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Recycled Glass as Aggregate for Architectural Mortars

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Abstract

The possibility of recycling mixed colour waste glass as it is for manufacturing decorative architectural mortars, has been investigated. In mortars, the 0–33–66–100% of calcareous gravel volume has been replaced with recycled glass cullets, with no other inorganic addition. To mitigate the possible alkali–silica reaction, mixes with a hydrophobic admixture were also compared. The obtained results show that the replacement of calcareous gravel with glass cullets of similar grain size distribution permits to reduce the dosage of the superplasticizer admixture to obtain the same workability of fresh mortar; it does not affect significantly the mechanical performances, the water vapour permeability and the capillary water absorption but it reduces significantly the drying shrinkage deformation. The used recycled glass is classified as no reactive in terms of alkali–silica reaction neither in water nor in NaOH solution following the parameters of the current normative, even in the absence of the hydrophobic admixture. The hydrophobic admixture further delays the expansion trigger but not the speed of its propagation.

Keywords: waste glass, architectural mortar, alkali–silica reaction, recycling, durability

1 Background

1.1 Waste Glass

Three different types of glass are produced: flat glass, hollow glass, and wool and glass yarn. The production of hollow glass includes glass packaging (bottles, flasks, and demijohns), flamingos for the pharmaceutical, cosmetic and perfumery industry, household articles; in Italy the production of hollow glass amounts to 3,656,582 tonnes/year (Associazione Nazionale degli Industriali del Vetro – Assovetro 2017).

In Western world, generally, glass recycled crop is reused to produce new glass. However, not all glass scraps are suitable to produce new glass. Different colours glass can be manufactured by adding in the mixture dies as FeO (green–blue), Fe_2O_3 (green), Cu_2O (red), CuO (blue-green), Cr_2O_3 (green-yellow), CoO (dark blue), $AuCl_3$ (ruby red). During the waste collection processes, hollow glass, especially post-consumer beverage bottles, becomes broken, colour-mixed and contaminated by paper labels or other substances that can highly affect the properties of the produced new glass. Due to the high cost of cleaning and colour sorting, the recycling rate for glass bottles is only about 25% and most waste glass is sent to landfill as residue (Ling et al. 2013); since glass is not biodegradable, landfills do not provide an environmentally-friendly solution.

Other methods to recycle waste glass are the production of abrasives, rock wool, or means for water filtering; however there is still a need to develop markets for mixed colours waste glass. In the construction sector, recycled glass is used in concrete glass asphalt (glass-phalt), back-fill, substrate, tiles, masonry blocks, flooring and other decorative purposes, but the practical applications of recycled glass in structural concrete is fairly limited (Kou and Poon 2009).

On the other hand, the extraction of sand and gravel as aggregates for mortars and concretes amounts to 130 millions of cubic metres every year and represent the 59% of all materials excavated in Italy (Legambiente 2017). Therefore, the application of by-products for replacing natural fillers/sands/aggregates (Tittarelli and Shah 2013; Tittarelli 2013; Aciu et al. 2018; Dang et al. 2018) as waste glass seems to be a very interesting approach to create ecological composites.

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1.2 Recycled Glass in Mortars and Concretes

Using glass waste instead of virgin natural sand/aggregate in the composition of mortars is feasible and the cost of replacement indicates an advantage (Ling et al. 2013). Additional benefits are: (1) less use of natural aggregates resulting in minimal cost of quarrying, less invasiveness of the extraction in the quarries, extension of the useful life of the quarry, less use of non-renewable natural resources. (2) Recycle that part of glass that would otherwise end up in landfills and thus greater eco-sustainability throughout the production cycle. (3) More architectural value of mortars/concretes since the visible coloured glass particles will produce a pleasing visual effect on the surfaces where the mortar is applied (Ling and Poon 2014). These mortars/concretes, due to their esthetical properties, can satisfy not only traditional properties but also decorative functions for fair-faced concrete finishes, both in external and indoor applications.

Recycled glass aggregate is potentially able to improve resistance to freeze–thaw attack, drying shrinkage and abrasion of mortars and concretes (Carsana et al. 2014), thanks to the low porosity and water absorption capacity. Moreover, waste glass can also improve the resistance to high temperatures (Guo et al. 2015; Rashad 2014). Since the increasing demands in construction as functional, aesthetic, economic and insulating criteria has to be fulfilled, the use of cullet of different colours in cementitious materials is a good alternative.

Unfortunately, the presence of waste glass in cementitious composite may provoke the possibility of its expansion and cracking. The amorphous silica can be dissolved in glass under alkaline conditions and form alkali–silica reaction (ASR) gel which absorbs water and subsequently expands leading to tensile stresses. When tensile stress exceeds the tensile strength of the material, irregular cracks will occur. This phenomenon may seriously affect the durability of mortars and concretes (Rashad 2015; Bignozzi et al. 2015).

