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Article

Effect of the Incorporation of Olive Tree Pruning Sawdust in the Production of Lightweight Mortars

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Abstract: In order to reduce energy consumption in buildings, this study used olive pruning sawdust (OTPS) instead of natural sand in the production of lightweight mortars. Different percentages of natural sand substitution were tested: 0, 10, 25, and 50% by volume of sand over 7 and 28 days of curing time. Additionally, the influence of a chemical pretreatment in an aqueous solution of calcium hydroxide on the OTPS was also evaluated to mineralize the wood before its addition to the mortar mixture. Mortars with OTPS incorporations were characterized by volumetric shrinkage, bulk density, and capillary water absorption. Mechanical behavior was tested through compression and flexural tests. The addition of this byproduct decreased bulk density and increased mortar porosity. Pretreating olive pruning sawdust with an aqueous solution of calcium hydroxide was effective for wood mineralization, resulting in physical and mechanical properties superior to mortars without pretreatment. The results showed that a maximum addition of 10% by volume of OTPS treated with calcium hydroxide solution produced lighter mortars with similar mechanical properties to the control mortar. Adding higher amounts of pretreated olive pruning (25–50% by volume) led to a more pronounced deterioration of mechanical properties.

Keywords: olive tree pruning sawdust; lightweight mortars; compressive strength; wood mineralization

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1. Introduction

The cultivation of olive groves is one of the most important agricultural activities in Southern Europe, occupying a total cultivated area of 2.4 million hectares in Spain [1]. On average, it can be considered that 1 hectare of olive grove generates 3 tons of pruning materials, amounting to over 7 million tons of olive tree pruning biomass generated per year [2].

Olive tree pruning is typically crushed in the field and spread on the soil or burned for electricity generation through combustion processes. However, this process can increase CO_2 emissions and contribute to the greenhouse effect. The biochemical pathway, which holds greater potential for the future, is still not optimized, and there are economic aspects that need to be resolved. Currently, the only use for these residues is as fuel or compost [3].

Since construction materials are suitable for absorbing waste, many researchers have investigated the benefits of adding various types of waste to mortars or ceramic materials. Using wood-derived products as a substitute for sand in mortars has not shown significant improvement in mechanical properties due to the chemical incompatibility between biomass and cement [4–6]. Therefore, to enhance chemical compatibility between Portland cement components and ensure proper cement hydration to form a network of silicates that connect particles, various treatments have been studied to remove inhibitory substances from wood surfaces [7].

Some substances used in mineralization include Na_2SiO_3, $CaCl_2$, or $Al_2(SO_4)_3$ [8,9], which have also been employed to protect wood against fire, insect attack, or fungal infestation. Other pre-treatments studied include calcium chloride solution [10]; aqueous calcium hydroxide solution [11]; or combinations of sodium silicate and aluminum sulfate solution, sodium silicate and calcium chloride solution, or calcium chloride solution [12].

The use of wood in cementitious materials offers advantages not only in terms of economics but also environmentally [11]. Vegetable "aggregates" are competitively priced and, unlike mineral alternatives such as sand, are renewable resources. Mortars incorporating vegetable biomass efficiently sequester carbon dioxide; approximately 200 to 300 kg of wood residues per cubic meter of mortar can immobilize around 500 kg of carbon dioxide in the cement matrix. This carbon dioxide would otherwise be emitted into the atmosphere if the wood were burned. Therefore, the valorization of waste and its environmental benefits constitute significant advantages of using lightweight aggregates in cement-based materials [11].

In line with the growing emphasis on sustainable materials, various types of lightweight aggregates are being explored for concrete, including wood chips [13], lightweight crushed bricks [14,15], waste glass [16], polyethylene terephthalate (PET) waste [17,18], lightweight expanded clay aggregates [19], styrene butadiene rubber (SBR) or polyurethane (PU) waste particles, rubber [20], polystyrene [21,22], and polyethylene [23].

The use of sawdust as a partial substitute for sand in concrete mixes has been investigated by various studies. Research by Osei and Jackson [24] suggests that sawdust can be used in non-structural concretes where compressive strength is not critical. Bdeir [25] found that replacing 10% of the sand with sawdust can increase the compressive strength of concrete. Conversely, studies such as that by Oyedepo et al. [26] suggest that replacing more than 25% of the sand with sawdust can have a negative impact on the strength and density of the concrete. Overall, sawdust shows potential as a material for lightweight concretes, especially with moderate replacements and careful consideration of its effects on concrete properties [27–29].

The use of sawdust in the construction industry can be beneficial for creating sustainable and environmentally friendly building materials, reducing CO_2 emissions associated with natural materials, and preserving non-renewable resources. It is suggested that developing countries consider sawdust as a valuable byproduct rather than waste. However, sawdust-based compounds may have limitations, so appropriate measures are needed to improve these properties [30].

