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INFLUENCE OF RECYCLED GLASS ADDITION ON MORTAR PROPERTIES

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***Abstract*—This work was aimed at studying the possibility of reusing waste glass from crushed containers as aggregate for preparing mortars. At present, this kind of reuse is still not common due to the risk of alkali–silica reaction (ASR) between alkalis of the cement and silica of the waste glass. This expansive reaction can cause great problems of cracking and, consequently, it can be extremely deleterious for the mortar durability. The influence of both size and colour of recycled glass coming from post-consumer domestic containers on the properties of mortars was studied. The attention was focused on both mechanical behaviour, investigated by means of bending and compression tests, as well as durability, studied by means of accelerated tests for evaluating the tendency to expand under alkaline environment due to ASR. Several mortars were prepared by replacing at different rate the quartz sand with coarse glass cullet of different colours: clear (i.e. uncoloured), green and amber. Then, pulverized clear glass was added to the mortar mixtures, also in the presence of class F fly ash. Results obtained showed that by using both green and amber glass cullet the mortars are stable, as well as by using powder glass, which also showed a significant pozzolanic effect. On the other hand, considerable expansion due to ASR was detected by using clear glass cullet.**

***Keywords*—Alkali–silica reaction, Durability, Glass powder, Pozzolanic effect, Recycled glass, Waste glass.**

I. Introduction

Post-consumer waste glass represents one of the major components of the solid waste stream. Today, discarded waste glass has become a substantial burden on the landfills throughout the world. In fact, the practice of recycling glass containers is growing in many countries. Unfortunately, a significant portion of the collected glass is not actually recycled into new glass; mainly due to the prohibitive shipping costs from collection points to recast facilities. In addition, in Italy the majority of domestic container glass production is in clear and amber colours; which makes recycling of the imported green containers challenging and costly. In fact, in Italy the whole domestic container production is about 1,500,000 tonnes per year, of which 63% is clear, 23% is amber and 13% is green, but varies significantly geographically and seasonally. Similar problems have been reported in the rest of Europe, US, Australia, and the Middle East [1–4]. Large quantities of the post-consumer glass are currently land-filled or stockpiled in hopes that future technologies would allow a profitable use of this material [4].

Concrete construction provides a significant market potential for waste glass recycling. Extensive studies have been carried out to utilize crushed recycled glass as partial replacement of aggregates into conventional concrete and mortar [5–8].

The use of recycled glass in concrete as cement or aggregate replacement can be environmentally and sometimes economically advantageous as it converts large quantities of waste materials to value-added products and reduces the need for transportation by offering a local material resource.

In particular, the feasibility of using recycled glass as sand in concrete has been explored by many authors; and it was determined that concretes with desirable strength and workability can be produced by proper mixture proportioning and the use of water reducing admixtures. The major technical obstacle, however, is the deleterious alkali-silica reaction (ASR). In fact, the amorphous silicate structure of glass dissolves in the alkaline pore solution of concrete and forms an alkali-silica gel which, in the presence of water, swells and cracks the concrete [9–10].

Previous research [2,11-15] has focused on relating the severity of ASR expansions to the size, content, and colour of glass aggregates. In particular, it was found that expansions and cracking generally decrease by reducing the particle size of glass [2]. In terms of the influence of glass colour on ASR expansion, some literature reported that green glass showed the lowest ASR expansion compared with brown and clear glass, due to the presence of Cr_2O_3 [2,6,16]. However, Ozkan and Yuksel [17] observed very small difference among green, brown and clear glasses in ASR reactivity. On the other hand, Dhir et al. [18] reported that green glass showed the highest ASR expansion while clear glass showed the lowest.

II. Research significance

This work aimed at evaluating the influence of both size and colour of recycled glass coming from post-consumer domestic containers on the properties of recycled glass mortars. The attention was focused on both mechanical behaviour, studied by means of bending and compression tests, as well as durability, investigated by means of accelerated tests for evaluating the tendency to expand under alkaline environment due to alkali-silica reaction.

