

Utilization of waste glass as sand replacement in cement mortar

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In this study, alkali silica reaction (ASR) expansion and strength characteristics of mortar containing waste glasses are analyzed in terms of waste glass content and glass color. Three different colors of waste glasses (white, green and brown) are replaced with sand at ratios of 10%, 30% and 100% by weight. The mixtures used in this study did not show a considerable ASR expansion. All batches had expansions less than 0.10% is indicative of non-deleterious expansion. However, the samples continued to expand beyond 14 days which makes the test period questionable for glass containing samples. The strength depends upon the level of waste glass replacement and age. With high replacement percentages of sand by waste glass, the glass containing mortar exhibited lower values of compressive strength. This effect is more pronounced for 100% glass containing mortar. The reduction in flexural strength is generally higher than the reduction in compressive strength of the similar samples. It can be concluded that up to 30% replacement level of waste glass, the glass containing mortar can achieve improved or equivalent strength performance compared to 100% limestone mortar.

Keywords: Composite materials, Mechanical properties, Waste glass, Alkali silica reaction

The recycling of waste glass is a major problem for municipalities worldwide due to high disposal costs and environmental concerns. Recycling glass from the municipal solid waste stream for use as a raw material in new glass product is limited due to high costs, impurities and mixed color. Although colorless waste glasses have been recycled effectively, colored waste glasses with their low recycling rate have been dumped into landfills sites.

The utilization of waste glass in construction has attracted a lot of interest worldwide due to the large quantity consumptions and widespread construction sites. Recently, many studies have focused on the uses of waste glasses as partial replacement of natural aggregates in concrete. The use of waste glasses as concrete aggregates did not have a significant effect on the workability and strength but decreased the slump, air content and fresh weight of concrete¹. Finely ground glass powders exhibited very high pozzolanic activity^{2,3}. A major concern for using waste glass in concrete is the alkali-silica reaction (ASR) that takes place between the alkalis in cement and the reactive silica in glass. This reaction can be very detrimental to the stability of concrete. Recent

studies have shown that there are several approaches that can effectively control the expansion of ASR due to glass aggregate. It has been reported that the usage of by-product and wastes such as fly ash, silica fume and granulated blast-furnace slag decreased the expansion from ASR. The combined usage of waste glass with industrial by-products can be more suitable instead of using it alone in mortar^{4,5}. Lithium salt also can be a very effective additive in reducing ASR expansion of concrete containing waste glass⁶.

The ASR expansion is directly proportional to the content of waste glasses regardless of their type⁷. The particle size of glass aggregate was found to have a major influence on ASR expansion. As mentioned, ASR expansion increases with increasing fineness of glass up to a certain point and then decreases afterwards^{8,9}. Also recent studies reported that if the waste glass is finely ground under 100 µm ASR expansions does not occur¹⁰. The types of glass were found to have a significant effect on the ASR expansion. Glasses containing boron such as Pyrex glass were found to be more reactive than soda-lime silica glasses¹¹. The glass color also has an effect on ASR expansion. For instance clear soda-lime glass was found to be most reactive followed by brown glass. It was also indicated that green glass was more

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usable than brown because its expansion was less than that of brown glass. Depending on the size of glass particle, green glass of fine particles can reduce expansion. This may be due to the chromium oxide which is added to the glass to create its green color¹². However, the study at University of Sheffield in UK found that there was no difference in green, amber and flint glasses¹³. In another study, the relative effects of glass color on the ASR expansion were not found clear and appeared to change with particle size¹⁴.

The aim of this paper is to investigate the influence of waste glasses as a replacement material for sand on the strength characteristics and ASR expansion of the mortar containing waste glasses with the color of the waste glasses (white, green and brown) and content of waste glasses (10%, 30% and 100%).

Materials and Methods

Material properties

Cement used in the mortar mixture was ordinary Portland cement (CEM I) had a strength class 42.5 N according to Turkish standard TS EN 197-1¹⁵. The alkali content of this cement ($\text{Na}_2\text{O}_{\text{eq}}$) was 0.83%. Limestone aggregate (LS) conforming to TS 706 EN 12620¹⁶ was used in this study for preparing cement mortars. Physical properties of LS are given in Table 1.

