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Article

Potential Use of Rendering Mortar Waste Powder as a Cement Replacement Material: Fresh, Mechanical, Durability and Microstructural Properties

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Abstract: The difficulty of decomposing solid waste over time has made it a significant global problem because of its environmental impact and the need for large areas for disposal. Among these residues is the waste of the rendering mortar that is produced (falls to the ground) while applied to wall surfaces. The quantity of these materials may reach 200 to 500 g/m^2. As a result of local urban development (in Iraq), thousands of tons of these wastes are produced annually. On the other hand, the emission of greenhouse gases in the cement industry has had a great environmental impact. One of the solutions to this problem is to reduce the cement content in the mix by replacing it with less emissive materials. Residues from other industries are considered a relatively ideal option due to their disposal on the one hand and the reduction of harmful emissions of the cement industry on the other hand. Therefore, this research aims to reuse rendering mortar waste powder (RMWP) as a possible alternative to cement in mortar. RMWP replaced the cement in proportions (0, 10, 15, 20, 25, and 30% by weight). The flow rate, flexural and compressive strengths, ultrasonic pulse velocity, bulk density, dynamic modulus of elasticity, electrical resistivity, and water absorption tests of the produced mortar were executed. Microstructural analysis of the produced mortar was also investigated. Results indicated that, for sustainable development, an eco-friendly mortar can be made by replacing cement with RMWP at a rate of 15%, resulting in a 17% decrease in compressive strength while maintaining or improving durability properties. Moreover, the microstructure became denser and more homogeneous in the presence of RMWP.

Keywords: rendering mortar waste powder; cement replacement; compressive strength; electrical resistivity; microstructural analysis

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1. Introduction

As the global population expands, economic sectors also experience growth, leading to a significant rise in energy consumption and the use of natural resources [1]. Construction and demolition waste (CDW) has become a pressing environmental concern [2,3]. Eurostat [4] reported that in 2014, a staggering 868 million tons of CDW was generated. To promote the adoption of recycled aggregates, the European Parliament's Waste Framework Directive 2008/98/EC set a goal for all European Union member states: a minimum of 70% reduction, reuse, and recycling of CDW by 2020. The construction industry significantly contributes to global waste generation and environmental degradation, primarily due to its high consumption of natural resources and energy-intensive practices [5,6]. As the demand for sustainable construction methods grows, researchers and practitioners have been increasingly focusing on the potential of waste materials as a valuable resource for creating novel, eco-friendly construction solutions [7–9]. One often-overlooked opportunity for waste reduction lies in waste-rendering mortar (WRM), a byproduct formed when mortar falls to the ground during application to wall surfaces [10,11]. The potential use of WRM, a byproduct generated during the application of mortar to wall surfaces, has been explored in various studies to mitigate environmental impact and promote sustainability [12,13]. One key advantage of WRM utilization is the reduction of landfill waste, which, in turn, decreases the demand for virgin raw materials and conserves natural resources [14]. Moreover, reusing WRM leads to cost savings, as it eliminates the need for disposal fees and reduces the costs of procuring new materials [14]. Using waste-rendering mortar (WRM) as a sustainable construction material offers significant benefits. By repurposing WRM in mortar mixes, it is possible to achieve multiple objectives, such as reducing environmental impact, enhancing cost-effectiveness, and improving material performance [15].

Environmentally, incorporating WRM into mortar mixes helps minimize landfill waste and decrease the carbon footprint of construction activities [16]. This strategy aids in lowering greenhouse gas emissions linked to the extraction of raw materials and cement manufacture; ultimately, this promotes a circular economy in the building industry [17]. Economically, the use of WRM presents notable advantages. Disposal fees can be eliminated by reusing this byproduct, and demand for virgin raw materials is reduced, resulting in cost savings for construction projects [18]. This practice benefits individual projects and the broader construction industry by fostering a more sustainable and resource-efficient approach [19]. From a performance standpoint, WRM has been found to maintain, and in some cases enhance, the properties of mortar mixes. Studies have shown that WRM can partially replace cement, sand, or both without compromising key attributes like workability, mechanical properties, and durability [20]. For example, some research has reported improved bonding with the substrate, increased resistance to crack formation, and reduced drying shrinkage when WRM is incorporated into mortar mixes [21].

Waste-rendered mortars exhibit a decreased need for water to maintain a homogenous consistency [22–24], which can be attributed to the filler impact [25]. As fine particles fill the voids within the mortar structure, less water is needed for the hydration and lubrication of the aggregates [26,27]. Compared to reference mortars, mechanical properties such as bending, compression, and adherence strength significantly improve when filler wastes are added. This incorporation leads to more compact mortars because of the filler impact [27,28]. Waste-rendered mortars containing fine waste demonstrate better adherence strength than those with only sand as an aggregate [29]. The inclusion of fines enhances the mechanical behavior of mortars, which can be explained by the cement, water, and fines being partially absorbed by the substrate and forming a stronger bond [30]. Moreover, mortar compactness also affects water absorption. Modified mortars absorb less water than conventional mortar when adding fine waste material [31], which can be attributed to a denser microstructure associated with the filler effect. Although the incorporation of fines leads to increased compactness in modified mortars, offering several benefits, some drawbacks have been reported, including a higher modulus of elasticity and greater susceptibility to cracking [32,33]. Modified mortars are more likely to crack inside and externally if their modulus of elasticity is greater than that of the unmodified mortar [34,35].

Some previous authors have re-used powdered concrete waste as a substitute for cement in concrete. For example, Xiao et al. [36] explored the use of recycled concrete powder (RCP) as a substitute for cement at varying proportions ranging from 0 to 45% (by weight). Mechanical tests indicated that up to 30% content, the effect of RCP was positive or slightly negative. However, at 45%, it caused a significant reduction in the mechanical properties. Overall, the authors recommended that the replacement rate should fall within the 15–30% range. Moreover, Chen et al. [37] investigated cement replacement by RCP in proportions of 10%, 20%, 30%, and 40%. According to the mechanical tests conducted, it was found that the impact of RCP on strength is small if the replacement rate is less than 20%.

Among the construction waste produced in large quantities locally (in Iraq) is the WRM generated or fallen during the process of wall plastering. The rendering mortar usually consists of a blend of cement: sand in proportions of 1 to 2 or 2.5 with water. When the walls (internal or external) are plastered and leveled to show them acceptably or to prepare them for the painting stage, some of the mortar used in the plastering falls off. According to what has been investigated in the field (through personal conservation with the building workers and field inspection), this waste is about 200 to 500 g/m^2. The traditional Iraqi houses range from 100 to 200 m^2 (150 m^2 on average). According to what was monitored for one of the houses under construction, which has an area of 140 m^2, the plastering area for the faces of the building walls (internal and external) exceeded 350 m^2. In other words, the WRM for a house of 140 m^2 is about 120 kg. As a result of the urban development undergone by the country during recent years as a result of population expansion, as well as for the reconstruction of housing destroyed as a result of military actions, thousands of housing units are built annually, which means thousands of tons of WRM are produced and thrown into landfills without any benefit.