There is still no agreement regarding the ASR in mortars and concrete containing waste glass aggregate. Occurrence of ASR is mainly related to the amount, particle size, and colour of waste glass. Studies show that the ASR expansion increases with the increasing glass aggregate content (Sikora et al. 2016), whereas it decreases with the increasing of glass sand fineness (Corinaldesi et al. 2005; Idir et al. 2011; Du and Tan 2014). The coarse glass particles seem to be the most dangerous, and several authors have concluded that glass grains will not cause cracking when the grain size is reduced to 300 μm or finer (Letelier et al. 2017). Green and brown glass sand mortars proved to be innocuous, regardless of the replacement level, whereas clear glass can exhibit potential deleterious properties (Sikora et al. 2016).

Supplementary cementitious materials, such as fly ash (FA) (Kou and Poon 2009; Parghi and Shahria Alam 2016), metakaolin (MK) (Guo et al. 2015; Ling and Poon 2011), ground granulated blast furnace slag (GGBS) (Ling and Poon 2014; Li et al. 2017) and nanosilica (Sikora et al. 2016; Aly et al. 2012) are well-known to be able in reducing the alkali–silica reaction in concrete because the amount of alkali hydroxide can be reduced by the pozzolanic reaction (Carsana et al. 2014; Shayan and Xu 2004; Topçu et al. 2008; Corinaldesi et al. 2016). Also fine glass powder ($d < 150$ μm) is effective in suppressing ASR thanks to its pozzolanic activity (Bignozzi et al. 2015; Parghi and Shahria Alam 2016; Afshinnia and Rangaraju 2015; Nunes et al. 2013; Serpa et al. 2013). De Azevedo et al. (2017) investigated the influence of wastes (85% of particles smaller then 100 μm) from the wastewater treatment plant of the glass polishing process in the rheological properties of adhesive mortar with partial replacement of cement and fine aggregate (up to 20%). In general waste glass increased the incorporated air in mortars since the glass particles are grainy, thus causing their worst arrangement. This fact increases the mortar retraction but also its fluidity, particularly required to settle ceramic coating, giving also higher availability of empty spaces to accommodate the gel associated to the possible alkali–silica reaction.

Despite the high amount of papers related to the influence of waste glass on the properties of cementitious composites, most of the studies aims to replace sand with waste glass in small amounts (e.g. 20%). Moreover, mortars and concretes with coarse recycled glass have been generally tested in the presence of a pozzolanic addition in order to prevent ASR.

1.3 Research Significance

In this work, the possibility to recycle mixed colour scrap glass in its unaltered state, to manufacture decorative architectural mortars without any other inorganic addition and to exploit the aesthetic characteristics of glass, has been considered.

The glass sample came directly from a waste management system of hollow glass as it is, just to test a mix of very different waste glasses without additional expensive treatments. In particular, the effect of replacing calcareous gravel volume with increased dosages of glass cullets on the workability, mechanical behaviour, in terms of bending and compression tests, water vapour permeability, and durability, in terms of capillary water absorption, shrinkage and alkali–silica reaction, has been investigated.

The effect of adding a hydrophobic admixture (Carsana et al. 2013; Tittarelli et al. 2013, 2014) in the mortar mixture was also considered. Sustainable building development includes a judicious use of resources, that can be achieved not only by using industrial by-products, but also producing structures that would function more efficiently over time, thanks to the enhancement of their durability. The durability of mortar/concrete is strongly influenced by its aptitude to transport aggressive agents through the connected porosities (Mobili et al. 2016). Aggressive ions, dissolved in water, such as sulphates and chlorides in polluted area and coastal zone (Corinaldesi et al. 2003; Ozga et al. 2014), promotes concrete deterioration and corrosion of embedded reinforcements (Tittarelli et al. 2018; Mobili et al. 2015). Mortar/concrete protection through hydrophobic treatments, which make concrete less susceptible to water saturation (Moriconi et al. 2002), enhances their durability.

Moreover, since ASR is an expansive reaction that occurs between soluble silica and the cement alkalis only in the presence of water (Penacho et al. 2014), hydrophobic treatments, which make concrete less susceptible to water saturation, could mitigate also the possible arising of the phenomenon.

2 Experimental Investigation

2.1 Materials

2.1.1 Cement

A white cement (WC) CEM II/B-LL 32.5 R (AQUILA BIANCA Italcementi S.p.A.), with an average clinker:limestone ratio of 2.6 by weight, was chosen for aesthetic and architectural mortar applications. White cement can guarantee the most versatile range of colours by possible additions of pigments. Moreover, white cement is particularly suitable for exposed decorative glass aggregate finishes because it contains comparatively low alkali content, and thus it can reduce a potential deterioration due to ASR expansion. The chemical composition of WC is presented in Table 1.