Waste glasses (WG) were used as replacement of LS sand with different colors (white, green and brown) and content. WG used in the experiments were soda-lime glasses that have been widely used for bottles. The chemical properties of Portland cement (PC) and WG are given in Table 2. After the gathering process, these bottles were kept in water to remove organic contaminants and were then dried and crushed in the laboratory to five different sizes. The grading of LS sand and WG aggregates are given in Table 3.

ASR expansion test

RILEM AAR-2, the ultra-accelerated mortar test (AMBT) was used to determine the ASR expansion of mortar bars. The ratio of cement, sand and water was

1:2.25:0.47, respectively. WG were used as replacement of LS sand with different colors and contents. In all mixtures, three different colors of WG were substituted in weight ratios of 10%, 30% and 100% of each LS size fraction, respectively. The mixtures were designated as weight ratio-glass color, e.g., 10 white; the mixture containing no glass is designated as 100 LS.

Three 25×25×285 mm mortar bars were cast for each mixture. After 24 h curing the mortar bars were placed in water at 80°C for another 24 h to measure the reference length. Then the mortar bars were transferred to a solution of 1 M of NaOH at 80°C for the following test period. The length differences of the mortar bars were compared to the reference bars at 14 and 21 days, respectively.

Strength tests

For strength tests, mortar specimens were prepared according to procedure described in TS EN 196-1¹⁷. However, the mortar mixtures were proportioned in accordance with AAR-2 test method. The grading of

Table 2—Chemical composition of PC and WG

Chemical composition (%)	PC	WG		
		White	Green	Brown
SiO ₂	18.80	69.72	64.03	57.41
Al ₂ O ₃	5.13	1.02	1.6	1.68
Fe ₂ O ₃	2.78	0.55	0.52	0.86
CaO	63.31	8.76	12.41	4.83
MgO	1.58	3.43	3.31	2.75
Na ₂ O	0.25	8.42	7.76	6.42
K ₂ O	0.88	0.13	0.32	0.60
SO ₃	2.63	0.20	0.11	0.16
Total	95.36	92.55	94.14	94.08
LSF*	---	4.45	6.84	9.08
MS**	---	44.44	30.1	22.56
AF***	---	1.88	3.06	1.95
LOI****	3.91	0.31	4.07	9.37

*Lime saturation factor, ** Modulus of silica, *** Alumina factor
**** Loss on ignition

Table 3—Grading of LS sand and WG aggregates for ASR expansion and strength tests

	Sieve size (mm)		Mass, %
	Passing	Retained	
	4	2	
2	1	25	
1	0.5	25	
0.5	0.25	25	
0.25	0.125	15	

Table 1—Some important physical properties of LS

Aggregate property	Relevant standard	Obtained value
Loose bulk density	TS EN 1097-3	1.639 Mg/m ³
Void content	TS EN 1097-3	40.42 %
SSD particle density	TS EN 1097-6	2.754 Mg/m ³
Water absorption	TS EN 1097-6	0.25 %
Fines content <63µm	TS 3530 EN 933-1	32 %

LS was kept constant while each size fraction of WG was replaced with corresponding size fraction of the LS. The investigated mortar specimens were cast into three-gang (40×40×160 mm) prism mold and compacted as described in the related standards¹⁷. After the compaction procedure, the molds were placed in a humidity cabinet for 24 h (21±2°C, 95% RH). Following this period, the specimens were removed from the molds and kept in water until the testing time. Compressive strength and flexural strength of the mortar specimens were determined in accordance with TS EN 196-1¹⁷. Flexural strength of the specimens was determined by using three 40×40×160 mm prismatic specimens. Compressive strength test was applied on six broken portions of flexural test specimens. Strength tests were carried out at 7, 28 and 90 days. The compressive strength results indicated the average of six values and flexural strength results are the average of three values.

Results and Discussion

ASR Expansions

ASR expansions of the mixtures are given in Fig. 1. The 14-day expansions of all mixtures are below the proposed limits (0.10%) by many standardization agencies for the specimen dimensions used in this study^{18,19}. ASR expansions of less than 0.10% are indicative of non-deleterious expansion. Considering all of the glass types used in this study, generally there is an increasing trend of expansion by increasing amount of WG used in the mixture. White-WG containing mixtures reveal the highest expansion values when compared with the other mixtures having same amount of green or brown-WG. ASR expansion readings were taken beyond 14-days, an increase in

