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Recycling Plaster Waste as a Substitute for Aggregates in Obtaining Plastering Mortars

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Abstract: The current context regarding the management of waste obtained from the construction industry, according to European Union laws and directives, requires the imposition of an integrated waste management system. The main objective of this study was to integrate and reuse old plaster waste as a substitute for aggregates in significant proportions in mortar composition and analyzing the impact on the physical and mechanical characteristics of mortar in fresh state and in hardened state. Over periods of 7, 14, and 28 days, the experimental program studied three types of plastering mortars: a standard recipe (without waste) and another two proposed recipes, in which construction waste was re-used as a substitute for aggregates in proportions of 10% and 15%. Results obtained on the fresh properties of the proposed plastering mortars (apparent density, consistency, and segregation trend) indicated a variation (increase/decrease) of 1% to 2.5% compared with the standard recipe. Mechanical strengths showed decreased values; that is, the compressive strength decreased by 11.09% and the flexural strength decreased by 22% when waste replaced aggregates in a proportion of 15%. The results of the experimental program identified the potential of waste plaster, which can replace up to 15% of the aggregates in plaster mortars, which still guarantees their successful use in practice. To reduce the influence of the use of waste on the mechanical strengths, we propose to conduct further investigations (nuclear magnetic resonance, electronic microscopy, and X-ray diffraction) on these mortars reinforced with different types of fibers. The large amount of waste resulting from the rehabilitation of damaged building facades and the fact that there are currently no experimental studies on the reuse of waste from old plaster mortars were the main reasons for the present study examining the possibility of their use in the production of new building materials.

Keywords: sustainable development; construction wastes; cement; plastering mortars

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1. Introduction

The concept of sustainable development has emerged since the early 1970s due to pollution and deterioration of the environment. Thus, the foundations were laid for a short, medium, and long-term strategy to diminish the negative effects of economic development in all areas on the ecological limits of the environment and on the planet's resources. The construction sector is the sector with the largest share worldwide (40%) in waste generation, resource consumption, and carbon emissions generation, which is why up to the current period, numerous research studies have been carried out aiming to achieve the recycling of these wastes by including them in different percentages in the masses of construction materials, and for this reason, it is also very important that this research should continue on all levels to find viable solutions in the future [1,2].

Reusable waste is abundant and can be sourced from various fields, including the following: wheat straw, ash obtained from the burning of rice husks, bamboo leaves, straw, banana leaves, oyster shells, natural sisal fiber, latex paint, demolition concrete, polystyrene granules, plastic granules (PET), corn cobs, sunflower stem, glass, marble dust, sheep wool, sawdust, coconut core, cork granules, brick pieces, silica ash, marble and granite waste, silica ash, and coarse/fine aggregates, etc.

As for methods of reusing construction waste, the current research emphasizes its reuse in the composition of concrete and mortars, either as a substitute for aggregates (sand and gravel) in proportions from 0% to 100%, or as a substitute for cement in various proportions [3–12].

Nedeljković et al. [3] analyzed the replacement of fine natural aggregates with 100% fine recycled aggregates, showing a decrease in elastic modulus of 17%; in terms of mechanical resistance, the compressive strength decreased by 50%; and tensile strength decreased by up to 33% compared to standard concretes, explained by the fact that the water-cement ration was increased in the concrete mixtures to achieve the workability of standard concrete made with natural sand. Zega et al. [4] studied the mechanical properties (compressive strength, static modulus of elasticity, and drying shrinkage) in the durability of absorption, sorptivity, water penetration under pressure, and carbonation of a concrete in which the aggregates were replaced in percentages of 0%, 20%, and 30%, indicating a behavior conforming to the limits mentioned in the international codes for structural concrete. Increasing the amount of waste introduced in the composition of concrete as a substitute for aggregates leads to an increase in porosity, and thus to a reduction in the apparent density of concrete due to the low density of recycled waste, as shown by Agrela et al. [7].

All research conducted on concrete with recycled aggregates indicates a decrease in mechanical strength (up to 50%) as the percentage of waste increases at 28 days, especially in concrete where recycled coarse aggregates exceed 30%, according to Patra et al. and Bao et al. [8,9]. Gombosuren C. et al. [10] studied the increase in concrete properties (mechanical strength, shrinkage and creep, and durability) caused by CO_2 treatment of recycled fine aggregates, observing that the reduction in mechanical strength was lower in concrete with treated recycled aggregates compared to untreated ones. The results also showed a reduction in water absorption by recycled coarse aggregates, leading to an increase in density. In terms of durability, the shrinkage performance of the concrete studied did not differ [10].

Figures 1 and 2 present the results on the mechanical characteristics of concrete and mortars prepared with several types of wastes, where wastes replaced the aggregates in different proportions in the composition.

The results used in the comparisons shown in Figures 1 and 2 regarding the compressive and tensile strengths were extracted from the studied and analyzed research according to the reference list.

Tam V. analyzed the long-term deformation behavior in drying and shrinkage and creep by changing the replacement ratios of water to cement and aggregate to cement ration, observing that the results were inconclusive for the prediction, and drying shrinkage and creep increased with increasing recycled aggregates replacement ratios [11].

Using recycled coarse aggregates in the composition of concrete as a replacement for aggregates or cement affects the characteristics in both the fresh and hardened states of concrete as their proportion increases in the composition, as presented by Wang et al. [12].

Malindu et al. studied the feasibility of using waste from plastic cups with ground coffee residue as sand replacement, and the results indicated that sand replacement up to 10% in concrete can reduce its environmental impact, reducing gas emissions by 10.74% [5].

Another approach to reducing the consumption of natural aggregates in the composition of concrete could be the replacement of aggregates with waste glass, based on the idea that it has a composition very similar to aggregates (SiO_2), and studies carried out on such concrete show that a 10% replacement of aggregates does not affect either mechanical or fire resistance compared to the values mentioned in the standards in force [6].

Given the fact that global cement production is one of the main polluters of the environment through the release of greenhouse gases and dust or particulate matter, there are numerous studies on the replacement of cement with different additives in concrete and mortars to reduce the effects and at the same time to improve the characteristics of concrete/mortars. The studies show that when different types of fly ash or ash obtained by burning different agricultural wastes (bamboo leaves, wheat straw, corn cobs) were used as replacements for cement in proportions up to 20%, the compressive strength and the tensile strength was increased [6,13,14].

In terms of mortars, the research programs also studied the possibility of reusing wastes as replacements for aggregates or cement. Mora-Ortiz et al. study the physical-mechanical characteristics of masonry mortars in which natural aggregates have been replaced in different percentages (maximum 60%) with fine recycled aggregates, noticing that both the apparent density and the strengths to bending, compression and adhesion to the support layer have an almost linear decreasing tendency of the values with increasing percentage of fine recycled aggregates in the mortar composition [15].

Kajanan et al. analyzed the possibility of using open burnt rice husk ash as a replacement for river sand in mortar, and the results showed that with 30% of the sand replaced, the thermal conductivity of the mortar was lower by 62%, and in terms of mechanical strengths, the values obtained were within the standard recommended range [16,17].

Other studies examined the properties of mortars made with aggregates from marble and granite waste. The samples made with these wastes had a better bond between admixtures, cement, and aggregates. The results of these studies show that these wastes can be used as aggregates and can improve the mechanical properties and workability of these waste mortars [18,19].

The use of recycled aggregate powder, fine glass powder, brick powder in the composition of mortars as a cement substitute in proportions of 20–30% is another approach to reducing construction waste and obtaining new building materials. Research conducted on cement paste containing fine powder obtained by grinding concrete reduces the hydration process of cement [20–23].

Over time, various types of mortars have been developed, such as high-performance mortars used to produce ferrocement, in which cement is successfully replaced in the proportion of 9–10% with silica ash powder and metakaolin, leading to increased mechanical strength and modulus of elasticity [24].

Another application on waste reuse was the proposal of an autoclaved mortar, in which the effect of wheat straw ash on mechanical properties was investigated [25].

Another study showed that the use of glass nano powder waste in the composition of alkali-activated mortars as a replacement for blast furnace slag leads to increased mechanical strength and durability of mortars [26].