2.1.2 Aggregates

As white aggregates, crushed calcareous gravel with 4–8 mm grain size and crushed calcareous sand with 0–4 mm grain size were used. The water absorption, was 1.4 and 4.0%, respectively. As reported in the technical data sheet, the mineralogical composition was $CaCO_3$ 98.32%, Fe (as Fe_2O_3) 63.4 ppm, Mg 0.32%, Al (as Al_2O_3) 165.0 ppm, Si (as SiO_2) 24.4 ppm, with 2% in porosity. For aggregates, the Bolomey grain size distribution was chosen as the ideal distribution which assures the good workability necessary for an architectural mortar. Following this law, with the available natural calcareous gravel and sand, the best aggregate combination is that obtained with 60 and 40% of gravel and sand weight, respectively.

A recycled waste glass coming directly from a waste management system was used as it is. As reported in the technical data sheet, the chemical composition of recycled glass in oxides (wt%) is shown in Table 2 and its water absorption was $\leq 0.1\%$ due to its very low porosity ($\leq 0.1\%$). The recycled glass aggregate is flat and angular in shape with a much smoother surface texture than calcareous gravel (Fig. 1).

The grain size distribution curve of glass aggregates, calcareous gravel and calcareous sand are shown in Fig. 2. Recycled glass has a grain size distribution very similar to that of calcareous coarse aggregate.

2.1.3 Admixtures

An acrylic-based superplasticizer with 30% of active ingredient by emulsion weight was used to give satisfactory fluidity to the different mixes.

As hydrophobic admixture, a 45% water solution of butyl-ethoxy-silane was used.

2.2 Mix Proportions

All the mixtures were proportioned with a fixed water/cement (w/c) ratio of 0.47 and aggregate/cement (a/c) ratio equal to 2.25 by weight. These ratios were chosen following literature data (Ling and Poon 2011).

To enhance the aesthetic value of glass based mortars, glass of larger sizes proportions should be included in the mortar mix. Since calcareous gravel grain size distribution is comparable with that of glass, to investigate

Table 1 Chemical composition of WC cement in oxides (wt%).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3	Loss on ignition
%	21.4	5.3	0.2	67.5	1.2	0.05	0.08	2.6	1.6

Table 2 Chemical composition of recycled glass in oxides (wt%).

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	SO_3
%	73.3	1.5	0.06	9.8	0.35	14.2	0.6	0.2

Fig. 1 Calcareous gravel (left) and recycled glass (right).

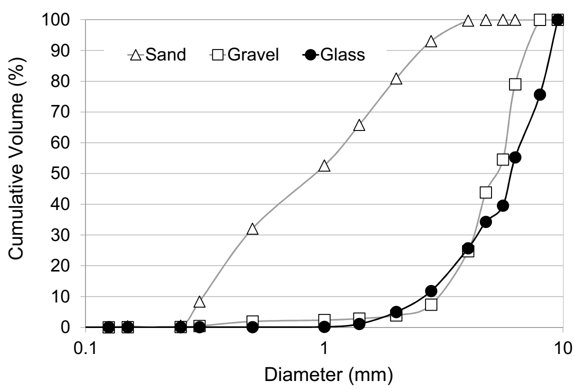

Fig. 2 Grain size distribution of calcareous sand, calcareous gravel and recycled glass.

the influence of large glass particles on the properties of mortars, the calcareous sand was replaced by recycled glass at the dosage rate of 0–33–66–100% in volume. In this way the widest possible replacement range was considered in order to exploit all the potentials of valorising waste glass in mortars/concretes.

The superplasticizer dosage of 0.2–0.5% by weight of cement was added in the mix to obtain the targeted slump flow values of 18–20 cm. These values correspond to a plastic mortar, according to "EN 1015-6:2007: Methods of test for mortar for masonry—Part 6: Determination of bulk density of fresh mortar", necessary for good fair-faced concrete finishes.

Analogous mixtures with the addition of a 1% by cement weight of hydrophobic admixture were considered (labelled with H in Table 3). The proportions of the mixes are given in Table 3.

2.3 Sample Preparation

The mortar batches were mixed in a laboratory planetary mixer and the specimens were prepared following the procedures described in "EN 1015-2:2007: Methods

Table 3 Mix design of mortars (kg/m^3).

Specimen	Water (kg/m^3)	Cement (kg/m^3)	Sand (kg/m^3)	Gravel (kg/m^3)	Glass (kg/m^3)	Superplasticizer (kg/m^3)	Silane (kg/m^3)
0%	286	609	548	822	0	0.5	–
33%	286	609	548	551	256	0.4	–
66%	286	609	548	280	512	0.3	–
100%	286	609	548	0	776	0.2	–
0% + H	282	609	548	822	0	0.5	6.77
33% + H	282	609	548	551	256	0.4	6.77
66% + H	282	609	548	280	512	0.3	6.77
100% + H	282	609	548	0	776	0.2	6.77

H hydrophobic addition.

of test for mortar for masonry—Part 2: Bulk sampling of mortars and preparation of test mortars".

