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Performance Assessments of Plastering Mortars with Partial Replacement of Aggregates with Glass Waste

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Abstract: The rising concern for the environment and the need for a sustainable economic model has stimulated experimentation in the field of construction materials, notably in replacing certain components from cementitious materials with construction and demolition waste. The main objective of this study is to replace a significant proportion of natural aggregates with glass waste, in the composition of plastering mortars, and to observe the evolution of physical–mechanical characteristics in the fresh state: apparent density, consistency, and segregation tendency, and in the hardened state: apparent density, flexural strength, compression strength, and adhesion to the substrate, across time, at 3, 7, 14, and 28 days. SEM and EDX tests were also performed to observe the microscopical characteristics. The experimental program studied four types of plastering mortars: the reference mortar—CS IV, and three mortars in which aggregates have been replaced with glass waste in the following proportions, by mass: 15%, 30%, and 45%. Results obtained on fresh properties (apparent density and consistency) indicate a decrease in values as the percentage of glass increases, with the exception of the mortar with 30% aggregated glass replacement. The flexural strength and the compressive strength were improved by replacing 30% of the aggregates with glass waste and were not significantly impacted by a replacement of 15%. Mechanical properties decreased at a replacement level of 45%. All glass aggregate mortars had lower adhesion strength to the brick substrate than the reference mortar by up to 70%. SEM and EDX analyses showed the morphology of the studied mortars and the processes taking place to increase mechanical strength. Further research directions are proposed, including studying the glass particles, the occurrence of alkali–silica reactions, durability, and improvement of adhesion to the substrate, for progressing towards the most viable, locally sourced, waste-containing plastering mortar.

Keywords: eco-efficient mortars; glass aggregates; glass waste; plastering mortars; CDW management

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1. Introduction

In 1987, a Commission led by Norwegian Prime-Minister Gro Harlem Brundtland was drafting a report titled "Our Common Future" and defining sustainable development as "fulfilling present needs without compromising the capacity of future generations to fulfill theirs" [1]. This was one of the first of numerous international efforts to set the global development on a trend that would have a positive impact on social, economic, and environmental aspects. In 2015, the UN has adopted 17 sustainable development goals as the agenda for 2030, and in 2020 the EU adopted the Green Deal, a plan to reach carbon neutrality by 2050 [2].

One of the key elements that need to change in order to reach sustainability is the transition from a linear economy to a circular one. This implies a fundamental shift of mindset and consumption, because, in a sustainable economy, the "waste" status is eliminated. As the European Commission defines it: "in a circular economy when a product reaches the end of its life cycle, it is re-used to create additional value" [3]. A study from 2018 found that 36% of the global energy consumption and 39% of the carbon dioxide generation can be attributed to the construction industry [4]. Thus, it could have a considerable positive impact by becoming more sustainable.

To reduce its negative impact, a more sustainable management of construction and demolition waste (CDW) is required as well as reducing the amount of natural resources being exploited for producing new construction materials. This is one of the reasons why the EU has requested that at least 70% of CDW is handled by reducing, reusing, and recycling and a CDW waste management protocol is followed for creating secondary products and stimulating the growth of the market for reused construction materials [5].

One type of material in which CDW could successfully be used are plastering mortars. Mortars are materials obtained from mixing a binding material (such as lime or cement), fine aggregates, and water, as well as additives. Eco-efficient mortars are mortars where a part of the cement or natural aggregates have been replaced by CDW [6]. In a study from 2021, the Life Cycle Assessment (LCA) of eco-efficient mortars was compared. The results of the study showed that the most negative environmental impact of plastering mortars is caused by cement and transport. In conclusion, the distance between the CDW origin and the reuse is the most important aspect when replacing aggregates with waste [7]. This paper introduces three recipes for plastering mortars where the natural aggregates were partially replaced with clear and mixed-color locally sourced glass waste.

Using glass to replace parts of cement and of recycled aggregates in mortars has been researched extensively. The five most common types of use for waste glass in mortars are the following: used as a raw material for producing cement; used for the partial replacement of cement; used for the partial or total replacement of natural aggregates; combined use for the partial replacement of cement and fine aggregates; and used for the partial replacement of aggregates [8–11]. Notably, glass waste is used also in other cement-based materials, such as concrete [12]. One of its most known utilizations is for Portland cement replacement. Fine glass powder was found to perform similarly or even better than coal fly ash when used in cement recipes [13].

Letelier et al. enumerate in their findings some advantages of using glass waste powder as a replacement for concrete and natural aggregates: glass powder has a filler role, resulting in characteristics of the mortar being similar to the reference mortar, at 90 days; the size of the glass powder affects the mechanical characteristics of the mortar more than the proportion of replacement; the environmental impact of glass powder production is considerably lower than that of cement. In the case of natural aggregates, their most significant environmental impact is the environmental footprint of transporting them [14].

Although the resistance of the mortars has generally increased through the partial replacement of aggregates with glass, the risk of alkali–silica reactions between the cement and the glass waste, that would produce cracking, have prevented the large-scale use of these recipes [15]. For example, a review from 2014 reports that the alkali–silica reactions increased with the particle size and glass content in Portland cement, depending on the color [16].

However, Corinaldesi et al. mentioned that if waste glass is finely ground, up to a maximum of 75 μm [17], the alkali–silica reactions are prevented and do not affect the durability. Moreover, the same study has found that even with a particle size of up to 100 μm there have been no alkali–silica reactions (ASRs), improving the mechanical performance of the mortar [17]. Interestingly, alkali–silica reactions did not occur in the case of green and brown glass [18]. However, these results have not been consistent across different studies. For instance, Ozkan and Yuksel [19] did not observe significant differences

between green, brown, or clear glass in terms of alkali–silica reactions. On the other hand, Dhir et al. [20] found that clear glass showed the lowest ASR reactivity and green glass showed the highest values of reactivity [21–23].

Glass waste is used also to replace sand in mortars. In a study from 2012, brown, green, clear, and mixed-color glass particles were used to replace fine aggregates in percentages between 25% and 100%, by mass. The results showed that the durability was enhanced through the addition of glass waste. Glass is also used in alkali-activated silica fume mortars, where it has been found that at a replacement level of 30%, the flexural strength of the mortars is improved by 12.65% [23].

Glass waste is also used in architectural mortars, where the durability and the aesthetic were considerably improved in the study of Lu et al. [22] who have utilized glass powder and glass aggregates to prepare a cement-based architectural tile with over 70% glass waste, by weight. They found that the drying shrinkage of the mortar was reduced significantly, regardless of how fine the glass waste was. They also noticed an improved resistance to sulfuric acid and fire. By replacing 20% of the cement with fine glass aggregates, they were also able to notice that alkali–silica reactions were suppressed.

A literature review from 2014 showed that studies report contradictory results. Some studies showed that the workability of the mortars was improved by incorporating glass waste aggregates; others reported the opposite. Some of them showed a decrease in mechanical strength when increasing the glass waste aggregate replacement; others reported an increase in strength, in the case of a particle size of 75 μm, due to the pozzolanic reactions. Some studies reported an increase in abrasion resistance, while others reported a decrease. Some studies reported a reduction in water absorption, while others reported the opposite impact. There is some consensus in regard to an increase in segregation and a decrease in density, as the glass contents increased. Also, alkali–silica reactions have been reported to increase along with the glass waste quantity, dependent also on the color: amber more than brown glass, and green glass less than brown. Some options to mitigate this effect are to add 50–60% slag, 10–30% metakaolin (MK), or 20–50% fly ash (FA). There is more consensus about the chemical, fire, and long-term carbonation resistance, which were improved through adding glass waste [24,25].

To conclude, there is a clear potential for glass waste to be used as a partial replacement of cement and natural aggregates in mortars, due to the improvements of physical and mechanical characteristics, as well as fire and chemical resistance, to which aesthetics and a lower carbon footprint are added. Additionally, alkali–silica reactions are not a deterrent of waste glass use, as there are different particle sizes and additives that can be used, in order to prevent them from occurring.

Research Significance

Due to the contradictions found in studies that assess the impact of using glass waste aggregates in mortars, and the clear potential of glass waste to be used in plastering mortars, more research is required [26]. This research proposes new uses for glass resulting from construction and demolition waste, in order to reduce the raw material consumption. By observing the characteristics of the new mortars in which natural aggregates have been partially replaced with glass waste, the influence of glass replacement in various proportions is observed, and conclusions for future research and practical applications of glass aggregate mortars are drawn. This study brings the novelty of preparing plastering mortars with glass waste from local sources and trying to obtain an improved plastering mortar that could become a local construction material.

2. Materials and Methods

In the experimental program, locally sourced clear and colored waste glass were used. Three recipes were created, named "MGA" (Mortar, Glass, and Aggregates) with different proportions of glass waste replacement: 15%—MGA 15%, 30%—MGA 30%, and 45%—MGA 45%. The physical–mechanical proprieties of the obtained mortars were

studied in comparison with the reference mortar. Modern methods of electronic microscopy (SEM) and EDX (energy dispersive X-ray spectroscopy) have also been applied to study the morphology and the homogeneity of the mortars. All the materials used in the experimental program comply with current regulations [27–29].

2.1. Materials

In the experimental program, the following materials were used: composite Portland cement, natural aggregates, glass waste with particle sizes of 0–0.5 mm; 0.5–1 mm; 1–2 mm; and 2–4 mm, and drinkable water from the municipal water supply of Cluj-Napoca, Romania.

A general overview of the experimental program, materials, and proposed recipes is illustrated in Figure 1.

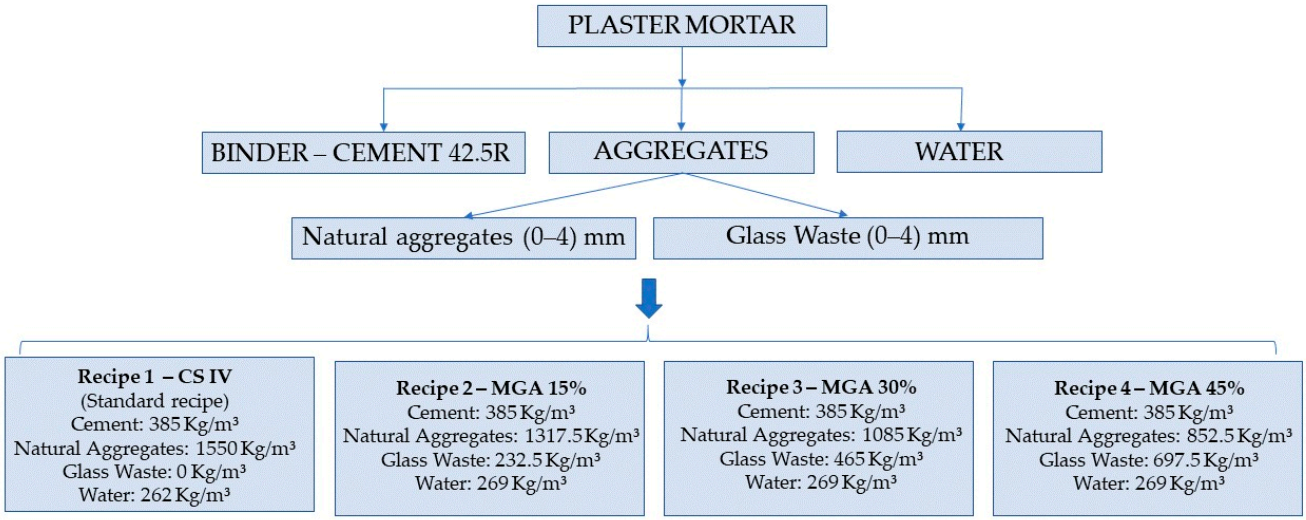


Figure 1. Graphical diagram of the recipes and materials used.