In this study, the potential of using olive tree pruning sawdust (OTPS) as a partial substitute for sand in the production of lightweight mortars is investigated. The main motivation stems from the need to find sustainable applications for olive pruning waste, given the significant volume of biomass generated annually. The underlying hypothesis is that the incorporation of OTPS, especially when pre-treated with calcium hydroxide, can enhance the properties of mortars without compromising their strength and durability.

This study aims to contribute to the field of sustainable construction materials by evaluating how variations in the quantity and treatment of OTPS affect the physical and mechanical characteristics of the resulting mortars. It is expected that the findings of this study will provide valuable information for the development of new technologies for valorizing agricultural waste and creating more ecological construction materials.

The methodology involved manufacturing mortars with different proportions of sand substitution by OTPS, both in wet form and treated with calcium hydroxide, followed by a detailed analysis of their properties after curing periods of 7 and 28 days. The physical and mechanical characterizations conducted will help determine the potential practical applications of these lightweight mortars in various construction areas.

2. Materials and Methods

2.1. Characterization of Mortar Raw Materials

The chemical composition of Portland cement type CEM II/A-L 42.5 R (Holcim) was determined using X-ray fluorescence (XRF) on a Philips Magix Pro spectrometer (PW-2440, Amsterdam, The Netherlands). The crystalline phases were evaluated using X-ray diffraction with an automatic X'Pert Pro MPD diffractometer (PANalytical, Almelo, The Netherlands) equipped with a primary Ge (111) monochromator, utilizing monochromatic Cu Kα radiation (λ = 1.5406 Å) and an X'Celerator detector. The carbonate content in the cement was determined via calcimetry. Elemental analysis was performed using a Thermo Finnigan Elementary Analyzer Flash EA 1112 HNS-O system. The Blaine method was employed to determine the specific surface area of the raw materials [31]. Relative density was obtained using the Le Chatelier volumetric method.

The content of cellulose and hemicellulose in the OTPS was calculated by the percentages of neutral detergent fiber (NDF) and acid detergent fiber (ADF) following the method proposed by Van Soest and Wine [32].

2.2. Mortar Preparation and Testing

Mortars were prepared with cement type CEM II/A-L 42.5 R and a water/cement ratio of 0.5 according to UNE standards [33]. The olive tree pruning was crushed and sieved. The fraction used was the one considered sawdust, which is what passes through the 0.3 mm sieve. The sand (CEN DIN-EN-196–1) was partially replaced with different volumes of OTPS (10, 25, and 50%). Two series of mortars were made with the same amount of OTPS but with different pretreatments (water or a 10% solution of calcium hydroxide). The mixing procedure used was defined by the standard UNE-EN 1015-3 (2000) [34]. The mixtures used in mortar production are shown in Table 1. Six prismatic specimens measuring 40 × 40 × 160 mm were manufactured for each mortar mixture in steel molds. Curing was conducted in a chamber at 20 °C and 95% relative humidity for 7 and 28 days. The mortars were designed as CSW-xOTP, where x indicates the OTPS volume percentage. "UT" stands for OTPS pre-soaked with water, and "T" stands for OTPS treated with calcium hydroxide.

Table 1. Composition of the mortar mixes.

Mortars	OTPS (g)	Sand (g)	Water (g)	Cement (g)
CSW-0OTP	0	1350	225	450
CSW-10OTP	22.9	1215	225	450
CSW-25OTP	57.25	1012.5	225	450
CSW-50OTP	114.5	675	225	450

Once the mortars were manufactured, the physical and mechanical properties were studied after 7 and 28 days of curing. The bulk density and water absorption by capillarity were determined according to UNE-EN 1015-10 (2020) [35] and UNE-EN 1015-18 (2003) [36], respectively. Volumetric shrinkage was obtained by measuring the dimensions of mortars before and after the cured stage using a caliper with a precision of ±0.01 mm. The mechanical properties were determined using a Universal Testing Machine MTS 810 following the standards of UNE-EN 1015-11 (2020) [37]. The fracture surfaces after bending tests were analyzed by stereoscopic microscopy (BMS S-05-L 76095).

2.3. Data Analysis

Microsoft Excel software 2019 version has been used for the statistical treatment of the experimental data. The results are expressed as the mean value, followed by the standard deviation. Also, the t-Student (*t*-test) statistic was utilized to assess the statistical significance of observed differences in mean values of the tested OTPS mortar characteristics.

3. Results and Discussion

3.1. Characterization of the Raw Materials

Table 2 shows the characteristics of the raw materials used in the manufacturing of the mortars.

Table 2. Characteristics of the raw materials.