Initially, aggregates (in saturated surface dry condition) and cement were mixed for about 90 s to obtain a uniform mix in dry conditions. Then, the superplasticizer, thoroughly mixed with water, was added to the mix, and the mechanical mixing process was resumed for another 90 s. To avoid the dry materials becoming stuck at the bottom part of the mixer, the mixture was mixed manually by turning it over twice or thrice using a steel trowel. Finally, the mixture was mechanically mixed for an additional 2 min to complete the whole mixing process.

After mixing, the fluidity of freshly prepared mortar was evaluated (see 2.4).

Finally, mortars were poured into moulds of various geometries depending on the test.

Specimens were cured at RH = 90 ± 5% and T = 20 ± 1 °C for the first week and then at RH = 50 ± 5% and T = 20 ± 1 °C until testing, if not differently specified. Visual aspect of architectural mortar after curing is shown in Fig. 3.

2.4 Testing Details

2.4.1 Fresh Properties

After mixing, the fluidity of freshly prepared mortar was evaluated by measuring the spread diameter of the mortar in two perpendicular directions in accordance with "EN 1015-3:2007: methods of test for mortar for masonry—Part 3: Determination of consistence of fresh mortar (by flow table)".

A slump flow truncated cone with an internal base diameter of 100 mm was used to evaluate the fluidity of fresh mortar. Before the test, the truncated cone mould was placed on the centre of the defined disk of a shaky table and the freshly prepared mortar mixture was poured into the cone. Once the cone was fully filled with the mortar, it was lifted vertically and the mortar was then subjected to 15 vertical impacts. The spread diameters of the freshly prepared mortar were measured in two perpendicular directions. The fluidity value was measured by means of the average diameter of the fresh mortar.

2.4.2 Mechanical Properties

To investigate the effect of replacing calcareous gravel with increasing dosages of recycled glass on the mechanical performances of mortars, the compressive and flexural strength of mortars were measured after 2, 7, and 28 days of curing on 40 × 40 × 160 mm specimens according to "EN 1015-11:2007: Methods of test for mortar for masonry—Part 11: Determination of flexural and compressive strength of hardened mortar".

After 28 days of curing, the density of hardened mortars was also calculated.

Three prismatic specimens (40 × 40 × 160 mm) were used to evaluate the dynamic modulus of elasticity (E_d) after 28 days of curing according to "EN 12504-4:2004: Testing concrete—Part 4: Determination of ultrasonic pulse velocity. The two 40 × 40 mm opposite surfaces were covered with a thin layer of grease and exposed to the direct test using the portable ultrasonic non-destructive digital indicator tester (PUNDIT). The tester measures the time value of the ultrasonic pulse through the specimen. Knowing the specimen length (160 mm), the velocity of the ultrasonic pulse can be calculated.

$$E_d = \frac{\nu^2 \rho[(1 + \gamma_d)(1 - 2\gamma_d)]}{1 - \gamma_d}. \quad (1)$$

Equation (1) gives the formula for calculating Ed where v is the velocity of the ultrasonic pulse (m/s) and γ_d is the Poisson's modulus. The Poisson's modulus, equal to 0.20, was estimated as the average value between 0.15 and 0.25 reported in literature for cementitious materials (Lamond and Pielert 2006).

2.4.3 Drying Shrinkage

If mortars are applied in environment with a RH less than 95% they are subjected to change in length, expressed as millimetres per meter (mm/m) referred as drying shrinkage.

Drying shrinkage was measured in laboratory according to "EN 12617-4:2002: Products and systems for the protection and repair of concrete structures—test methods—determination of shrinkage and expansion".

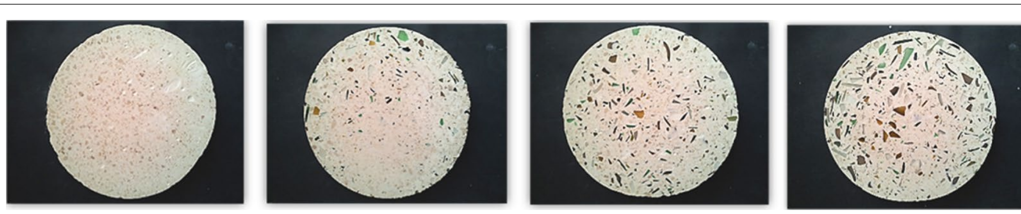

Fig. 3 Architectural mortars manufactured with 0, 33, 66, 100 (from left to right) of calcareous gravel volume replaced with recycled glass, respectively.

Specimens were prisms of 40 × 40 × 160 mm, cured at 20 ± 2 °C and RH 95 ± 5% for 24 h. Specimens were demoulded after 24 h and then exposed at T = 20 ± 2 °C and RH 50 ± 5% in a climatic chamber.