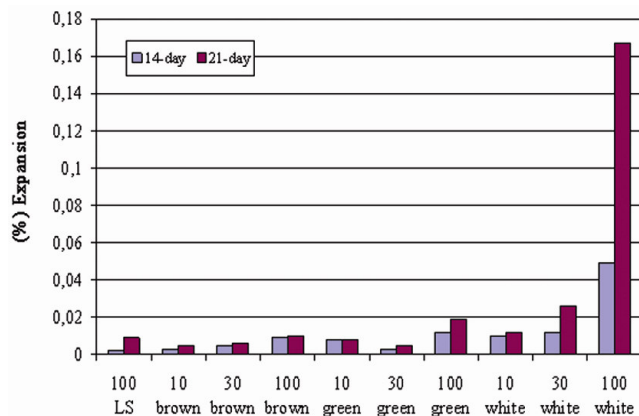


Fig. 1—ASR expansions of glass containing mixture

the expansion values were observed for white-WG bearing mixtures. 21-day expansion of 100% white-WG containing mixture is considerably above the ASR expansion limit. The mortars containing 100% white-WG exhibited expansion less than 0.10% at 14 days however exceeded the 0.10% limit at 21 days. This value was between 0.10% and 0.20% at 21 days and so this expansion is indicative potentially detrimental expansion. Map cracking was also observed for these samples. The ASR expansion results reveal that white-WG serves as a slowly-expanding aggregate in the mixture. It should be noted that, the expansion period for accelerated mortar bar test should be revised for white-WG containing mixtures.

Compressive and Flexural Strength

In the present research, WG was used as replacement of LS sand with different colors and contents in production of the cement mortar. In all mixtures, three different colors of WG (white-WG, green-WG, and brown-WG) were substituted in weight ratios of 10%, 30%, and 100% of each LS sand size fraction. The Portland cement, limestone sand and water mixing proportions were 1:2.25:0.47, respectively.

Figure 2 shows the test results of the compressive strength depending on the changes in the mixing rate of the WG and the age of testing. The rate of compressive strength depends upon the level of WG replacement and curing age. As expected, the compressive strength increased with curing age. The strength development of the cement mortar containing WG was compared with that of the mortar containing 100% LS sand at the same age. It was

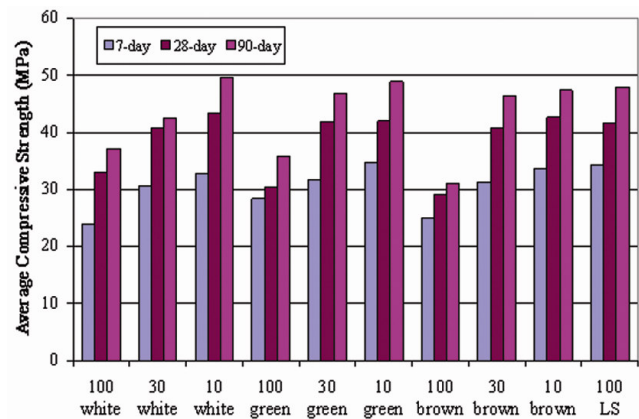


Fig. 2—Average compressive strength of the mixtures at different ages (7, 28, 90 days)

observed that with increase of the WG content, the compressive strength of the mortars decreased. This effect is quite considerable at 100% WG containing mixtures. Brown-WG incorporation reduces the compressive strength of mixtures more than the other mixtures. However, there are some exceptional results such as the results obtained for 10% WG replacement level. The maximum compressive strength values were measured at 10% WG replacement level for all curing days.

The mortar containing 100% LS exhibited generally a higher compressive strength than the other mixtures especially at early ages. As seen in Fig. 2, the mortar containing 100% LS achieved a compressive strength of 34.23 MPa at the age of 7 days whereas, the mortars containing 100% white-WG, 100% green-WG and 100% brown-WG achieved the compressive strengths of 23.89 MPa, 28.42 MPa and 25.07 MPa, respectively. Also, the mortars containing 30% white-WG, 30% green-WG and 30% brown-WG aggregates achieved the compressive strengths of 30.68 MPa, 31.71 MPa and 31.37 MPa, respectively at 7 days. At 7 days, the mortars containing 10% white-WG, 10% green-WG and 10% brown-WG achieved the compressive strengths of 32.75 MPa, 34.75 MPa and 33.74 MPa, respectively. The maximum compressive strength value was obtained at 10% green-WG replacement level for 7 days.

