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Cement-Based Mortars with Waste Paper Sludge-Derived Cellulose Fibers for Building Applications

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Abstract: This study assesses the mechanical properties of mortars incorporating waste paper sludge-derived cellulose fibers. Compression and flexural tests were carried out on specimens prepared with cellulose fibers at different proportions, ranging from 0% to 2% of the total weight of the solid mortar constituents (cement, sand, and lime). In addition, a comparative analysis was carried out to evaluate the influence of the preparation method on the mechanical properties of the mortars. To this end, two series of mortars were studied: one prepared following a rigorous control of the preparation parameters and the other made without systematic parameter control to simulate typical on-site conditions. Finally, the applicability of both traditional and eco-friendly mortars in the construction of small-scale masonry walls was assessed through compression tests. Overall, the mechanical properties of mortars with cellulose fibers were comparable to those with 0% waste material, regardless of the production process. Regarding the compressive behavior of masonry walls, experimental tests showed significant similarities between specimens made with traditional and eco-friendly mortar. In conclusion, incorporating cellulose fibers into cement-based mortar shows considerable potential for building applications, enhancing the environmental benefits without compromising the mechanical behavior.

Keywords: cellulose fibers; cement-based mortar; masonry wall; waste material; waste paper sludge

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1. Introduction

The construction industry has been increasingly focusing on the development of sustainable practices to address the environmental challenges posed by traditional cement-based materials [1–6]. The production of cement, a key component of cement-based materials, accounts for a substantial portion of global carbon dioxide (CO_2) emissions [7–9]. Indeed, the calcination of limestone to produce clinker releases significant amounts of CO_2, around 850 kg per ton of clinker, contributing to the greenhouse effect and global warming. Moreover, traditional cement production consumes vast amounts of non-renewable resources, such as limestone, clay, and fossil fuels, leading to resource depletion and habitat deterioration [10,11].

These issues have prompted extensive experimental research into the development of eco-friendly cement-based materials that can reduce the environmental impact while maintaining or even enhancing the mechanical properties essential for construction applications. One promising alternative to traditional solutions involves the incorporation of industrial byproducts and waste resources into cement-based materials [12–14]. In particular, paper sludge-derived cellulose fibers, a residual product of the paper recycling industry, have emerged as a potential candidate for such incorporation owing to their potential to enhance mechanical performance while concurrently mitigating the environmental impact [15–17]. For instance, only about 100,000 tons/year of deink paper sludge is produced in Italy, of which about 46% is disposed of for incineration and 4% is disposed of in landfills, with considerable costs but especially with significant environmental repercussions. Furthermore, as indicated in [18], the total production of paper and paperboard waste globally reached around 417.3 million metric tons in 2021. In this context, by incorporating paper sludge-derived cellulose fibers into cement-based materials (e.g., mortar), it is possible to divert them from landfills, reducing the demand for virgin resources, conserving forests and ecosystems, and mitigating the environmental impacts associated with their extraction. It is also worth mentioning that mixing paper sludge-derived cellulose fibers and cement-based mortar aligns with the principles of the circular economy, where resources are continuously reused and recycled. Apart from the environmental benefits, the incorporation of this waste resource into cement-based materials presents the potential for improving the material performance. Indeed, cellulose fibers effectively bridge microcracks within the mortar, thereby enhancing the tensile and flexural strength of the material [19]. In addition, cellulose fibers can help mitigate the shrinkage cracks that often occur in cement-based materials during the curing process, contributing to an increase in durability, which can particularly be advantageous in harsh environments [20].

Although there are advantages, challenges related to fiber dispersion, workability, and interface bonding emphasize the need for careful consideration during the mix-design and production of this eco-friendly material. For instance, poor dispersion can lead to localized variations in the mechanical properties, compromising the overall performance of the material. In addition, the inclusion of cellulose fibers can alter the rheological properties of the fresh mix, potentially resulting in reduced workability. This limitation highlights the importance of defining a proper mix design to balance the fiber content with the workability requirements. Moreover, ensuring strong interfacial bonding between the cellulose fibers and the cement paste is crucial for obtaining optimal mechanical performance. Inadequate bonding may lead to weak interfaces, limiting the load transfer and reducing the overall effectiveness of the additions.