Drying shrinkage was monitored for 2 months from the cast and calculated as $\varepsilon = \frac{\Delta}{L}$ (mm/m), where: ε is the strain due to drying shrinkage (mm/m); Δ is the longitudinal contraction of the specimen (mm); L is the initial length of the specimen (m).

The percentage of weight loss corresponds to evaporation of free water and is calculated by: $w_i = \frac{m_i - m_0}{m_0} \times 100$ (%), where: w_i is the percentage of weight loss (g); m_i is the weight at i-day (g); m_0 is the weight 24 h after the casting (g).

Both drying shrinkage and weight loss were evaluated and plotted against time.

2.4.4 Water Vapour Permeability

Reduced water vapour permeability is a negative factor in mortars since it does not allow a proper drying of penetrating water and impairs the elimination of water vapour that occurs within buildings. Water vapour permeability measurements were carried out according to "EN 1015-19:2008: Methods of test for mortar for masonry—Part 19: Determination of water vapour permeability of hardened rendering and plastering mortars" after 28 days of curing.

One side of each specimen was sealed over a cylindrical recipient containing a saturated potassium nitrate solution (KNO_3), which gives a RH = 93% at T = 20 °C. During the test, specimens were stored at RH = 50 ± 5% and T = 20 ± 1 °C. The mass loss due to water evaporation through the specimen was measured during that time and results were expressed in terms of water vapour diffusion resistance factor (μ). Three cylindrical specimens (140 mm diameter and 30 mm thickness) for each mixture were tested to evaluate the water vapour flux on stationary conditions and the average value reported.

2.4.5 Capillary Water Absorption

Water is the medium and the main carrier of aggressive ions as Cl^- or SO_4^{2-}. To this reason, the study of water absorption is considered of primary importance to stand the durability of a construction material (Hughes 1985).

Water absorbed per unit area (Q_i) was measured according to "EN 15801:2009: Conservation of Cultural Property—Test Methods—Determination of Water Absorption by Capillarity". After 28 days of curing, before testing, cubic specimens (40 mm) for each mortar mix were dried at T = 60 ± 2 °C until constant mass was achieved. A dried bedding layer was placed on the bottom of the vessel. Water was added until the bedding layer was saturated and the water level did not exceed the upper surface of the bedding layer. The test evaluates the amount of water absorbed by a dried specimen placed on the saturated bedding layer through capillary suction, monitoring the specimen mass against time until 8 days. Three specimens for each mixture were tested and the obtained average values were reported.

To evaluate the effect of replacing calcareous gravel with recycled glass on capillary water absorption at short contact time with water (90 min), also the test described in "EN 1015-18:2004: Methods of test for mortar for masonry—Part 18: Determination of water absorption coefficient due to capillary action of hardened mortar" was carried out. In this case, dried specimens were placed in a basin, kept at a distance from the base of the tray using appropriate supports, and immersed in water at a depth of 5 ÷ 10 mm for the duration of the test. The water absorption coefficient is defined as C = 0.1 (M_2–M_1) measured in kg/(m^2 $min^{0.5}$) where M_2 is the specimen weight after 90 min of testing and M_1 is the specimen weight after 10 min of testing.

2.4.6 Expansion Due to Alkali–Silica Reaction

For each mix, three 25 × 25 × 285 mm mortar-bar specimens were used for the ASR test in accordance with the Italian standard "UNI 8520-22:2002: Aggregati per calcestruzzi—Parte 22: Metodologia di valutazione della potenziale reattività alcali-silice degli aggregati" describing the accelerated mortar-bar method reported in the ASTM standard "ASTM C227-03: Standard Test Method for Potential Alkali Reactivity of Cement-Aggregate Combinations (Mortar-Bar Method)". Very recently in Italy this Standard has been replaced by UNI 8520-22:2017. However, this new standard provides for a coexistence period of 18 months in which it is still possible to label the aggregate according to the old version of the standard.

According to UNI 8520-22:2002, a zero reading was taken after storing the prisms in distilled water at T = 80 °C for 24 h. The mortar-bars were then transferred and immersed in a 1 N NaOH solution at T = 80 °C during all the testing period. In parallel, at the same temperature, also expansion in water, a more representative condition of real conditions, was monitored in some specimens. The expansion of the mortar-bars was measured within 15 ± 5 s after they were removed from the 80 °C water or alkali storage condition by using a length comparator. The measurements were conducted at the 1st, 4th, 7th, 14th, 21st and 28th day.

3 Results and Discussion

3.1 Workability

Flow values of mortars are reported in Table 2. All mortars are maintained at plastic workability, as defined by EN 1015-6:2007 (slump flow ~ 18–20 cm). However,

Table 4 Workability (cm) and hardened density of mortars (kg/m^3).

Specimen	Workability (cm)	Hardened density (kg/m^3)
0%	20.0	2130
33%	18.8	2120
66%	19.5	2110
100%	18.5	2100
0%+H	18.3	2130
33%+H	18.7	2120
66%+H	18.5	2110
100%+H	18.5	2100

H hydrophobic addition.

