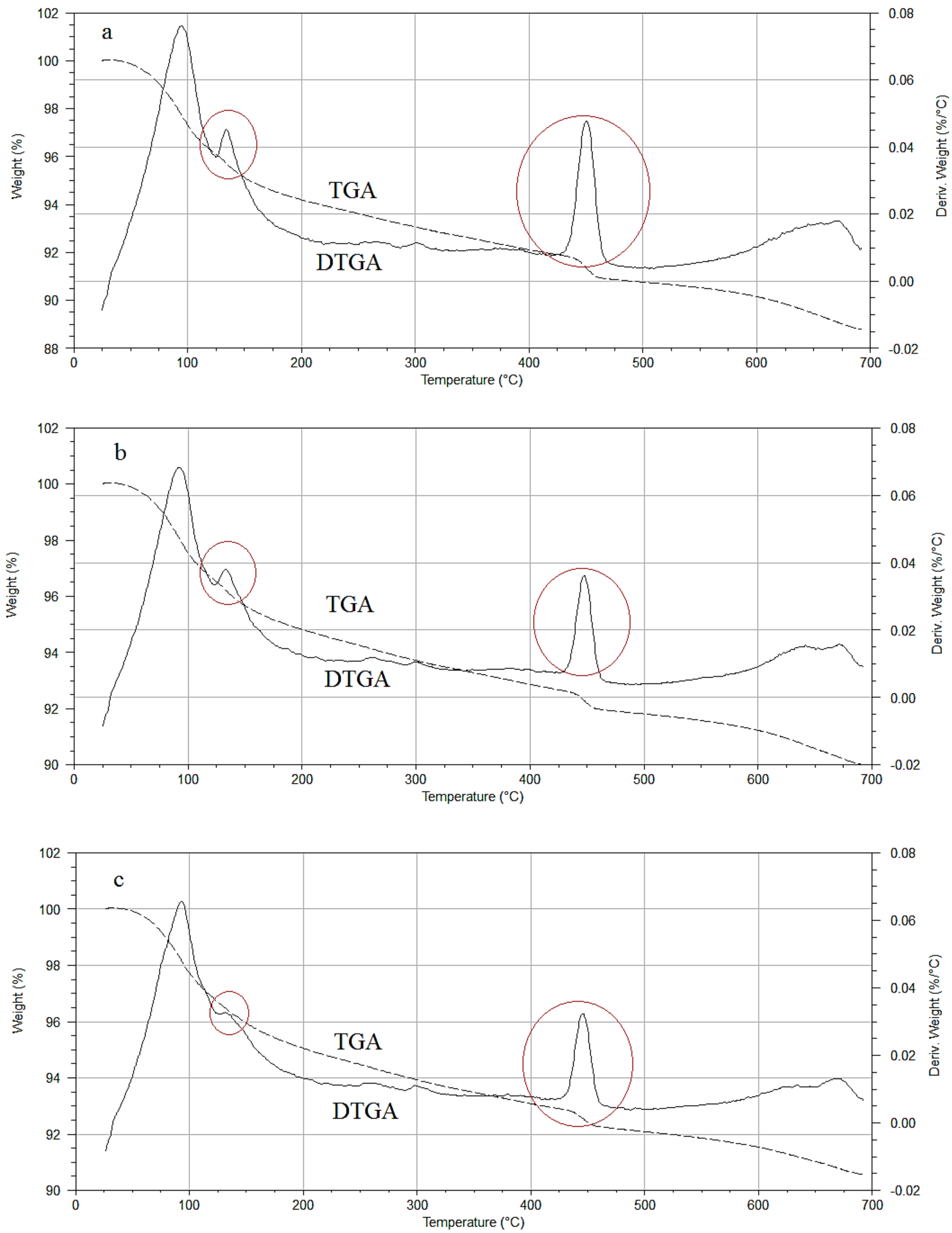


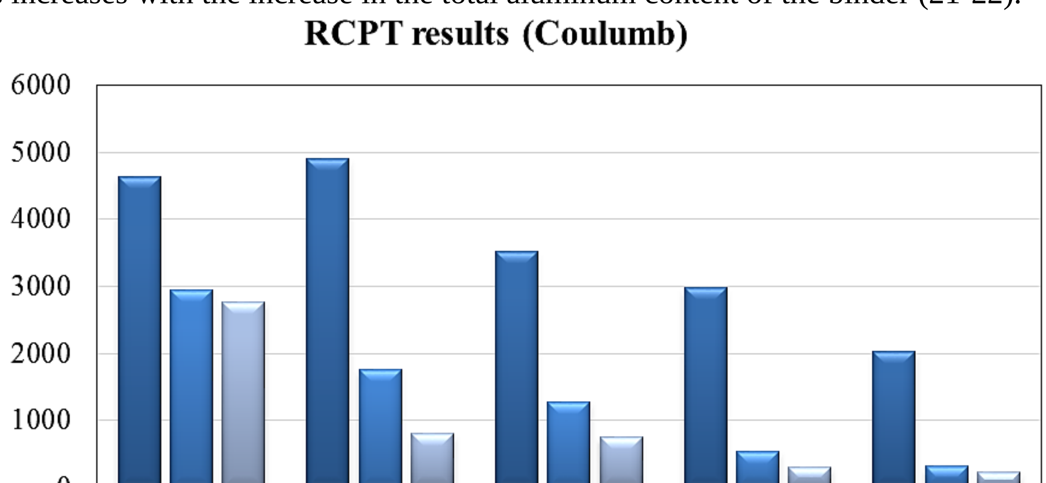
FIGURE 5. TGA and DTGA results of mortar samples immersed in 5% sodium-sulfate solution for 200 days: (a) CTRL-1 (b) CTRL-2 (c) GGF-30

3.5 Chloride Permeability

The results from Rapid Chloride penetration Test (RCPT) at 7, 28 and 56 days are presented for all the mixtures in Figure 6. These results show the clear advantage of using GGF in the concrete mixtures in reducing the penetration of chloride ions. From the results, it is evident that the amount of charge passing decreases with the increase in the replacement level of GGF dosage. As it can be seen in this figure, GGF-20 and GGF-30 samples showed very low chloride ion permeability (in the range of 100-1000 Coulombs based on the ASTM C1202) at 28 days. In the case of CTRL-2 samples, although test results showed a high amount of passing charge at 7 days, a lower value for the passing charge was registered at later ages (i.e. 56 or 28 days) in comparison to the CTRL-1 sample. The comparison between CTRL-2 samples and GGF-10 samples indicates better performance of GGF in reducing the Coulomb value, as the measured values of this parameter for GGF-10 were lower than CTRL-2 at all the measured ages.

The improved performance of GGF samples is thought to be mainly as a result of refinement in the paste pore structure. As it has been discussed earlier, this is the result of fine particle size of the GGF as well as the pozzolanic reactivity. Moreover, the results of earlier studies on mixtures containing glass fiber powder have shown its effect in reducing pore content and electrical resistivity, which can cause lower ion permeability of the GGF containing mixtures (10).

It is also thought that the lower chloride ion penetrability could be related to the presence of a relatively high amount of Al compounds in GGF. It is known that the availability of the Al compounds in the paste structure increases its ability in binding the chloride ions by the formation of insoluble Friedel's salt. Earlier studies have reported that the capacity of the chloride binding in binders increases with the increase in the total aluminum content of the binder (21-22).