Despite the importance of this topic, the information available in the literature about the mechanical performance of cement-based materials mixed with paper sludge-derived cellulose fibers remains limited [20–23].

For instance, Azevedo et al. [20] evaluated the viability of integrating paper sludge waste materials into cement-based mortars. The experimental investigation involved the replacement of lime with waste sludge at proportions of 5%, 10%, 15%, and 20% of the cement weight. The main objective of the authors was to provide further insights into parameters such as the consistency index, heat of hydration, entrapped air content, water retention, mechanical strength, and capillarity coefficient. Overall, the authors found that for applications such as wall coatings and ceiling mortars, the percentage of sludge should not exceed the threshold value of 10%. This is explained by the fact that higher incorporation levels lead to reduced mechanical strength (not in line with market demands). According to the authors, the reduction in the mechanical properties of the material can be attributed to the waste material's reduced heat of hydration, which leads to a slower reaction rate. On the other hand, higher amounts of waste material, exceeding 10%, are suitable for utilization in mortars specifically designated for minor masonry repairs (not requiring strict property control). Rezende et al. [21] studied the impact of incorporating waste paper cellulose fibers into cement-based mortar mixtures at proportions of 5%, 10%, 15%, and 20% over cement weight. Concerning the properties at a fresh state, the authors found that the inclusion of cellulose fibers within the mortar resulted in a reduction in the density of 4.3% and 7.2% for mixtures containing 5% and 10% cellulose fibers, respectively. In terms of the mechanical response (hardened state, 7-day curing period), the results obtained showed that the presence of fibers leads to a reduction in both the 7-day compressive and flexural tensile strength proportional to the amount of fibers incorporated. On the other hand, the fibers' ability to effectively limit crack propagation and distribute stress resulted in better results in the post-crack behavior, showing increased deformability and tenacity (compared to traditional cement mortar).

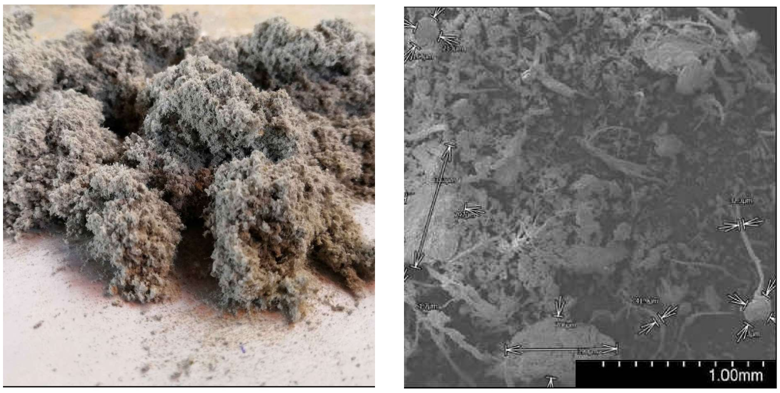
The physical and mechanical properties of mortar samples containing varying quantities of deink paper sludge were also studied by Yan et al. [22]. The authors observed that the incorporation of deink sludge into cement-based mortar at a consistent water-to-cement ratio notably decreased the flow characteristics and extended the setting time. In addition, as the dosage of sludge increased, the water absorption and volume of the permeable voids within the cement mortar increased, consequently leading to a reduction in the bulk density. The retained compressive strength of mortar specimens (after 90 days of curing) with sludge at proportions of 2.5% and 20% was 83% and 62%, respectively, compared to the reference mortar.