With this purpose several mortars were prepared by replacing at different rate (either 50% or 100% by weight) the quartz sand with coarse (particle size up to 8 mm) glass cullet of different colours: clear (i.e. uncoloured), green and amber.

Then, very fine glass powder (particle size under 0.300 mm) was added to the mortar mixtures, by replacing 50% by weight of quartz sand. In the presence of glass powder, also a class F fly ash was used at a dosage of 150 kg/m^3 by replacing the same amount of either cement or sand.

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The effectiveness of fly ash addition besides to glass powder was evaluated bearing in mind the experimental results found by some authors [19-20], showing that ASR expansion is significantly reduced by the use of fly ash.

III. Experimental procedure

A. *Materials*

As binder, commercial portland-limestone blended cement type CEM II/B-LL 32.5 R according to the European Standards EN-197/1 [21] was used. Its relative density (specific gravity) was 3,050. Also a low-calcium fly ash (ASTM C 618 Class F) produced by a thermal generating station was used. Its relative density (specific gravity) was 2.25. Chemical composition as well as Blaine fineness values of both cement and fly ash are reported in Table 1.

As aggregate for mortars, either quartz sand (not susceptible to ASR) or recycled glass were used. Four different fractions of waste glass were prepared at all: three of them were obtained by crushing domestic containers made of either clear (uncoloured) or green or amber glass by means of a jaw crusher, then sieved in order to collect only the fraction passing 8 mm sieve. They showed the same grain size distribution (see 'glass cullet' in Fig. 1), but different colour. Their chemical compositions are reported in Table 2.

Then a fourth fraction was produced by finely ground clear glass cullet by means of a jaw crusher before, then refined by means of a rotating ball mill. Finally, this fraction (represented as 'glass powder' in Fig. 1) was sieved in order to collect only the fraction passing 0.300 mm sieve.

The particle size distributions of quartz, sand and recycled glass fractions, were determined according to EN 933-1 [22]; the curves obtained are shown in Figure 1.

B. *Mortar mixture proportions*

Ten different mortars were prepared, their mixture proportions are reported in Table 3. The cement to sand ratio was 1:3 (by mass) and the cement content was maintained equal to 450 kg/m^3 for all the mixtures with the only exception of a mix (GP-50%+FAc), in which cement was partially replaced by 150 kg/m3 of fly ash, and reduced to 300 kg/m^3. The water content of each mortar was set to achieve the same consistence (125 ± 10 mm), evaluated according to EN 1015-3 [23]. Several combination of quartz sand and recycled glass were tried. Firstly, a reference mixture (REF) was prepared by only using quartz sand; then in three mixtures quartz sand was partially replaced (50% by weight) by glass cullet of different colours, alternatively uncoloured (mix ClearGC-50%), green (mix GreenGC-50%), and amber (mix AmberGC-50%). Further three mixtures were prepared by fully replacing sand with glass cullet of different colours: uncoloured (mix ClearGC-100%), green (mix GreenGC-100%), and amber (mix AmberGC-100%).

Finally, glass powder (GP) was added to the mortar mixtures, by replacing 50% by weight of quartz sand (mix GP-50%). In the presence of glass powder, also other two mixtures were prepared, in which class F fly ash was used at a dosage of 150 kg/m^3 by replacing either cement (mix GP-50%+FAc) or sand (mix GP-50%+FAs).

TABLE I. CHEMICAL COMPOSITION AND BLAINE FINENESS OF BINDERS

Composition (% by mass)	*Cement CEM II/B-LL 32.5R*	*Fly Ash ASTM Class F*
Silica (SiO_2)	22.6	56.8
Calcium oxide (CaO)	61.9	2.2
Alumina (Al_2O_3)	4.8	28.2
Iron oxide (Fe_2O_3)	4.8	5.3
Magnesium oxide (MgO)	1.1	5.2
Sodium oxide (Na_2O)	0.1	0.4
Potassium oxide (K_2O)	0.5	1.3
Sulfur trioxide (SO_3)	2.4	0.7
Blaine fineness (m^2/g)	0.36	0.39