Moreover, one of the main aspects that need to be taken into consideration during the evaluation of the suitability of new material to partially replace conventional material like cement is to evaluate its environmental impact. One of the best options to accomplish this is to conduct Life Cycle Assessment (LCA) for mortar made with different rendering mortar waste powder RMWP contents and compare it with that of mortar made with 0% RMWP [38].

According to the above, RCP has been used as a replacement for cement in the literature. However, very limited studies have dealt with the reuse of fallen WRM during wall plastering as a replacement for cement. Moreover, as a result of the production of these wastes in significant quantities locally and the lack of an actual application for recycling them other than throwing them in landfills, it is believed that re-including WRM in the construction sector is a promising solution for removing their damages, in addition to opening the door for the production of environmentally friendly concrete or mortar. Furthermore, reusing these wastes as a substitute for cement contributes to reducing greenhouse gas emissions, thus reducing its harmful impact on the environment and helping to improve the climate. In addition, relatively few studies have been conducted to examine the sustainability of RMWP and compare the results to those obtained with RMWP-free mixes. Thus, this study was conducted to discover the potential use of (RMWP) as a partial substitute for cement and to produce sustainable mortar. Various tests were performed to study the resulting mortar's fresh, mechanical, durability, and microstructural properties as well as LCA.

2. Materials and Methods

2.1. Cement

All mortar blends were made with limestone cement of the CEM II/A-L 42.5 R type, which was manufactured locally. The specific gravity, particle size, and fineness of cement are 3.05, 17.99 µm, and 399 m^2/kg, respectively. Cement meeting the requirements of Iraqi Standard (IQS) No. 5 [39] are listed in Table 1 below. Figure 1 illustrates the dispersion of cement particles according to their sizes. The consistency, initial, and final setting times of cement are, respectively, 32%, 150 min, and 3.4 h.

Table 1. Cement and RMWP chemical composition.

Oxide	Content, %	
	RMWP	Cement
SiO_2	49.11	16.91
CaO	20.85	60.51
Fe_2O_3	1.387	4.360
Al_2O_3	2.475	3.194
SO_3	2.282	3.146
MgO	0.6456	2.479
Na_2O	1.227	1.429
K_2O	0.892	0.495
TiO_2	0.1244	---

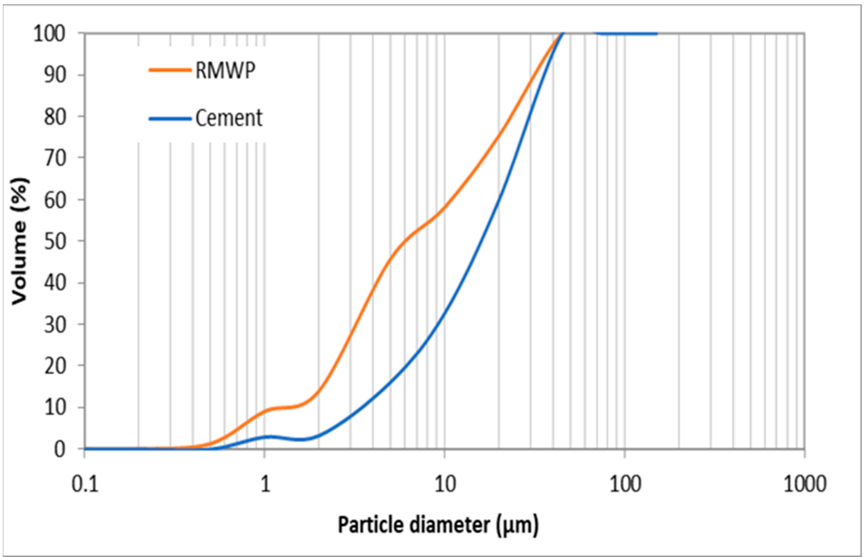

Figure 1. The cement and RMWP particle size distribution.

2.1.1. Fine Aggregate

Locally accessible natural sand with a grain size between 4.75 and 0.15 mm was used in the mortar formulations. Table 2 displays the fine aggregate's gradation results, which shows that it complies with Iraqi Standard No. 45 [40].

Table 2. The sieve analysis findings of the sand.

Sieve Opening (mm)	Accumulative Passing, %	Iraqi Standard Limits
4.75	94	90–100
2.36	82	75–100
1.18	69	55–90
0.60	43	35–59
0.30	12	8–30
0.15	1	0–10

2.1.2. Rendering Mortar Waste Powder (RMWP)

The rendering mortar waste was prepared by bringing them from one of the residential houses under construction in Babylon (middle of Iraq). The consisted form cement: sand in a ratio of 1: 2 to 2.5 rendering mortar. The waste was collected from the mortar that fell while rendering the walls (five days after rendering was finished). After that, the waste was dried in an oven at 100 to 110 °C to remove any residual moisture. Then it was ground by a grinding mill for 5 min. Then rendering mortar waste powder (RMWP) was produced and used as a substitute for cement in mortar mixtures, see Figure 2. The particle size and specific gravity of RMWP are 5.781 µm and 2.74, respectively. Figure 1 illustrates the chemical properties of RMWP, while Table 1 shows the particle size distribution.

Figure 2. The rendering mortar waste powder.

2.1.3. Water

In all mortar mixes, tap water (drinkable water) was utilized to mix the mortar components.

2.1.4. Superplasticizer

Glenium 54, a superplasticizer of the third generation that is commercially available, was used to modify the flowability of mortar mixtures. Glenium 54 meets ASTM C494 Types A and F [41] specifications.

2.2. Mix Proportions

Six mortar mixes were made for this study—a control mixture and five other mixtures in which cement was substituted with RMWP in proportions of 10, 15, 20, 25, and 30% of the cement weight. All the mixes had fixed water/binder ratios, sand, and superplasticizer amounts. The constituents of each blend are presented in detail in Table 3.

Table 3. Mortar mix details as a binder (cement + RMWP) weight ratio.

Mix Designation	Cement	RMWP	Sand	Superplasticizer	Water/Binder
Control	1	0.0	2.75	0.007	0.45
RMWP10	0.90	0.10	2.75	0.007	0.45
RMWP15	0.85	0.15	2.75	0.007	0.45
RMWP20	0.80	0.20	2.75	0.007	0.45
RMWP25	0.75	0.25	2.75	0.007	0.45
RMWP30	0.70	0.30	2.75	0.007	0.45

2.3. Mixing and Curing Procedures

An electric bowl mixer with two speeds (140 and 285 rpm) that conforms to ASTM C109 [42] was employed to mix the mortar raw materials according to the following method:

To prepare the fresh mortar, the dry ingredients, such as cement, sand, and RMWP, were blended for a minute at 140 rpm. Subsequently, the pre-mixed water and superplasticizer were incorporated, and the mixing process was continued at the same speed for two minutes. Finally, the speed increased to 285 rpm, and the wet ingredients were blended for an additional minute.