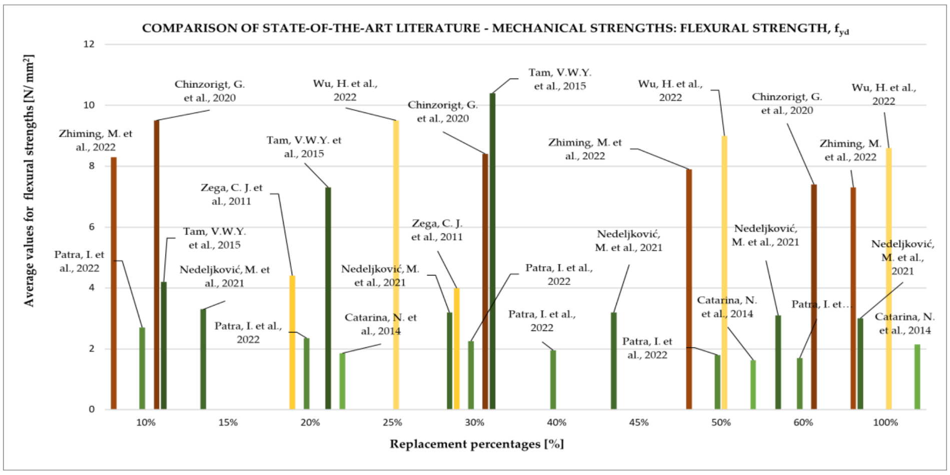

Figure 1. Comparative analysis of bending strengths according to the studies reviewed [3,4,9–11,15,16,20,27].

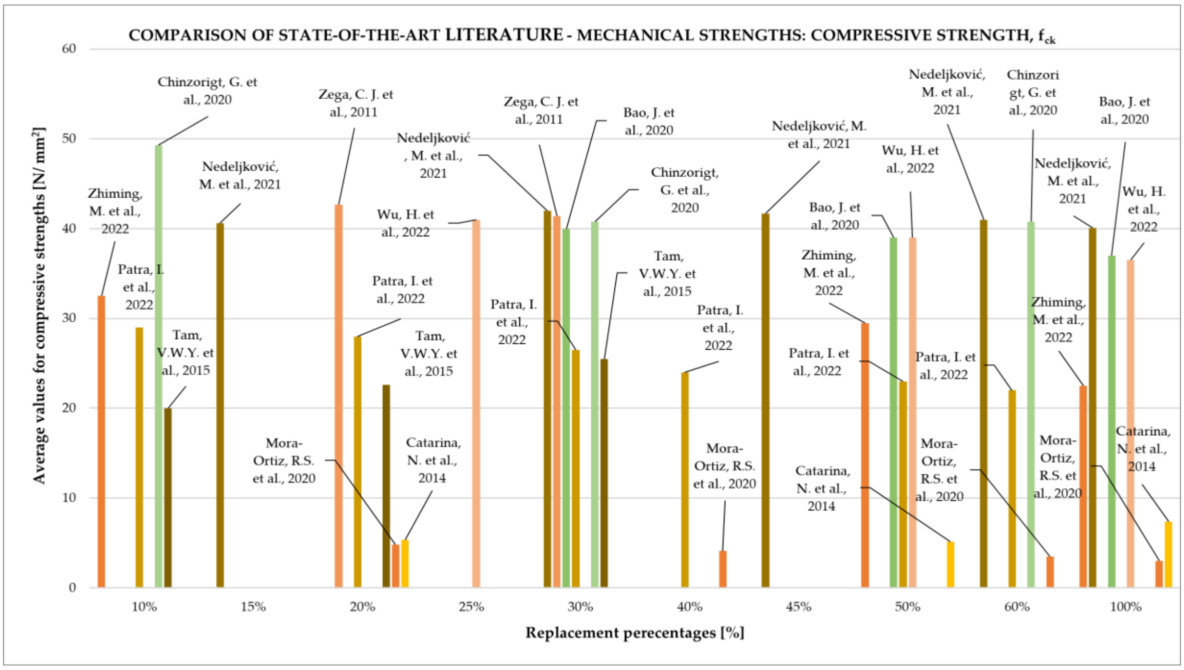

Figure 2. Comparative analysis of compressive strengths according to the studies reviewed [3,4,8–11,15,16,20,27].

Regarding the replacement of aggregates in mortars, the author Neno C. proposed the reuse of recycled aggregates from concrete, in which the aggregates were replaced in percentages of 20%, 50% and 100%, respectively. The results obtained indicated that the physical–mechanical characteristics were not affected when the percentage of aggregate was 20%, except for the adhesion to the support layer [27].

Another application of the use of construction waste is to make alkali activated or geopolymer concrete. Studies carried out on this type of concrete show that it can be used as an aggregate, although it leads to a slight reduction in mechanical strength in comparison with cement-based concrete [28].

Research Significance

The interest of specialists in reusing waste in the construction field by substituting raw materials from traditional materials, generally aggregates and/or cement, was the point of interest in the research of this article. The large amount of waste resulting from the rehabilitation of facades (plaster mortars) has been of little concern among researchers so far, which is why we propose replacing the aggregates in a higher percentage; we consider this to be a relevant idea for which an experimental program is worth conducting and the results disseminated.

Following the study of the above articles, three important general aspects were observed:

- the fact that although waste was used in various proportions both as a cement substitute and as aggregates, the chemical and physical–mechanical properties analyzed met the conditions of the norms in force;
- the fact that there is a vast diversity of ways to reuse waste in the composition of building materials, and that this diversity can still be exploited to help protect the environment and the resources of the planet;
- the fact that there is still a global trend in the development of new waste-based products, and in this context the present paper presents new approaches to the reuse of construction waste.

The main gaps that were identified in these studies are: decreased mechanical strengths because of adhered old cement and excessive water absorption, high porosity of samples, low density, low workability, increased carbonation depth, high chloride ion penetration, increased drying shrinkage and creep, and reduced elasticity modulus. Besides the research on replacing natural aggregates, also presented were other types of new and innovative mortars and concretes, where waste such as ashes [13,14,23], brick powder [22,27,28] with superplasticizers in some cases, and marble dust [18,19], etc., were used to replace the fine components of the samples, and as a result, different properties, such as mechanical strengths, water absorption, density, and porosity, etc., were improved.

Based on the information from the reviewed literature, the current study aimed to find a feasible type of mix for plastering mortars, where appropriate replacement of natural aggregates with old plaster mortars could be achieved so that the regulations from the norms in force were still met. Among the usual strengths presented in the literature, another analyzed characteristic was the strength of adhesion to the support layer, which was studied in only a few articles, and since we refer to plaster mortars, we consider that this feature is also worth treating with great care.

The novelty and the purpose of the study was finding the proper approach to the replacement of both fine and coarse aggregates with old plastering mortars in a proportion as high as possible and improving the weakened properties with the methods presented in the state-of-the-art literature.

2. Materials and Methods

Waste from plaster mortars of old buildings is becoming an increasingly acute problem in the context of the necessary rehabilitations that are required of these buildings. In the case of the more frequent facade rehabilitation works in recent years, this type of waste can represent from 10% to 100% of the quantities generated in such an intervention. Due to their already well-defined composition (plaster mortars), these materials are an ideal source of raw material that can be reused in making new mortars both for ordinary buildings and for historical buildings. Thus, this type of waste is suitable for a thorough study, because its reuse can generate numerous environmental benefits.

All the materials used in the experimental program comply with the regulations in force [29–31].

2.1. Materials Used

Figure 3 represents the diagram of used materials in the current study to create a general view on the procedures and methodology followed.

- Cement

The cement used was Portland 52.5 R type, from Holcim ExtraDur 52, city of Alesd, Romania, which in its composition has clinker (80–94%), blast furnace slag (6–20%), and other auxiliary components (0–5%).

The cement used was kept in laboratory conditions and showed no degradation at the time of preparation of the samples, respecting the requirements of standard SR EN 196 [32]. In Table 1 are presented the physical and chemical characteristics of the cement used in the experimental program [33].