- Cement

The cement used was composite Portland cement CEM II/B-M(S-LL) 42.5 R (STRUCTO PLUS) type, from Holcim, city of Aleșd, Romania. The composition of the cement was clinker (65–79%), blast furnace slag (S) and limestone (LL) (21–35%), and other components (0–5%), according to the performance report [30].

The setting time was also tested in the laboratory, according to SR EN 196-3:2017 [31], before using it in the recipes. The setting time obtained for normal consistency cement paste made with CEM II/B-M(S-LL) 42.5 R type is 3 h 20 min. The density of the cement used in the experimental program has also been studied: CEM II/B-M(S-LL) 42.5 R type, using the pycnometer method. The results showed that the density is equal to 3.125 [g/cm^3]. The cement used in the experimental program meets the conformity criteria required by the standards of SR EN 197-1:2011 [32].

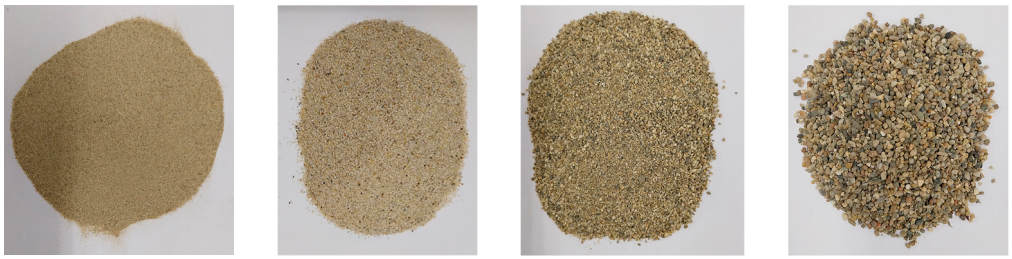
In Table 1, the characteristics of the cement are listed, according to the performance report [26].

- Natural aggregates

The aggregate which was used in the experimental program is a river sand with a grain size of 0–4 mm. Before using, the sand was washed in order to remove leachable parts and impurities and dried until a constant mass was achieved. After washing, the sand was separated into the following grain sizes: 0–0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm, and 2.0–4.0 mm, as presented in Figure 2.

Table 1. Characteristics of the composite Portland cement [12].

Cement Characteristics	Cement Performance Values
Setting time [min.]	min. 60
Soundness [mm]	max. 3
Initial compressive strength [MPa]	min. 20
Standard compressive strength [MPa]	min. 42.5–max. 62.5
Sulphates content [%]	max 4.0
Chloride content [%]	max 0.1
Release of dangerous substances: Hexavalent chromium content [%]	max. 0.0002



(0–0.5) mm (0.5–1) mm (1–2) mm (2–4) mm

Figure 2. Aggregates used in the experimental program.

The grading curve used for the preparation of the tested mortars is illustrated in Figure 3.

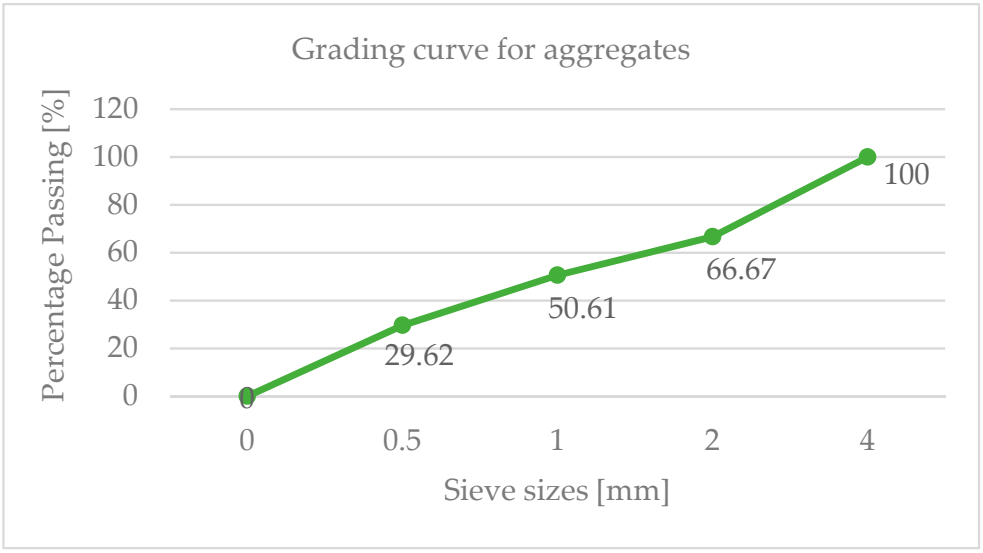
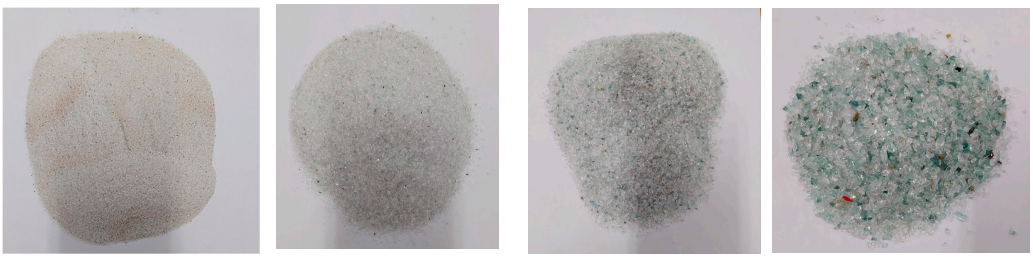


Figure 3. Graphic with grading curve for aggregates.

The bulk density obtained for the aggregates used in the experimental program was also studied and the results indicated an average value of 1817 kg/m^3.

- Mixed clear and colored glass waste

Waste glass replaces aggregates in percentages of 15%, 30%, and 45%, respectively, of each fraction according to the particle size curve presented in Figure 3. The glass was ground into fractions of the following grain sizes: 0–0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm, and 2.0–4.0 mm and separated into 4 categories, as seen in Figure 4. The origin of the glass waste was local, obtained from the demolition of a building in Cluj-Napoca, Romania.



(0–0.5) mm (0.5–1) mm (1–2) mm (2–4) mm

Figure 4. Glass waste fractions used in the recipes.

The bulk density of the glass has also been studied, and the results showed that the density is ρ = 1731 [kg/m^3], which is lower than the density of the aggregates. The specific gravity of the glass waste has been determined at 2.16 [g/cm^3].

The chemical composition of the glass was analyzed through the energy dispersive X-ray spectroscopy (EDX), and the values obtained by analyzing all the granulometric size in multiple sites are reported in Table 2.

Table 2. Chemical composition of the local glass used as an aggregate in the mortar.

Element	O	Na	Mg	Al	Si	K	Ca	Fe
Weight %	55.8	10.1	2.1	4.8	23.9	0.2	2.7	0.4

- Water

Water is an essential ingredient of mortars. The quantity of water in relation to cement and other ingredients has an important impact on mortar consistency. The water quantity was adjusted to maintain the same consistency. The water used was drinkable water from the municipal water supply in Cluj-Napoca.

2.2. Studied Recipes

In this study, one reference mortar CS IV and three eco-efficient mortar recipes were prepared and tested comparatively, as presented below:

1. Recipe 1 CS IV—cement mortar type, with no glass waste added;
2. Recipe 2 CS IV—cement mortar type, in which only the aggregates are replaced by 15% for each type of grain size (0–0.5 mm, 0.5–1 mm, 1–2 mm, and 2–4 mm) with glass waste according to Table 3;
3. Recipe 3 CS IV—cement mortar type, in which only the aggregates are replaced by 30% for each type of grain size (0–0.5 mm, 0.5–1 mm, 1–2 mm, and 2–4 mm) with glass waste according to Table 3;
4. Recipe 4 CS IV—cement mortar type, in which only the aggregates are replaced by 45% for each type of grain size (0–0.5 mm, 0.5–1 mm, 1–2 mm, and 2–4 mm) with glass waste according to Table 3.

Table 3. Mix proportions for 1 m^3.

Recipe	**Replacement**		**Cement Kg/m^3**	**Aggregates Kg/m^3**				**Glass wastes Kg/m^3**				**Water Kg/m^3**
	%	**Kg/m^3**		**0–0.5 mm**	**0.5–1 mm**	**1–2 mm**	**2–4 mm**	**0–0.5 mm**	**0.5–1 mm**	**1–2 mm**	**2–4 mm**	
CS IV	0	0	385	186	317.75	418.5	627.75	0	0	0	0	262
MGA 15%	15	232.5	385	158.1	270.05	355.8	533.55	27.9	47.7	62.7	94.2	269
MGA 30%	30	465	385	130.2	222.35	293.1	439.35	55.8	95.4	125.4	188.4	269
MGA 45%	45	697.5	385	102.3	174.65	230.4	345.15	83.7	143.1	188.1	282.6	269

2.3. Methods for Testing the Glass Waste Mortars

The study of the mortars within the experimental program was carried out both from the point of view of the physical–mechanical characteristics and also from a microscopical point of view, in order to be able to evaluate the influence of the glass waste used with respect to the behaviour of the analyzed mortars, as presented in Table 3.

The experiments were performed in the Building Materials Laboratory of the Faculty of Civil Engineering at the Technical University of Cluj-Napoca, Romania and also in the Raluca Ripan Institute of Research in Chemistry at Babeș-Bolyai University.

The determination of the physical–mechanical characteristics of the studied mortars was carried out both on fresh mortars and on hardened mortars. Analysis of the characteristics of the mortars studied in the hardened state was carried out at 3, 7, 14, and 28 days, respectively.

The mortars were prepared using a mixer, where the dry component materials were introduced first, to be mixed as homogeneously as possible, and then water was introduced. To obtain the samples to investigate in the hardened state, after preparation, the obtained composition was poured into prismatic metallic molds of 40 × 40 × 160 mm. The casting in molds was carried out in three stages and after each stage they were compacted using the vibrating mass.

All samples were kept in a room with humidity of 65–70% and temperature of 20–24 °C, in accordance with the standard [30], as described in Table 4.

Table 4. Methods for testing the characteristics of fresh and hardened state mortars.

Physical-Mechanical Characteristics				Microscopical Characteristics	
Fresh Mortars State	**Testing Time**	**Hardened Mortars State**	**Testing Time**	**Hardened Mortar State**	**Testing Time**
Apparent density	Immediately after preparation	Apparent density	3, 7, 14, 28 days	Optical microscopy (SEM)	28 days
Consistency		Compressive strength		EDX (energy dispersive X-ray spectroscopy)	
Segregation tendency		Flexural strength			
		Adhesion to the substrate	28 days		

2.3.1. Determination of Fresh Mortar Characteristics

- Apparent density

After homogenization of the mixture of tested mortars, the composition is placed in the cylindrical vessel of known volume V = 1 L and known mass (m_v) on which an extension frame is fixed. The vessel is filled with mortar up to halfway up the rim, the extension frame is removed, and the excess mortar is removed with a metal blade using a saw movement from the middle to the edges. The cylindrical vessel is weighed in order to obtain the final mass (m_m) [33]. The apparent density is calculated with the following relation:

$$\rho_a = \frac{m_v - m_m}{V} \times 1000 \left[\frac{\text{Kg}}{\text{m}^3}\right] \quad (1)$$

where the terms have the following descriptions:

ρ_a—apparent density;
m_m—mass of vessel;
m_v—mass of the vessel filled with the mortar mixture obtained;
V—volume of the vessel.

- Consistency of mortars

The determination of the consistency of the mortars was carried out according to SR EN 1015-3:2001 using the flow table as the apparatus [33].