TABLE II. CHEMICAL COMPOSITION OF COLORED GLASS CULLET

Composition (% by mass)	*Uncoloured glass cullet (ClearGC)*	*Amber glass cullet (AmberGC)*	*Green glass cullet (GreenGC)*
Silica (SiO_2)	71.2	70.2	70.4
Calcium oxide (CaO)	10.7	10.3	10.1
Alumina (Al_2O_3)	1.8	1.9	1.8
Iron oxide (Fe_2O_3)	-	0.4	0.5
Magnesium oxide (MgO)	2.5	2.6	2.8
Sodium oxide (Na_2O)	13.4	13.2	12.9
Potassium oxide (K_2O)	0.5	0.6	0.4
Sulfur trioxide (SO_3)	-	1.3	0.2
Chromium III Oxide (Cr_2O_3)	-	0.1	0.3
$CaO/(SiO_2+Na_2O)$	0.126	0.123	0.121

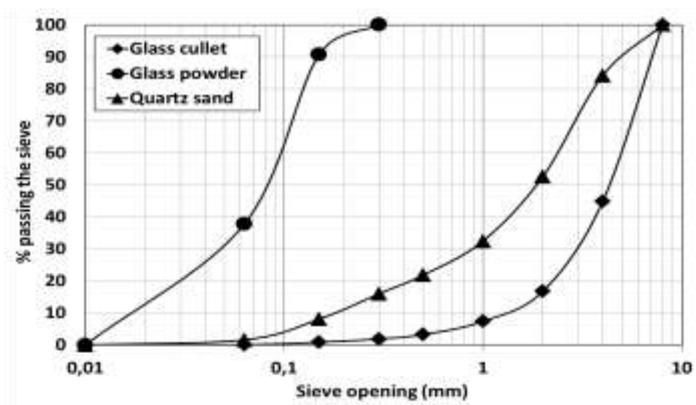

Figure 1. Grain size distributions of quartz sand, glass cullet and powder.

C. *Mechanical characterization*

Prismatic specimens (40x40x160 mm) were manufactured, cast and wet cured at 20°C up to 180 days. The compressive and flexural strengths were evaluated after 3, 28 and 180 days according to EN 1015-11 [24].

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D. ASR Evaluation

The ASR expansion was determined by accelerated mortar bar tests according to ASTM C 1260 [25]. For each mixture, three 70 x 70 x 280 mm mortar bars were prepared. Mortar specimens were cured for 1 day at 25 °C and 100% R.H., then submitted to accelerated curing at 80 °C in a 1 N NaOH solution. This procedure closely resembles that suggested by ASTM C1260 standard. Mortar stability was determined by means of a mechanical comparator (0.001 mm accuracy) on samples cooled at room temperature, as prescribed by ASTM C1260 (80 °C).
The initial lengths of the mortar bars were firstly recorded before they were immersed into 1 N NaOH solution. The expanded lengths were subsequently measured after 2, 4, 7, 14, 21, 28, 35 and 42 days.

E. Microscope observation of sample

Samples were taken from all the specimens maintained for 42 days in 1 N NaOH solution, in order to observe the likely presence of ASR products at the interface between glass particles and the surrounding cement paste. These samples were observed by means of both optical macroscope and scanning electron microscope (SEM); also energy dispersive x-ray (EDX) spectroscopy was carried out in some cases, for detecting the chemical composition of the observed products.