Once the mortar was mixed entirely, it was cast into standard molds measuring $40 \times 40 \times 160$ mm^3 and $50 \times 50 \times 50$ mm^3. After 23–24 h, the molds were taken off and the specimens were positioned in water until the test.

2.4. Experimental Tests

2.4.1. Flow Rate

After the mortar mixing process, the flow rate was measured in line with ASTM C1437 [43].

2.4.2. Compressive Strength

To determine the compressive strength, 50 mm cubes were used and the failure load was divided by the sectional area of the cubes according to the guidelines outlined in ASTM C109 [42]. The test was conducted twice, once at 28 days and again at 56 days. Three readings were taken at each age, and an average was calculated. The test was performed using a compressive-flexural machine (50–300 kN) type MATEST S.r.l. Treviolo, Italy.

2.4.3. Flexural Strength

According to BS EN 196-1, $40 \times 40 \times 160$ mm^3 prisms were used to measure flexural strength [44] at the 28-day age. Three readings, on average, were chosen. The test was performed using compressive-flexural machine (50–300 kN) type MATEST S.r.l. Treviolo, Italy.

2.4.4. Water Absorption and Bulk Density

To determine the dry bulk density and water absorption, prism halves tested in the flexural machine were utilized per the guidelines stated in ASTM C642 [45] at 28 days of age. Three samples were used as a mean.

2.4.5. Ultrasonic Pulse Velocity and Dynamic Elastic Modulus

At the age of 28 days, ultrasonic pulse velocity (UPV) and dynamic elastic modulus (Ed) measurements were taken on a cube of 50 mm using the method given in ASTM C597 [42]. An Ultrasonic tester (54 kHz-transducer) from MATEST company was utilized for the UPV test. Three cubes were used, with each cube providing a single reading. Ed was determined using Equation (1) based on the speed and density [46]:

$$v = \sqrt{\frac{\mathrm{Ed}(1-\mu)}{\rho(1+\mu)(1-2\mu)}} \tag{1}$$

where: μ is the dynamic Poisson's ratio, Ed is the dynamic elastic modulus and ρ is the density.

2.4.6. Electrical Resistivity

The two-metal plate approach was utilized to investigate mortar samples' electrical resistivity [47]. A 50 mm cube was put between two plates, with a wet sponge in between to ensure connectivity. Two wooden pieces were added to the cube's top and bottom, with a four-kilo weight on top. The impedance was measured using an LCR meter and a frequency of 1000 Hz [48]. LCR DE-5000 from DER EE company, Taiwan, was employed. The specimen's electrical resistivity was then determined using Equation (2). The investigation was conducted after 28 days, with three readings taken on average for each result.

$$ER = \frac{A}{L}R \quad (2)$$

where:

L: The height of the specimen in cm.
A: The cross-sectional area of the specimen (in cm^2).
R: The impedance.
ER: The electrical resistivity ($\Omega\cdot$cm).

2.4.7. Microstructure Studies

The SEM (scanning electron microscopy) examination was chosen to analyze the microstructure of mortar specimens made from selected mixtures. The SEM images were taken using an Axia ChemiSEM device from Thermo Fisher Scientific company. The samples of the mortar used in this test had dimensions of approximately 20 × 20 × 10 mm^3 and were taken from samples cured in water for 28 days.

2.4.8. Life Cycle Assessment (LCA)

OpenLCA software was used in this research to conduct the LCA using the method of the CML-IA.

According to the definition of waste materials [49], RMWO can be considered to be waste material and only the energy required for grinding (medium-voltage electricity consumption) will be used as input for the LCA impact inventory.

In this research, the "cradle to gate" system boundary was used for any complication of transportation and post-use. The scope used in this research consists of the following stages:

- The final target is the production of 1 m^3 of mortar.
- The 100-year Global Warming Potential (GWP) of mortars with different content of RMWP was calculated.
- In this research, the normalization approach was used as not all the mixtures have the same compressive strength. The normalization was performed based on the GWP impact per MPa of the compressive strength of the mortar at 28 days and 56 days.

3. Results and Discussions

3.1. Flow Rate

Figure 3 presents the findings regarding the flow rate for the mortar mixes with and without RMWP. The results showed that the flowability of mortar was somewhat enhanced (5.61%) for the RMWP10 mix, then reduced by 7.43% at the 15% replacement rate. Increased water absorption of RMWP granules may be the reason for this decrease in flow rate [50]. Thereafter, the flow rate tended to increase with the growth of RMWP content. The flow rate for the RMWP20 mixture was comparable to that for the plain mixture. On the other hand, the RMWP25 and RMWP30 blends enhanced the mortar's workability by 6.03% and 4.21%, respectively. Due to its small particle size, RMWP can fill the spaces between cement particles, allowing free water to escape [51]. This increase in free water can lead to better mix flow.

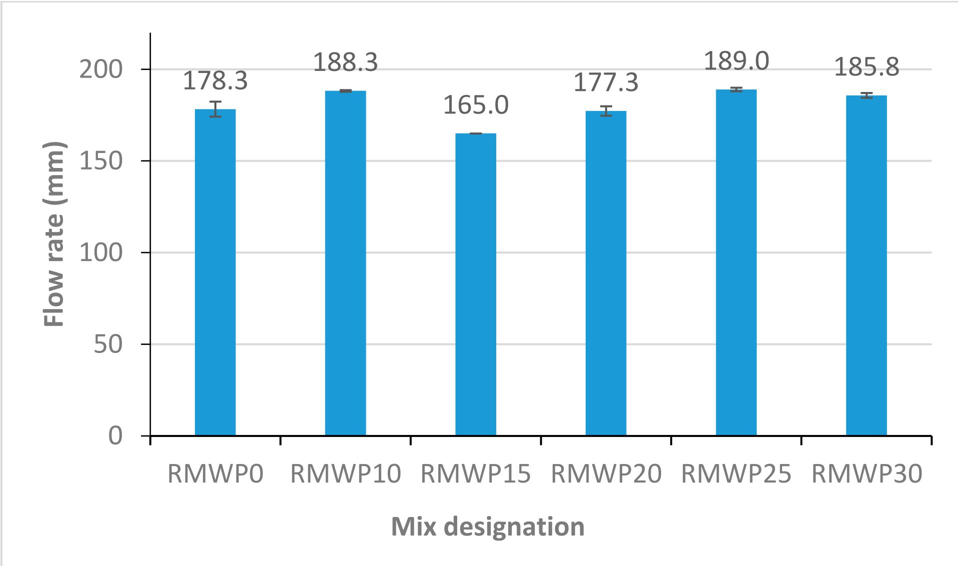

Figure 3. Flow rate findings of the mortar mixes.