Cement	**Humidity (%)**	**pH**	**Carbonates (%)**	**Specific Area (cm^2/g)**	**Relative Density (g/cm^3)**
	0.25%	11.8	16.98 ± 0.96	3670	2.840
OTPS	**Humidity (%)**	**Ash (%)**	**Cellulose (%)**	**Hemicellulose (%)**	**Lignin (%)**
	4.49	0.178	18.51	20.71	23.67

The chemical composition of the Portland cement was determined by XRF (Table 3). Portland cement is rich in CaO (58.8%) with significant quantities of SiO_2 (21.4%). Lower quantities of Al_2O_3 (5.9%) and Fe_2O_3 (3.9%) are also present, highlighting the presence of SO_3 sulfates (4.0%).

Table 3. Chemical composition of the Portland cement.

	Oxide Content (%)
SiO_2	21.33
Al_2O_3	5.89
Fe_2O_3	3.87
CaO	58.32
MgO	1.39
K_2O	0.88
Na_2O	0.91
MnO	0.06
TiO_2	0.43
P_2O_5	0.08
SO_3	4.03
ZnO	-
Cl	0.08
Sr	0.07
Cr	0.02
Ni	0.01
Cu	0.03
Zn	0.03
Ba	0.07
Zr	82.7
LOI	2.61

The particle size distribution of the pruning waste matches that of standard sand. The average particle size (D_{50}) ranged from 10.64 to 64.00 µm. The particle distribution of Portland cement consists of 86.30% sand-sized particles, 1.75% silt-sized particles, and 11.95% fine particles (<2 mm). Ninety percent of the cement particles are below 35.56 microns. This fine particle size influences pozzolanic activity due to the increased particle surface area and hydraulic reaction rate.

The CNHS analysis shows that the Portland cement does not contain significant amounts of nitrogen; the hydrogen content is 0.160%, and the sulfur content originates from the decomposition of calcite (0.657% carbon content).

The chemical composition of Portland cement was determined by XRF and shows high levels of CaO (58.8%) and SiO_2 (21.4%). It contains lower amounts of Al_2O_3 (5.9%) and Fe_2O_3 (3.9%), with sulfate presence at 4.0%.

The XRD data of the Portland cement (Figure 1) indicate the presence of tricalcium silicate or alite (C_3S), dicalcium silicate or belite (C_2S), and a minor content of tricalcium saliminate $3\,CaO{\cdot}Al_2O_3$ (C_3A) and tetracalcium aluminoferrite $4\,CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$ (C4AF).

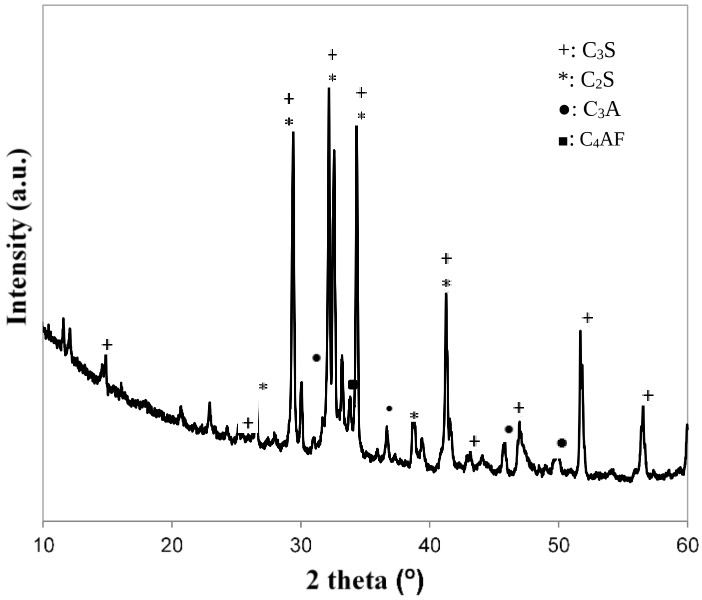


Figure 1. XRD pattern of Portland cement.