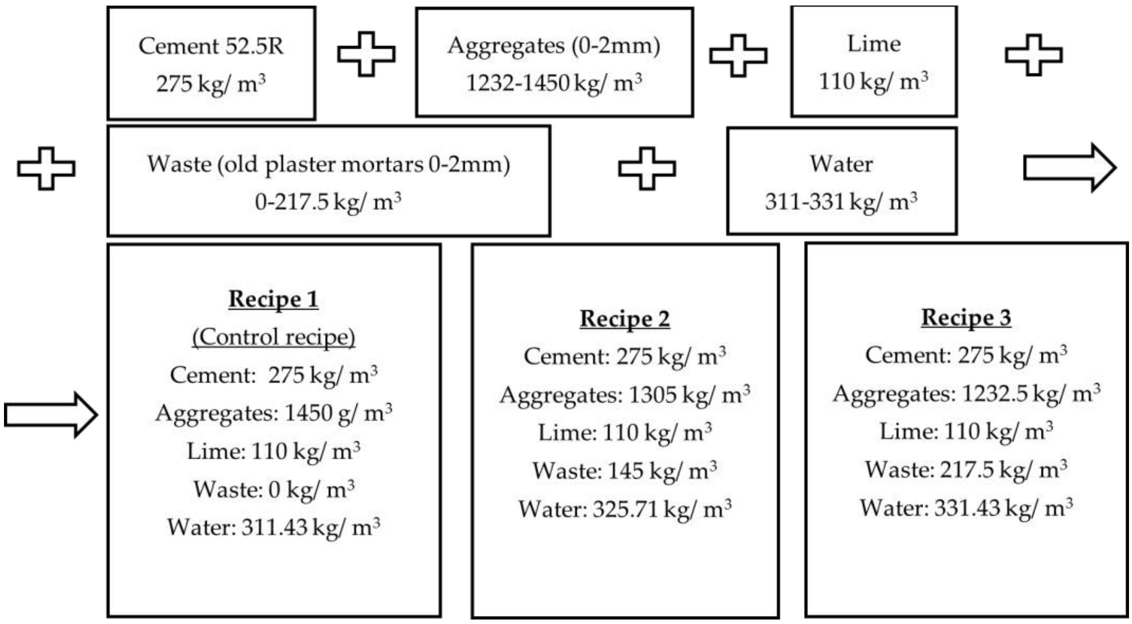

Figure 3. Graphic diagram of the materials used and the recipes.

Table 1. Essential characteristics and performance of cement.

Cement Characteristics	Cement Performance
Plug time [min.]	Min. 45
Stability (expansion) [mm]	Max. 10
Compressive strength (initial) [MPa]	Min. 30
Compressive strength (standard) [MPa]	Min. 52.5
Sulphates content (as SO3) [%]	Max. 4
Chloride content [%]	Max. 0.1
Hexavalent chromium content [%]	Max. 0.0002

- Aggregates

The aggregates used in the experimental program were river sand with dimensions between 0–2 mm, and for the preparation of samples, they were separated into 3 sorts. The amount of sand used was divided equally into each sort, as follows: (0–0.5) mm–483.33 kg/m^3, (0.5–1) mm–483.33 kg/m^3 and (1–2) mm–483.33 kg/m^3. The aggregates used in the experimental program were washed and cleared of impurities and dried until constant mass was achieved.

- Lime

The lime used was a calcic type hydrated for mortars and plasters, type Carmeuse Supercalco M, product made by Carmeuse Holding SRL, Brasov city, Romania.

The quantity of the lime used in the experimental program was the same for all the recipes tested.

Table 2 presents the physical–chemical characteristics according to the technical data sheet [34].

Table 2. Essential characteristics and performance of lime.

Characteristics of Lime	Lime Performances
$CaO + MgO$ [%]	Min. 80
Ca $(OH)_2$ available [%]	Min. 65
MgO [%]	Max. 5
CO_2 [%]	Max. 15
SO_3 [%]	Max. 2
Finesse—rest on 0.2 mm [%]	Max. 2
Finesse—rest on 0.09 mm [%]	Max. 7
Free water [%]	Max. 2
Apparent density [kg/dm^3]	0.3–0.6
Stability [mm]	Max. 20

- Waste from old plastering mortars

The waste used in the experimental program was waste from the rehabilitation works of a facade of a historic building in Cluj-Napoca, Romania, which involved the removal of all existing, degraded exterior plaster.

The old plaster waste was collected directly from the brick support layer of the facade to be rehabilitated. Subsequently, they were separated from other types of waste, and then sorted into different sorts, so that they could be used as substitutes for aggregates in plastering mortar recipes.

According to the project of the historical building from which the waste resulted, the initial exterior plastering mortars were made based on lime binder.

The sorting of waste was done within the testing laboratory of building materials at the Technical University of Cluj-Napoca, Faculty of Civil Engineering.

In Figure 4 can be observed the plastering mortar that was taken from the support layer. Under the experimental program, the waste used replaced the aggregates in percentages of 10% and 15% of each sort respectively, in the proposed mortars.

Figure 4. Plaster waste gathering from the brick support layer.

Figure 5 presents the façade that was to be rehabilitated by removal of the damaged plastering mortar in the first step. This is the place where all the waste was collected from.

Figure 5. Facade to be rehabilitated.

In Figure 6, it can be observed that the plastering mortar waste was shredded and then divided into 3 grain sizes, 0–0.5 mm, 0.5–1 mm, and 1–2 mm, to be used in the preparation of mortars by replacement of the aggregates in proportions of 10% and 15%, respectively.

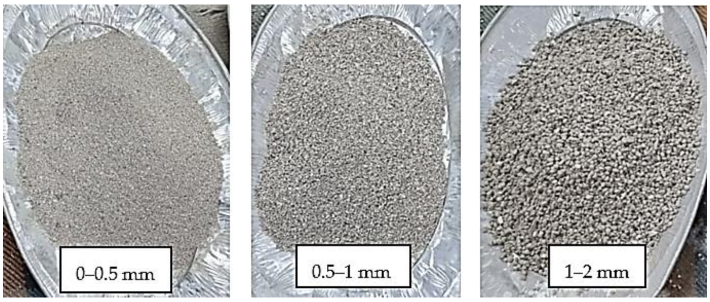

Figure 6. Plastering mortar waste divided into each grain size.

Due to the large amounts of waste, in this experimental study it was desired to create plastering mortars in which to use as large amounts of waste from old plasters as possible.

2.2. Studied Recipes

Currently, the research is in its early stages, with 3 types of mortars.

1. Recipe 1 CS III R.S.—cement-lime mortar type, with no waste added.
2. Recipe 2 CS III 10%—cement—lime mortar, in which only the aggregates are replaced in 10% from each type of grain size (0–0.5, 0.5–1 and 1–2 mm) with construction wastes according to Table 3.

Table 3. Mortar recipes for 1 m^3.

Recipe	Cement 52.5 R [kg]	Sand [kg]	Lime [kg]	Old Plastering Mortar Waste [kg]	Water [L]
1—CS III R.S.	275	1450	110	-	311.43
2—CS III 10%	275	1305	110	145	325.71
3—CS III 15%	275	1232.5	110	217.5	331.43

3. Recipe 3 CS III 15%—cement—lime mortar, in which only the aggregates are replaced in 15% from each type of grain size (0–0.5, 0.5–1 and 1–2 mm) with construction wastes according to Table 3.

2.3. Methods

The studied mortars (standard plastering mortars and plastering mortars with plastering mortar waste) were prepared and tested according to the standards in force, that is, dividing the aggregates into the required dimensions (0–0.5, 0.5–1, 1–2 mm), weighing the materials used (cement, lime, aggregates, water), and mixing them in automatic mortar mixer. After the homogenization process, the plastering mortar samples were studied in fresh state and hardened state by being introduced into the standard prisms (40 × 40 × 160 mm). For a better compaction, the prisms were placed on the vibrating table and kept in a humid room until the testing of the mechanical strength at the different ages of 7, 14, and 28 days.

For a better understanding of the procedures used in analyzing the samples of the mortars, Table 4 shows the characteristics to be studied.

Table 4. Analyzed characteristics of fresh and hardened state mortars.

Type of Mortars	Analyzed Characteristic	Testing Time
Fresh mortar characteristics	Apparent density Consistency Segregation tendency	Immediately after preparation
Hardened mortars characteristics	Apparent density Compressive strength Flexural strength	7, 14, 28 days
	Adhesion to the support layer	28 days

Adhesion to the support layer strength could be one of the characteristics that should be analyzed more carefully by future researchers, especially when studying plaster mortars. Future controls to be considered to reduce the influence of waste on the mechanical strengths are nuclear magnetic resonance, electronic microscopy, and X-ray diffraction on these mortars, which could be also reinforced with several types of fibers.

2.3.1. Determination of Fresh Mortar Characteristics

- Apparent density

The apparent density of fresh mortars was determined by means of a cylindrical vessel of volume V = 1 L and the mass m_v to be filled with the obtained mortar mixture, and after proper compaction, the excess material was removed, and the jar filled with mortar weighed to obtain the mass m_m [35,36]. With these data, the apparent density can be calculated with the following formula [37]:

$$\rho_a = (m_m - m_v)/V \times 1000 \left[kg/m^3\right] \quad (1)$$

where:

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 consistency of the mortars was determined by means of the flow table (Figure 7).

Figure 7. Flow table apparatus.

