CSCE Annual Conference

Growing with youth – Croître avec les jeunes

Laval (Greater Montreal)

June 12 - 15, 2019

SHRINKAGE AND EXPANSION OF GLASS AGGREGATE CEMENT MORTARS

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Abstract: The use of recycled glass aggregates in concrete materials initiated around the 1970s as a means of controlling the disposal of refuse glass. Many researchers have found that cementitious materials containing recycled glass are sustainable and feasible; however, since its beginnings, uncertainties in its durability have limited its applications. Thus, this research investigated the durability of glass aggregate cement mortars by evaluating its susceptibility to volumetric changes. Shrinkage and expansion of concrete and cement mortar can cause unwarranted cracks which can affect long-term durability and serviceability. In this study, crushed glass and glass beads were used as fine aggregate replacements to determine their effects on plastic and drying shrinkage and alkali silica reaction expansion. It was found that the type, size, and amount of glass greatly influence shrinkage and expansion of glass aggregate cement mortar specimens. Further, the inherently low absorption capacity of the glass improves dimensional stability and minimizes detrimental shrinkage. Incorporating finer glass particles was also found to reduce the effects of alkali silica reaction expansion.

1 INTRODUCTION

In recent years, there have been global initiatives towards the development of environmentally-friendly, sustainable building materials. This specifically applies to concrete materials. The production of cement used in concrete is a major concern with regards to sustainability. Nevertheless, the quarrying of natural aggregates also presents adverse environmental impacts. Hence, environmental improvements in either concrete component can enhance the material from a sustainability standpoint. One approach to achieving environmentally-friendly concrete materials is by using recycled aggregates, namely glass. The use of glass as aggregate replacement in concrete and cement mortars improves waste management through the repurposing of landfilled glass (Shayan and Xu 2004; Corinaldesi et al. 2005; Taha and Nounu 2009; Ling and Poon 2011, 2012). In the United States alone, approximately 7 million tons of consumer glass were landfilled in 2015 (United States Environmental Protection Agency 2018). The use of landfilled glass as aggregate replacement reduces production costs associated with mining and transportation of aggregates and helps conserve natural aggregates. According to literature, the use of recycled glass in concrete is both sustainable and feasible (Topçu and Canbaz 2004; De Castro and De Brito 2013).

Glass aggregates in concrete and cement mortars generally decrease mechanical properties such as compressive, flexural, and tensile strength (Park et al. 2004; Tan and Du 2013). However, the literature suggests that the reduction in strength is acceptable at certain glass replacement levels and when specific glass particle sizes are used. Studies have shown that incorporating up to 60% of fine glass aggregates with particle sizes ranging from 0 to 4 mm results in acceptable mechanical properties (Mardani-Aghabaglou et al. 2015). Nonetheless, Taha and Nounu (2009) found an insignificant difference in strength between concrete without glass aggregates and concrete with 50% and 100% glass. In general, studies have found that the reduction in strength is linked to the weak bonding of the glass aggregates and cement matrix (Wright et al. 2014; Mardani-Aghabaglou et al. 2015; Chen et al. 2013).

Although acceptable mechanical properties can be obtained using glass aggregates, issues regarding durability have limited its use in the concrete industry. Specifically, expansion of glass aggregate concrete and cement mortars due to alkali silica reaction (ASR) is of major concern. In general, it is has been found that silica-rich glass aggregates cause detrimental expansion of concrete and cement mortar, which can ultimately impair durability and serviceability (Ling and Poon 2012; Shayan and Xu 2004). Nonetheless, it has been shown in countless studies that these deleterious expansions ensue at specific glass amount and glass particle size. According to Jin et al. (2000), detrimental ASR expansion can be prevented if glass aggregates with particle sizes below 300 μm are used. Likewise, Idir et al. (2010) found that glass aggregates smaller than 1000 μm results in tolerable levels of ASR expansion. Nevertheless, the inclusion of admixtures such as supplementary cementitious materials and lithium compounds have been shown to mitigate excessive ASR expansions (Taha and Nounu 2009; Afshinnia and Rangaraju 2015; Guo et al. 2017).