The mold is placed in the middle of the flow table disc and the mortar is introduced in two layers; each layer being compacted by at least 10 short strokes with the mortar trowel. The excess mortar is removed with a levelling trowel and the free surface of the disc is

wiped. After about 15 s, the mold was lifted slowly and vertically, and the mortar was spread on the disc by executing 15 table vibrations at a frequency of about 1 vibration per second. The diameter of the mortar was measured in two perpendicular directions, using the caliper.

The consistency value is to be calculated as the average value of two measurements.

- Segregation tendency

Segregation tendency indicates the property of composite materials to separate into component materials, due to the differences in density and mass of their constituent granules, following shocks or even at rest.

Determination of segregation tendency is performed in a 30 cm high container, which will be filled in three stages with the tested mortar composition. After each stage, the mortar is compacted by pressing 25 times with a metal rod of 10 to 12 mm diameter over the entire height of the mortar layer. After pouring the last layer, the surface of the mortar is smoothed and allowed to rest for 30 min. After resting, the consistency of the upper layer C_s and then the consistency of the lower layer C_i was determined using the standard cone. The segregation tendency, characterized by the segregation coefficient "S", of the mortar is calculated with the following relation:

$$S = \frac{\pi}{48} \cdot \left(C_s^3 - C_i^3 \right) \left[\mathrm{cm}^3 \right] \quad (2)$$

where the terms have the following descriptions:

S—segregation tendency;
C_s^3—consistency of the layer in the upper third;
C_i^3—consistency of the layer in the lower third.

2.3.2. Determination of Hardened Mortar Characteristics

- Determination of apparent density

The determination of the apparent density of the hardened mortar was conducted according to SR EN 1015-10:2002 [34]. The apparent density test was carried out after 28 days on three specimens of 40 × 40 × 160 mm. The mass (m_s) of the tested specimens was determined and then the apparent volume (V_s) was calculated. Density was calculated as a ratio of the specimen mass to the specimen volume:

$$\rho_a = \frac{m_s}{V_s} \left[\frac{\mathrm{Kg}}{\mathrm{m}^3} \right] \quad (3)$$

where the terms have the following descriptions:

ρ_a—apparent density;
m_s—mass of the sample;
V_s—volume of the sample.

- Determination of flexural strength

The determination of flexural strength was carried out on three prisms for each day of testing with dimensions 40 × 40 × 160 mm, using the automatic machine for loading from bending (Figure 5), according to SR EN 1015-11 [32]. Three specimens have been tested on each of the 4 days: 3rd, 7th, 14th, and 28th. A shock-free load is applied with a uniform velocity in the range of 10 N/s and 50 N/s so that rupture occurs within a period of 30 s to 90 s after which the maximum applied load in newtons has been recorded. The mechanical flexural strength, f, is calculated in $\mathrm{N/mm}^2$, using the following formula:

$$f = 1.5 \frac{Fl}{bd^2} \left[\frac{\mathrm{N}}{\mathrm{mm}^2} \right] \quad (4)$$

where the terms have the following representations:

f—bending strength;
F—the maximum applied load;
l—distance between the bearings;
b, d—the inside dimensions of the mold.



Figure 5. Apparatus used for determinations on hardened mortars. (**a**) Automatic machine for loading from bending. (**b**) Hydraulic press 250 KN Technotest. (**c**) Digital bond strength.

- Determination of compressive strength

The compressive strength was determined at 3, 7, 14, and 28 days, respectively, according to the standards SR EN 1015-11:2020. The samples were kept in a box with humid air until testing. The samples on which the test was carried out are the prism scrap obtained after testing them for the determination of the resistance to flexural strength. The total number of specimens tested was 24, with 6 specimens per testing day. The specimens were tested perpendicular to the casting direction, using a hydraulic press apparatus (Figure 5b).

The calculation relation used is the following:

$$f_{ck} = \frac{P}{A}\left[\frac{\mathrm{N}}{\mathrm{mm}^2}\right] \quad (5)$$

where the terms have the following descriptions:

f_{ck}—compressive strength;
P—breaking force;
A—section area;

- Determination of adhesion to the substrate

The determination of adhesion to the substrate was conducted at 28 days, using a pull-off digital apparatus, Model 58-C0215, with a load capacity of 16 KN (Figure 5c). The specimens were prepared as follows: a test substrate compact brick (240 × 120 × 65 mm) was used; before applying the mortar layer the substrates were saturated with water to not influence the absorption of water by the tested mortar; and a circular test area of approximately 50 mm in diameter was made on the specimens. The specimens were enclosed within a sealed, air-tight polyethylene bag at a temperature of 20 °C (+3/−2) for 7 days, and after that they were removed from the polyethylene bag and stored in air at a constant temperature of 20 °C (+3/−2) and relative humidity of 65% ± 5%, according to SR EN 1015–12:2016 [35].

Pulling force is applied to a disc bonded to the test surface, the disc being bonded to the surface of the specimen within the incised surface, which is prepared one day before the test by bonding it with an epoxy resin recommended by the apparatus manufacturer.

Adhesion force is measured as the maximum tensile stress applied by loading directly perpendicular to the surface of the plastering and plastering mortar on a substrate. The adhesion force is the ratio between the breaking force and the corresponding surface.

$$f_u = \frac{F_u}{A} \quad (6)$$

where the terms have the following descriptions:

f_u—Adhesion force;
F_u—breaking force;
A—test surface of the cylindrical specimen.

Three possibilities may occur after testing:

- Adhesion fracture—Fracture at the interface between mortar and substrate. Test value equals the adhesive strength;
- Cohesion fracture—Fracture in the mortar itself. The adhesive strength is greater than the test value;
- Cohesion fracture—Fracture in the substrate material. The adhesive strength is greater than the test value;
- The scanning electron microscopy (SEM) and the energy dispersive X-ray spectroscopy (EDX).

The SEM method allows for the observation of the microscopic structure of the materials, showing the morphology of the structural constituents of the samples. With this method, the appearance of ettringite crystals, responsible for increasing the resistance of mortars, can be analyzed, in order to observe the differences at different ratios of glass aggregates in the mortars. For the present study, the used SEM devices were JEOL JSM 5600 LV (Tokyo, Japan) electron microscope and Inspect S, FEI (Einhoven, The Netherlands). For SEM, the samples were studied in a fractured and in a polished section. The polished sections were obtained by embedding the samples in resin and polishing them with SiC paper (380 and 500 grit). For a better observation, all the samples were covered by sputtering with gold. The images were recorded using the secondary electron signal for the fractured samples and backscattered electron signal for the polished samples, at an accelerating voltage of 15 kV.

EDX microanalysis was also performed using a UltimMAX65 Oxford Instrument detector (High Wycombe, UK), controlled with AZtec software (version 4.2). For this, the spectrometer provided with the scanning electron microscope was used. The results of these analyzes indicate the chemical composition and distribution maps of the elements detected in the samples.

3. Results

Determinations have been conducted in a fresh and hardened state, at 3, 7, 14, and 28 days, for the purpose of observing the effect of glass wastes, across time, on the mortar characteristics—in fresh and hardened states, as well as through electronic microscopy analyses.

3.1. Results Obtained on Fresh-State Mortars

In Table 5, the results obtained for apparent density, consistency, and segregation tendency on the studied mortars are presented.

- Apparent density

By analyzing the results in Figure 6, it can be observed that the apparent density values are decreasing as the percentage of glass wastes is increasing, with the exception of the mortar MGA 30%, which had values that were 1.81% higher than CS IV. The lowest value of apparent density was obtained for the MGA 45% mortar, the mortar with the highest content of glass waste, as can be seen in Figure 6. Its registered value was 8.35% lower than

CS IV. The decrease in apparent density values is due to the fact that the bulk density of the glass waste is lower than the density of natural aggregates.

Table 5. Results of tests on fresh mortars.

Recipe	Average Value of Apparent Density ρ_a [kg/m^3]	Average Value of Consistency d_{med} [mm]	Average Value of Segregation Tendency S [cm^3]
CS IV	2155	196	24.17
MGA 15%	2138	191	25.60
MGA 30%	2194	190	28.50
MGA 45%	1975	184	23.50

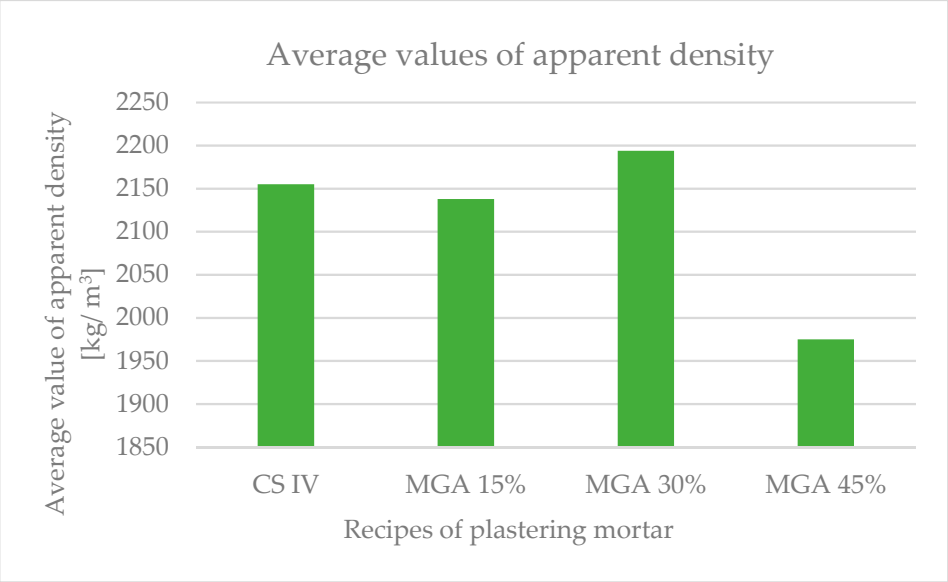


Figure 6. Results obtained on apparent density of fresh mortars.

- Consistency of studied mortars

Consistency was determined with the flow table on the studied mortars. As can be seen in Figure 7, the lowest value was registered by MGA 45%, the mortar with 45% replacement of aggregates with glass waste, which had values 6.12% lower than CS IV. The closest value to the reference mortar was obtained with MGA 15%, only 2.55% lower than CS IV. MGA 30% obtained values that were 3.06% lower than CS IV. The results indicate that with an increase in glass waste in the composition, the mortars are less workable, due to the difference in particle shape between the crushed glass waste and the rounded and semi-rounded appearance of natural aggregates.

Figure 8 shows the reference mortar CS IV and MGA 15% recipe as they were measured on the flow table.

The same procedure of determination of consistency of the four mortars was applied to MGA 30% and MGA 45%, and the average values have been inserted in Table 4.

- Segregation tendency

As seen in Figure 9, for all the studied mortar types, the values obtained for the segregation tendency fell within the limits required by norms: for plastering mortars the maximum value admitted is 40 cm^3 [36]. The highest value of segregation tendency was obtained for the MGA 30%, higher than CS IV by 17.91%. MGA 15% also obtained higher results than CS IV by 5.92%.