3.2. Characterization of the Olive Tree Pruning Sawdust Mortars

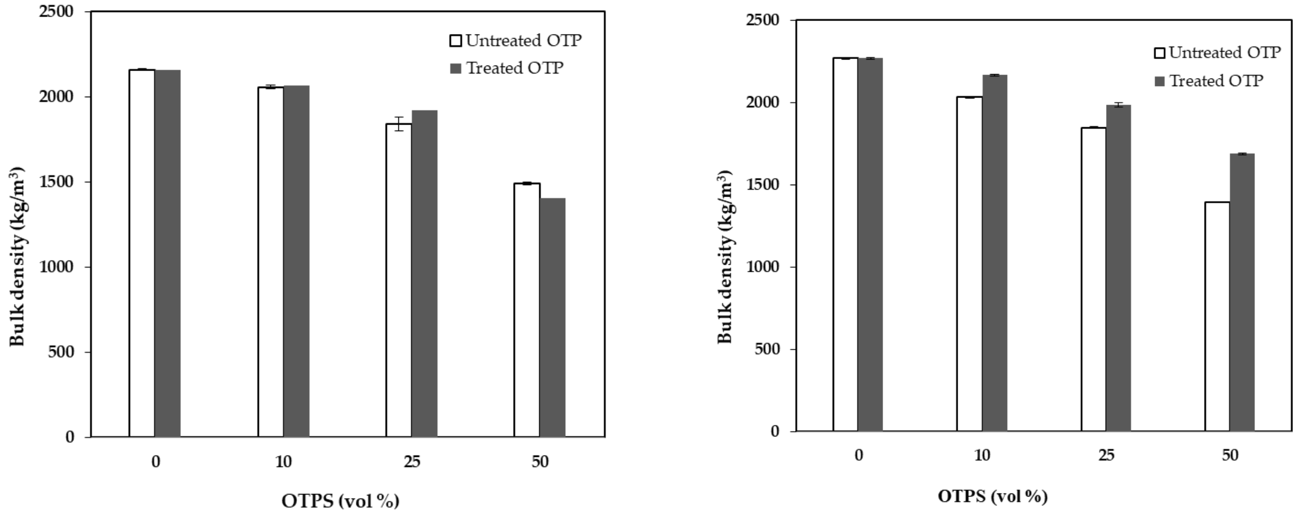
The bulk density of the mortar primarily depends on its components, sand and OTPS, as well as their particle size distribution and the volume they occupy in the mix. Additionally, the water/cement ratio of the mortar affects its bulk density, as it implies a more porous mortar.

Overall, the bulk density in the hardened state of the mortars decreased with increasing OTPS content, both for the control mortar and the mortars containing 10% to 50% of treated or untreated OTPS. This decrease in bulk density may be attributed to the lower density of OTPS (305 kg/m^3) compared to sand (1800 kg/m^3). At 28 days of curing, standard mortars have a bulk density of 2267 kg/m^3, decreasing by 38.4% and 25.6% with the addition of 50% volume of untreated and treated OTPS, respectively (Figure 2). In all cases, the bulk density of mortars incorporating treated OTPS is higher than that of mortars incorporating untreated OTPS, possibly due to the increased hygroscopic nature of the treated biomass owing to its mineralization. However, the differences observed between the untreated OTPS mortars and treated OTPS samples are not statistically significant (Appendix A). Considering that the maximum bulk density for lightweight mortars is 1800 kg/m^3, only mortars containing 50% olive pruning waste can be classified as belonging to this class. Similar results have been found by other authors who incorporate wood as a substitute for sand [38].

The ability of a mortar to retain water inside depends on the amount and configuration of its porosity, so studying water absorption by capillarity can indicate the capillary structure of the material. If the mortar is permeable to water, it will be transferred inside, causing moisture to appear due to filtration.

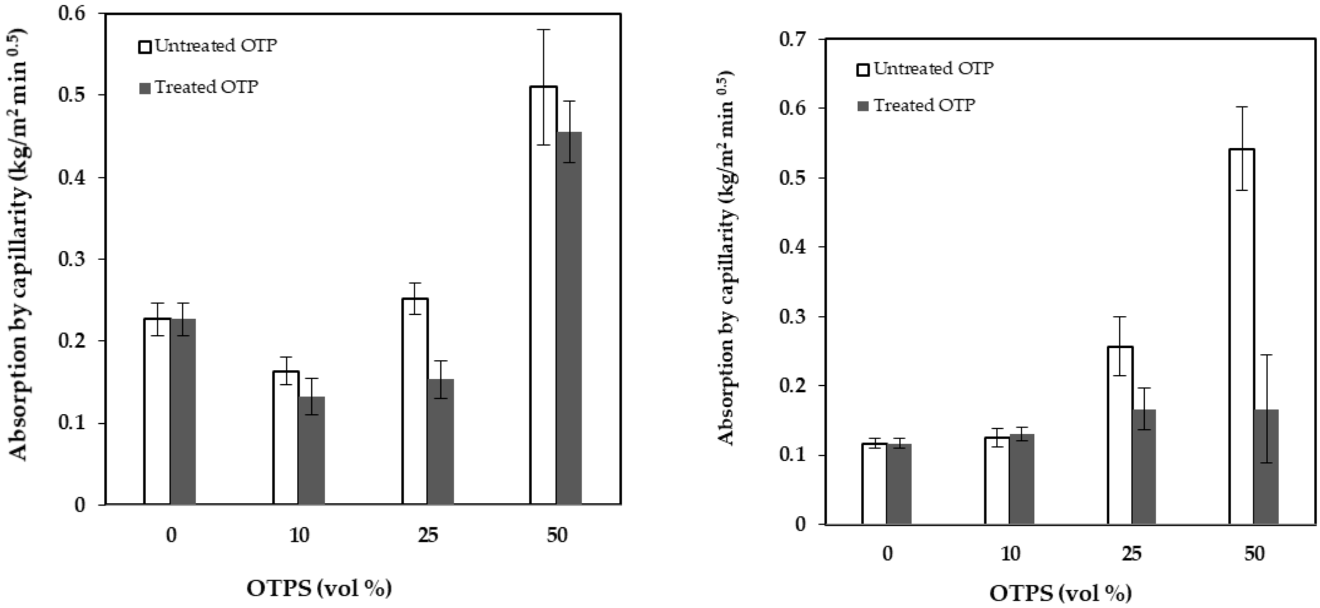
Figure 3 shows that the addition of OTPS (10% and 25% by volume), both treated and untreated, results in a decrease in the coefficient of water absorption by capillarity at 7 days of curing. This could indicate that the treatment with an aqueous solution of $Ca(OH)_2$ of olive tree pruning sawdust makes the biomass more hygroscopic. However, samples with a 50% volume content of OTPS had higher total porosity than the control samples. For the control samples, water absorption by capillarity decreased by 49% over time, indicating that after 7 days of curing, hydrated calcium silicates, or CSH phases, continue to form, resulting in a more compact pore network. The coefficient of water absorption by capillarity for mortars containing OTPS waste showed similar behavior at both curing times, decreasing significantly with the addition of a 50% volume of untreated pruning waste. In contrast, significant differences were observed with the addition of a 50%