IV. Results and discussion

A. Mechanical characterization

In Figure 2 the results obtained from compression tests are reported. The only mixture showing a mechanical performance comparable to that of the reference mixture was that prepared by using 50% clear glass replacing sand, while at the dosage of 100% this clear cullet produced the lowest value of compressive strength after 180 days. The reason of this loss of resistance could be the presence of widespread cracking in the specimens made of 100% clear waste glass, that was detected by visual inspection.
Concerning the mixtures with green cullet, a certain difference between 50% and 100% replacement was detected again, but in this case is less evident than in clear cullet mixtures, and evidence of cracking wasn't detected in any case. On the other hand, in the case of amber cullet almost the same behaviour in compression was found for both 50% and 100% substitution.
Concerning the addition of glass powder, a great pozzolanic effect was detected in every case, with a 180-day compressive strength at least 80% higher than the related 28-day compressive strength. In particular, this increase between 28 and 180 days was even equal to about 120% in the case of glass powder used together with fly ash replacing cement. The final values of compressive strength was close to that reached by the reference mixture, but the water to cement ratio adopted was 60-65% higher in order to reach the same fresh mortar workability (due to the greater water absorption of glass powder with respect to quartz sand). Therefore, if used together with a water-reducing admixture, powder glass could be extremely effective in improving mechanical performance of mortar, as also outlined in a previous work [26].

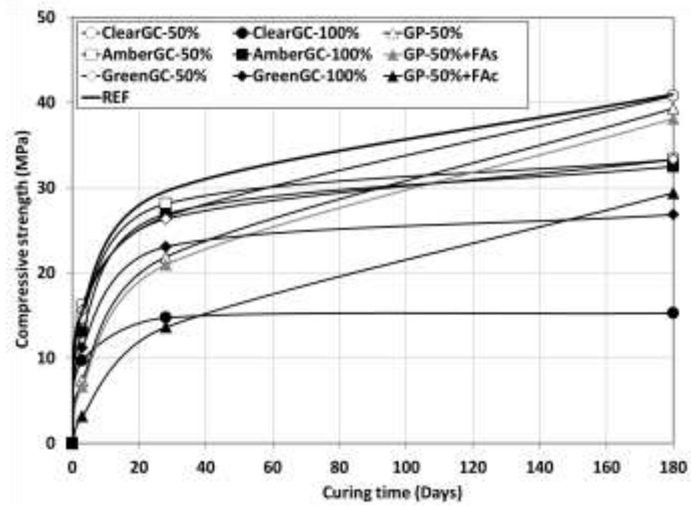

Figure 2. Compressive strength vs. cruing time.

In Figure 3 the results obtained from bending tests are reported. The only mixture showing a mechanical performance comparable to that of the reference mixture was again that prepared by using 50% clear glass replacing sand, while at the dosage of 100% this clear cullet produced the lowest value of flexural strength after 180 days. In general, all the mixtures prepared with 100% glass cullet, independently of the colour, are less resistant in bending than those prepared with 50% replacement. The reason could lie in the grain size distribution of aggregate particles, which is close to that optimized according to the suggestions of Bolomey [27], only if 50% sand is replaced by glass cullet (see Fig. 1), while is too poor of fine particles if only glass cullet is used. Also in the case of flexural strength, the use of glass powder confirmed its evident pozzolanic effect, with a 180-day compressive strength growing of about 10%, 22%, and 50% with respect to the related 28-day compressive strength, for the mixtures GP-50%, GP-50%+FAs, and GP-50%+FAc, respectively.

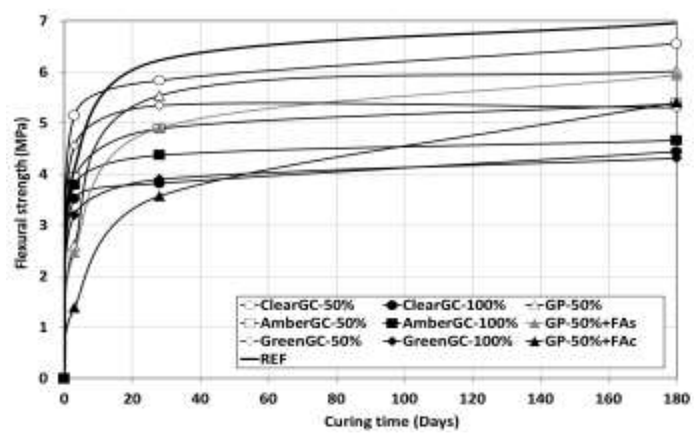

Figure 3. Flexural strength vs. cruing time.