3.2. Compressive Strength

Figure 4 shows the compressive strength outcomes for mortars that included RMWP waste at 28 and 56 days of age. It is evident that when cement was replaced with these residues, the compressive strength was reduced compared to the reference mix. At 28 days, it was discovered that there was a drop in compressive strength by 30.97% with a replacement rate of 10%. The decrease was slightly lower (28.97%) at 15% RMWP but declined further with a higher waste content. The reduction reached 50.65% at a replacement rate of 30%. It is possible to attribute the decrease in compressive strength after replacing the cement with RMWP to the dilution effect, which results in lower levels of hydrated compounds due to the reduced clinker content in the blended cement [52].

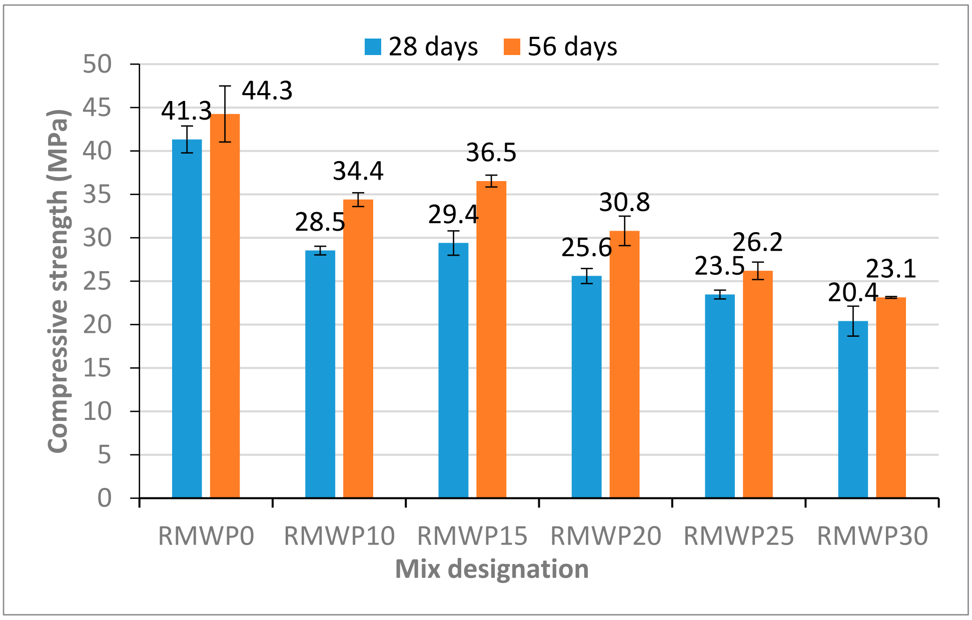

Figure 4. Compressive strength results at 28 and 56 days.

As per the literature [53], the compressive strength is directly related to the bulk density. Hence, the decrease in density (as mentioned in Section 3.4) is another reason for the decline in compressive strength. The mixtures containing RMWP have shown a reduction in mortar density.

Moreover, the results showed that, after 56 days, there was a partial recovery of strength compared to 28 days. Furthermore, the results followed a similar trend for the 28 days but with lower reduction rates. This improvement in compressive strength at 56 days compared to 28 days may be attributed to the reduced porosity and pore size of the mortar matrix due to the filling effect of RMWP and the continuous hydration of cement. For the RMWP10 mixture, the compressive strength decreased by 22.29%; then, the reduction fell to 17.47% for the RMWP15 mixture. This slight improvement in compressive strength at the 15% replacement rate indicates an enhancement of the packing (or filling effect) at this percentage when compared to previous and subsequent contents. After that, the decrease continued for the RMWP20, RMWP25, and RMWP30 mixtures, which recorded a drop in compressive strength of about 30.42%, 40.81%, and 47.74%, respectively, related to the plain sample.

3.3. Flexural Strength

The flexural strength findings of mortar prisms at 28 days are illustrated in Figure 5. The results suggest that the mix with 10% RMWP showed a decrease of approximately 2.5% compared to the reference mix, while the one with 15% substitution displayed the same strength as the control sample. This behavior is attributed to the RMWP fine particles filling the gaps between the cement and fine aggregate [54]. However, a significant reduction in flexural strength was noticed with the further growth in RMWP content. Specifically, the flexural strength decreased by 18.75%, 21.25%, and 31.25% for replacement rates of 20%, 25%, and 30%, respectively. This weakening can be explained by the same dilution action that lowers compressive strength, raising the effective water/cement ratio [55].

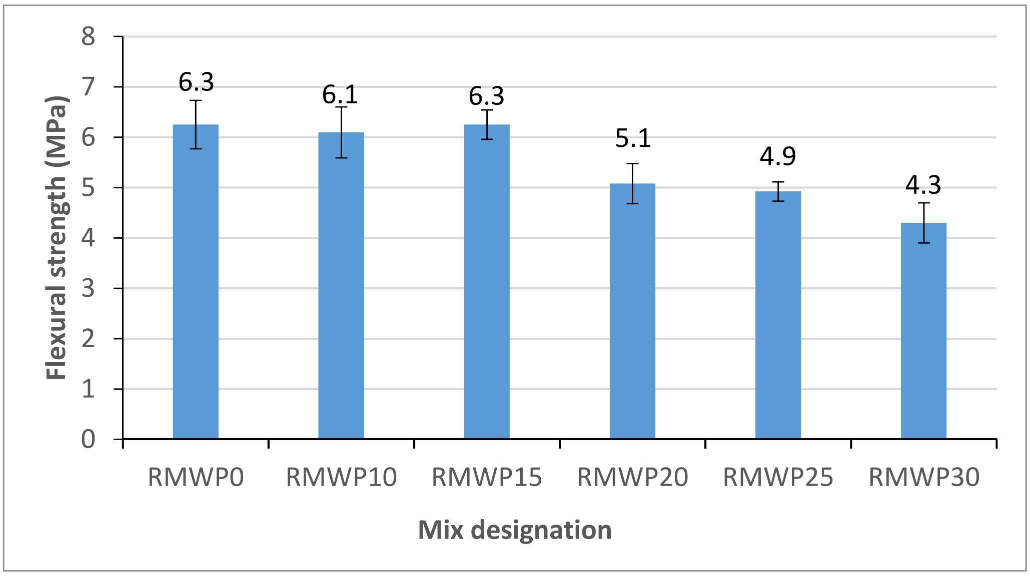

Figure 5. Flexural strength results at 28 days.