Durability in terms of volumetric contraction or shrinkage is an important property to consider as unforeseen shrinkage can result in the formation of cracks. Shrinkage cracks can directly affect strength and can also pose durability concerns, specifically in terms of permeability. There are different types of shrinkage that can occur in concrete and cement mortar specimens. Two specific types of shrinkage are early-age plastic shrinkage and drying shrinkage. Plastic shrinkage is rarely reported in the literature and to the authors' knowledge, no studies on the plastic shrinkage of glass aggregate concrete or cement mortars exist. On the other hand, there are several studies on drying shrinkage. From the literature review, it was found that glass aggregates are effective in reducing drying shrinkage. Some reasons for this conclusion is the low absorption capacity of glass aggregates compared to natural sand aggregates and the higher modulus of glass aggregate concrete compared to ordinary concrete (Tan and Du 2013; Wright et al. 2014). According to Kou and Poon (2009), the replacement of natural sand with glass aggregates can decrease drying shrinkage by as much as 18%.

The gap in the literature on plastic shrinkage of glass aggregate concrete or cement mortar prompted the current study. Drying shrinkage was also investigated for comparison with plastic shrinkage results. Since glass is presumed to be a reactive aggregate, assessment on ASR expansion was conducted as a common practice. This study also aimed to broaden the field of study by evaluating the response of two types of fine glass aggregates used individually and in combination.

2 EXPERIMENTAL PROCEDURE

2.1 Materials

Type 10 general use Portland cement conforming to CSA A3001 (CSA 2013) and natural sand aggregates with a fineness modulus of 2.63 were used in the production of all cement mortars. Two types of recycled glass aggregates were also used as the fine aggregate replacement. The first type of glass used was irregularly shaped crushed glass (CG), which had particle sizes ranging from 600 to 850 μm (Figure 1). The second type of glass used was spherically shaped glass beads (GB), which had particle sizes ranging from 250 to 425 μm (Figure 2). The density of CG and GB particles were 2499 kg/m^3 and 1249 kg/m^3, respectively. The chemical compositions of all materials used are presented in Table 1.

Figure 1: Crushed glass aggregates

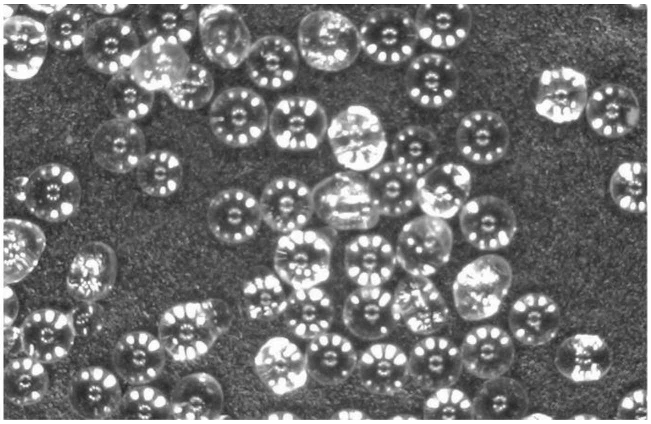

Figure 2: Glass bead aggregates

Table 1: Chemical composition of materials

Analyte symbol	Cement (%)	Sand (%)	Crushed glass (%)	Glass bead (%)
CaO	62.3	19.17	10.46	9.17
SiO_2	18.2	46.65	70.88	71.55
Al_2O_3	4.5	6.6	2.25	0.72
Fe_2O_3(T)	2.76	3.07	1.29	0.66
MnO	-	0.063	0.024	0.01
MgO	3.1	2.68	1.3	3.72
Na_2O	0.22	1.13	12.85	13.82
K_2O	0.45	1.24	0.64	0.13
SO_3	3.47	-	-	-
TiO_2	0.21	0.27	0.09	0.03
P_2O_5	-	0.07	0.02	0.01
Co_3O_4	-	< 0.005	< 0.005	< 0.005
CuO	-	0.006	0.023	< 0.005
NiO	-	< 0.003	< 0.003	< 0.003
Cr_2O_3	-	< 0.01	0.08	0.01
V_2O_5	-	0.007	< 0.003	< 0.003
LOI	4.8	16.43	-	-