Table 4 evidences that increasing the amount of recycled glass, the superplasticizer amount to guarantee the same workability decreases. The smoother surface of glass compared to that of the crushed calcareous gravel, as detected by visual observation (Fig. 1), allows a better mix workability at the same water dosage. The same results have been obtained by Jian-Xin Lu and Chi Sun Poon in Alkali Activated Cement (AAC) mortars as the replacement level of natural sand by glass cullet was increased (Lamond and Pielert 2006). This implies a further economic advantage in manufacturing waste glass mortars, instead of traditional sand mortars.

3.2 Mechanical Properties

Figure 4 shows the effect of replacing calcareous gravel with recycled glass on the mechanical performances of mortars up to 28 days of curing. A slight penalty in compressive mechanical performance (16% max) (Fig. 4a) with the increase of the percentage of glass is observed. This is due to the smoother surface of glass aggregate compared to calcareous sand which decreases the cohesion between the glass aggregates and cement paste at the interface. However, the slight mechanical penalisation does not prevent the use of waste glass mortars also for structural uses, since the European standard "EN 1504-3:2005: Products and systems for the protection and repair of concrete structures—Definitions, requirements, quality control and evaluation of conformity—Part 3: Structural and non-structural repair" fixes at 25 MPa the limit above which a mortar can be considered structural. Only when glass replaces the 100% of calcareous gravel (Fig. 4b), after 28 days of curing, there is a significant decrease in flexural strength of about 20% for the same reason reported above.

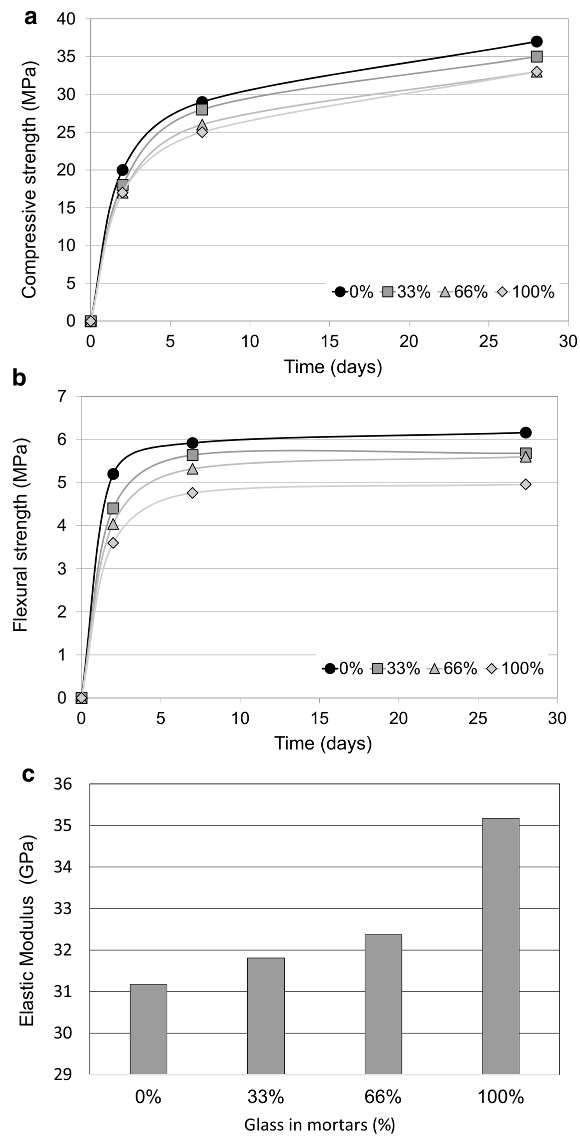

Fig. 4 Mechanical properties of mortars: **a** compressive strength; **b** flexural strength; **c** elastic modulus.

Due to the greater stiffness of glass compared to limestone grit, the dynamic modulus of elasticity of mortars (Fig. 4c) increases with the increasing dosage of recycled glass in place of gravel up to a value of 12%.

Moreover, due to the lower density of glass cullets (2.5 g/cm^3) compared to calcareous gravel (2.65 g/cm^3), the replacing in volume gives a slight decrease of density in the hardened compound (Table 2).