The literature review reported above suggests that waste cellulose fibers, often relegated to disposal or incineration, hold significant potential as additions for cement-based mortars. However, the limited information about the mechanical properties of this eco-friendly material is still hindering its application in sustainable construction practices. In this context, the aim of this work is to fill this research gap by providing a comprehensive study of the mechanical performance of cement-based mortar incorporating paper sludge-derived cellulose fibers. First, compression and flexural tests were performed on cement-based mortar specimens without cellulose fibers (0%) and reinforced with 1% and 2% of cellulose fibers, by weight of the solid constituents. This analysis is crucial for determining the optimal fiber proportions required to achieve specific mechanical performance, given the wide range of potential applications. Subsequently, the influence of the mixture preparation method on the mechanical behavior of this eco-friendly mortar was also assessed. To this end, two types of mortars were produced: one with rigorous control of all the preparation parameters and another without parameter control, simulating on-site conditions during construction processes. Finally, the practical use of this eco-friendly mortar was evaluated by employing it in the construction of masonry walls. In order to achieve this objective, compression tests were performed on 20 small-scale masonry walls: 10 specimens were made with the traditional mortar and the remaining 10 with the eco-friendly mortar incorporating 1% of cellulose fibers. The results obtained from these tests were also used to assess the accuracy of the predictive formulas available in the literature.

2. Experimental Preparation

2.1. Waste Paper Sludge

The conversion of waste paper sludge into cellulose fibers is a crucial step in the sustainable use of this waste material. Indeed, this process represents a key step for the repurposing of a waste product into a valuable resource, ultimately enhancing the mechanical performance of cement-based mortars while promoting environmental responsibility. It is worth mentioning that the cellulose-milled fibers used in this study were obtained through various processing stages developed by other partnership laboratories within a previous research project. The process initiates with the collection of paper sludge, which is obtained from the recycling of paper products. This sludge is a mixture of calcium carbonate (about 65% by weight), paper fibers (about 30%), and moisture (about 5%). The sorted sludge is then mixed with water to create a pulp. Subsequently, mechanical and/or chemical treatments are performed to dislodge and remove ink, coatings, and impurities from the sludge. Once the deinking process is completed, the mixture is subjected to mechanical and centrifugal forces to separate the cellulose fibers from the remaining pulp. This step is necessary to ensure the extraction of clean cellulose fibers while minimizing contamination. After fiber separation, the pulp is then subjected to a grinding process (using a RETCH lab scale hammer mill, Figure 1a). This step is essential for improving the quality and strength of the cellulose fibers. As shown in Figure 1b, the Scanning Electron Microscopy (SEM) analysis shows the presence of both fibers and inorganic particles in the mixture, thus indicating a bimodal distribution. Finally, the cellulose fibers are dried to reduce their moisture content (for 4 h at 105 °C). Adequate drying is essential to prevent microbial degradation during storage and transportation.



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

Figure 1. Deink paper sludge: (**a**) sample of cellulose fibers milled with a hammer mill and (**b**) SEM analysis.

It is worth mentioning that a dimensional analysis of the ground paper sludge was performed by the authors in a previous experimental campaign. Further information about this aspect can be found in [24].

2.2. Materials and Methods

2.2.1. Mortar Specimens

The materials used in this experimental campaign were Portland Cement Type II-B/L, hydraulic lime, river quartz fine sand (size range of 0/2 mm), water, and waste cellulose fibers. Traditional mortars with 0% cellulose fibers were initially prepared to serve as a reference for comparison with eco-friendly mortars. Subsequently, mortars with cellulose fibers at proportions of 1% and 2% of the total weight of the solid constituents were prepared. Considering the few studies on this topic, the authors selected to use relatively small percentages of cellulose fibers, 1% and 2%, percentages similar to those used with other types of fibers, to avoid problems with the dispersion and homogenization of the fibers within the matrix as well as limit a large decrease in the mechanical properties. It is worth mentioning that the mortar constituent materials were added in a 1:1:5 ratio (cement:lime:sand) for all the specimens. As reported in the introduction section, the role of the preparation method in the mechanical performance of the eco-friendly mortars was also assessed. In particular, this aspect was addressed through two distinct approaches: one in which all the preparation parameters were meticulously controlled (series I) and the other that simulated real construction site conditions, where the parameters were not rigorously regulated (series II). In the first series, the fibers were used in a saturated but surface-dry state, aiming to prevent excessive water absorption during the mixing process. This condition was achieved by immersing the fibers in water before mixing and allowed for maintaining a stable water-to-binder ratio for each mortar composition. On the other hand, the cellulose fibers used in the second series were not subjected to any preliminary treatment, and the water-to-binder ratio of the mortar was not controlled during the manufacturing process. These specimens were produced with the aim of achieving the same workability as that of the specimens of series I. The mixing ratios of both the traditional and eco-friendly mortars are listed in Table 1. It is worth noting that each specimen is labeled according to the following nomenclature: (i) type of mortar, traditional (TM) and eco-friendly (CM) mortars; (ii) type of preparation method, series I (I) or II (II); and (iii) cellulose fibers percentage (0, 1, or 2). For instance, the mortar incorporating 1% of cellulose fibers produced in the first series is identified as CM-I-1. Concerning the manufacturing process, all the materials were mixed using a mortar mixer and then used to cast $40 \times 40 \times 160$ mm^3 prismatic specimens. During the casting process, both traditional and eco-friendly mortars were positioned into metallic molds in two layers (Figure 2a), each layer being compacted using a vibrating table. Then, all the specimens were covered with a plastic film and stored in a room with a controlled environment (25 °C and 95% humidity) for one day. Subsequently, they were demolded (Figure 2b) and then reintroduced into the same controlled environment, where they underwent an additional curing period of 28 days.