volume of treated pruning waste, resulting in a maximum porosity value. The differences observed between the untreated OTPS mortars and treated OTPS samples are statistically significant (Appendix A).



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

Figure 2. Bulk density of OTPS mortars: (**a**) 7 days of curing; (**b**) 28 days of curing.



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

Figure 3. Absorption by capillarity of OTPS mortars: (**a**) 7 days of curing; (**b**) 28 days of curing.

Figure 3 shows that the addition of 10% OTPS, both treated and untreated, as well as the mortar with 25% of treated OTPS, resulted in a decrease in the coefficient of water absorption by capillarity at 7 days of curing. However, with higher incorporations of OTPS, an increase in absorption occurs. These results are expected due to the ability of OTPS to absorb water. On the other hand, at 28 days, an increase in water absorption is observed with the increase of OTPS in all percentages. However, this increase is lower, especially in the mortars with treated OTPS. This could indicate that treatment with an aqueous solution of $Ca(OH)_2$ makes the OTPS less hygroscopic. The differences observed between the untreated OTPS mortars and the treated OTPS samples are statistically significant for the mortars with 25% and 50% OTPS (see Appendix A for details).

During cement curing, expansions and contractions occur in the mortar, potentially leading to the appearance of cracks. Table 4 presents the data on volumetric shrinkage of samples incorporating untreated and treated OTPS after 28 days of curing. It can be observed that the control samples experienced a volumetric shrinkage of 0.30%. The addition of increasing amounts of treated and untreated OTPS sawdust resulted in a change in this property by causing the specimens to expand, with greater expansion observed when the olive pruning is untreated, i.e., in its natural state. The expansion of the samples with OTPS may be due to the fact that olive pruning sawdust is less dense than sand and to the lower water absorption of the OTPS (pre-soaked in water or pre-soaked in an aqueous solution of calcium hydroxide), which requires less water addition to the mixture to achieve the same consistency.

Table 4. Volumetric shrinkage of OTPS mortars after 28 days of curing.

	Shrinkage (%)	
Mortars	**Untreated [(a)]**	**Treated [(b)]**
CSW-0OTP	0.296 ± 0.080	
CSW-10OTP	−0.295 ± 0.069	−0.174 ± 0.078
CSW-25OTP	−0.503 ± 0.095	−0.225 ± 0.032
CSW-50OTP	−0.547 ± 0.078	−0.249 ± 0.095

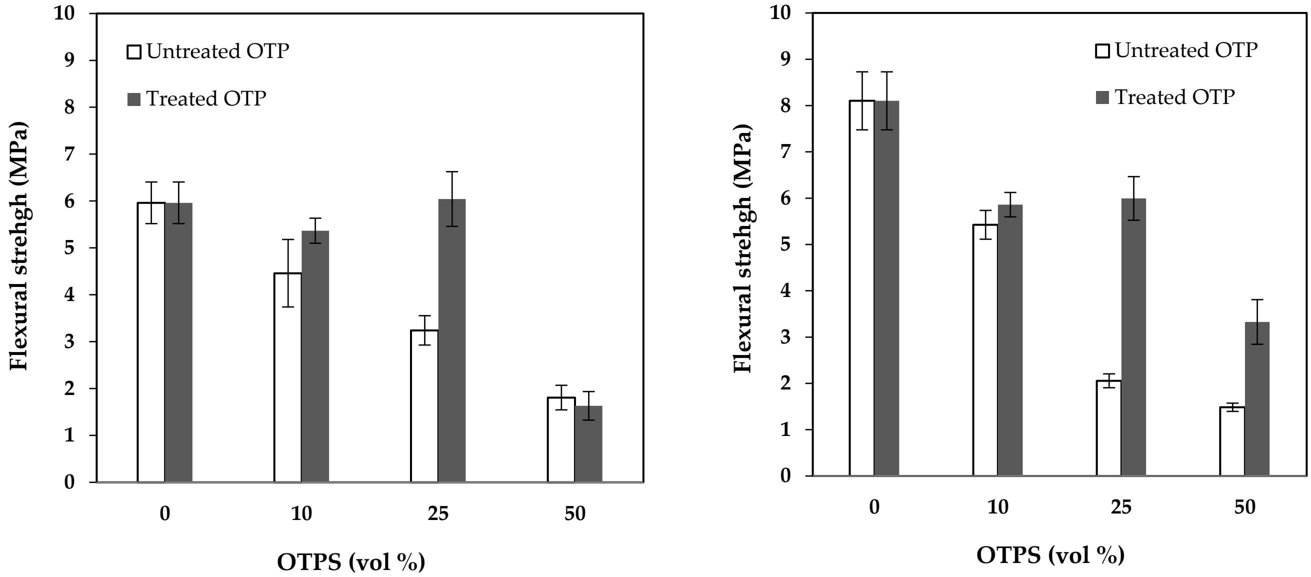
[(a)] Untreated: pre-soaked in water. [(b)] Treated: pre-soaked in an aqueous calcium hydroxide solution.