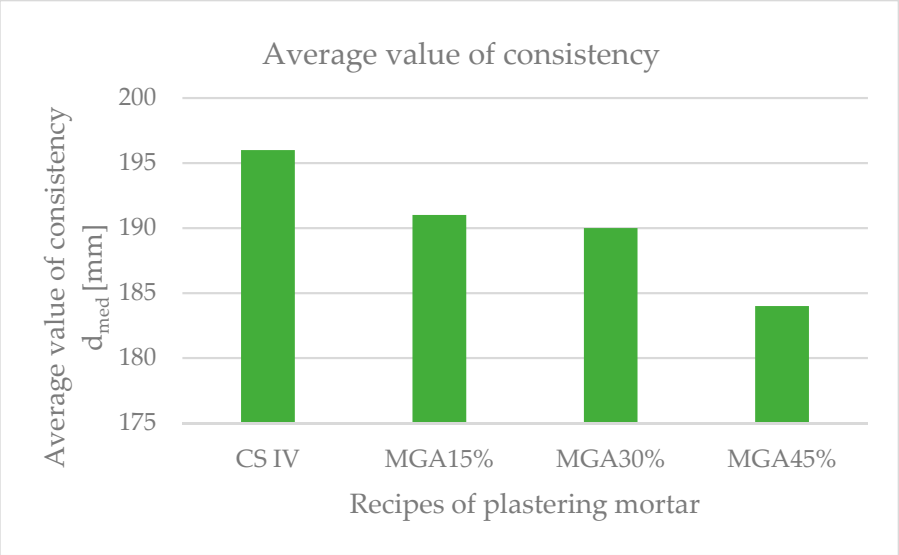
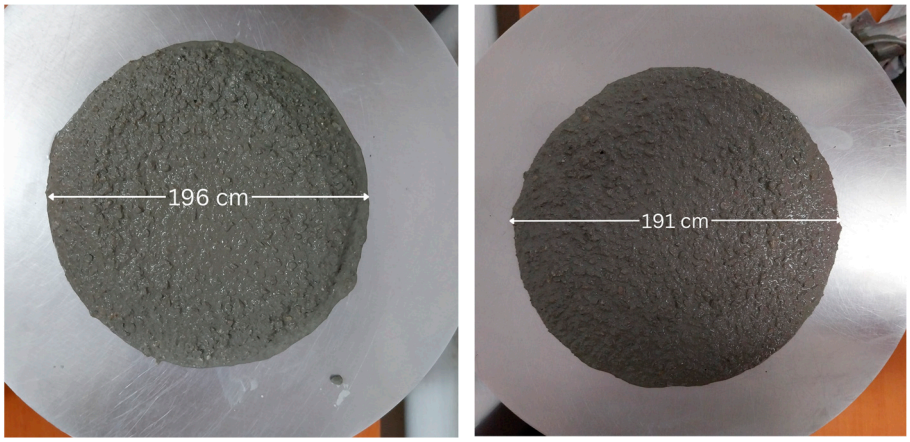


Figure 7. Results obtained on consistency of fresh mortars.



(**a**) CS IV (**b**) MGA 15%

Figure 8. Flow table determination of consistency.

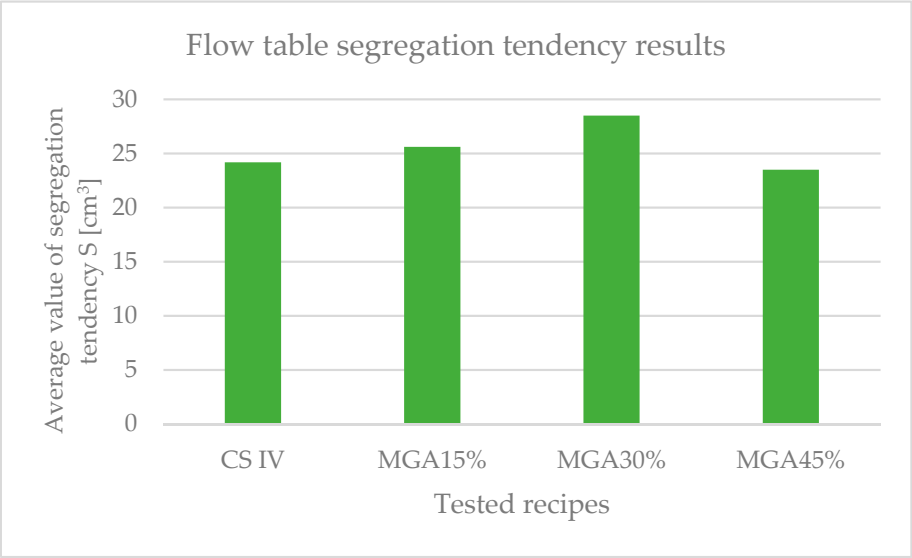


Figure 9. Average values of segregation tendency for all four recipes.

This is due to the higher density of these two mortars.
All four values correspond to the norms.

3.2. Results Obtained on Hardened State Mortars

3.2.1. Determination of Apparent Density on Mortars in a Hardened State

In Figure 10, the evolution of the average values obtained for the apparent density of mortars in a hardened state is observed, at the ages of 3, 7, 14, and 28 days, for each of the four recipes studied.

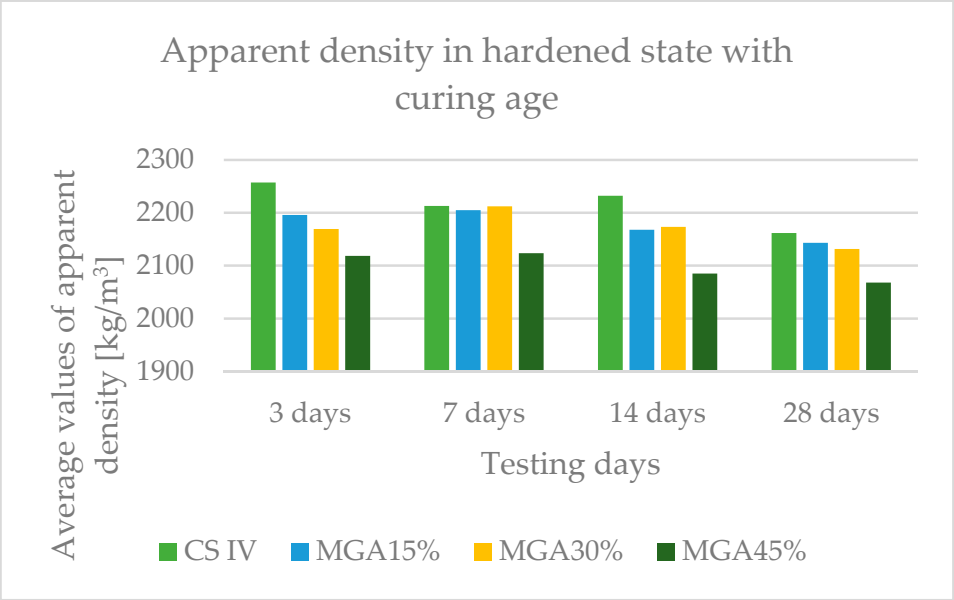


Figure 10. Average values for apparent density in a hardened state, with curing age.

- At 3 days, CS IV obtained the highest value, followed by a decrease corresponding to the percentage of replacement: MGA 15% lower by 2.72%, MGA 30% lower by 3.89% lower, and MGA45 lower by 6.14%;
- At 7 days, CS IV had the highest values, higher than MGA 15% and MGA 30% only by 0.37%. MGA 45% obtained lower results than CS IV by 4.04%;
- At 14 days, CS IV had the highest values, followed by MGA30, with 2.64% lower values. MGA 15% had values that were 2.89% lower than CS IV, while MGA 45% had values 6.60% lower than the reference mortar;
- At 28 days, CS IV stabled itself, with values lower than on the previous days. The highest values obtained with glass mortars were for MGA 15%, lower by 4.12% than CS IV, followed by MGA 30%, with values 4.66% lower than CS IV, and MGA 45%, whose values were 7.59% lower than those of the reference mortar.

Throughout all of the testing days, the values of MGA 15% and MGA 30% were very close, equal on day 7, and were higher for MGA 30% on day 14 and higher for MGA 15% on day 28 but only by 0.54%, as seen in Figure 10. This indicates that a replacement percentage between 15% and 30% affects the apparent density values in the hardened state of the plastering mortar in a similar way, the decrease from the values of the reference mortar CS IV being less than 5%. All the results fell within the norms, indicating that these mortars belong to the heavy mortars category (densities higher than 1800 kg/m^3). Following the results obtained from determining the density in a hardened state, it could be observed that the mortars containing glass were lighter than the reference mortar.

3.2.2. Determination of Flexural Strength of Hardened Mortars

Table 6 shows the values of the flexural strength determination for all four types of mortars studied in the experimental program. The results indicate that the average values of flexural strength increase steadily over time, for all the studied mortars (Figure 1).

Table 6. Average values for determination of flexural strength, standard deviation, and comparison percentages to the reference mortar on the 28th day.

Mortar Type	Average Values of Flexural Strength [N/mm^2]								
Age of the Mortar	**3 Days**	**Std. Dev.**	**7 Days**	**Std. Dev.**	**14 Days**	**Std. Dev.**	**28 Days**	**Std. Dev.**	**% Difference 28th Day**
CS IV	3.45	0.10	3.96	0.15	4.86	0.59	5.69	0.26	0
MGA 15%	3.45	0.32	4.11	0.22	4.72	0.50	5.71	0.26	+0.35%
MGA 30%	2.96	0.35	4.46	0.34	5.51	0.60	6.53	0.49	+15%
MGA 45%	3.15	0.73	3.92	0.33	4.32	0.52	4.70	0.17	−17%

- On the 3rd day, CS IV and MGA 15% obtained identical values, while MGA 30% and MGA 45% have lower values than CS IV by 14.20% and 8.70%, respectively;
- On the 7th day, MGA 30% obtained the highest values, more than CS IV by 12.63%. MGA 15% obtained values higher than CS IV by 3.79%. MGA 45% obtained lower values than CS IV by 1.01%;
- On the 14th day, MGA 30% had the highest values, increased from CS IV by 13.37%. MGA15 and MGA 45% had lower values than CS IV, by 2.88% and 11.11%, respectively;
- On the 28th day, MGA 30% had the highest values, higher than CS IV by 14.76%, while MGA 15% had values higher than CS IV by 0.35%. MGA45 had values lower by 17.40% than the reference mortar.

The replacement of natural aggregates with glass waste in a proportion of 30% had a significant positive effect on flexural strength, obtaining a score 15% higher than the reference mortar, as seen in Figure 11. For the average results, standard deviation was calculated to be between 0.10 and 0.73, indicating that variation between values was not very high.

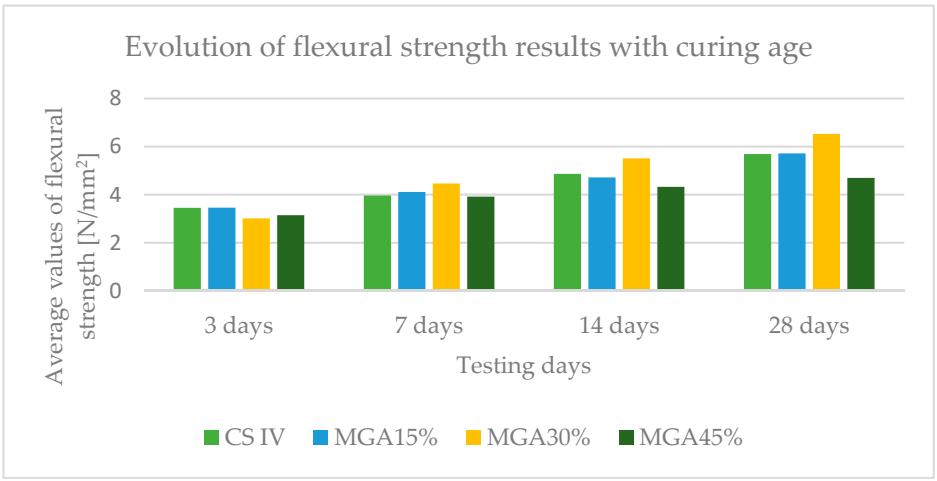


Figure 11. Average values for flexural strength, with curing age.