Furthermore, when compared to compressive strength, it was noted that flexural strength exhibited a similar trend with increasing RMWP content in the mixture. However, at 15% content, the flexural strength recorded a value equal to the reference mixture, while the compressive strength corresponding to this percentage decreased. This behavior could be because the presence and structure of voids within the microstructure have a more significant impact on flexural strength than compressive strength [56,57]. The RMWP has densified the microstructure and reduced the voids, minimizing the dilution effect on the flexural strength compared to the compressive strength.

3.4. Bulk Density

The density test outcomes are depicted in Figure 6. It was found that the density of the RMWP-containing mixtures was lower than that of the reference mixture by percentages ranging from 4.09 to 10.16%. First, a decrease in density of 5.72% was recorded for the mixture RMWP10, and subsequently, the decrease was dropped to 4.09% for the mixture RMWP15. After that, increasing the amount of RMWP in the mixture caused a corresponding increase in the density reduction, which brought it up to 10.16% at a replacement ratio of 30%. This reduction in density can be because the specific gravity of the RMWP is lower than that of cement [58,59]. On the other hand, the slight improvement in density at 15% replacement compared to other ratios (10% and 20 to 30%) may be due to the filling of voids within the matrix by RMWP granules (improving packing), which led to an increase in density [60,61].

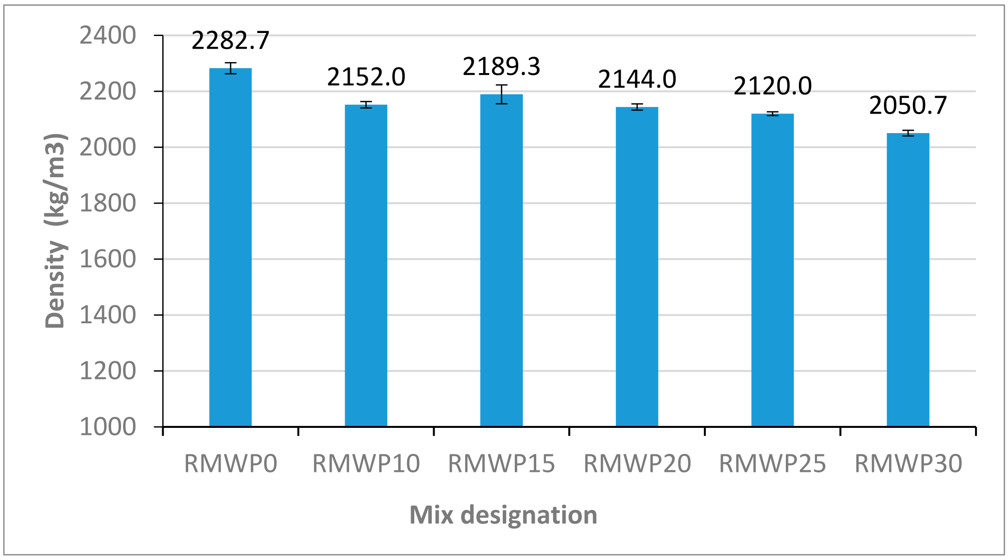

Figure 6. Bulk density results at 28 days.

3.5. Ultrasonic Pulse Velocity

In the past few decades, the ultrasonic pulse velocity test has become a primary method for determining the density, homogeneity, and damage of cementitious materials [62]. The advantage of UPV testing is that it is a non-destructive testing (NDT) method that can provide useful supplementary information when used in conjunction with a physical or mechanical characterization methodology (destructive testing) [62]. The findings of the UPV are displayed in Figure 7. In general, the findings suggested that the presence of RMWP resulted in a slower pulse velocity when compared to the control sample. Except for the 15% replacement percentage in the mixture, which recorded a lower drop in velocity than the before (10%) and after (≥20%) percentages, the reduction in velocity was proportional to the increase in the replacement percentage in the mixture. The lower specific gravity and, consequently, the density of the waste compared to cement could explain this reduction in the pulse velocity [63]. Moreover, the literature [64] has classified the durability of mortar into multiple categories depending on the speed values: very poor, poor, doubtful, good, and excellent if the speed values are 2000 m/s or less, 2000–3000, 3000–3500, 3500–4500 and 4500 m/s or higher. The obtained UPV values ranged from 3807 m/s (RMWP30) to 4310 m/s (RMWP0), and therefore they lay within the “good durability” category.

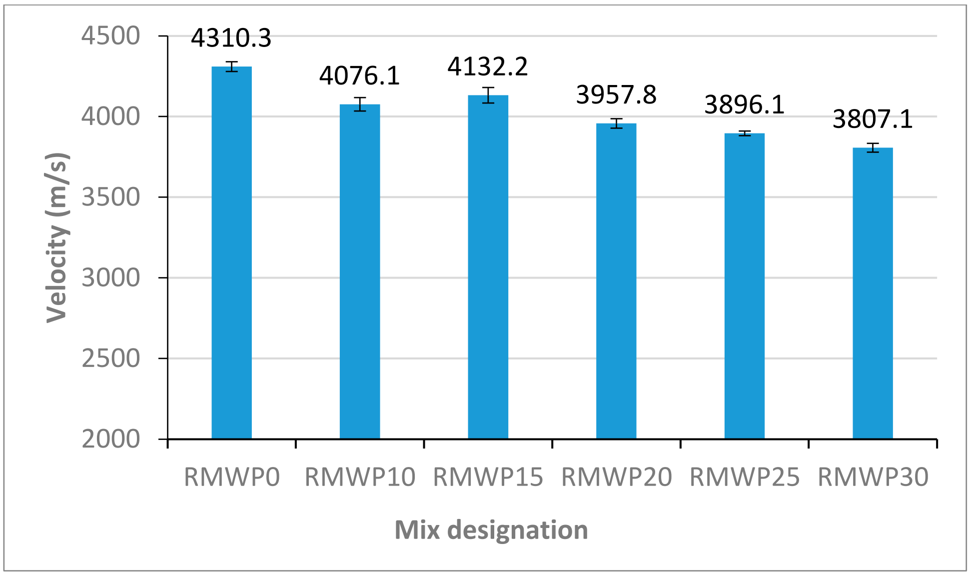

Figure 7. UPV results at 28 days.

3.6. Dynamic Modulus of Elasticity

Figure 8 illustrates the dynamic elastic modulus (Ed) results. The figure demonstrates that the Ed values of the mortar decreased after the cement was replaced with RMWP. The Ed value of the RMWP10 mixture was lower than that for the reference mixture (38.17 GPa) by 15.69%. However, it was partially recovered at the substitution ratio of 15%, resulting in a decrease of 11.85% (or 33.65 GPa). However, the modulus of elasticity continued to decline until it was 26.75 GPa (29.92% lower than the control sample) at the replacement rate of 20% or more. This drop in Ed can be ascribed to several variables that determine the value of the material, such as porosity, UPV, density, and compressive strength [65,66]. As a result, low compressive strength, density, and UPV values can lead to reduced values for the mortar's modulus of elasticity.