As a principle of operation, this appliance is used to determine the consistency of mortars and lime used in construction. The model used is motorized and works by actuating the engine speed reducer by setting several automatic beats that stop at the end of the cycle [38–40].

In case of a spreading mass, the mortar sample was placed on the metal table by means of a tapered mold, which was easily removed so that the mortar maintains its shape. Then, the table is put into operation, which picks up the sample and lets it fall from a known height leading to the spread of the mortar. The determination was made by measuring the diameter of the mortar sample in 2 perpendicular directions, the final value being the arithmetic mean of the 2 values read.

- Segregation tendency of the mortars

The segregation tendency of the mortars is based on the difference between the consistency of the layer in the upper third of the vessel in which the determination is made and the consistency of the layer in the lower third. The determination was made in a vessel with a height of 30 cm, in which the properly compacted and vibrated mortar was inserted, after which the consistency determinations of the above 2 layers were made, respectively, calculating the segregation with the following formula [37–39]:

$$S = \pi/48 \times \left(C_s^3 - C_i^3\right) \left[cm^3\right] \quad (2)$$

where:

S—segregation tendency;
$C^3{}_s$—consistency of the layer in the upper third;
$C^3{}_i$—consistency of the layer in the lower third.

2.3.2. Determination of Hardened Mortar Characteristics

- Apparent density

The determination was conducted on 3 prisms 28 days after the casting of the samples. Density can be obtained by measuring the 3 sides, calculating the volume $V_{a,}$ and then calculating the apparent density ρa with the following formula [37,41,42]:

$$\rho_a = m_a/V_a \left[kg/m^3\right] \quad (3)$$

where:

ρ_a—apparent density;
m_a—mass of the sample;

V_a—volume of the sample.

- Bending strength

The determination was conducted on 3 halves of prisms of 40 × 40 × 160 mm (remaining after the bending strength determination) using the specific apparatus as shown in Figure 8 (left). The determinations were made at the ages of 7, 14, and 28 days. The formula used to calculate the strength was [37,43,44]:

$$f_{yd} = 3/2 \times F \times l/a^3 \left[N/mm^2\right] \quad (4)$$

where:

f_{yd}—bending strength;
F—force applied by the apparatus to break the prism;
l—distance between the bearings of the apparatus;
a—length of side of the prism.

- Compressive strength

The determination was conducted on 3 prisms of 40 × 40 × 160 mm at the hydraulic press perpendicular to the direction of casting, as shown in Figure 8 (right). The determinations were made at the ages of 7, 14, and 28 days. The formula used to calculate the strength was [25,43,44]:

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

where:

f_{ck}—compressive strength;
F—force applied by the apparatus to break the prism;
A—area of prism section.

Figure 8. Determination of bending (**left**) and compressive (**right**) strength.

- Adhesion to the support layer

The determination was made with the pull-off tester shown in Figure 9, and it began at the stage when the mortar was fresh. The mortar was placed on the future support layer (brick in this case) and was delimited with a ring on the entire thickness of the mortar, creating 2 spherical areas, after which, at 28 days, 2 circular metal plates were pasted onto the delimited areas, making the inner-ripping [45,46].

Figure 9. Apparatus for testing adhesion to the support layer.

As a principle of operation, this device is a dynamometer equipped with load cell and digital display. After proper bonding of the traction pills in the center of the surface of the test specimens (at the age of 28 days), the tensile force was applied manually and perpendicularly to the tested surfaces (without shocks and with uniform speed). The value obtained can be read on the screen.

Depending on the results of this determination, the breaking of the test specimens may be of 3 types:

- ○ An adhesive tear—on the surface between the mortar and the backing layer;
- ○ A cohesive tear 1—in the thickness of the mortar;
- ○ A cohesive tear 2—in the thickness of the support layer.

3. Results

The determination on the plastering mortars proposed was carried out both in a fresh state and in a hardened state at 7, 14, and 28 days after preparation to observe the impact of construction wastes on the characteristics of mortars.

3.1. Results of Determinations on Fresh Mortars

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

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 III R.S.	2083	195	20.09
CS III 10%	2058	197	17.72
CS III 15%	2056	200	15.07

- Apparent density

The lowest value of apparent density was obtained for the mortar in which the aggregates were replaced, as shown in Figure 10. All the tested mortars obtained values of apparent fresh densities above 2000 kg/m^3, falling within the values stipulated in the normative. The lowest apparent density value was obtained for the mortar in which 10% of natural aggregates had been replaced, followed by the CS III 15% mortar with an apparent density value higher by 1%. The highest apparent density value was obtained for standard mortar. This decrease in value was due to the addition of waste, which was lighter than the natural aggregates.

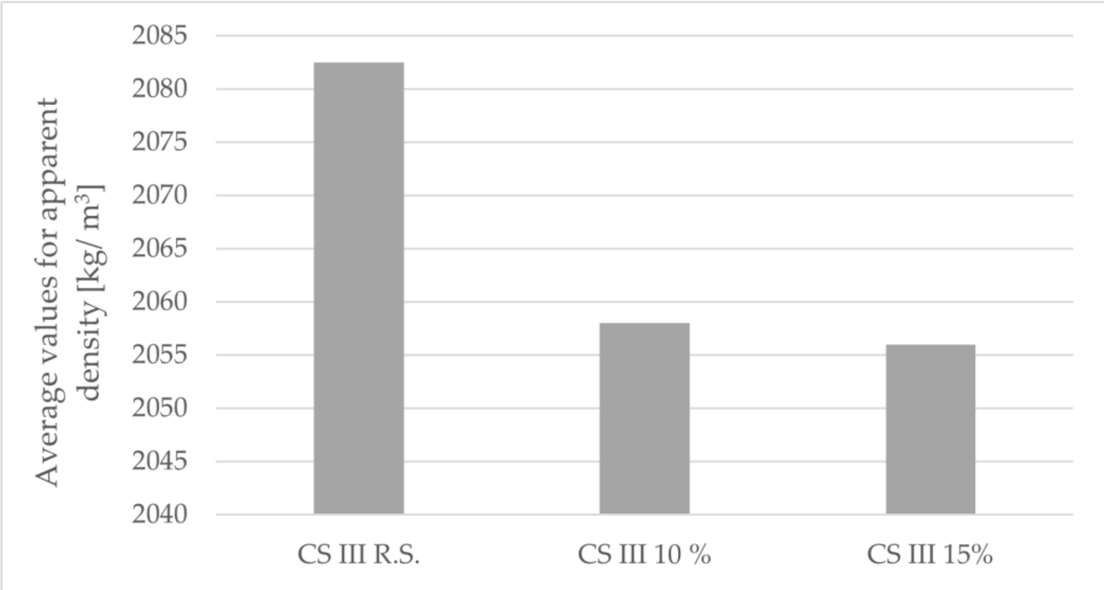

Figure 10. Apparent density depends on the percentage of dislocated aggregates.

In Figure 10 is presented the evolution of the apparent density of fresh mortars for all the 3 recipes studied.

- Consistency of mortars

Consistency values for the fresh mortars determined with the flow table apparatus are presented in Figure 11. For the CS III R.S. recipe, the lowest value was obtained, and compared to CS III 10% and CS III 15%, the results showed an increase of about 1% and 2%, respectively. The results indicate that with an increase in waste in the composition, the consistency also showed higher values, so the mortars were much more workable.

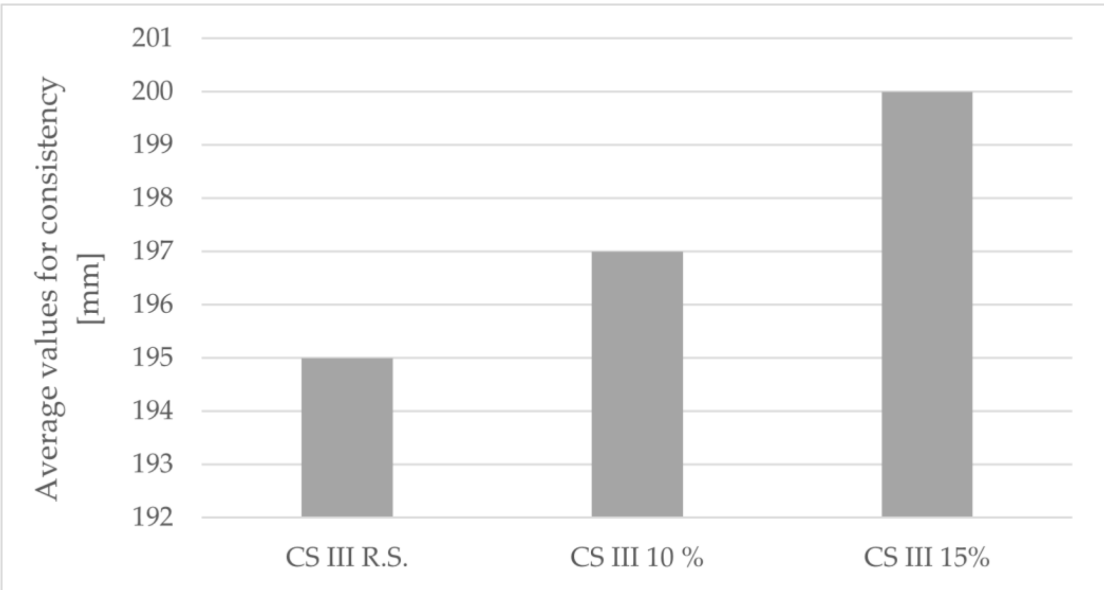

Figure 11. Mortars consistency depends on the percentage of dislocated aggregates.