Table 1. Mixing ratios of traditional and eco-friendly mortars.

Mortars	Cement	Lime	Sand	Cellulose Fibers (%)	W/B
TM-I-0	1	1	5	0	0.50
CM-I-1	1	1	5	1	0.53
CM-I-2	1	1	5	2	0.56
TM-II-0	1	1	5	0	0.50
CM-II-1	1	1	5	1	N.C.
CM-II-2.	1	1	5	2	N.C.

N.C.—Not controlled.

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

Figure 2. Cement-based mortar preparation: specimens in (**a**) fresh and (**b**) hardened state.

After this period, compression and flexural tests were carried out, in accordance with EN 1015-11:2019 [25], to determine the compressive and flexural tensile strengths of the mortars. To this end, 108 (18 × 6 types of mortar) specimens were subjected to a three-point flexural test using the set-up illustrated in Figure 3a.

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

Figure 3. Mechanical characterization tests: (**a**) flexural and (**b**) compression test set-up.

Concerning the compression tests, 216 (36 × 6 types of mortar) specimens having a cross-section of 40 × 40 mm^2 were also tested up to failure using the test set-up depicted in Figure 3b. Both the traditional and eco-friendly mortars were loaded until failure under displacement control at a cross-head displacement speed of 0.3 mm/min using a 100 kN Instron machine.

2.2.2. Masonry Walls

Compression tests were performed on small-scale masonry walls with the aim of evaluating the potential of cement-based mortars incorporating cellulose fibers for structural applications. Figure 4 illustrates the procedure followed for preparing the masonry walls. The specimens were made of modern clay bricks (nominal dimensions of 245 × 120 × 55 mm^3) produced with standard industrial process separated by eco-friendly mortar with 1% of cellulose fibers (CM-II-1 series). This mortar was chosen because it was made using the traditional production method on site and, as will be seen in the results presented later, it is the mortar with cellulose fibers that presents the best performance in terms of mechanical properties. Note that masonry walls with traditional mortar joints were also prepared for comparison; in both cases, the bed joints had a thickness of about 10 mm.

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

Figure 4. Masonry wall preparation: (**a**) application of the mortars and (**b**) bricks soaked in water.

Following the recommendation given in EN 1052-1:1998 [26], the panels were built with dimensions of 510 × 125 × 315 mm^3 (height × thickness × width). Compression tests were carried out, in accordance with EN 772-1:2011 [27], to determine the mechanical behavior of the bricks employed for the construction of the walls. From the results obtained, average values of the compressive strength (f_b = 68.20 MPa) and characteristic compressive strength (f_{bk} = 40.96 MPa) were found. As shown in Figure 4b, the bricks were soaked in water for 2 h to prevent the absorption of the mixing water.

All the masonry walls were tested after 28 days of curing in a controlled temperature environment (25 °C and 95% relative humidity). The test set-up is illustrated in Figure 5. Before testing, all the walls were capped using a leveling mortar and had an average flexural tensile strength of f_{tm} = 8.24 MPa and an average compressive strength of f_{cm} = 38.72 MPa. This procedure was chosen to level the contact surface between the specimen face and the testing machine, thus ensuring a uniform load application. Since the mechanical properties of the leveling mortar were much higher than that of the mortar joints, it is reasonable to assume that the influence of the capping on the result is negligible.