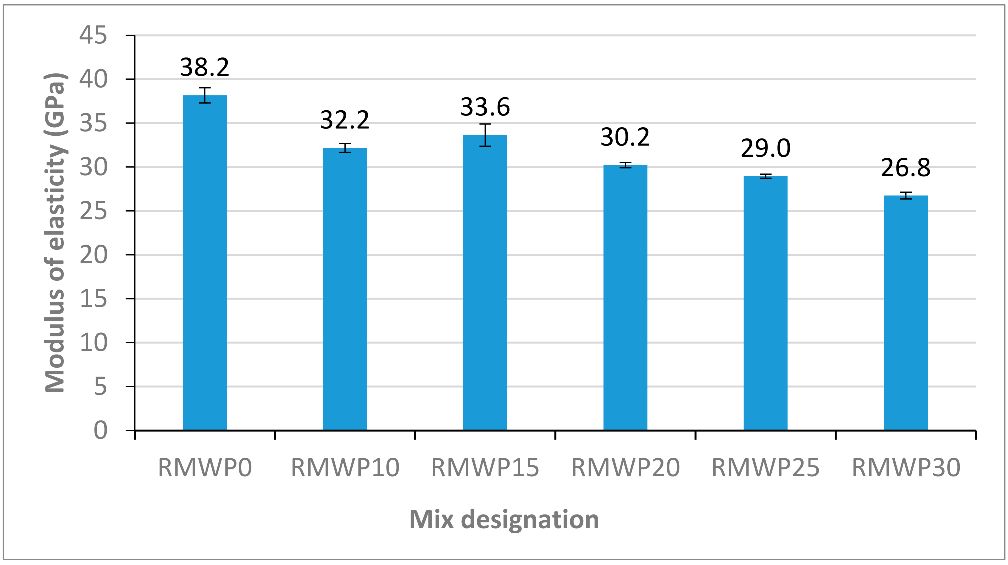

Figure 8. Dynamic modulus of elasticity results at 28 days.

3.7. Electrical Resistivity

Figure 9 presents the outcomes of the electrical resistivity (ER) tests conducted on the various mortar formulations. According to the findings, substituting RMWP for 10% of the cement reduced ER by 9.62% while maintaining an electrical resistivity level similar to that of the control sample at 15% content. On the other hand, percentages of 20% or higher have been shown to improve electrical resistance. The RMWP25 mixture showed the greatest improvement, with a value of 12.84 percentage points higher than that of the control sample. This increase in the electrical resistance of concrete suggests that the presence of waste has impeded the movement of electrons [55]. This could lead to better corrosion resistance of the concrete. When comparing the results of ER with UPV, a difference is noted in the general behavior in the presence of RMWP, where it was noticed that the speed decreases with increasing the content of residues; in contrast, the electrical resistance increases. The reason for this may be that UPV is sensitive to electromagnetic energy propagation phenomena while the ER is affected by conduction phenomena [67]. Moreover, the pore size distribution (pore microstructure network) is one of the key elements impacting the electrical resistance, along with the porosity [68,69].

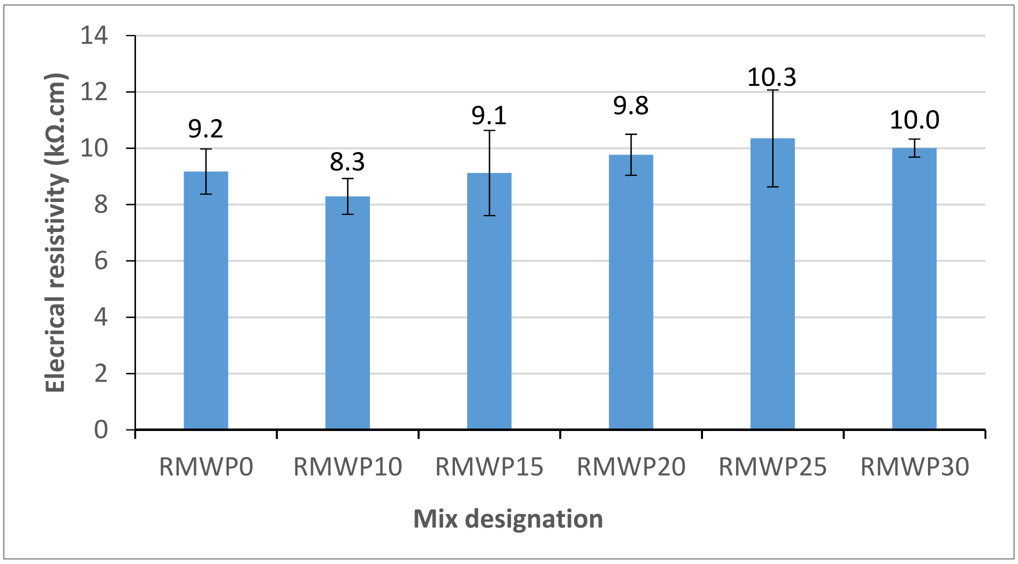

Figure 9. Electrical resistivity results at 28 days.

3.8. Water Absorption

One of the key factors determining the concrete's durability is its resistance to water absorption [70]. Figure 10 shows the results of mortar mixtures' water absorption. The results demonstrated that the absorption of the control mixture was not affected by replacing 10% of the cement with RMWP. Moreover, water absorption was slightly lower (1.64%) for the RMWP15 blend. Densification of the microstructure and nano-micro filling of gaps may be to blame for the decline in water absorption [71] as a result of the smaller particle size of RMWP compared to the cement. However, the absorption increased gradually for mixtures comprising 20, 25, and 30% RMWP; the increase was, respectively, 3.58, 5.45, and 7.56% compared to the reference specimen. The dilution of the cement produces voids inside the matrix, which may explain the increased water absorption [72].

Moreover, according to previous works [73,74], concrete or mortar is considered to have good durability if its water absorption value is less than 10%. According to the results of the current study, the water absorption values were within the range of 8.5 to 9.2%, and therefore the RMWP-based mortar is durable.