Figure 12 shows the dimension of the sample of fresh mortar for the CS III R.S. recipe spread on the flow table apparatus.

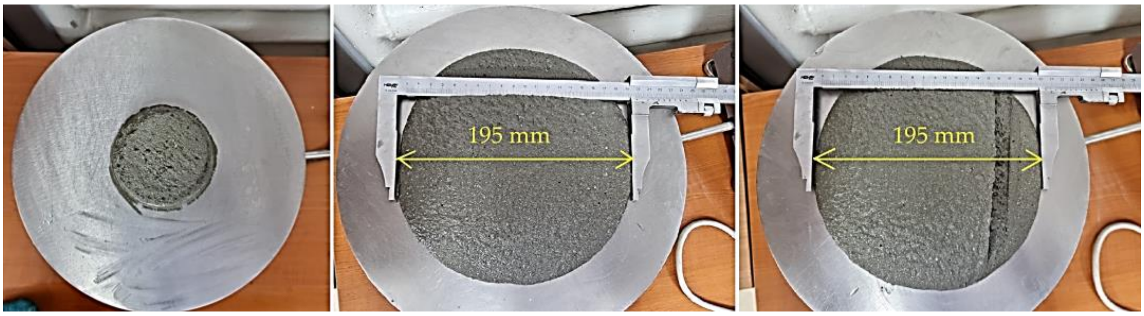

Figure 12. Determination of consistency with the flow table.

The same method to determine the consistency of the mortars was applied to the other two recipes, CS III 10%, and CS III 15%, and the values from Table 5 were obtained.

- Segregation tendency of mortars

The highest value was obtained for the first recipe, because standard aggregates are heavier than waste, which is why they tend to settle at the base of the material. However, all of them fall within the value stipulated in the norms in force as shown in Figure 13.

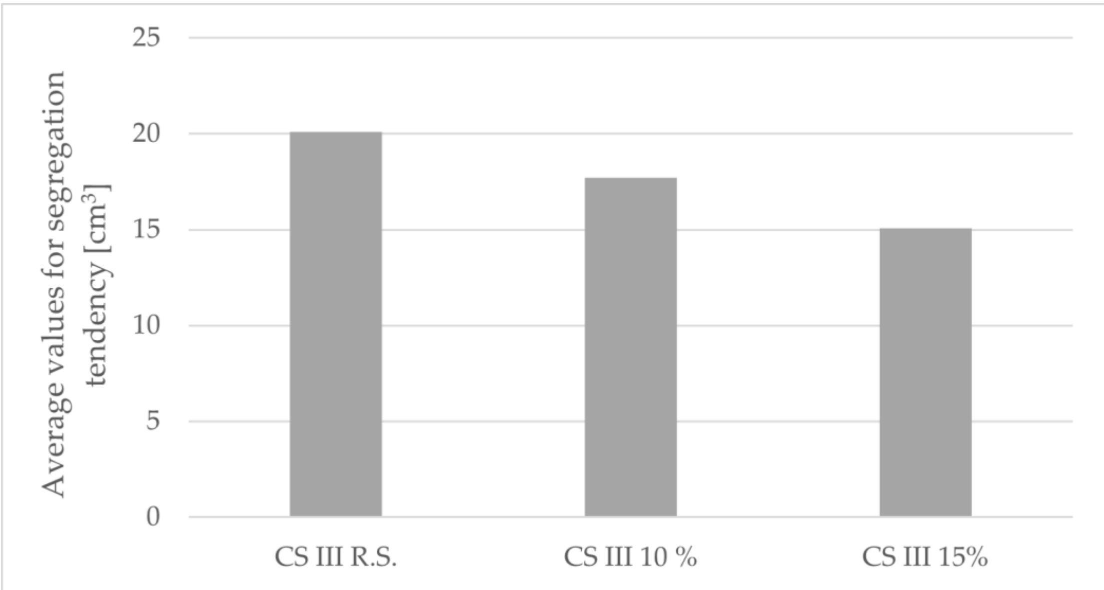

Figure 13. Segregation tendency depending on the percentage of dislocated aggregates.

The lowest value was obtained for CS III 15%, with a 25% decrease compared to CS III R.S., and a 12% decrease compared to CS III 10%. The recipe with 15% aggregates replaced with plastering mortar waste presented the best behavior in terms of the segregation tendency property.

3.2. Results of Determinations on Hardened Mortars at 7, 14, and 28 Days of Age

- Apparent density

Table 6 shows the values obtained for apparent density at the age of 7, 14 and 28 days for each recipe studied.

Table 6. Results for apparent density on hardened mortars.

Recipe	Apparent Density ρ_a [kg/m^3]		
	7 [Days]	14 [Days]	28 [Days]
CS III R.S.	1969.92	1957.03	1915.23
CS III 10%	2000.39	1921.88	1914.45
CS III 15%	2031.45	2002.34	1905.47

In Figure 14 are specified the following results by age:

- 7 days—at this age, the values decreased as waste was added by approximately 1.5% from one recipe to another;
- 14 days—the highest value at this age continued to be for CS III 15%, whereas an interesting value was obtained for CS III 10%, the lowest one; the differences between CS III R.S. and the other two recipes were 2% (lower) and 4% (higher) for CS III 10% and CS III 15%, respectively;
- 28 days—the values reversed at this age, as the highest value obtained was for CS III R.S., and the lowest one was for CS III 15%; the differences between the recipes were much lower this time, being under 1% in each case.

The results indicated that the mortars made with plastering mortar waste were lighter than the ones with no waste added. All the results were within the norms in force. Following the results obtained on the studied mortars it can be observed that the cement hydration process took place, and the hardening process of the mortars was not significantly influenced by the addition of waste in the proposed mortar recipes at the age of 28 days, because of the evaporation of the water. Equivalent results with a slight decrease in the value of apparent density were obtained by Wang B. [12] or Agrela F. [7] when replacing the natural aggregates with recycled aggregates/recycled concrete aggregates. This decrease in value appeared due to the lower weight of the waste compared to the natural aggregates.

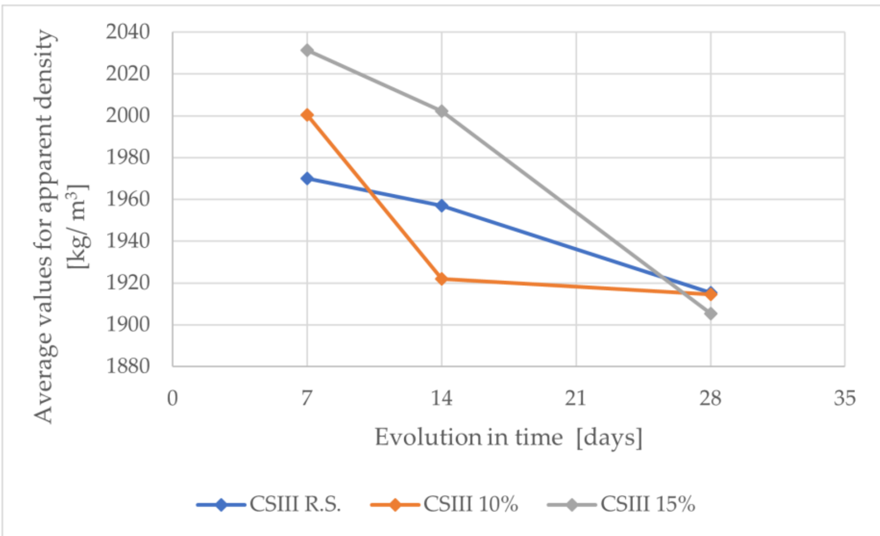

Figure 14. Apparent density in the hardened state.