B. Accelerated mortar bar tests

The average value of three mortar bar specimens for each mixture was reported as ASR expansion in Figure 4. According to ASTM C 1260, expansion larger than 0.2% at 14 days is considered potentially deleterious, while less than

0.1% is innocuous. Results obtained showed that after 14 days all the mortars had ASR expansion lower than 0.1%, so they resulted durable according to ASTM C 1260. But, after 14 days some mixtures showed significant expansions: those containing clear glass cullet. In fact, all the other mortars showed again expansion lower than 0.1% up to 42 days, while ASR expansions of 0.3% and 0.7% were detected for the mixtures 'ClearGC-50%' and 'ClearGC-100%', respectively. These measurements were accompanied by visual inspection of tested specimens, and those prepared with clear cullet appeared widespread cracked at the end of accelerated mortar bar test (see Figure 5), while all the others were sound. Moreover, specimens prepared with clear glass cullet showed some typical signs of pop-out (see Figure 5), that is the expulsion of a portion of mortar due to the expansion of the underlying reactive glass particle. This evidence was confirmed by means of optical macroscope and scanning electron microscope observations (see Figure 6). The clear glass cullet appeared covered by a thin layer of white gel (see Fig. 6a), this layer was analysed by means of energy dispersive x-ray spectroscopy (see Fig. 6c), and it was found the presence of sodium (Na^+), besides to silicon (Si^{4-}) and calcium (Ca^{2+}), typical of ASR gel of soda–lime glass.

Some other researchers [2,6] pointed out that green colour glass would be the least reactive in ASR due to its high content of Cr_2O_3, which is added for greenish colour. In [14], this effect was clearly observed, by comparing the results of green and clear glass sand mortars. However, in spite of the lesser content of Cr_2O_3, in [14] brown glass sand mortar also exhibited similarly small ASR expansion as green glass sand mortar, as in the present work. Dhir et al. [18] has attributed the different alkali resistance of coloured glasses to the manufacturing process more than to the chemical content, which differs only slightly. Shi [28] reviewed the ASR expansion in glass concrete and proposed that the mechanism of expansion of concrete caused ASR expansion. According to Shi [28], Na^+ and Ca^{2+} are firstly dissolved from glass, when the OH^- in pore solution attacks the glass surface, then the silicate network depolymerizes. Finally, the reaction occurs to form ASR gel of C–N–S–H, as shown in Eq. (1):

$$Ca^{2+} + Na^{+} + [SiO(OH)_3]^{-} \rightarrow C-N-S-H \qquad (1)$$

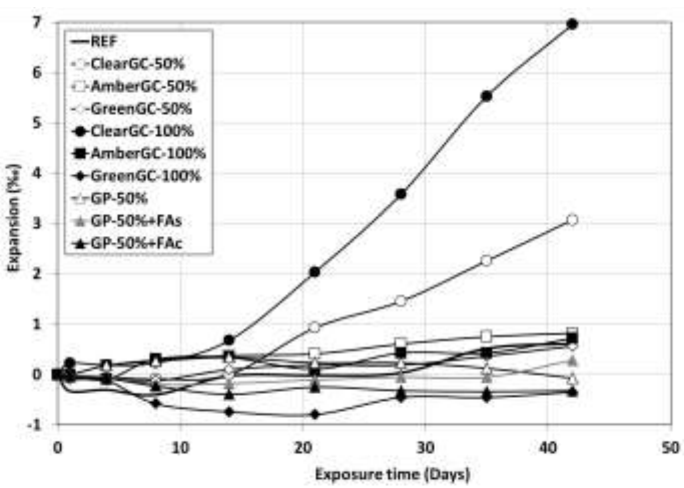

Figure 4. Expansions vs. time of exposure to 1 N solution of NaOH at 80°C.