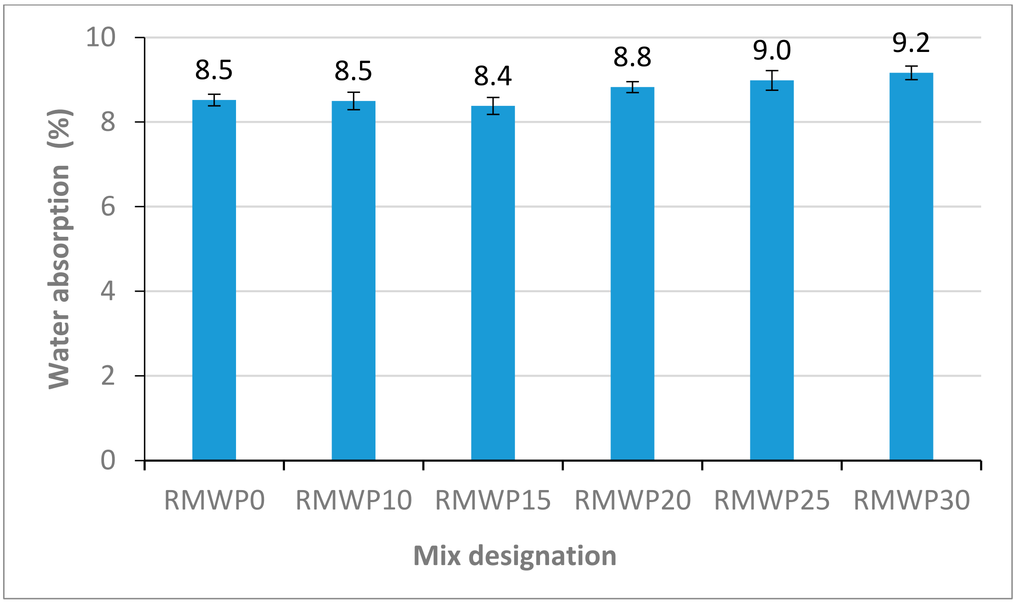

Figure 10. Water absorption results at 28 days.

3.9. Microstructural Analysis

Figure 11 presents the scanning electron micrographs of the reference and RMWP15 (which gave the lowest reduction in compressive strength) mixes at 28 days. It can be observed from the figure that the morphology of the reference mixture was more heterogeneous compared to the morphology of the mixture containing RMWP. In addition, a comparison of the micrographs of the two aforementioned mixtures reveals that RMWP has densified the microstructure of the mortar. This is the case despite the RMWP being chemically inactive. The reason for this is that its granules are very small compared to those of cement, allowing them to fill the spaces between the cement granules more effectively. In addition, it has been noticed that these findings are in agreement with other results found in the literature [36,75], as well as findings obtained during this research, such as compressive strength, water absorption, and electrical resistivity.

Furthermore, it was observed that the RMWP-free mortar (Figure 11a) had developed quite sizable crystals and contained numerous large voids within its microstructure. Conversely, the sample containing 15% RMWP (Figure 11b) exhibited a much denser and more compressible texture, with noticeably fewer large crystals present. Similar findings were also recorded in the literature [76].

3.10. Life Cycle Assessment (LCA) Results

Figure 12 presents the results of the GWP of the production of 1 m^3 of mortars made with different percentages of RMWP. According to Figure 12, increasing the content of RMWP resulted in decreasing the GWP of the mortars. The reduction in the GWP ranged between 8.5% for RMWP10 and 25.6% for RMWP30.

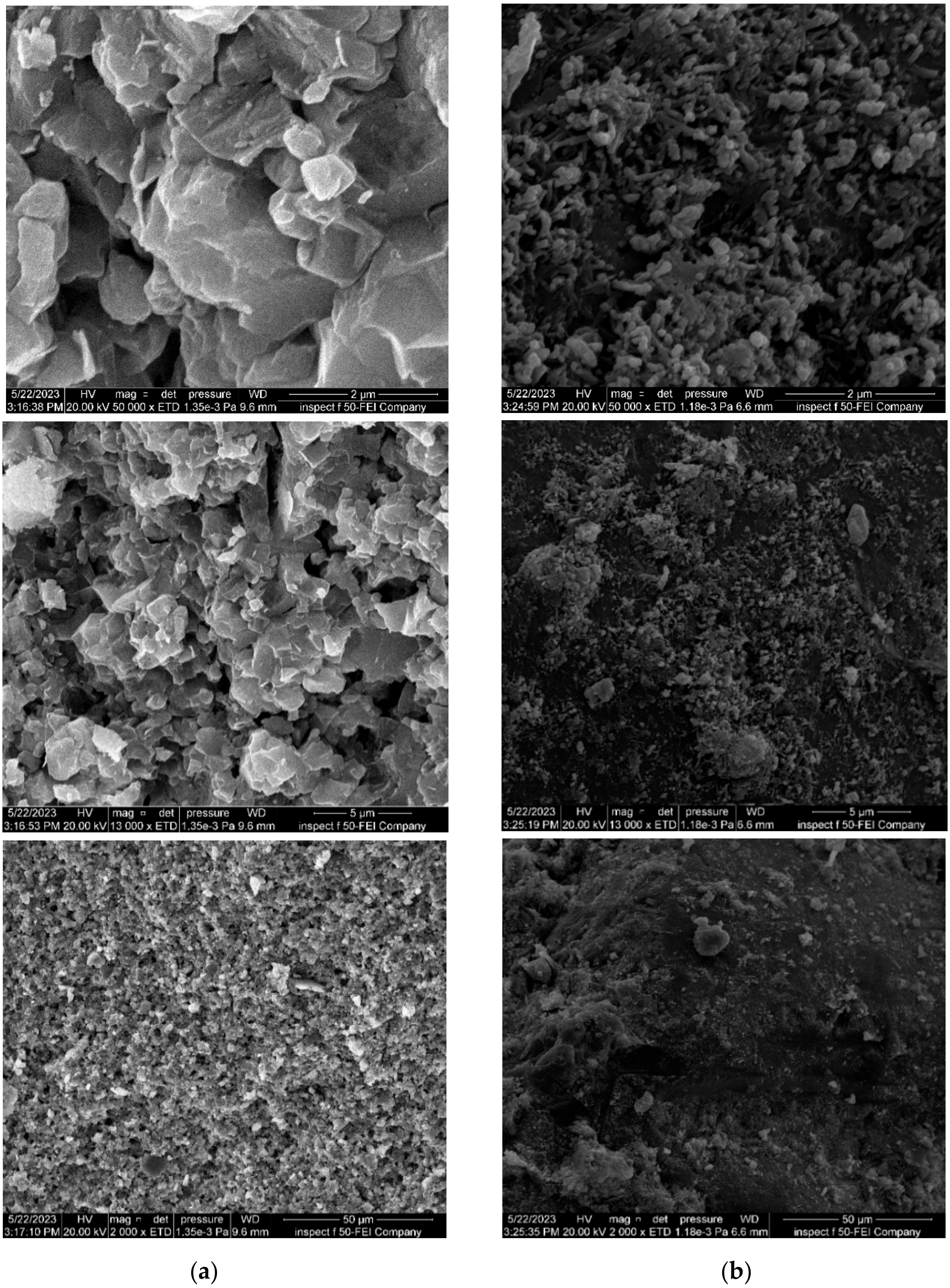

Figure 11. SEM images of (**a**) the control and (**b**) RMWP15 mixtures after 28 days.