- Bending strength

To observe as objectively as possible the performance of the proposed and studied mortars, taking into consideration the fact that in their composition were introduced plastering mortar wastes resulting from rehabilitation works on the facades of historical buildings, the experimental program involved the monitoring of the physical–mechanical properties of the mortars over time at 7, 14, and 28 days.

Table 7 shows the values obtained for the bending strength at the age of 7, 14, and 28 days for each recipe studied.

Table 7. Results for bending strength on hardened mortars.

Recipe	Bending Strength [N/mm^2]		
	7 [Days]	14 [Days]	28 [Days]
CS III R.S.	4.60	4.62	4.51
CS III 10%	2.55	3.23	3.94
CS III 15%	2.30	2.88	3.49

In Figure 15 is specified the following results by age:

- 7 days—at this age, the values decreased as waste was added by approximately 48% for CS III 10% and 45% for CS III 15% compared with CS III R.S.;
- 14 days—the highest value at this age continued to be for CS III R.S. and the lowest value obtained was for CS III 15%; the differences between CS III R.S. and the other two recipes were 30% (CS III 10%) and 38% (CS III 15%);
- 28 days—the order of the values remained the same as the highest value obtained was for CS III R.S. and the lowest one was for CS III 10%; it can be observed that the difference between the values became smaller with aging, so that there was a 22% and 18% difference between the standard sample and CS III 10% and CS III 15%, respectively.

The replacement of natural aggregates with old plastering mortar led to lower values for bending strength. Equivalent results were obtained in most of the studies when waste replaced aggregates [3,4,6,9,16], etc. This problem appears to be due to the excessive water absorption, high porosity, and lower restraining capacity of recycled aggregates and the mixture of the microstructures of new and reused materials.

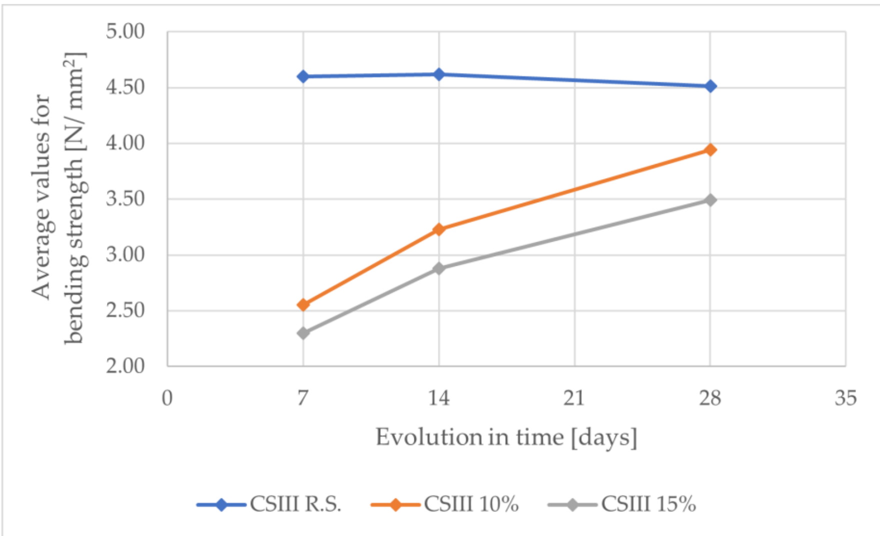

Figure 15. Bending strength results.

- Compressive strength

Table 8 shows the values obtained for compressive strength at the ages of 7, 14, and 28 days for each recipe studied.

Table 8. Results for compressive strength on hardened mortars.

Recipe	Compressive Strength [N/mm^2]		
	7 [Days]	14 [Days]	28 [Days]
CS III R.S.	12.57	13.30	15.05
CS III 10%	11.35	13.20	13.66
CS III 15%	9.88	12.19	13.38

In Figure 16 are specified the following results by age:

- 7 days—at this age, the values decreased as waste was added by approximately 10% for CS III 10% and 14% for CS III 15% compared with CS III R.S.;
- 14 days—the highest value at this age continued to be for CS III R.S., and the lowest value obtained was for CS III 15%; the differences between CS III R.S. and CS III 10% was small, under 1%, whereas compared to CS III 15% the difference was approximately 8%;
- 28 days—the order of the values remained the same, as the highest value obtained was for CS III R.S., and the lowest one was for CS III 15%; it can be observed that the values of the samples with wastes became closer and both were lower than CS III R.S. at 10%–11%.

The same decrease in values was noted for the compressive strength as for the bending strength, for the same reasons as the ones mentioned above. Generally, adding waste (recycled aggregates/concrete aggregates) to a mortar/concrete mix leads to a decrease in mechanical strengths, as presented in the state-of-the-art literature [3,4,6,9,16], but one of most important aspects was the proportion of replacement, which led to obtaining samples that have test results that meet the conditions stipulated in the norms in force. At the age of 28 days, all the tested samples in this study met the values stipulated in the regulations.

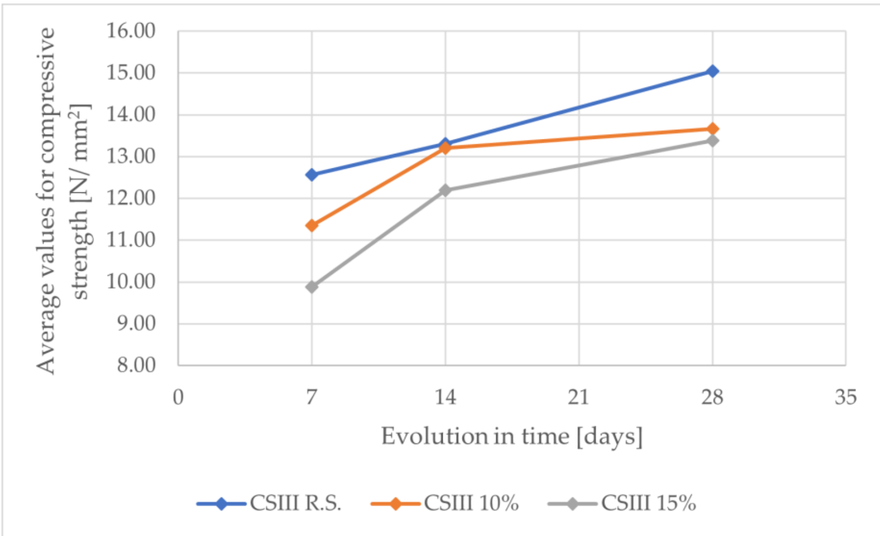

Figure 16. Compressive strength results.

According to SR EN 1015, the minimum average value was 4.5–7 N/mm^2, and by analyzing the results, the compressive strength was higher even from the 7th day for all the samples studied, and continued to attain higher values until the 28th day, when the mortars with plastering mortar wastes attained 13.38–13.66 N/mm^2, which was almost 1.95 times higher. These results are encouraging for the development of new mortars in which waste could replace natural aggregates in higher percentages.

- Adhesion to the support layer

Table 9 shows the values obtained for the adhesion to the support layer at the age of 28 days for each recipe studied.

Table 9. Results for adhesion to the support layer on hardened mortars.

Recipe	Adhesion to the Support Layer [N/mm^2]
CS III R.S.	19
CS III 10%	11
CS III 15%	3.5

The adhesion to the support layer was determined at the age of 28 days, and as shown in Figure 17, it decreased with the increase in the percentage of wastes by about 42% for CS III 10% and 80% for CS III 15% compared to CS III R.S.

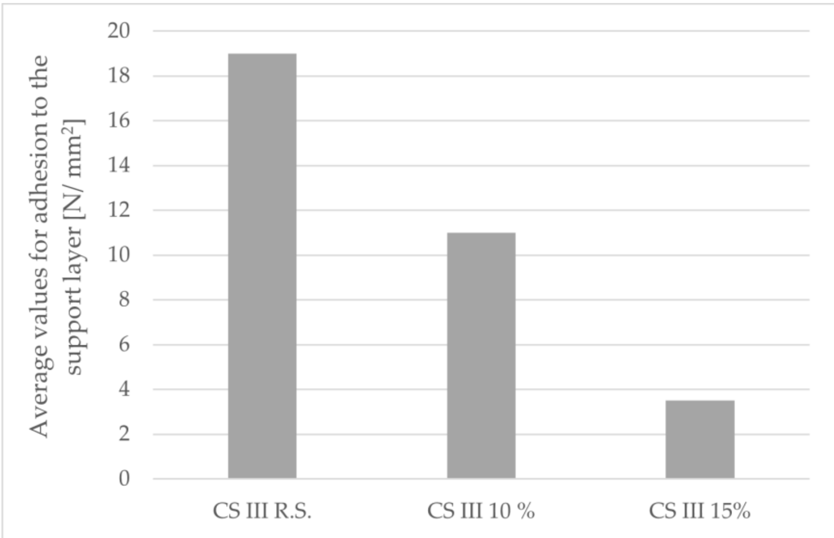

Figure 17. Results obtained for adhesion to the support layer.