	CTRL-1	CTRL-2	GGF-10	GGF-20	GGF-30
7 days	4640	4896	3512	2979	2024
28 days	2948	1758	1274	539	316
56 days	2768	796	759	309	223

FIGURE 6. Result of rapid chloride penetration on concrete samples

4 CONCLUSION

The results from characterization and use of GGF as an SCM in portland cement concrete can be summarized as follows:

1- At all the cement replacement levels (i.e. 10, 20 and 30%) evaluated in this study, the use of GGF showed a strength activity index greater than 100% at 28 days.
2- Results of TGA up to 56 days did not show any significant pozzolanic reaction for 10 and 20% replacement levels. The maximum reduction in the CH content was 17%, which occurred for the 30% replacement level after 56 days
3- The results from tests conducted to evaluate mechanical properties showed that addition of GGF at cement replacement levels up to 30% did not lead to any significant reduction in the compressive strength, split-tensile strength and modulus of elasticity.
4- At replacement levels of 20% and 30%, GGF was able to meet the expansion limit of 0.10% after 14 days in the accelerated mortar bar test to indicate its ability to mitigate ASR. Both these replacement levels showed better performance in ASR mitigation compared to control mixtures (CTRL-1 and CTRL-2 mixtures).
5- Results from sulfate attack studies revealed that at all levels of cement replacement, GGF containing samples showed a lower level of expansion compared to control (CTRL-1 and CTRL-2) mixtures.
6- Use of GGF at all levels of cement replacement reduced chloride ion permeability values in concrete significantly (2768 coulomb for CTRL-1 versus 223 coulomb for GGF-30, after 56 days).

Overall, it can be concluded from this study that a finely ground GGF with an average particle size of 4 microns can be successfully used as an SCM at cement replacement levels as high as 30% by mass of cement with no loss in mechanical properties compared to control concrete mixtures, while significantly improving the durability properties of concrete mixtures. In all regards, the performance of GGF as a pozzolan was better compared to a typical Class F fly ash at comparable dosage levels.

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