The flexural strength of the mortars is shown in Figure 4. All mortars with OTPS exhibit lower flexural strength than the control mortar. In mixes incorporating untreated OTPS, a decrease in flexural strength is observed with the amount of biomass at 7 and 28 days of curing. However, it can be observed that the decrease is greater over time of curing because for mortars containing 10 vol. % of OTPS, there is a decrease of 25.1% at 7 days of curing, which increases to 33% at 28 days of curing. A similar behavior is noted for the rest of the incorporations. It is also observed that, except in the case of 10% vol of OTPS, the flexural strength decreased over time of curing, indicating that the OTPS had not integrated during cement hardening in the material and concentrated stresses, significantly worsening the properties.

In the case of mortars with treated OTPS, the curing time improved the properties, so in this case, the mineralization of the pruning increased the pozzolanic activity, and the OTPS was integrated into the material without reducing the properties. It is observed that the flexural strength reaches a maximum with 25% OTPS and then decreases, following a different trend compared to the untreated OTPS series.

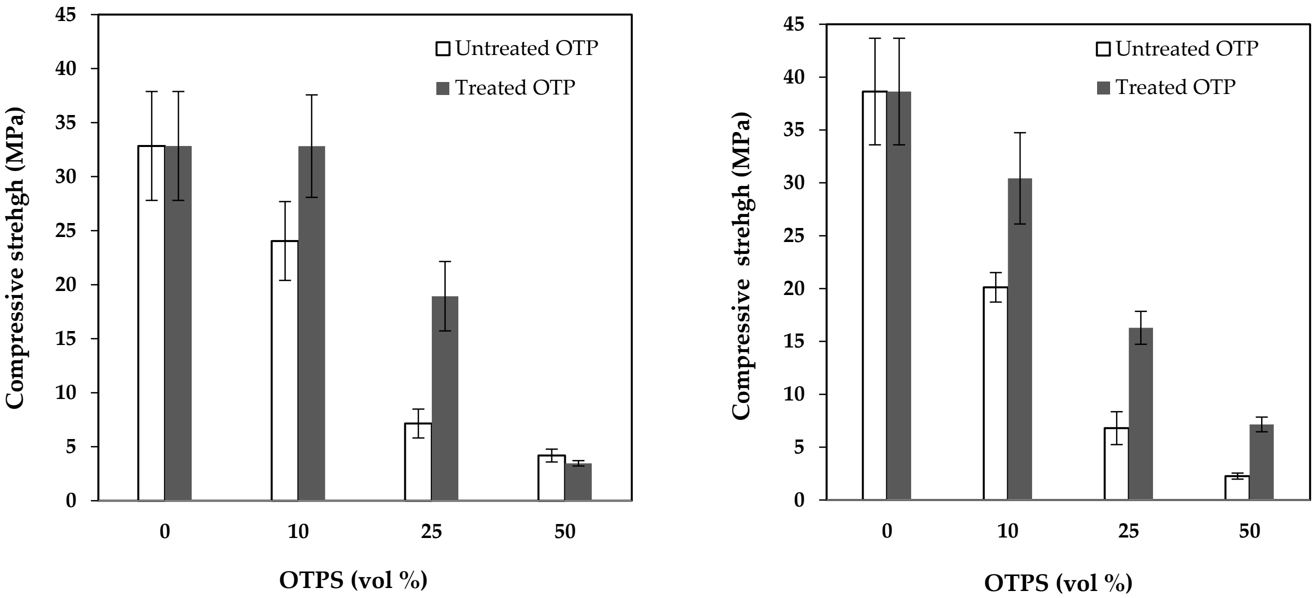
However, the differences observed between the untreated OTPS mortars and treated OTPS samples are not statistically significant (Appendix A).