In each case of determination, the breaking in the test samples was in the thickness of the mortar, and in addition, this was a cohesive tear for every recipe studied.

4. Discussion

At this moment, the quantities of construction and demolition waste generate real problems in terms of their proper storage. In Romania, their management is at an early stage, and there are currently few centers for collecting construction and demolition waste; therefore, their improper storage will lead to a negative impact both on the environment and on population health.

There are currently numerous studies analyzing this topic and trying to find solutions for the reuse of construction waste. One of the possible uses is to make new building materials by re-using these wastes as recycled aggregates in concrete and mortars, which would reduce the use of natural resources.

The use of these wastes has advantages. One is the reduction in the quantities of raw materials used, thus according with environmental sustainability; one is reducing the quantities of waste generated by their reuse in the composition of mortars; another is the reduction in air and environmental pollution due to fine particles scattered by the wind, which occurs when waste is not stored properly; and a further advantage is the reduction in problems related to the generation of hydrogen sulfide (toxic and smelly gas) that comes from demolition waste There are also disadvantages, such as additional costs in terms of recycling materials, and the need for specific technology and qualified personnel to achieve the correct recycling.

This article proposes the reuse of plastering mortars of old buildings as substitutes for aggregates in plaster mortar recipes. The results obtained for the three types of the studied mortars show that mechanical strengths fall slightly as the percentage of natural aggregates is replaced with plaster waste. Additionally, due to the high water-absorption capacity and low density, the use of plaster waste can lead to a decrease in the workability of mortars. However, the average values of the results obtained are higher than those provided for in the European norms in force.

To highlight the physical–mechanical behavior of the proposed mortars over time, they were analyzed at different time intervals of 7, 14, and 28 days, and it was that the values of the mechanical strengths (tensile strength and compressive strength) increased over time.

As revealed by the literature review, many studies have been conducted, in which different components of the samples were either partially replaced of totally replaced (aggregates or cement), or the properties of mortars were improved by the addition of other chemical components.

Most results obtained showed a slight decrease in the values of mechanical strengths when waste was added. Results obtained for the studied samples tended to have lower values when compared with the ones in the literature, especially because of the presence of lime in the composition of mortars, and because in the prepared recipes, only raw materials and waste were used without the addition of any additives that could improve the weakened characteristics. This behavior can be observed in Figure 18 for compressive strength and in Figure 19 for flexural strength.

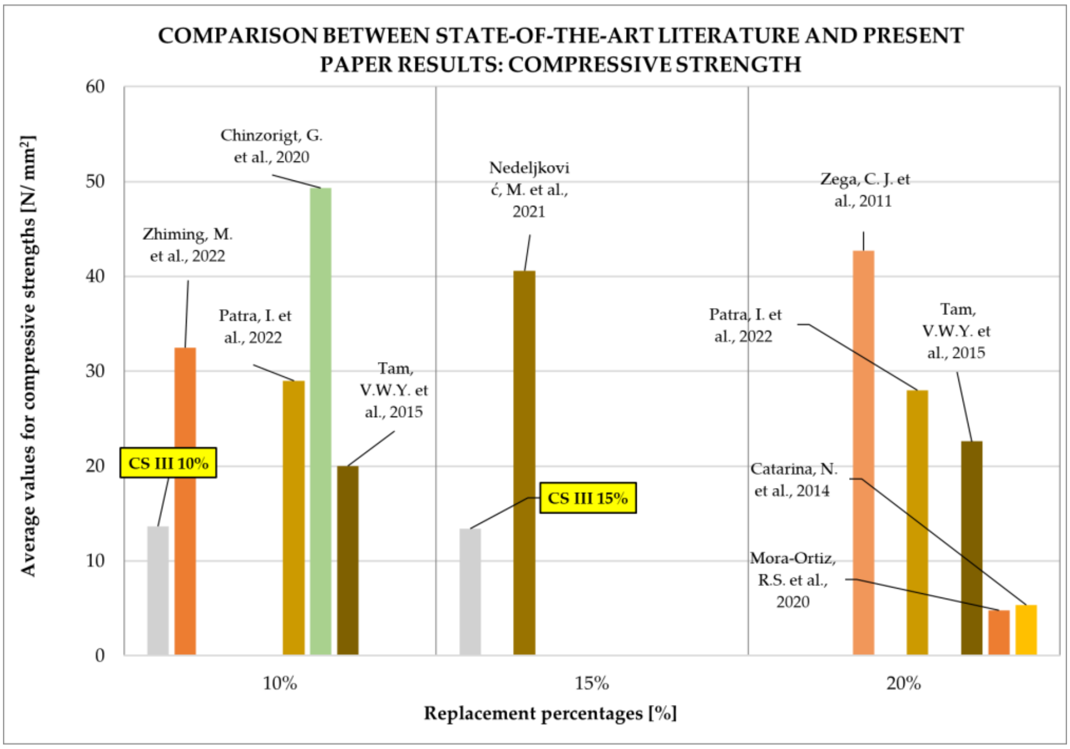

Figure 18. State-of-the-art and present research results for compressive strength [3,4,9–11,15,16,27].

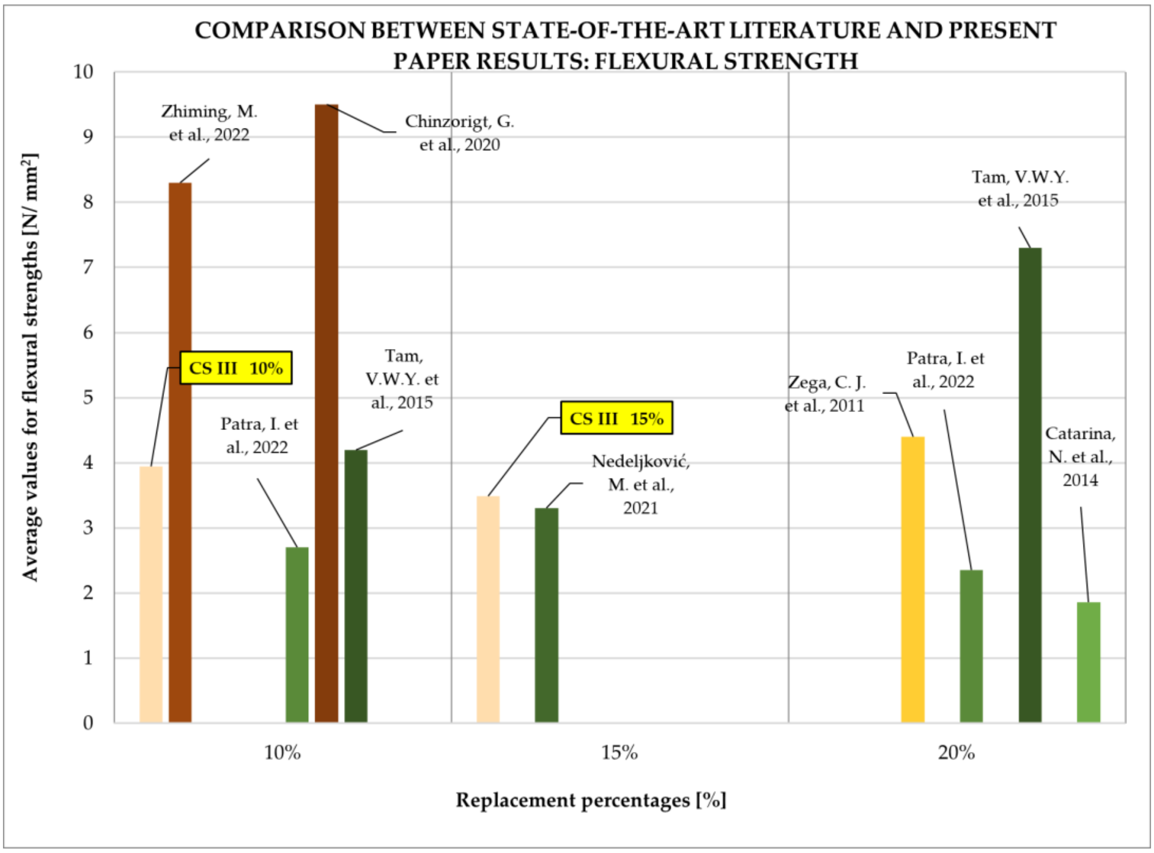

Figure 19. State-of-the-art and present research results for flexural strength [3,4,9–11,16,27].