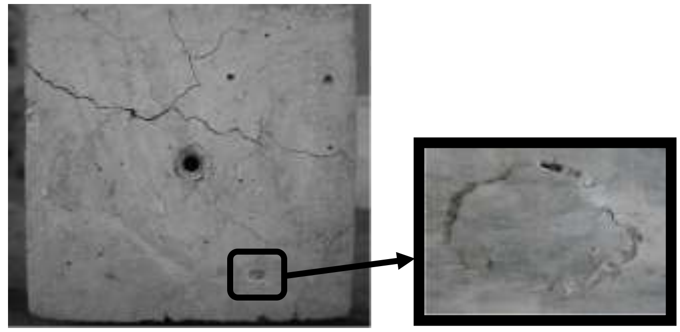

Figure 5. Pictures of a specimen with 100% uncolored glass cullet.

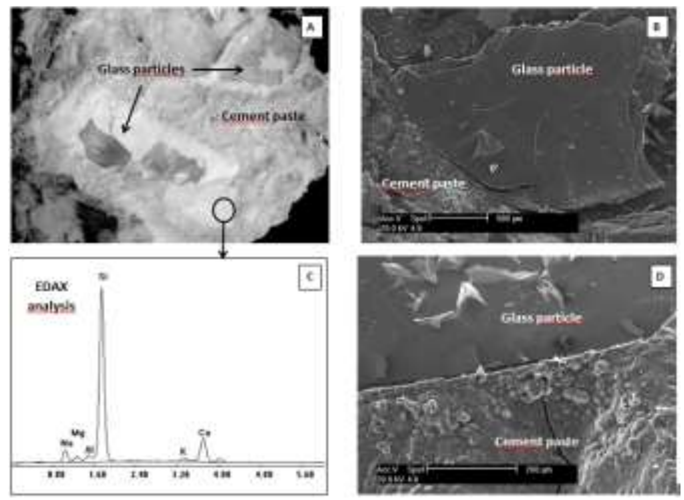

Figure 6. Observations of a mortar specimen made of uncolored cullet by optical macroscope (A), and SEM (B, C and D).

The swelling capacity of the ASR gel depends on its chemical composition, especially on the ratio of $CaO/(SiO_2 + Na_2O)$. It is hypothesized that in the ASR gel of soda–lime glass the content of calcium is relatively higher than in other types of glass or natural sand. Therefore, the non-swelling ASR gel in recycled glass mortar would lead to a less expansion. The same conclusion was also made by Saccani and Bignozzi [29]. In this case the values of this ratio are quite similar for the three differently coloured cullet (see Table 2), but only the clear type showed significant ASR expansion.

V. Conclusions

Based on the results of this experimental investigation, the following conclusions can be drawn:

- The use of clear glass cullet replacing sand at 50% by weight permitted to obtain good mechanical performance, but the ASR expansion remained under the threshold value of 0.1% only up to 21 days of exposure to 1 N NaOH solution;
- The use of clear glass cullet fully (100%) replacing sand produced very low mechanical strengths both in compression and in bending tests, and very high ASR expansion, which reached the value of 0.7% after 42 days of exposure to 1 N NaOH solution (this expansion, and the consequent mortar cracking, were confirmed by visual and microscopy observations);

- Therefore, concerning clear glass cullet with grain size up to 8 mm, no more than 50% replacement ratio is recommended on the basis of the experimental results obtained, and, even if the requirement prescribed by ASTM C 1260 is satisfied a dosage even lower should be used for durability assurance;
- The use of green and amber glass cullet, whichever the percentage of replacement, slightly compromised the mechanical performance of mortars, in particular flexural strength was lowered when 100% replacement was made, due to the bad grain size distribution of the glass cullet used (which is improved by combining it with 50% quartz sand);
- However, no evidence of ASR expansion was detected in any case when either amber or green coloured glass were used;
- The use of glass powder proved to be very effective in terms of mechanical strength at long ages, thanks to strong pozzolanic effect (180-day compressive strength was at least 80% higher than 28-day compressive strength);
- No evidence of ASR expansion was detected when powder glass (with particle size up to 0.300 mm) was added to the mortar mixture, independently on the presence of fly ash;
- Further studies should be carried out in order to optimize the promising use of glass powder: in fact, this powder if properly added together with a water-reducing admixture, for compensating its huge request of water, can significantly improve mortar mechanical performance, and if used together with clean glass cullet could reduce its ASR expansion.

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