3.2.3. Determination of Compressive Strength of Hardened Mortars

Table 7 shows that on the 28th day, the mortar MGA 15% had a lower compressive strength than CS IV by −2% and MGA 30% had a 12% higher compressive strength than CS IV. Average values of compressive strength obtained through the experimental

program indicate higher results than 6 N/mm^2, the value specified by the current norm SR EN 998-1:2011 [37].

Table 7. Results of the determination of compressive strength and comparison to reference mortar on the 28th day.

Mortar Type	Average Values of Compressive Strength [N/mm^2]								
Age of the Mortar	**3 Days**	**Std. Dev.**	**7 Days**	**Std. Dev.**	**14 Days**	**Std. Dev.**	**28 Days**	**Std. Dev.**	**% Difference 28th Day**
CS IV	12.78	0.14	17.20	1.30	19.83	2.49	24.21	1.66	0
MGA 15%	13.70	1.22	16.61	2.19	21.93	1.78	23.65	2.31	−2%
MGA 30%	12.04	0.25	18.03	0.55	25.26	0.85	29.80	1.25	+12%
MGA 45%	12.69	0.48	16.61	0.26	18.79	0.8	20.40	0.88	−16%

- On the 3rd day, the highest compressive strength results were obtained with MGA 15%, 7.20% higher than CS IV. MGA 30% and MGA 45% obtained lower results than CS IV, by 5.48% and 0.63%, respectively;
- On the 7th day, the highest compressive strength results were obtained with MGA 30%, more than CS IV by 4.84%. MGA 15% and MGA 45% obtained lower results than CS IV, by 3.29% and 3.49%, respectively;
- On the 14th day, the highest compressive strength results were obtained with MGA 30%, 27.42% higher than CS IV. MGA 15% also obtained higher results than CS IV by 10.61%. The mortar MGA 45% obtained lower results than CS IV by 5.19%;
- On the 28th day, the highest compressive strength results were obtained with MGA 30%, 23.09% more than CS IV. MGA 15% and MGA 45% obtained lower results than CS IV, by 2.24% and 15.74%, respectively.

The results indicate that a 30% replacement of natural aggregates with glass waste improved the compressive strength. These results were consistent with Chen et al. [38], which could be caused by the silica gel reacting with the calcium hydroxide due to the cement hydration. Through the consequent production of C-S-H gel, that augmented the density of impermeable pores inside the mortar, an increase in the compressive strength of the mortar resulted. Another possible explanation could be the higher density of the microstructure in the interstitial transition zone.

Conversely, a percentage of replacement of 45% with glass waste negatively affected the compressive strength. This is mainly due to the fact that the angle of the glass aggregate particles might be increasing the internal pores of the mortar. Despite the fact that the waste glass presents as a smooth surface, the strength of the bond is lower once an external force acts upon the mortar. As the interface was easily damageable, the compressive strength of the mortar was not as high.

As seen in Figure 12, the compressive strength increases steadily over the testing days, indicating that the process of hydration is occurring in the case of the glass waste aggregate mortars.

3.2.4. Determination of Adhesion to the Substrate

Adhesion to the brick substrate tests were performed on all four studied mortars (Figure 13). Five specimens were tested for each of the mortars. The results were inserted in Table 8.

- The mortar MGA 15% obtained 47% lower values than the reference mortar;
- The MGA 30% mortar obtained 69% lower values than CS IV;
- The mortar MGA 45% obtained the lowest values compared to the other recipes, 69% lower than the reference mortar.

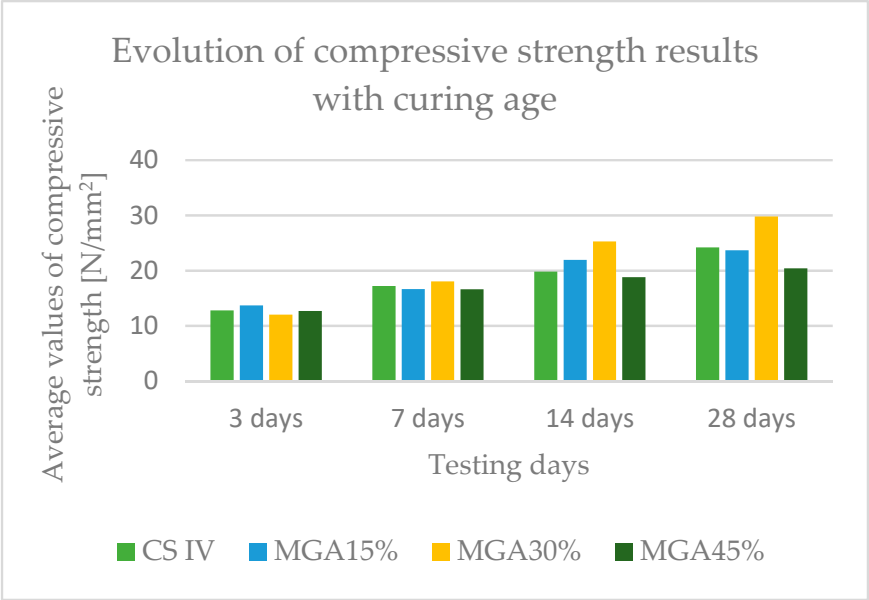


Figure 12. Average values for compressive strength, with curing age.



Figure 13. Specimens tested for adhesion to the substrate.

Table 8. Average values of the adhesion to the brick substrate and standard deviation.

Mortar Type	Adhesion to the Substrate Results	
	Average Values [N/mm^2]	Std. Dev.
CS IV	0.1263	0.0065
MGA 15%	0.0671	0.0008
MGA 30%	0.0397	0.0020
MGA 45%	0.0380	0.0021

The results signify that replacing aggregates with glass waste in plastering mortars negatively affects their adhesion to the brick substrate.

After analyzing the test results, two situations of adhesion to the substrate were observed:

- The first situation is that of the reference mortar CS IV, where the rupture occurred in the mortar (cohesion fracture). This signifies that the adhesive strength is higher than the test value;
- The second situation is that of all the mortars where the aggregates were partially replaced with glass waste, where the rupture occurred at the interface between the

substrate and the mortar (adhesion fractures), signifying that the adhesion strength is equal to the test value. A possible cause could be the increased water absorption in the substrate layer.

In Figure 14, it is visible that the adhesion strength values decreased as the percentage of aggregate replacement increased.

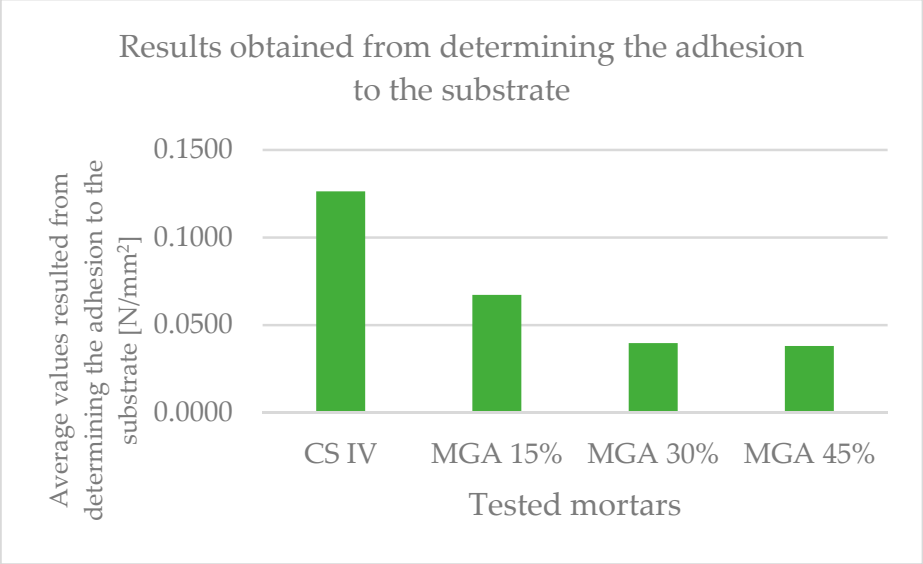


Figure 14. Average values for adhesion to the brick substrate for the four types of mortars at 28 days.

3.3. Results of SEM and EDX Analyses

Electronic microscopy analyses SEM and EDX have been performed on CS IV, MGA 15%, and MGA 30% mortars, as the best performing ones, in order to observe the morphology and elemental distribution of the constituents. In order to study the fracture of the materials, the images were recorded on unpolished surfaces [39].

In Figure 15a–c, the ettringite crystals forming in the CS IV mortar can be seen. The images also show nucleation sites and high porosity zones, where bubbles of air might have been caught. In Figure 15d, the image depicts the interface between the glass and mortar morphologies.

In Figure 16, the elemental distribution map distribution for CS IV, MGA 15% and MGA 30% mortars is shown. The images present an apparent good compacting bonding of mortar components with glass, which is important for the modification of the mechanical strength of the samples.

For an accurate recording of the characteristic X-ray signals of the elements, the analyses were performed on flat polished surfaces. The SEM images recorded with backscattered signal are presented in Figure 17, along with the elements' distribution.

In Figure 18, different areas corresponding to different morphologies visible in SEM images are presented and analyzed. For each area, several spectra were recorded and the chemical contents are presented.

The chemical analysis reveals the typical elements of mortars (cement and aggregates) as well as glass. As an example, in area 1, the presence of Ca, Si, and Fe indicate the existence of the mineralogical compound brownmillerite. In area 2, the presence of Ca, O, and Si indicate the presence of Ca_2SiO_4 (belit) or Ca_3SiO_5 (alit). In areas 3, 6, and 8, the presence and ratio of O, Ca, and Si indicate the presence of hydrated calcium silicates. In areas 4 and 7, particles of sand are identified. In area 5, the presence of O and Si indicate that the area consists of glass.