Mora-Ortiz et al. [15], Zhiming et al. [16], Wu et al. [20], and Catarina et al. [27] published studies that analyzed mortar samples by substituting natural aggregate fine and/or gross components with recycled concrete aggregates in different percentages.

With the replacement percentage of 10%, it was observed (Figure 18) that Zhiming et al. [16] obtained a value for compressive strength at the age of 28 days that was 2.5 times higher than that obtained in the present paper for CS III 10%. One of the reasons behind this difference could be the composition of the studied mortars, namely cement-lime based mortars (in the current research) and cement-based mortar with high-quality recycled aggregates in the research of Zhiming et al. [16].

With the replacement percentage of 20%, Mora-Ortiz et al. [15] and Catarina et al. [27] obtained lower values compared to CS III 15% for the following characteristics: fresh and hardened mortar apparent density, compressive strength, flexural strength (Figure 19), and adhesion to the support layer. The main identified lower results were the following: compressive strength—2.5 times lower for both Catarina et al. [27] and Mora-Ortiz et al. [15]; flexural strength—2 times lower for Catarina et al. [27]; fresh mortar density—7% and 10% lower for Catarina et al. [27] and Mora-Ortiz et al. [15], respectively; hardened mortar density—8% lower for Catarina et al. [27] and 17% lower for Mora-Ortiz et al. [15]; adhesive strength—10 times lower for both Catarina et al. [27] and Mora-Ortiz et al. [15].

Nedeljković et al. [3], Zega et al. [4], Patra et al. [9], Chinzorigt et al. [10], and Tam et al. [11] published research studies on concrete samples by substituting the natural aggregate fine and/or gross components with recycled concrete aggregates in different percentages in percentages from 10% to 100%. These were compared with the present paper for the effects of the 10%, 15%, and 20% replacements both for compressive and flexural strengths.

With the replacement of 10%, referring to compressive strength (Figure 18), Patra et al. [9], Chinzorigt et al. [10], and Tam et al. [11] obtained higher values than the ones for found here CS III 10%, as follows: two times higher for Patra et al. [9], more than three times higher for Chinzorigt et al. [10], and 65% higher for Tam et al. [11].

With the replacements of 15% and 20%, referring to compressive strength (Figure 18), Nedeljković et al. [3], and Zega et al. [4], respectively, also obtained higher results for compressive strength compared to CS III 15%, as follows: 3 times higher for Nedeljković et al. [3] and 3.2 times higher for Zega et al. [4].

With the replacement of 10%, referring to flexural strength (Figure 19), comparable results were obtained for CS III 10% as for Patra et al. [9] and Tam et al. [11], whereas Chinzorigt et al. [10] obtained values 2.4 times higher. Patra et al. [9] obtained a value lower by 31%, and Tam et al. [11] obtained a value higher by 6%.

With the replacements of 15% and 20%, referring to flexural strength (Figure 19), Nedeljković et al. [3] and Zega et al. [4] obtained mixed results compared to CS III 15%, as follows: values were higher by 5% for CS III 15% compared to Nedeljković et al. [3], and lower by 19% compared to Zega et al. [4].

A factor worth noting for all the comparisons above is that the studied recipes in the present paper (CS III 10% and CS III 15%) were cement-lime based mortars, which means that by its own composition, lower results for mechanical strengths were to be expected when compared to cement-based mortars or concretes. Despite the lower analyzed results, all the values met the conditions stipulated in the norms in force, which is the reason why higher aggregate replacements are proposed for complex analysis.

Further investigations will be made on the proposed plastering mortars, especially at the microscopic and nanoscopic level, to analyze the impact of mortar waste on the hydration processes of mortars, and to study the interaction between cement paste and waste and the impact of the porosity samples on the increase in mechanical strength. Different types of methods, such as optical microscopy/scanning electron microscopy (SEM) and nuclear magnetic resonance (NMR) will be used to identify the characteristics of plastering mortars.

Nuclear magnetic resonance (NMR) represents a suitable method for analyzing the microscopic parts of the elements that leads to a better understanding of the macroscopic characteristics (the evolution of mechanical strengths in time and the comparison with the control recipe). NMR could be used in measuring the distributions of spin–spin relaxation times for the water that exists in the pores, the dimension of the pores (small, medium, large) or the water hydration. Many studies have been conducted analyzing plastering mortars at a nanoscopic level; for instance, Pintea et al. [47] used this method to discover the homogeneity of the water media in the pores of mortar samples, the quantity of water in the pores, and the level of saturation. Jumate et al. [48] also used the NMR method to establish the influence of cellulose ether polymer and $CaCO_3$ on plaster mortar microstructure, namely the large distribution of channels and pores, the decrease in small pores, or the increase in large pores.

5. Conclusions

All the results obtained for the samples with 10% and 15% replacement of natural aggregates with old plastering mortars allowed a better understanding of the macroscopic behavior of the proposed mortar recipes.

Concerning the fresh state of the mortars, the following could be observed:

- Apparent density—values tended to decrease by the addition of waste, but all the results were higher than 2000 kg/m^3; in addition, they met the directives from the regulations.
- Consistency—higher values were obtained proportional to the waste ratio increase, and this determined a higher workability of the mortar mix.
- Segregation tendency—CS III 15% had the lowest value compared to the control mix by approximately 25%, which means that the improvement appeared when waste was added because of its lighter weight.
- Concerning to the hardened state of the mortars, the following could be observed:

- Apparent density—the values decreased with aging, and if at the age of 7 days, CS III R.S. presented the lowest value and CS III 15% the highest, at the age of 28 days, because of the water evaporation, all the samples had close values.
- Bending strength—the control recipe (CS III R.S.) had the highest values throughout; they were higher by 12% than those of CS III 10% and by 22% than those of CS III 15% at the age of 28 days. These proportions were similar at the ages of 7 and 14 days.
- Compressive strength—it can be observed that the highest values were obtained for CS III R.S. (control recipe), and comparing CS III 10% with CS III 15%, the better results were obtained by CS III 10%, although at the age of 28 days, the values were very close to each other. The lowest value of the standards in force is 4.5 $N/mm^{2,}$ whereas the lowest value obtained at the age of 28 days was 13.38 N/mm^2 (almost three times higher than the standard) [43,44].
- Adhesion to the support layer—in terms of the results obtained for adhesion to the support layer, it can be observed that the best values were obtained for the control sample of mortar. The mortar in which the aggregates were replaced by 10% construction waste (waste from old plaster) obtained a higher value than the sample in which the waste was replaced by 15%.

In conclusion, the substitution of 15% of the aggregate with waste from old plaster results in a decrease in the mechanical characteristics of new plaster mortars compared to standard mortar (as could be observed in the state-of-the-art literature), but we believe that the objective of the research was achieved, the waste representing a real alternative for reducing the use of natural resources, in accordance with the demands of sustainable development. Additionally, the research values indicate that all the results obtained for the physical–mechanical analysis were above the values stipulated in the norms in force (according to SR EN 1015 [38,39,41–45]).

To analyze the influence of the waste in the proposed recipes, the studied mortars will be analyzed with regard to their absorption of water by capillarity and by thermal conductivity. Further, a study will be carried at microscopic level by the latest-generation methods of nuclear magnetic resonance. Future investigations will be made for mortars in which aggregates are replaced by plastering mortar wastes in other percentages, if all the norms in force are respected.

Recycling the old plastering mortars could reduce landfill pollution and minimize the demand for natural materials in the construction industry.

Recommendation

Taking into consideration the actual situation of waste management, many steps toward sustainable development should be undertaken. Future researchers could approach subjects such as:

- highlighting the evolution over time of mechanical strengths following the introduction of waste into mortars by analyzing the characteristics of the studied samples at the age of 90 days;
- usage of several types of binders in recipe preparation;
- microscopic and nanoscopic analysis of the samples for a better understanding of the chemical processes that take part in the composition of new proposed recipes;
- increasing tensile strength by dispersed reinforcement of mortars with polypropylene fibers;
- given the increasing water/cement ratio with growing percentages of waste used as aggregate replacements in concrete or mortars, future studies should focus on reducing porosity by introducing water-reducing plasticizer additives;
- adhesion to the support-layer strength, especially when studying plastering mortars.

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