2.2 Mixture Proportioning

One control mixture and three sets of glass aggregate cement mortars were prepared for the current study. All mixtures had a water/cement ratio and cement/fine aggregate ratio of 1:2 by mass. The control mixture contained only natural sand aggregates, whereas the three sets of glass aggregate cement mortars consisted of either 30% or 50% replacement of natural sand aggregates with glass. The first set of glass aggregate cement mortars consisted of only CG replacement, while the second set consisted of only GB replacement. The third set of glass aggregate cement mortars consisted of a mixture of CG and GB at a 2:1 ratio. For simplicity, the combination of CG and GB was labelled as MG, for "mixed glass". Table 2 summarizes the mass proportions of all cement mortar mixtures. The mixture designation corresponds to the type of glass replacement followed by the amount of replacement. Hence, MG-30 refers to a cement mortar consisting of 30% mixed glass. Plasticizer was not required for any of the mixtures.

Table 2: Mass proportions of cement mortar mixtures

Mixture Designation	Cement	Water	Fine aggregates		
			Sand	Crushed glass	Glass bead
Control	1	0.5	2.0	-	-
CG-30	1	0.5	1.4	0.6	-
CG-50	1	0.5	1.0	1.0	-
GB-30	1	0.5	1.4	-	0.6
GB-50	1	0.5	1.0	-	1.0
MG-30	1	0.5	1.4	0.4	0.2
MG-50	1	0.5	1.0	0.7	0.3

2.3 Test Methodology

2.3.1 Plastic Shrinkage

Plastic shrinkage tests were conducted in an open-ended environmental chamber with an operating temperature of 40°C (± 2°C) and relative humidity of 15% (± 3%). The testing conditions were obtained and maintained using a heater fan connected to a temperature and humidity controller. The operating conditions were set to accelerate the formation of plastic shrinkage cracks on 30 mm mortar overlays by inducing an evaporation rate of 1 kg/m2/h. A similar setup was used by Branston et al. (2016) and Banthia and Gupta (2007).

The fresh mortar was placed in a form over a 40 x 80 x 500 mm concrete base with hemispherical protrusions to simulate internal restrains (Figure 3). The forms were removed after 1.5 hours of testing to increase exposure to the environmental conditions. The entire duration of the test was 4 hours, after which the average width of the cracks was measured using a digital microscope. The length of each crack was also measured, and the total crack area was calculated. The average of two specimens tested simultaneously in the environmental chamber is reported in this paper.

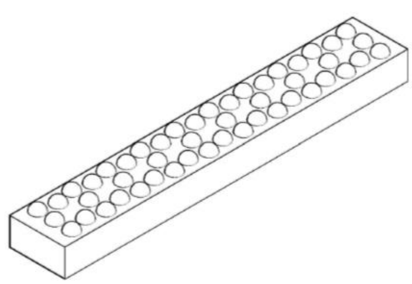

Figure 3: Typical 40 x 80 x 500 mm concrete base with hemispherical protrusions

2.3.2 Drying Shrinkage

Drying shrinkage tests were performed in accordance with ASTM C596 (ASTM 2009). Standard mortar bars (25 x 25 x 250 mm) with gage studs at each end were cast and cured in its molds for 24 hours. After demolding, the mortar bar specimens were further cured in water for 48 hours. The initial reading of surface dried specimens was taken after 72 hours of casting using a length comparator. The mortar bars were then placed in a controlled room with a set temperature of 22°C (± 1°C) and relative humidity of 40% (± 2%). Length readings were again taken after 25 days of storage (28 days after casting). The average of four mortar bar specimens is reported in this paper.