The compressive strength value of the mortar 100% LS containing was 41.60 MPa at 28 days whereas the mortars containing 100% white-WG, 100% green-WG and 100% brown-WG achieved the compressive strengths of 33.03 MPa, 30.47 MPa and 29.05 MPa, respectively. The mortars containing 30% white-WG, 30% green-WG and 30% brown-WG achieved the 28-day compressive strengths range of 40.74 MPa, 41.87 MPa, and 40.82 MPa, respectively which are close to or better than the strength of 100% LS mortar. The mortars containing 10% white-WG, 10% green-WG and 10% brown-WG achieved the compressive strengths of 43.27 MPa, 42.01 MPa, 42.61 MPa, respectively, at 28 days. At 10% replacement of WG the compressive strength values of the WG containing mortars were higher than that of the 100% LS mortar. The maximum compressive strength value was obtained as 43.27 MPa at 10% white-WG replacement level for 28 days.

Compared with results at 90 days, the 100% LS mortar achieved a compressive strength of 48.00 MPa whereas mortars containing 100% white-WG, 100%

green-WG and 100% brown-WG achieved the compressive strengths of 37.14 MPa, 35.81 MPa and 31.01 MPa, respectively. Also, the mortars containing 30% white-WG, 30% green-WG and 30% brown-WG aggregates achieved the compressive strengths of 42.49 MPa, 46.90 MPa and 46.36 MPa, respectively at 90 days. The mortars containing 10% white-WG, 10% green-WG and 10% brown-WG achieved the compressive strengths of 49.56 MPa, 48.88 MPa, and 47.38 MPa, respectively. The mortars containing 10% white-WG and green-WG exhibited higher strength values than that of 100% LS mortars.

The percentage of WG has a rather significant effect on compressive strength. With high replacement percentages of LS sand by WG, the WG containing mortar exhibited weaker values of compressive strength. The decrease in strength development could be attributed the decrease in adhesive strength between the surface of the WG aggregates and the cement pastes. The smooth and plane surface of the large WG particles could significantly weaken the bond between the cement paste and the WG particles.

However, the white-WG containing mortar exhibited generally high compressive strength at all ages, the color of the WG has a small effect on the compressive strength which could be ignored.

The mortars containing 10% WG demonstrated the best compressive strength. After 28 days of curing the compressive strength of the mortars containing 10% white and brown-WG was always higher than the minimum required limit (42.5 MPa) given in TS EN 197-1 for cement mortar. For 30% replacement, the compressive strengths of the mortars with WG were same as or close to 100% LS mortar. It is concluded that up to 30% WG replacement of sand, the WG containing mortars can achieve improved or equivalent strength performance compared to mortars made with 100% LS.

Average flexural tensile strength results for 7, 28 and 90-day old mixtures are given in Fig. 3. Flexural tensile strength of the samples were decreased by increasing WG replacement level, the decrease in strength becomes considerable for 100% WG containing samples. The 100% LS mortar achieved a flexural strength of 7.08 MPa at 7 days whereas the mortars containing 100% white-WG, 100% green-WG and 100% brown-WG achieved the flexural strengths of 5.05 MPa, 4.23 MPa and 3.41 MPa, respectively. The mortars containing 30% white-WG, 30% green-WG and 30% brown-WG aggregates

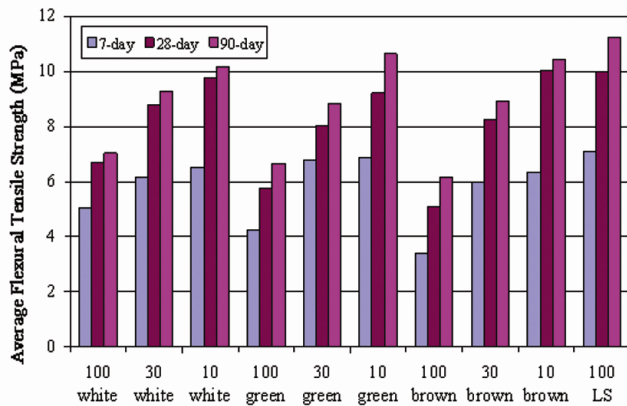


Fig. 3—Average flexural tensile strength of the mixtures at different ages (7, 28, 90 days)

achieved the flexural strengths of 6.16 MPa, 6.76 MPa and 5.97 MPa, respectively at 7 days. Also the mortars containing 10% white-WG, 10% green-WG and 10% brown-WG achieved the flexural strengths of 6.52 MPa, 6.89 MPa and 6.35 MPa, respectively.