The compressive strength test results are depicted in Figure 5. A decrease in compressive strength is noticeable with the addition of OTPS, particularly pronounced in the case of untreated OTPS. Vegetable particles exhibit lower chemical compatibility with cement when not subjected to mineralization treatment. Treatment with an aqueous $Ca(OH)_2$ solution for olive pruning sawdust mineralization enabled higher compressive strengths due to enhanced interaction between the sawdust and cement. The differences observed between the untreated OTPS mortars and treated OTPS samples are statistically significant (Appendix A).



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

Figure 4. Flexural strength of OTPS mortars: (**a**) 7 days of curing; (**b**) 28 days of curing.



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

Figure 5. Compressive strength of OTPS mortars: (**a**) 7 days of curing; (**b**) 28 days of curing.

Compressive strength values are lower at 28 days compared to 7 days of curing in mortars incorporating both natural and treated OTPS. Color and consistency changes in mortars suggest inadequate integration of olive pruning sawdust. The reduction in compressive strength as biomass proportion increases may be attributed to poor adhesion at the interface and the reduction of components capable of producing hydrated calcium silicates (CSH), thus reducing the volume of hydrated cementitious material in the mortar.

In contrast to the control mortar, mortars with OTPS exhibited higher compressive strength at 7 days of curing, possibly due to a faster biomass reaction with the cement. Incorporating 10% treated OTPS did not decrease resistance at 7 days, with a 21% decrease at 28 days of curing—a much lower loss than with 10% untreated OTPS (48%). However, all other additions resulted in clear property losses.

Mortars containing treated OTPS showed higher compressive strength after 28 days of curing, likely due to increased biomass reactivity with the cement. The UNE-EN 998-1 (2018) standard [39] specifies a minimum compressive strength of 6 MPa for plastering, rendering, and masonry applications. Therefore, except for mortars containing 50% untreated OTPS, all others meet these design requirements. The most suitable performance, akin to the control sample, is achieved with a 10% addition of OTPS.

The ratio between flexural and compressive strength for the same mixture and curing time averaged 0.20 (0 vol %), 0.26 (10 vol %), 0.30 (25 vol %), and 0.65 (50 vol %) for mortars with natural and pre-soaked olive pruning sawdust in aqueous calcium hydroxide solution after 28 days of curing, respectively. This last value (0.19) aligns with literature data for conventional mixtures [40], suggesting the fibrous structure of olive pruning sawdust may be beneficial under tensile stress in cement mortar.

The quality of the interface between cement paste and treated and untreated OTPS particles was observed by a stereoscopic microscope. As can be seen in Figure 6, better adhesion at the treated OTPS interface is observed, probably due to the effectiveness of the wood mineralization process carried out by the solution enriched with calcium hydroxide. The observed pores are smaller, the proportion of open pores is smaller, and the proportion of open pores in treated OTPS mortars is lower, resulting in higher compressive strength.