(**a**)

(**b**)

Figure 5. Compression test: (**a**) masonry wall specimen and (**b**) overview of the test set-up.

In terms of instrumentation, the vertical strains of the specimens were measured using four displacement transducers (two for each specimen's side), with a measurement range of 100 mm and a precision of 0.01 mm. The information given by the load cell and displacement transducers was recorded using an HBM data logger at an acquisition rate of 5 Hz. The monotonic compressive load was applied gradually, as recommended by EN 1052-1:1998 [26], using a universal hydraulic compression machine equipped with a 3000 kN load cell. The load was applied using force control at a rate of 0.6 N/(mm^2·min). Ten tests were carried out for each type of mortar, resulting in a total of twenty tests.

3. Results

3.1. Compressive and Flexural Properties of Mortars

Figure 6 presents the representative load vs. cross-head displacement curves obtained from the flexural tests carried out on the series II specimens.

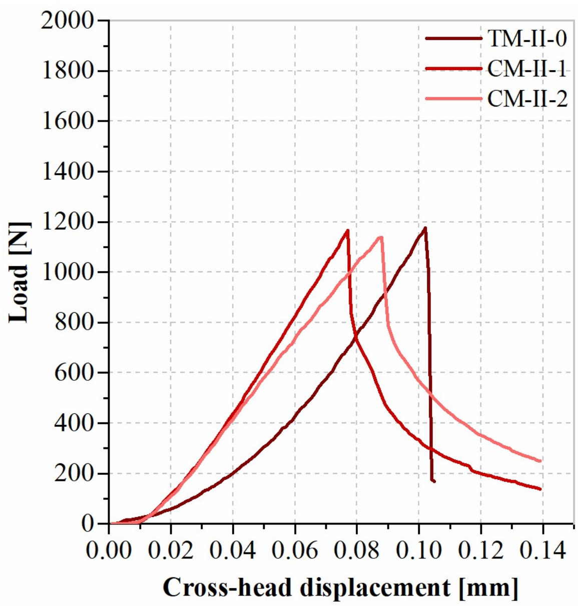


Figure 6. Load vs. cross-head displacement curves for representative flexural mortar specimens.

In general, it can be seen that increasing the percentage of the cellulose fibers within the mortar led to changes in the post-crack behavior of the specimens. The traditional mortars (with 0% of cellulose fibers) exhibited a sudden decrease in the load at the end of the tests.

On the other hand, all the mortars containing 1% and 2% of cellulose fibers continued to deform after the initial crack. This result is explained by the fact that the tensile stresses are transmitted to the fibers incorporated into the mortar, which absorb more energy, allowing the material to deform before collapsing. The influence of the addition of the cellulose fibers and the preparation method on the mechanical properties (both average and characteristic values at 5%) of cement-based mortars is also reported in Table 2 and Figure 7.

Table 2. Compressive and flexural tensile properties of traditional and eco-friendly mortars (average ± standard deviation).

Mortars	f_{tm} [MPa]	$f_{tm,k}$ [MPa]	f_{cm} [MPa]	$f_{cm,k}$ [MPa]
TM-I-0	3.68 ± 0.31	3.08	15.02 ± 0.57	15.02
CM-I-1	3.67 ± 0.26	3.15	13.38 ± 0.45	13.38
CM-I-2	3.52 ± 0.22	3.09	13.46 ± 0.46	13.46
TM-II-0	2.77 ± 0.48	1.86	7.17 ± 0.83	5.55
CM-II-1	2.95 ± 0.33	2.37	7.47 ± 0.52	6.56
CM-II-2	2.30 ± 0.19	1.95	5.14 ± 0.45	4.23