2.3.3 Alkali Silica Reaction (ASR)

The expansion of glass aggregate mortars was evaluated using the accelerated mortar bar method, as per ASTM C1260 (ASTM 2014). Standard mortar bars (25 x 25 x 250 mm) with gage studs at each end were cast and cured in its molds for 24 hours. After demolding, the specimens were immersed in a water bath at 80°C (± 2°C) for 24 hours. Initial length readings of surface dried specimens were taken, using a length comparator, within 30 seconds of removal from the water bath. The mortar bars were then immersed in 1 mol NaOH solution at 80°C (± 2°C) for a total of 14 days. Length readings were taken periodically within the 14 days of NaOH immersion to keep track of the progression of expansion; however, only the 14-day expansion is reported. According to ASTM C1260 (ASTM 2014), 14-day expansions less than 0.1% implies innocuous aggregates in the mortar, whereas expansions above 0.2% indicate the presence of potentially deleterious aggregates. Expansions between 0.1% and 0.2% indicate the presence of both innocuous and potentially deleterious aggregates. In total, the average of four mortar bar specimens is reported in this paper.

3 RESULTS AND DISCUSSION

3.1 PLASTIC SHRINKAGE

Plastic shrinkage cracks often occur in freshly placed concrete or cement mortar due to rapid evaporation of surface water. The formation of shallow plastic shrinkage cracks is a result of tensile stresses in the capillary pores of concrete and cement mortars, which exceed the tensile capacity of the cement paste (Uno 1998). Shallow plastic shrinkage cracks can ultimately become full-depth cracks, which can be detrimental in terms of durability and serviceability (ACI 1998). Hence, reducing plastic shrinkage cracks can positively enhance durability. In this study, it was found that glass aggregates have the ability to control the formation of plastic shrinkage cracks. Figure 4 shows an image of a typical plastic shrinkage crack observed under a digital microscope, and Figure 5 presents the reduction in the total crack area of cement mortars containing glass aggregates. From Figure 5, it is evident that the inclusion of CG and GB significantly reduces total crack area by at least 48%. In general, the positive influence of CG and GB in reducing plastic shrinkage cracks is attributed to the inherently low absorption capacity of glass. Regardless of the glass type, increasing the replacement level from 30% to 50% resulted in a further decrease in the crack area. Moreover, it was found that specimens containing CG performed far better than specimens containing GB because of the angular geometry and larger particle size of CG aggregates. The angularity of the CG aggregates provided better resistance to the tensile stresses induced by the increase in capillary pressure during rapid evaporation of surface water. Moreover, the angular shape of CG likely resulted in mixtures with greater voids that provided a network of passage for free water to reach the top surface of the specimen. The difference in the crack area between CG and GB is 76% and 85% at 30% and 50% replacement. As expected, the total crack area of MG specimens fell between CG and GB specimens at both replacement levels.

3.2 DRYING SHRINKAGE

Moisture loss in the pores of hardened concrete and cement mortars can result in drying shrinkage. Similar to plastic shrinkage, drying shrinkage can lead to cracking. In general, the high magnitude of drying shrinkage in concrete and cement mortar paste is resisted by the restraining effect of aggregates (ACI 1998). Nonetheless, for durability purposes, drying shrinkage should be minimized to prevent unnecessary crack formations. Figure 6 presents the drying shrinkage strains of glass aggregate mortars after 25 days of exposure to air (28 days after casting). From this figure, it is evident that glass aggregates have minimal effect on reducing drying shrinkage. At most, a 13% reduction in shrinkage strain was achieved when the glass aggregate mortars are compared to the control. This is comparable to the findings of Kou and Poon (2009). CG mortar specimens performed slightly better in shrinkage compared to GB and MG mortar specimens. It is likely that the angular shape of the CG aggregates provided better restraint compared to the spherical shape of GB aggregates. MG mortar specimens exhibited shrinkage between CG and GB mortar specimens as anticipated.