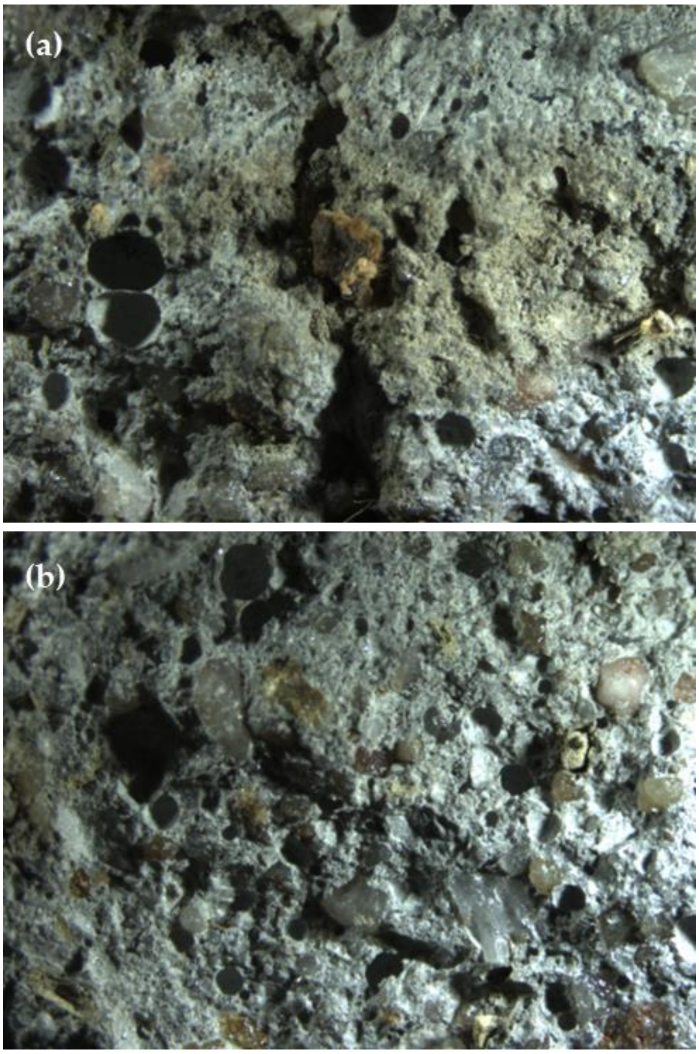


Figure 6. Image of the mortar surface with 10 vol % of OTPS at 28 days of curing. (**a**) OTPS without treatment, pre-soaked in water; and (**b**) OTPS treated, pre-soaked in an aqueous calcium hydroxide solution.

4. Conclusions

Based on the results of this experimental study, several key conclusions emerge:

The bulk density of mortars containing OTPS decreased as the volume of biomass increased, primarily due to the lower density of OTPS compared to sand. Conversely, mortars incorporating treated olive tree pruning sawdust exhibited a higher bulk density, likely attributed to mineralization that increased its hygroscopic nature. Only mortars with 50% volume of OTPS met lightweight criteria (bulk density below 1800 kg/m^3), with compressive strength exceeding 6 MPa achievable only with treated OTPS using a calcium hydroxide solution.

Capillary absorption and volumetric contraction after 28 days of curing indicated increased porosity and expansion in mortars, particularly notable in untreated samples due to the lower density of the biomass and reduced water absorption of pre-soaked OTPS.

Mortars containing treated OTPS showed higher mechanical properties compared to those with untreated OTPS. While the addition of 50% volume of OTPS significantly reduced mechanical properties, all mortars with treated sawdust met standards, whereas only 10% volume of untreated OTPS could be added to achieve compliant mechanical properties. The optimal biomass incorporation rate was determined to be 10% volume of treated OTPS, yielding compressive strength values of 30.40 MPa comparable to control mortars (38.64 MPa) at 28 days of curing, significantly exceeding the regulatory threshold of 6 MPa.

The reuse of OTPS offers substantial environmental benefits by incorporating recycled biomass into mortar for building construction. This recycling adds value compared to energy recovery or composting while also reducing energy consumption in construction and the production of thermally insulating materials, providing a practical solution to energy consumption challenges.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Table A1. Seven days.

Sample	Treatment	Bulk Density kg/m^3	Capillarity	Flexural Strength MPa	Compressive Strength MPa
CSW-10OTP	UT	2.057 ± 0.011	0.132 ± 0.018	4.460 ± 0.882	24.043 ± 3.997
CSW-10OTP	T	2.067 ± 0.011	0.163 ± 0.024	5.367 ± 0.327	32.824 ± 5.194
p-value (α = 0.05)		0.360	0.094	0.225	0.038
CSW-25OTP	UT	1.389 ± 0.051	0.252 ± 0.021	3.241 ± 0.384	7.147 ± 1.464
CSW-25OTP	T	1.921 ± 0.014	0.153 ± 0.025	6.042 ± 3.164	18.931 ± 3.520
p-value (α = 0.05)		0.148	0.010	0.247	0.011

Table A1. *Cont.*

Sample	Treatment	Bulk Density kg/m^3	Capillarity	Flexural Strength MPa	Compressive Strength MPa
CSW-50OTP	UT	1.491 ± 0.008	0.510 ± 0.078	1.808 ± 0.321	4.181 ± 0.651
CSW-50OTP	T	1.409 ± 0.005	0.455 ± 0.041	1.632 ± 0.373	3.463 ± 0.272
p-value (α = 0.05)		0.091	0.020	0.545	0.077

Table A2. Twenty-eight days.

Sample	Treatment	Bulk Density kg/m^3	Capillarity	Flexural Strength MPa	Compressive Strength MPa
CSW-10OTP	UT	2.032 ± 0.005	0.125 ± 0.014	5.425 ± 0.380	20.118 ± 1.527
CSW-10OTP	T	2.166 ± 0.007	0.130 ± 0.011	5.860 ± 0.323	30.425 ± 4.729
p-value (α = 0.05)		0.090	0.540	0.249	0.018
CSW-25OTP	UT	1.847 ± 0.006	0.257 ± 0.047	2.056 ± 0.184	6.797 ± 1.703
CSW-25OTP	T	1.985 ± 0.014	0.167 ± 0.033	5.995 ± 0.577	16.289 ± 1.706
p-value (α = 0.05)		0.091	0.002	0.092	0.010
CSW-50OTP	UT	1.396 ± 0.004	0.167 ± 0.086	1.485 ± 0.109	2.262 ± 0.313
CSW-50OTP	T	1.687 ± 0.004	0.542 ± 0.066	3.327 ± 0.591	7.149 ± 0.763
p-value (α = 0.05)		0.089	0.001	0.105	0.009

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