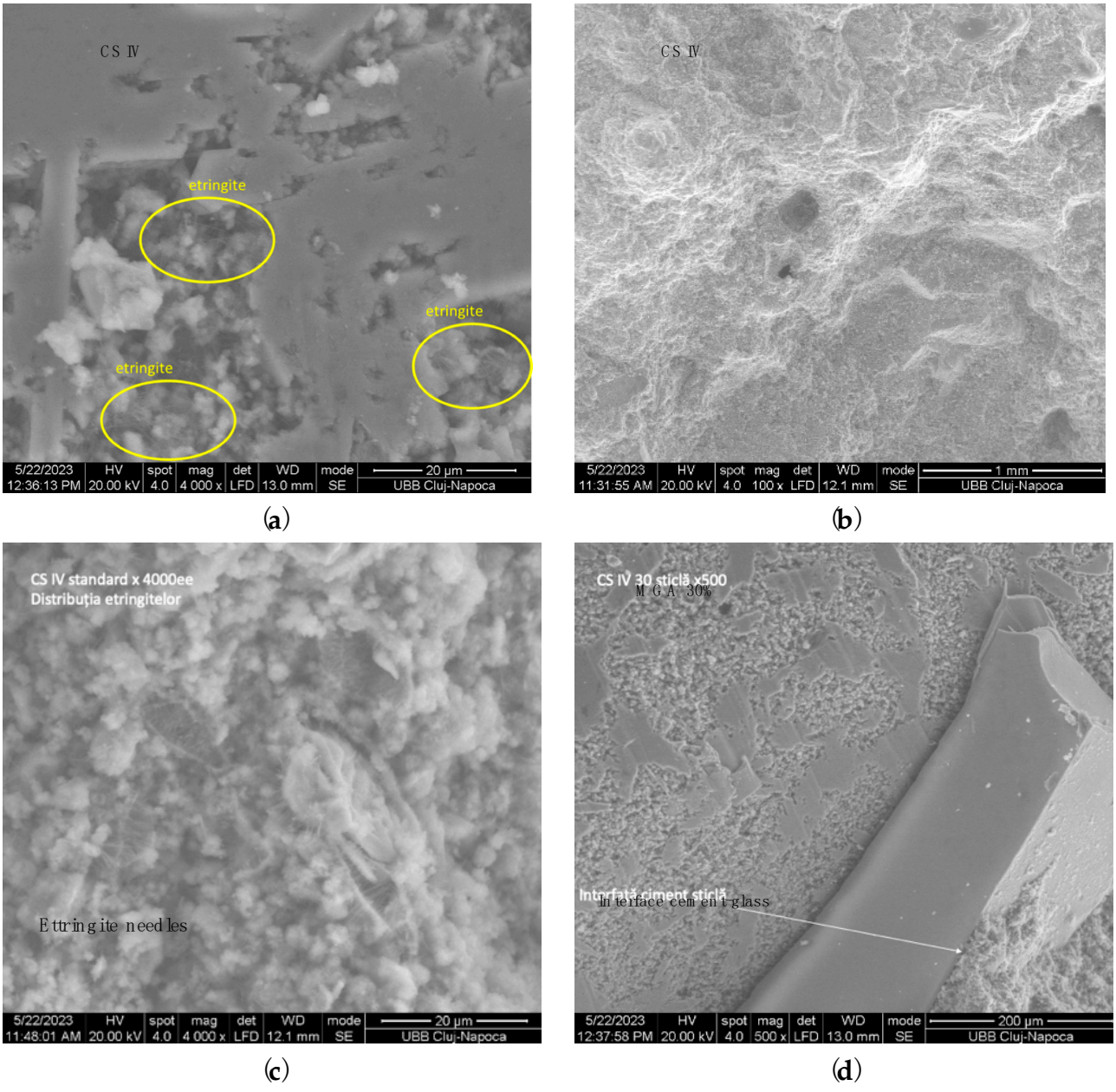


Figure 15. SEM images of (**a**) mortar CS IV ×4000 showing the general aspect and the presence of ettringite in the paste, (**b**) mortar CS IV ×100 showing nucleation sites, (**c**) CS IV ×4000 zoomed area of ettringite crystals, and (**d**) MGA 30% ×500 magnified interface between glass and cement.

A second result of the microscopical analysis was the evidence of ettringite crystals at high magnification, as indicated by arrows in Figures 19 and 20. The ettringite crystals are organized in clusters, and as Figure 19a shows, they are visible even at the glass–mortar interface. The upper left corner of the Figure 19a is showing the glass aggregate.

In Figure 20, the images obtained through SEM analysis for the plastering mortars are presented. The images of the mortar MGA 30%, in which 30% of the natural aggregates have been replaced with glass waste, and of the reference mortar CS IV, have been magnified ×5000. By increasing the glass waste content from 15% to 30%, the size and length of the ettringite crystals has reduced.

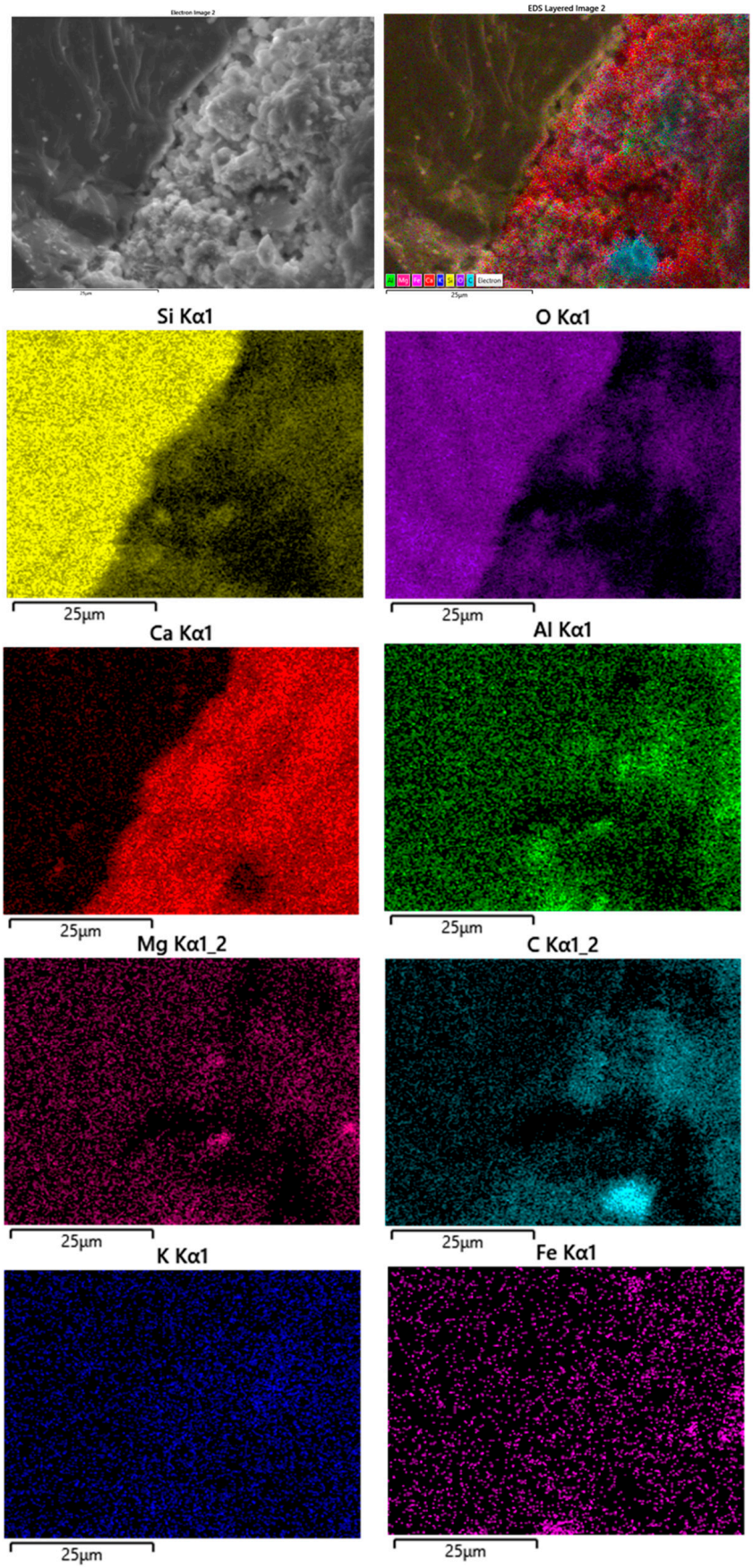


Figure 16. SEM image and EDX elemental distribution maps for mortar MGA 15% ×2000.

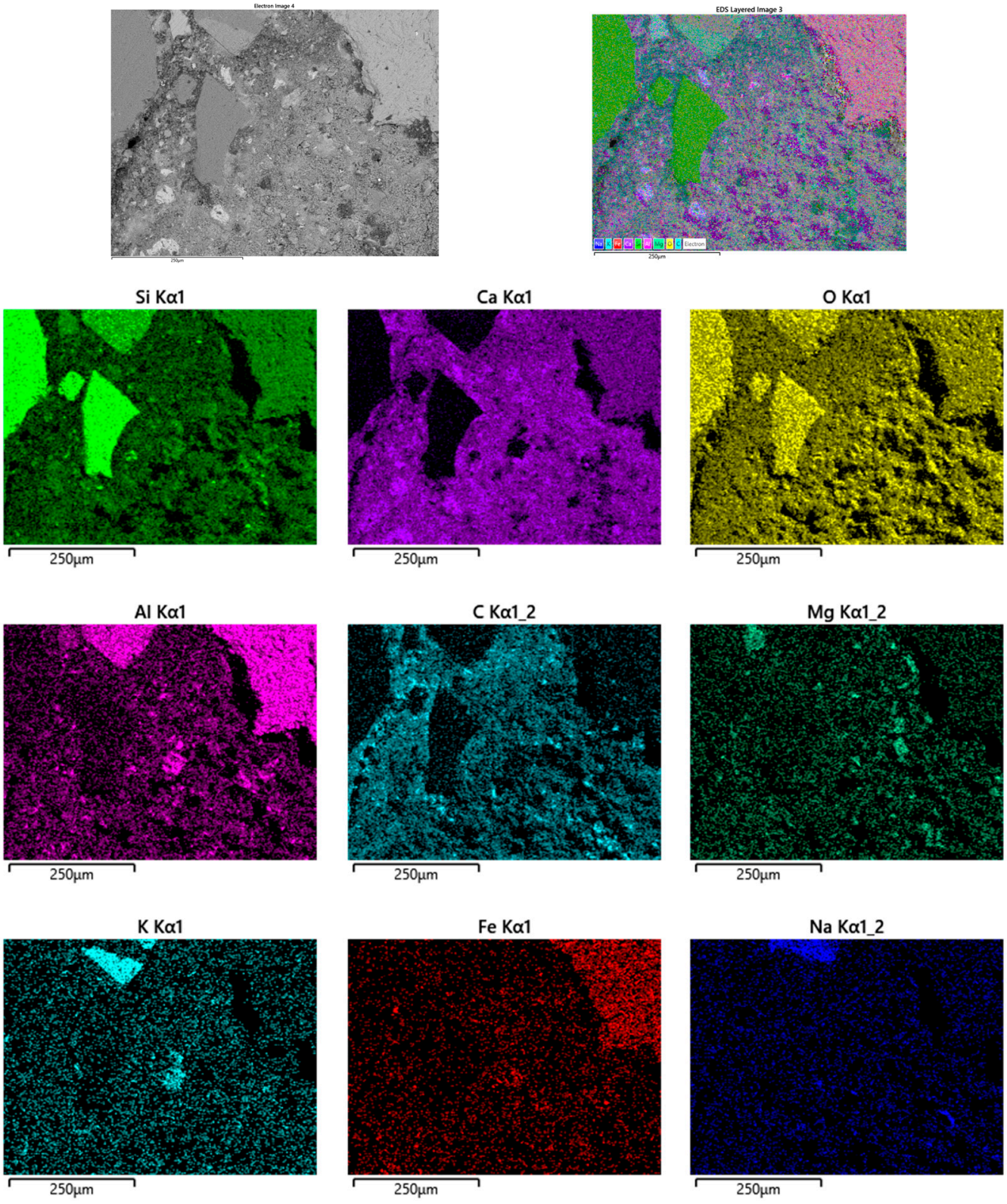


Figure 17. SEM backscattered electron image (×200) and EDX elemental distribution maps for mortar MGA 15%, recorded on polished surface.