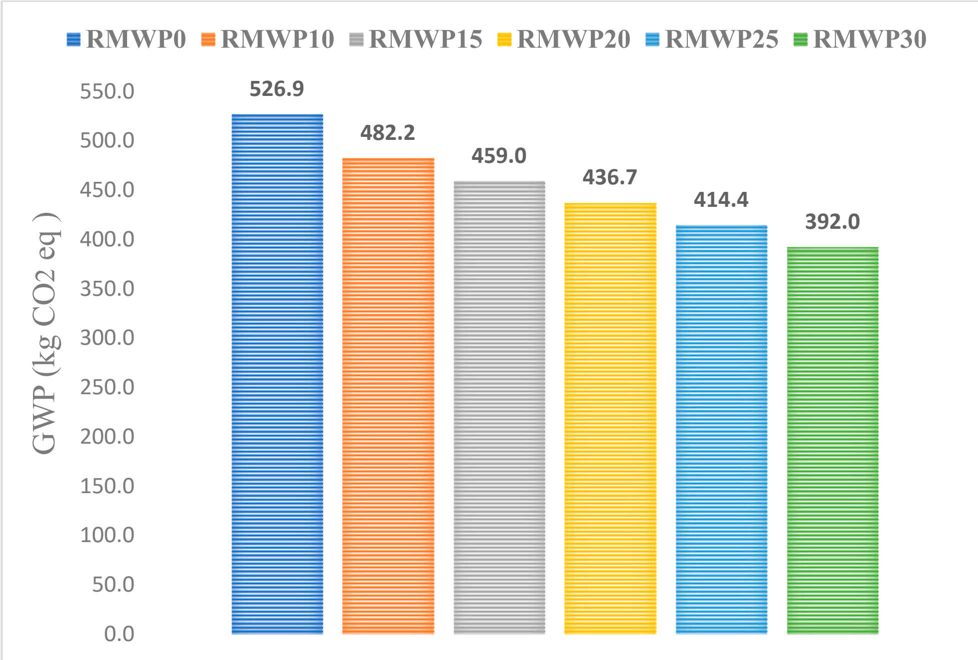

Figure 12. Global warming potential (kg CO_2 eq.).

Figure 13 presents the results of the GWP impact per MPa of compressive strength of the mortars at 28 days and 56 days. Figure 13 clearly shows that for all mixtures, the kg CO_2 eq./MPa decreased with increasing the age of curing from 28 days to 56 days. Figure 13 also shows the best performance for mixtures with RMWP was recorded for mixture RMWP15 which showed only about 5.6% kg CO_2 eq./MPa higher than the control mixture (RMWP0).

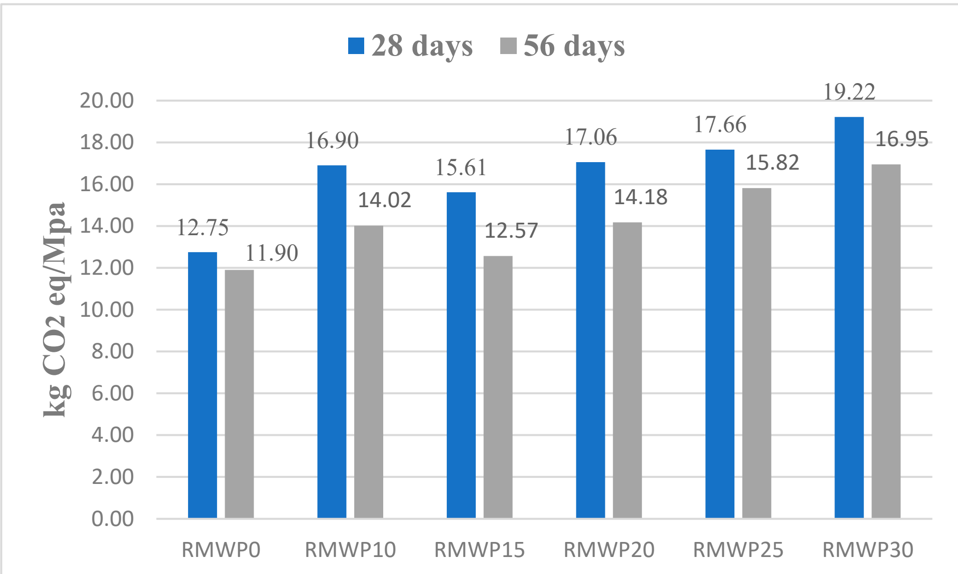

Figure 13. kg CO_2 eq./MPa.

4. Conclusions

The purpose of this research is to evaluate the potential effects of substituting RMWP for cement in producing environmentally friendly mortar in amounts ranging from 10 to 30%. Fresh, mechanical, durability, and microstructural examinations were performed. From the acquired results, the following was deduced:

1. At replacement ratios of less than 10% and greater than 20%, the RMWP enhanced the fresh mortar's flowability marginally, while at 15% content, it decreased it by 7%.
2. The RMWP caused a decline in the compressive strength of the mortar. However, the decrease in strength was partially recovered after 56 days compared to 28 days. The lowest reduction in compressive strength was recorded for the RMWP15 mixture, 17.47% lower than the reference mortar.
3. The partial recovery of compressive strength after 56 compared to the 28 days gives the impression of the possibility of greater strength improvement (greater recovery) over time. However, a comprehensive study that includes late ages, such as 180 days or longer, is recommended to verify this.
4. In terms of flexural strength, up to 15%, it was almost unaffected by RMWP use. After that, however, the strength dropped with the rise of the RMWP content.
5. The replacement of cement with RMWP resulted in a decrease in ultrasonic pulse velocity, bulk density, and dynamic modulus of elasticity. Among the RMWP variations, RMWP15 showed the lowest decreasing rates of 4.09%, 4.13%, and 11.85%, respectively.
6. At a low content of RMWP (10%), the electrical resistance decreased, but it was the same as the reference mixture at RMWP15. However, for higher replacement ratios, it improved by 6.50 to 12.84%.
7. Water absorption levels are comparable (or slightly lower) to the control sample, up to a 15% RMWP residue. However, at a 20% or higher ratio, the absorption increases proportionally with the RMWP content.
8. The use of RMWP in place of cement at a ratio of 15% densified the microstructure of the mortar and made it more homogenous compared to plain mortar.
9. Replacing the cement partially with RMWP resulted in a reduction in the GWP of mortars.
10. When the compressive strength (MPa) of mortars was used in the calculation of the optimum mixtures, results indicated that mortar with 15% RMWP provided the lowest GWP per MPa.
11. In summary, to promote sustainability, it is possible to use RMWP as a substitute for cement at a rate of 15% with approximately a 17% reduction in compressive strength and an equal or slight improvement in durability properties to produce eco-friendly mortar.

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