3.3 Drying Shrinkage

Drying shrinkage and weight loss due to water evaporation are given in Fig. 5a, b, respectively. Drying

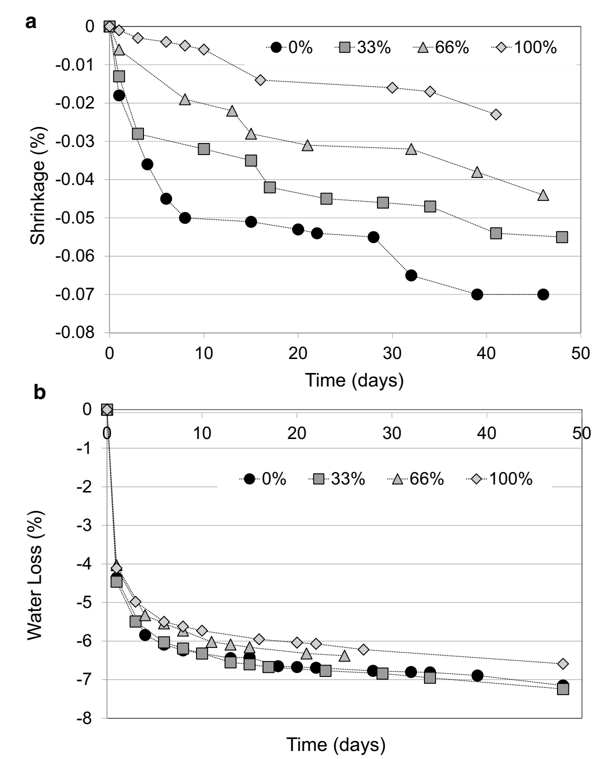

Fig. 5 Drying shrinkage (**a**) and related water loss (**b**) of mortars.

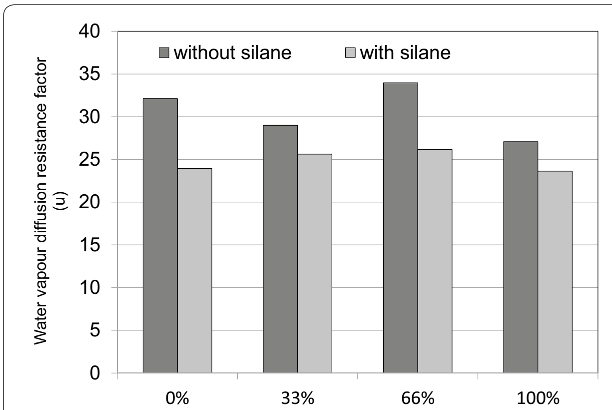

Fig. 6 Water vapour diffusion resistance factor of mortars.

shrinkage depends on: (1) open porosity, which facilitates water evaporation; (2) pore distribution, because the finer the capillary network, the higher the capillary stress that generates shrinkage; and (3) elastic modulus, because the higher the matrix stiffness, the lower the shrinkage generated at the same stress.

As expected, due to the lower porosity of glass cullets, increasing the replacing of gravel gives a slight reduction in water loss with time, regardless of the presence of silane.

However, the drying shrinkage of mortars reduces significantly by increasing the glass cullets dosage. When 100% calcareous gravel is replaced by waste glass, the shrinkage of the corresponding mortar becomes less than one-third of that of the reference mortar (0%). This is due to the higher modulus of elasticity of glass cullets compared to that of calcareous gravel. Again, the silane addition does not change significantly the behaviour of mortars.

3.4 Water Vapour Permeability

Figure 6 gives the water vapour diffusion resistance factor (μ) calculated for different mortars. It is clear that the replace of calcareous gravel with glass cullet does not significantly change the permeability of mortars.

On the other hand, the presence of the hydrophobic admixture slightly increases the breathability of about 25%. According to Poiseuille's law, the permeability depends on open porosity, connected pores size (permeability should be proportional to the product of porosity and square diameter of the main mode pore), connectivity and tortuosity of the microstructure. In particular, the greater the threshold pore diameter the higher the permeability of the material (Mobili et al. 2016). The hydrophobic admixture increases the porosity of the cement paste shifting the pore diameters to bigger values (Tittarelli 2013; Ramachandran 1984).

3.5 Capillary Water Absorption and Expansion Due to Alkali–Silica Reaction

Figure 7 gives the water absorbed per unit area (Q_i) by different mortars and the capillary water absorption coefficient (C). A significant variation in capillary water absorption is recorded only in 100% glass cullet mortars where the low porosity of glass cullet compared to calcareous gravel gives a reduction of capillary water absorption of about 10% both for short (90 min according to EN 1015-18:2004) and long contact time (8 days according to EN 15801:2009) with water. However, as expected, the presence of the hydrophobic admixture deletes all these differences and causes capillary water absorptions 70% lower than those of mortars without hydrophobic admixture.

The expansion induced by ASR in water, a more representative state of the real conditions, does not reach significant values (Fig. 8) indicating the absence of any deleterious reaction between mixed colours waste glass and the alkali of cement, even if at T = 80 °C, regardless of the hydrophobic admixture presence.