Compared with the test results at 28 days, the 100% LS mortar achieved a flexural strength of 10.00 MPa whereas mortars containing 100% white-WG, 100% green-WG and 100% brown-WG achieved the compressive strengths of 6.68 MPa, 5.77 MPa and 5.10 MPa, respectively. The mortars containing 30% white-WG 30% green-WG and 30% brown-WG aggregates achieved the compressive strengths of 8.79 MPa, 8.02 MPa and 8.24 MPa, respectively at 28 days. Also the mortars containing 10% white-WG, 10% green-WG and 10% brown-WG achieved the compressive strengths of 9.79 MPa, 9.23 MPa, and 10.02 MPa, respectively. For 10% replacement, the flexural strength values of the mortars with WG were same as or even better than 100% LS mortar at 28 days.

The flexural strength value of the mortar 100% LS containing was 11.24 MPa at 90 days whereas the mortars containing 100% white-WG, 100% green-WG and 100% brown-WG achieved the compressive strengths of 7.04 MPa, 6.65 MPa and 6.16 MPa, respectively. The mortars containing 30% white-WG, 30% green-WG and 30% brown-WG achieved the 90-day flexural strengths range of 9.27 MPa, 8.83 MPa, and 8.92 MPa, The mortars containing 10% white-WG, 10% green-WG and 10% brown-WG achieved the compressive strengths of 10.16 MPa, 10.64 MPa, 10.44 MPa, respectively, at 90 days. At 10% replacement WG aggregates,

the flexural strength values of the mortars were close to the 100% LS mortar. The color of the glass has no or less similar effects when the samples containing same amounts of glass are compared. However, 100% brown-WG containing samples reveal the minimum flexural strength results.

The reduction in flexural strength of samples is generally higher than the reduction in compressive strength of the same samples that were tested at similar ages. This might be due to the changes in the interfacial transition zone properties of WG containing samples.

Conclusions

In the present study, alkali silica reaction (ASR) expansion and strength characteristics of mortar containing waste glasses were analyzed in terms of waste glass content and glass color and based on the experimental results, the following conclusions can be made.

- (i) AMBT test results reveal that the mixtures used in this study did not show a considerable ASR expansion. All batches tested were able to mitigate ASR expansions to below 0.10% and therefore according to ASTM 1260-01, the expansions were within the permissible limits.
- (ii) The increase in expansion of 100% white-WG containing samples beyond 14-days makes the period of test method questionable for mixtures containing glass.
- (iii) The percentage of WG has a rather significant effect on compressive strength. With high replacement percentages of LS sand with WG, the glass containing mortar exhibited lower compressive and flexural strength than those made with 100% LS sand. The decrease in strength becomes considerable for 100% WG containing samples. It is believed that such a decrease in strength is due to the decrease in adhesive strength between the surface of the waste glass and cement paste.
- (iv) However, the reduction in flexural and compressive strength of brown-WG incorporating mixtures is higher than that of samples containing white-WG and green-WG, the color of the waste glass has a small effect on the compressive strength which could be ignored.
- (v) The reduction in flexural strength of samples is generally higher than the reduction in

compressive strength of the same samples. This may be attributed to the change in the interfacial transition zone properties of glass containing mixtures.

- (vi) The 10% WG replacement produced higher strength than the other mixtures. but they also showed that the mortar containing waste glass continued to develop further strength with age. After 28 days of curing the compressive strength of the mortars containing 10% WG was close to or higher than the minimum required limit (42.5 MPa) given in TS EN 197-1 for cement mortar.
- (vii) At 10% replacement glass aggregate the flexural strength value of the mortar was close to or higher than that of the 100% LS mortar.
- (viii) The mortars containing up to 30% waste glasses as sand can achieve the comparable strengths to that of 100% limestone sand. It could be observed that when 30% fine aggregate was replaced by waste glass, the 28 day strength was same as that of 100% LS mortar.

The study concluded that up to 30% waste glass replacement of sand, the waste glass containing mortar can achieve improved or equivalent strength performance compared to 100% LS mortar. Waste glass could be incorporated as fine aggregate replacement in cement mortar. The recycling of waste glass poses a major environmental problem for local municipalities everywhere. This problem can be reduced or eliminated by reusing waste glass in the construction industry. The reuse of waste glass in construction can also reduce the demand on the sources of primary raw materials. Utilization of waste glass offers important benefits both environmentally and economically.

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