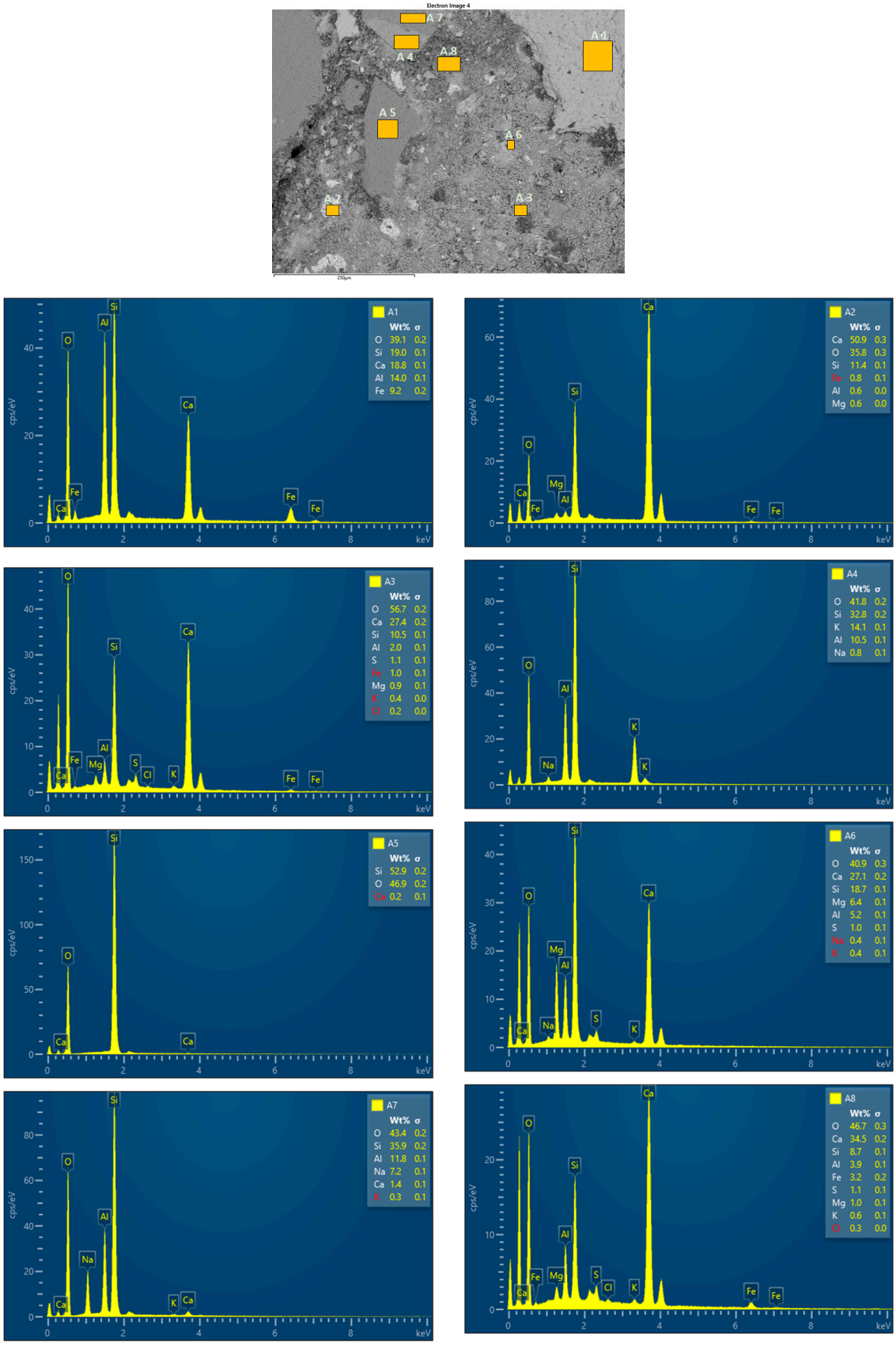
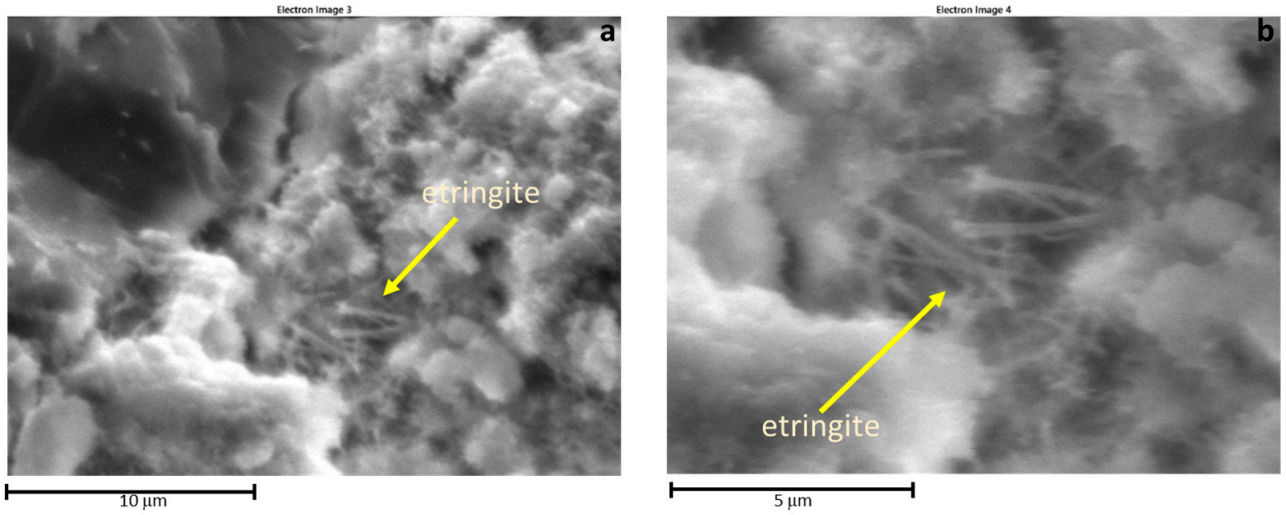
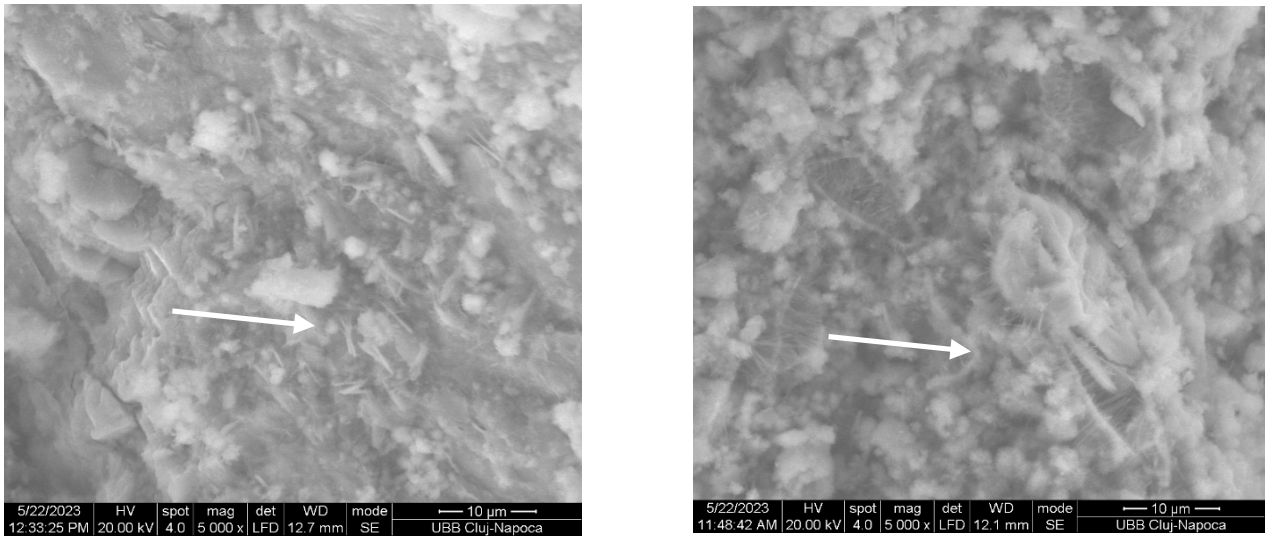


Figure 18. EDX analysis spectra recorded in the selected areas of sample MGA 15% (×200).



(**a**) (**b**)

Figure 19. SEM image of mortar (**a**) MGA 15% at the glass interface ×5000 and (**b**) MGA 15% cluster of ettringite crystals ×10,000.



(**a**) (**b**)

Figure 20. SEM image of mortar (**a**) MGA 30% ettringite crystals ×5000 and (**b**) CS IV ettringite crystals ×5000, marked by a white arrow.

4. Discussions

In spite of the fact that glass could be, in theory, recycled endlessly to make new glass, the costliness and high energy consumption of the recycling processes make it more cost-efficient to discard it at the landfill. As a result, more profitable ways to manage glass waste sustainably are sought, especially in the construction and demolition activities, in which glass is traditionally one of the most used materials, resulting in large quantities of waste.

Reusing construction and demolition waste for obtaining new building materials that are more sustainable and innovative would be a possible solution to reduce a part of the CDW and to save natural resources that are used for standard plastering mortars. By using CDW to fabricate new construction materials, the energy consumption could be reduced. Sourcing construction materials locally would reduce the transport and logistics costs and energy required at present to meet the construction industry demands.

This study focuses on observing the potential benefits of creating new, more sustainable plastering mortars, in which a part of the natural aggregates has been replaced in different proportions, of 15%, 30%, and 45%, with locally sourced CDW in the form of clear and colored glass. Three new mortars have been proposed and tested in comparison with the reference mortar CS IV, and with results of relevant studies found in the literature.

Overall, the results of the determinations of the four mortars indicate that MGA 15% and MGA 30% are the best performing mortars, with MGA 30% showing an improvement in mechanical strength results across time, compared to the CS IV reference mortar.

It can be deduced that the process of hydration occurred, for the reference mortar as well as for the glass waste aggregate mortars. Furthermore, it can be inferred that the process of hardening of the mortars was not influenced negatively by the glass waste replacement of 15–30% at the age of 28 days. This is consistent with the literature. For instance, Li et al. [9] and Chandra et al. [10] observed in their literature reviews that a replacement level of around 20–30% was optimal for plastering mortars with glass waste, resulting in improved physical–mechanical characteristics.

- ***Results of the determinations on the studied mortars, in the fresh state***

Considering the determinations in the fresh state, an increase in apparent density was obtained only for MGA 30%. The consistency was lower on all glass mortars compared to the reference mortar CS IV. Segregation tendency was also highest for MGA 30% and for MGA 15%, indicating that glass inside these mixtures had a higher tendency to sediment at the base.

As seen in Figure 21, the apparent density values are consistent with other results found in the literature. MGA 15% obtained 1.73% lower results than the mortar with 15% aggregate replacement tested by Malek et al. [40] and 5.52% more than the results obtained by Soberon et al., 2018 for the same percentage of replacement. The highest performing mortar in the present study, MGA 30%, obtained results 14.77% higher than the mortar with the same percentage of aggregate replacement studied by Soberon et al. [39]. This might be due to particularities of the glass. MGA 45% obtained lower values of apparent density than the mortars with 50% replacement by Tan and Du [18], but in their study the results obtained at a replacement level of 25% and of 50% are extremely close. Molnar et al. also obtained mechanical properties comparable to the reference mortar CS IV at a replacement proportion of 50% [41].

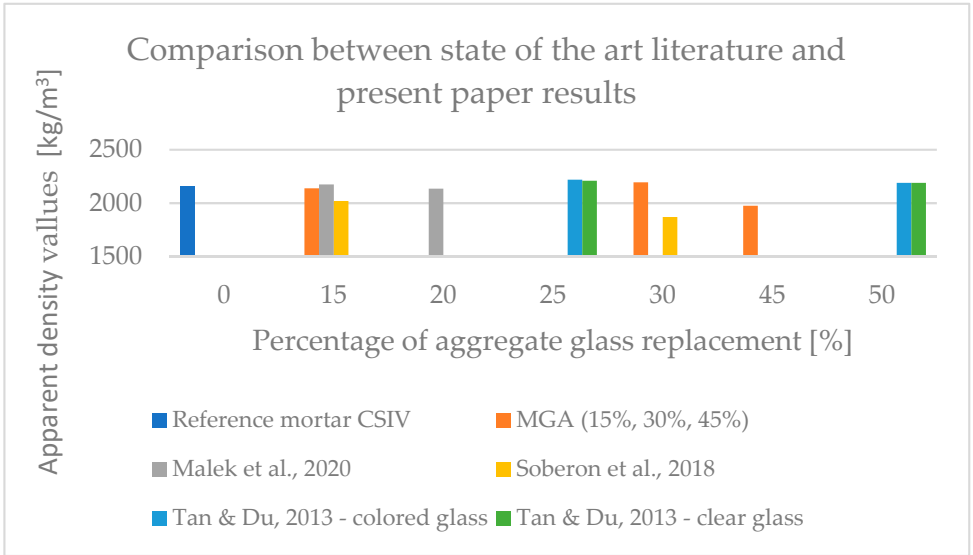


Figure 21. Comparison between state-of-the-art literature and present paper results of apparent density values of glass aggregate mortars [18,39,40].