However, also in the very aggressive environment (T = 80 °C and NaOH = 1 N) the expansion of the

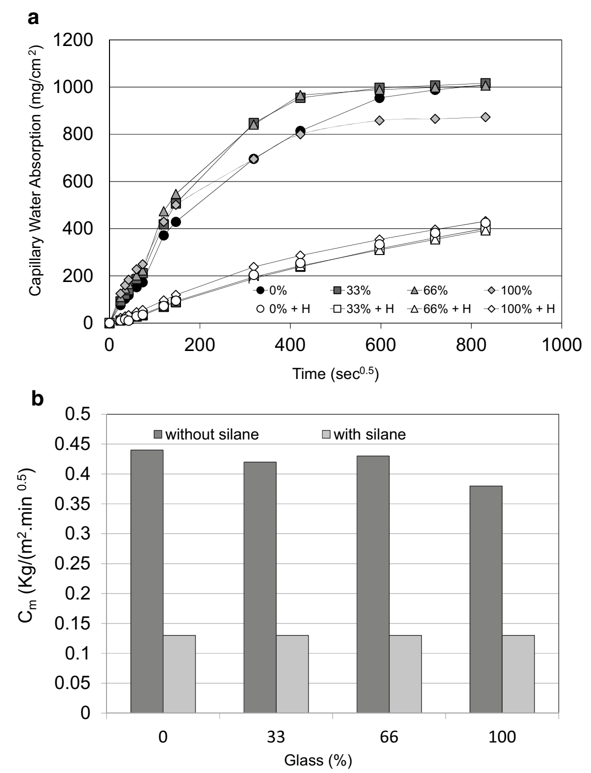

Fig. 7 Water absorbed per unit area (Q_i) by different mortars (**a**) and relative capillary water absorption coefficients (**b**).

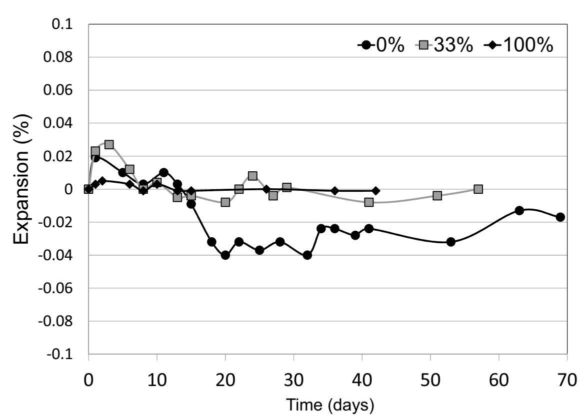

Fig. 8 Expansion in water at T = 80 °C.

cementitious mortar containing glass sand is very low. The expansion increases with the dosage of recycled glass in the mix, but also at the 100% of gravel replacement with waste glass it remains lower than the limits prescribed by the rule for classifying the aggregate as reactive (at t = 14 days the expansion must be less than 0.1%), both with and without the hydrophobic admixture (Fig. 9).

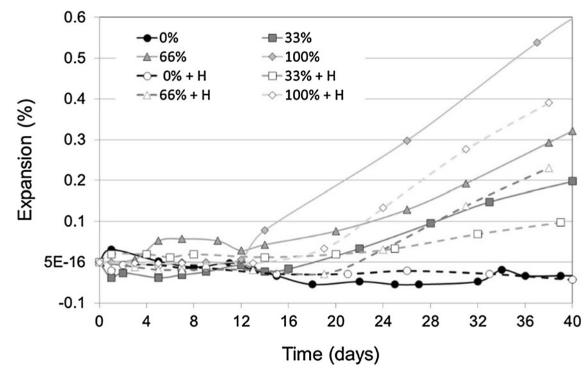

Fig. 9 Expansion in NaOH 1 N at T = 80 °C.

In addition, silane further delays the expansion trigger of about 1 week, but it does not significantly slow the speed of its propagation (since the slopes of the curves with and without silane at the same glass replacement are comparable).

4 Conclusions

The results of this study show that it is possible to fully replace traditional calcareous gravel with mixed colour waste glass as recycled aggregate for the production of architectural mortars, without any particular addition or admixture.

In particular, the replacement of calcareous gravel with recycled glass cullets in mortars up to the 100% in volume implies:

- Improved workability, with consequent reduction of the dosage of superplasticizer and less costs, to obtain a certain workability value;
- Only a small penalty (16% max) in the compressive and flexural strength which does not prevent the use of waste glass mortars also for structural uses ($R_c \geq 25$ MPa according to EN 1504-3:2005);
- An increase in the dynamic modulus of elasticity up to 12% at 100% replacement thanks to the greater stiffness of glass compared to the calcareous gravel;
- No decrease in the durability properties in terms of capillary water absorption;
- No decrease in water vapour permeability;
- Enhanced durability due to decreasing in drying shrinkage related to an increase of the modulus of elasticity.

Finally, the glass used in this experimentation is found to be non-reactive in water at T = 80 °C but also in NaOH 1 N at T = 80 °C, according to the parameters given by the regulations in force, even in the absence of the hydrophobic admixture. The hydrophobic admixture further delays the expansion, but does not slow down significantly the speed of its propagation.

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Authors' contributions
FT has coinceived, coordinated and supervised the project. She has analysed and interpreted the data and drafted and edited the manuscript. AM and CG edited the manuscript. All authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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