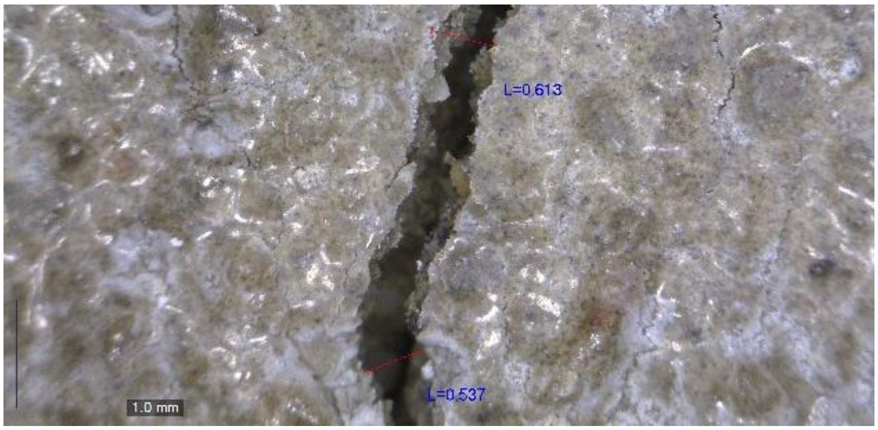

Figure 4: Typical plastic shrinkage crack observed under a microscope

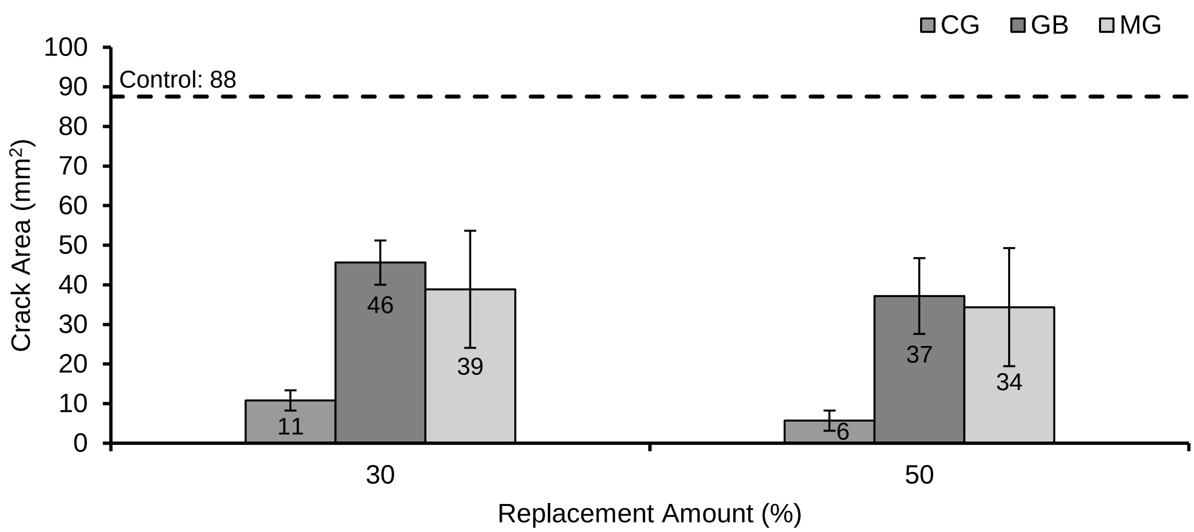

Figure 5: Total crack area due to plastic shrinkage

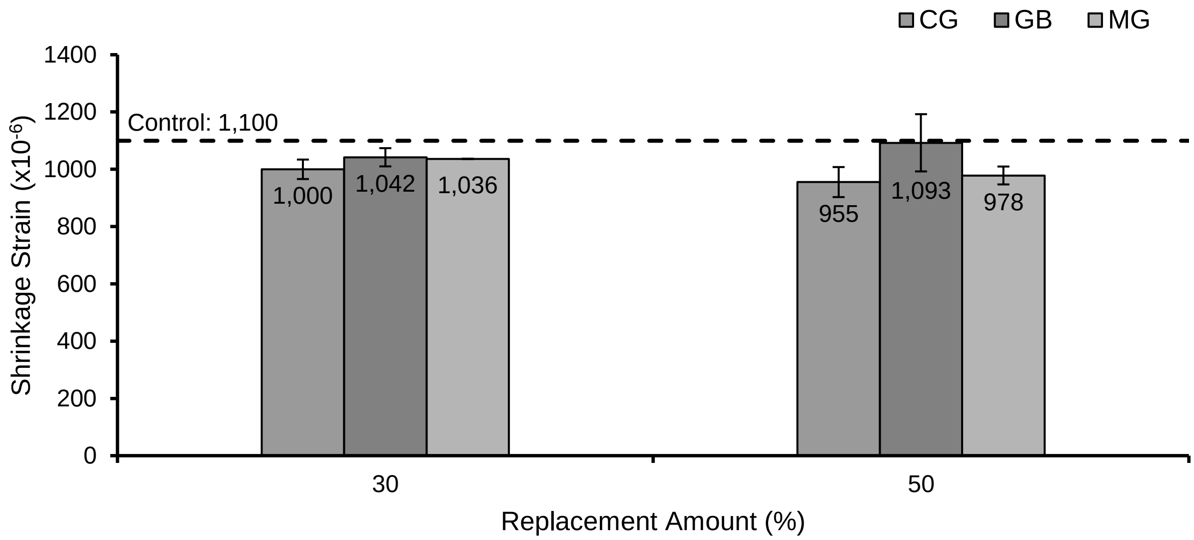

Figure 6: Drying shrinkage strain at 28 days

3.3 ALKALI SILICA REACTION

In general, the use of silica-rich glass aggregates in cement mortars results in deleterious expansions due to alkali silica reaction (ASR). However, studies have shown that deleterious ASR expansion does not always ensue when glass aggregates are used (Rajabipour et al. 2010; Du and Tan 2013). This study supports the aforementioned reports as test results indicate that different types of glass aggregates exhibit varying levels of ASR expansion. From Figure 6, it was observed that GB mortar specimens were less expansive compared to CG mortar specimens. The expansion of GB mortar specimens was 0.10% and 0.14% at replacement levels of 30% and 50%, respectively. Based on the expansion limits provided by ASTM C1260 (ASTM 2014), the expansion of GB mortar specimens just passes the 0.10% threshold, indicating the presence of innocuous and potentially deleterious aggregates. On the other hand, mortars containing CG exhibited excessive expansions well beyond the ASTM threshold of 0.2%, which suggests that CG aggregates are potentially deleterious. Specifically, the expansion of CG mortar specimens was 0.68% and 1.26% at replacement levels of 30% and 50%. The chemical composition of CG and GB are relatively similar; therefore, the superior performance of GB compared to CG is highly attributed to the greater fines proportion of GB compared to CG. Studies have shown that glass particle sizes below 300 μm causes little to no deleterious expansion; however, glass particle sizes above 600 μm experiences considerably high expansions (Shayan and Xu 2004; Rajabipour et al. 2010). Thus, the results obtained are reasonable because the particle size of GB is between 250 and 425 μm, which is slightly above and below the 300 μm boundary limit found in the literature. Moreover, the particle size of CG is between 600 and 850 μm, which meets the 600 μm boundary limit. As expected, the expansion of MG mortar specimens fell between CG and GB mortar specimens. It is evident that the CG content in the MG mortar specimens governed the expansion.