The results indicate that by adding more glass waste in the recipe, the mortars become less workable, due to the difference in particle shape of glass, which is more angled. This determines different connections between the particles and impact the rheological characteristics. This is also applicable for the apparent density of MGA 15% and MGA 45% in the hardened state, which decreased as the percentage of waste increased. The exception was the mortar MGA 30% which presented an increase in apparent density in the hardened state, resulting in higher values of mechanical strength than all of the other tested mortars.

- ***Results of the determinations on the studied mortars, in the hardened state***

As observed in Figure 22, the flexural strength results were consistent with the literature. However, for a 15% glass replacement, Malek et al. [40] obtained higher results by over 100%, by utilizing glass waste as fine aggregates. Tan and Du [18] also obtained higher results in the case of white and green glass aggregate replacement, by 40.11% and 38.35%, respectively. Noticeably, there has been no significant different in their study between the flexural strength of glass aggregate mortars with white and green glass, signifying that the color of the glass might not have a considerable impact on flexural strength increase.

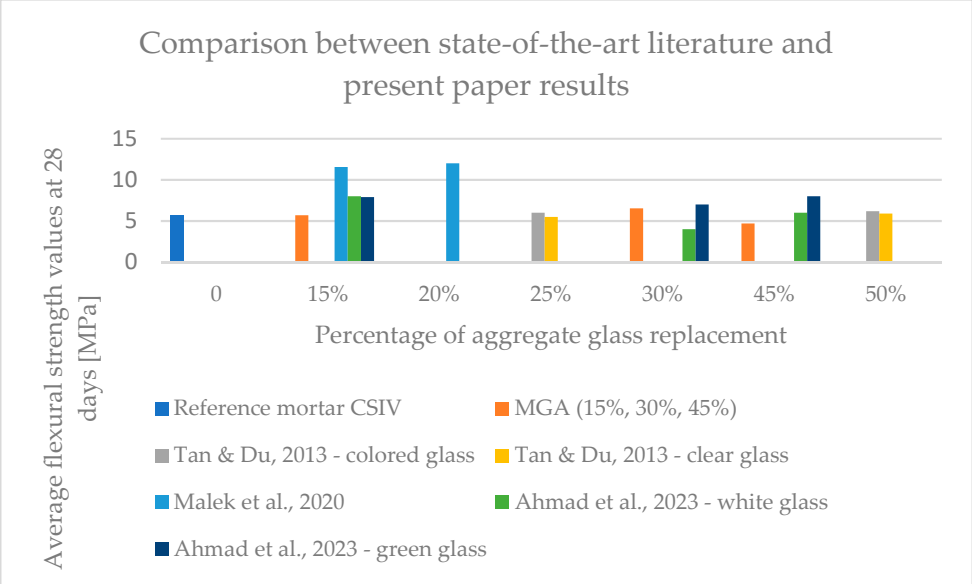


Figure 22. Average flexural strength values at 28 days, according to the percentage of glass replacement [18,40,42].

For a 30% glass replacement, the results of Ahmad et al. [42] were 38.74% lower for white glass and 7.20% higher for green glass. This is also the case for a replacement of 45% with glass aggregates. Ahmad et al. obtained results 27.66% higher than MGA 45% with white glass and 70.21% higher with green glass. This may be an indication that using green glass in plastering mortars can influence mechanical resistance positively, even as the percentage of replacement increases.

As observed in Figure 23, for a replacement percentage of 15%, the compression strength results obtained by Ahmad et al. for white and green glass are 11.21% lower and 6.98% lower, respectively. For a percentage of replacement of 30%, the same studies obtained compression strength values lower by 28.65% and 24.99% in the case of white and green glass, respectively. The results obtained by Chen et al. at a replacement level of 30% were higher by 41.93%. At 45% replacement, the results obtained by Ahmad et al. for white glass were 21.57% lower and 1.96% lower for and green glass. This indicates that using clear and colored glass, in the case of the mortars in the present study, and green glass, in the case of Ahmad et al., could lead to obtaining similar compressive strength results. This may be consistent with the studies indicating that using either green glass or clear glass might inhibit the occurrence of alkali–silica reactions [18,20]. As seen in all cases, the

study of Malek et al. [42] obtained higher results than all the others, signaling that the use of fine glass aggregates leads to an increase in mechanical properties. This can partly be attributed to the pozzolanic properties of glass powder particles smaller than 45 or even 100 µm [26,43], which cause a reaction between the amorphous components, such as silica glass powder, and the portlandite, producing silicates comparable to those produced by cement hydration.

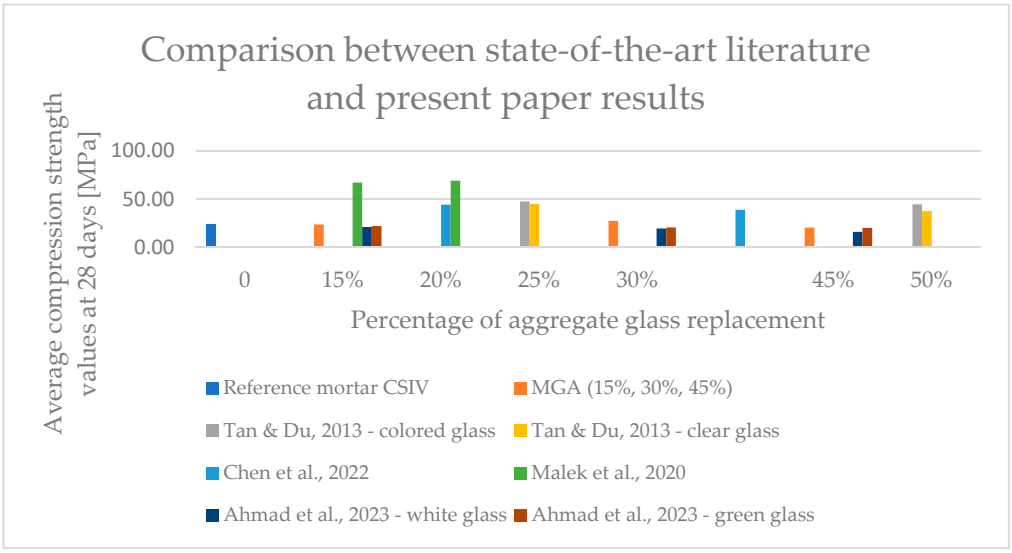


Figure 23. Comparison between state-of-the-art literature and present paper results of average compressive strength values at 28 days, according to the percentage of glass replacement [18,37,40,42].

As observed in the SEM analyses, there is a good incorporation of the glass waste aggregate with the cement paste, in the case of the MGA 30% mortar. This observation is correlated with the low dilatation of the cement paste. As seen in the mechanical strength results, an increase in glass waste replacement led to a decrease in the strength of the bonding comparted to the 30% replacement, due to the smoother surface of glass. This is also consistent with the findings of Chen et al. [37], where the mortar with 20% glass replacement exhibited improvements in compressive strength.

The conclusion is that replacing aggregates by 45% or more with glass waste in plastering mortars negatively affects their mechanical strength, due to the larger proportion of glass aggregates, which reduces the potential reaction of elements. The progressive strength increase in plastering mortars is achieved by the profound hydration through the absorption of water during the aging process. Since the glass particles do not retain water, the profound hydration processes are hindered as the aging process continues. At a 15–30% replacement, the impact of this phenomenon is experienced positively on the mortar, as glass particles act also as a filler between the aggregates and the cement, increasing the compactness of the material.

5. Conclusions

This article's main objective is to apply the concept of sustainable development, in order to reduce the natural resources consumption in the production of building materials, especially plastering mortars, by reusing the CDW waste (glass waste) as a partial replacement for aggregates, in order not to negatively influence the physical–mechanical properties of the proposed mortars.

This study proposes three plastering mortar recipes with locally sourced glass waste (0–4 mm). The goal was to verify whether the physical–mechanical performance values of the mortars would be improved by using various colored, coarsely grinded, locally sourced glass waste and what would be the optimal aggregate replacement percentage.

The applied research is transferred to the area of foundational research, with SEM and EDX investigations having the role of explaining the values obtained for the physical–mechanical characteristics of mortars made with glass waste, compared to the reference mortar.

The following conclusions can be drawn:

- All results obtained from determinations fell within the limits of the norms;
- The mortar MGA 30% had the highest apparent density compared to all the tested recipes. All glass mortars had lower consistency than CS IV; therefore, the glass replacement lowered the workability of the mortars. The mortars with glass contents, MGA 15% and MGA 30%, had higher segregation tendency than CS IV, due to the tendency of the glass particles of settling on the base. The mortar with the highest glass content, MGA 45%, had a similar segregation tendency as CS IV;
- A 15% glass replacement of aggregates resulted in no significant improvement of physical–mechanical characteristics compared to the reference CS IV mortar. The MGA30 mortar with 30% glass replacement showed significant improvement compared to the CS IV mortar, with higher flexural strength as well as compression strength;
- With the SEM/EDX analyses, the interface between the waste glass aggregates and the mortar was observed, and the influence of increasing the glass quantity was noticed;
- The MGA 15% mortar also obtained some improvements compared to the reference mortar, but overall, the percentage of aggregate replacement should be higher than 15%, in order for significant improvements to occur;
- The MGA 45% mortar obtained the lowest results, signaling that this percentage of glass replacement of natural aggregates, in the proposed recipes, did not obtain improvements in comparison to the CS IV reference mortar. Further investigation is planned to study which is the highest percentage of glass aggregate replacement, between 30% and 45%, for which the performance characteristics remain significantly higher than CS IV;
- Adhesion to the substrate was highest in the case of CS IV. This could partly be attributed to the smooth surface of the glass, preventing it to be as adherent as natural aggregates, and to the hardness of the brick substrate. Further investigations will be performed to improve these characteristics;
- Adhesive strength results for the glass waste mortars have been lower than 0.1 MPa, which suggests that a measurement error may have occurred. It can indicate that the contact between the plaster and the brick was damaged accidentally while testing the samples. The determinations have been realized according to the standards, with the same device and in the same conditions, thus future research may be required.

The most performant mortar was MGA30, with 30% aggregate replacement with locally sourced clear and colored glass waste, which registered higher mechanical strength values than the reference mortar CS IV. MGA15 with 15% replacement had similar mechanical strength values as the CS IV. The only mechanical determination where all MGA mortars performed inferiorly to the CS IV was adhesion to the substrate. This can be improved by adding additives, for the accumulated benefit of supporting a more circular economy in construction and demolition waste management and new material creation.

6. Further Research

Further research directions will be to continue experimenting with different replacement percentages between 15% and 30%, with statistical modeling to predict mechanical properties of the mortar, in order to have a more exact indication of what is the maximum replacement of aggregates with glass waste for improved performance. Observing the glass before using it in the glass aggregate mortars will also be a further study. Adjusting the recipes by adding additives to increase workability and adhesion to the substrate will also constitute future research. Observing the existence of alkali–silica reactions and their

impact on the performance of the new mortars will also be performed. Further studies on the durability of the mortars and the effects of aging will also be performed.

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