Figure 7 indicates that increasing the amount of glass aggregates generally increases ASR expansion as greater amounts of siliceous aggregates are available to react with the alkaline environment. The increase in expansion between CG-30 and CG-50 was 85%, whereas the increase in expansion between MG-30 and MG-50 was 67%. For GB mortar specimens, the increase in glass content from 30% to 50% resulted in a 29% decrease in the expansion. It is possible that a limit in the reaction was reached. Furthermore, Figure 6 also shows that the control mixture, which contained no glass aggregates, exhibited a 0.2% expansion. This level of expansion is classified as potentially deleterious by ASTM 1260 standards (ASTM

2014). The high alkalinity of the testing environment likely amplified ASR, thereby resulting in over-conservative values of expansion (Lu et al. 2006; Golmakani and Hooton 2016).

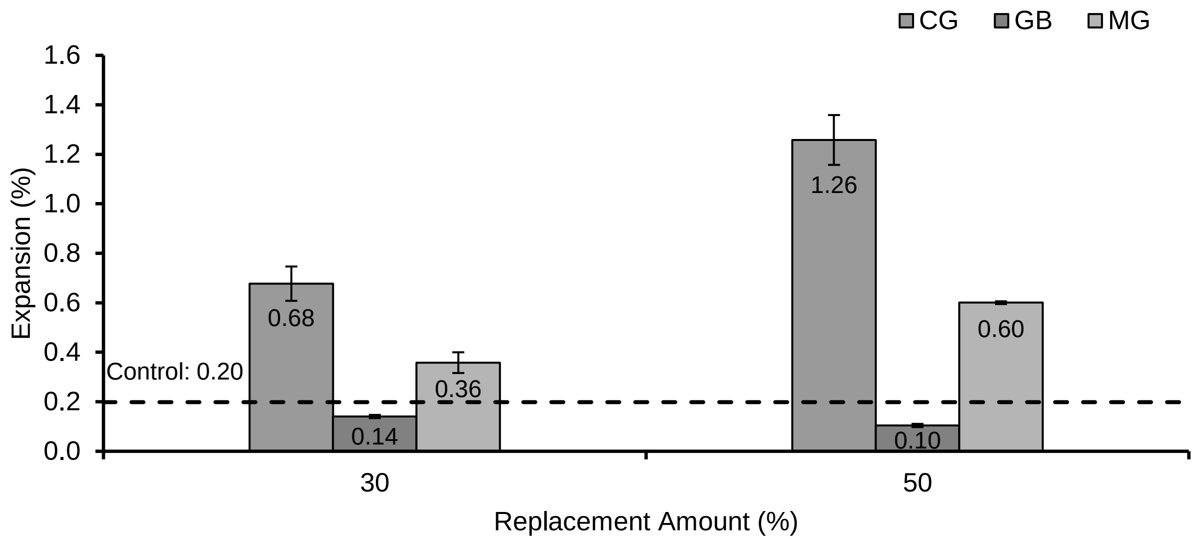

Figure 7: ASR expansion at 14 days

4 CONCLUSIONS

In this study, the effect of various types of glass aggregates on shrinkage and expansion of cement mortars was investigated. Based on the experimental study conducted, the following conclusions are drawn. It should be noted that the conclusions may be limited to the scope of the work.

1. Glass aggregates are effective in reducing plastic shrinkage cracks of cement mortar due to their inherently low absorption capacity. However, glass aggregates have minimal effect in decreasing drying shrinkage strains. In general, increasing glass replacement levels resulted in a greater decrease in shrinkage. Mortar specimens containing CG are more effective in reducing overall shrinkage because of the angularity of the aggregates.

2. Different types of glass aggregates exhibit varying levels of ASR expansion. The higher proportion of fines in GB aggregates resulted in GB mortar specimens having lower ASR expansion compared to CG mortar specimens. The control specimen, with no glass aggregates, exhibited high expansion due to the aggressive test conditions.

3. Long-term ASR tests should be considered in future studies to validate the results obtained using the accelerated mortar bar method. The inclusion of supplementary cementitious materials as partial replacement of cement should also be considered in future studies to reduce alkalinity in the pores of the cement mortars.

ACKNOWLEDGEMENTS

The authors acknowledge the Natural Sciences and Engineering Research Council of Canada for the financial support provided to Karla Gorospe in the form of the Canada Graduate Scholarship.

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