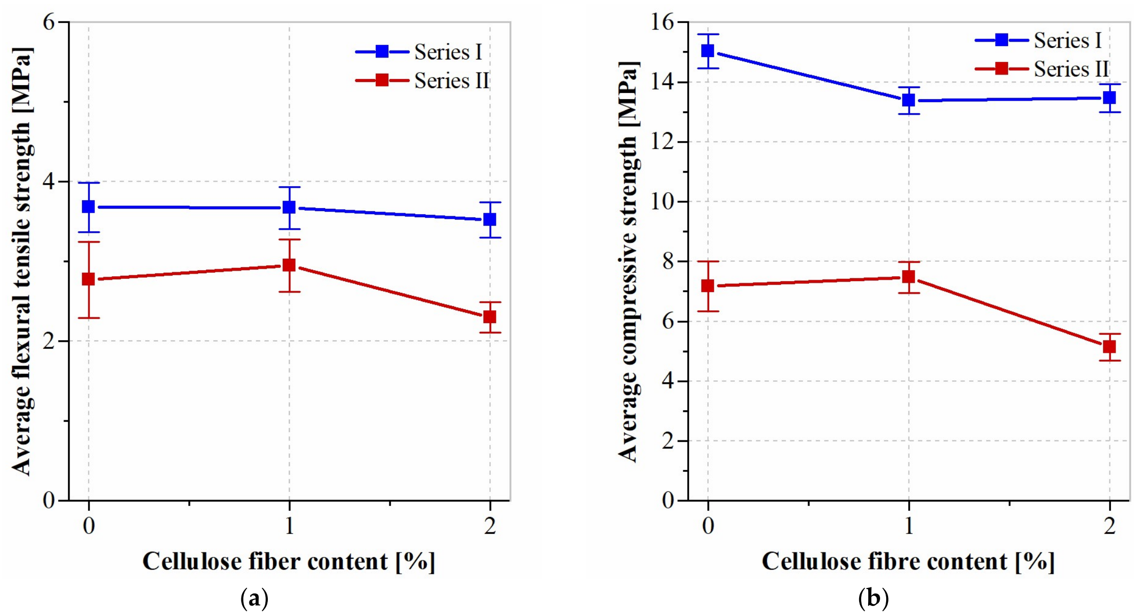


Figure 7. Mechanical property variations of the mortar with cellulose fiber content: (**a**) average flexural tensile strength and (**b**) compressive strength.

Concerning the specimens obtained from series I (CM-I-1 and CM-I-2), the flexural tensile strength values did not present significant variations compared to the traditional mortars (relative differences lower than 5%). These results confirm that in the case of the matrices prepared with a high degree of accuracy, it was possible to achieve a strong fiber–matrix bond, enabling effective stress transfer from the matrix to the fibers. Additionally, the limited variation in the flexural strength observed in this type of mortar can also be indicative of the homogeneous dispersion of fibers within the matrix, resulting in a composite with well-balanced mechanical properties.

Unlike the trend observed in the flexural tensile strength, all the series I mortars incorporating cellulose fibers exhibited compressive strength reductions of almost 10% compared to the traditional mortars (Table 2). As pointed out by [23], this result can be attributed to the increased porosity of the material due to the greater difficulty in releasing the air inside the matrix when cellulose fibers are used.

Regarding the series II specimens (CM-II-1 and CM-II-2), prepared without a rigorous control, they presented a different trend in the variation of the mechanical properties compared to that of the series I specimens. In general, it can be observed that the flexural tensile strength increases between 0% and 1% fiber content, likely due to the bridging effect of the fibers within the matrix. However, when the fiber percentage was increased to 2%, significant reductions in the flexural tensile strength were observed compared to the traditional mortar (approximately 17%). This result can be primarily attributed to a non-uniform dispersion of the fibers within the material. As for the series I specimens, the compressive strength of the specimens of series II also followed also a non-monotonic variation trend with increasing fiber content. In particular, the mortar specimens incorporating 2% of cellulose fibers (CM-II-2) presented compressive strength reductions of 30% compared to the traditional mortar (TM-II-0). In accordance with [15], this result should be related to the increased amount of voids and porosity resulting from the higher water content in the mortar. It is worth mentioning that, as reported in Section 2.2, the cellulose fibers used in the series II specimens were not used in a saturated state; therefore, it is likely that they absorbed more water during the production process. Overall, the results reported in Table 2 highlight the significant potential of cement-based mortars incorporating cellulose fibers as sustainable building materials. Indeed, all the eco-friendly mortars (even those made with a higher % of cellulose fibers) not only exhibit adequate mechanical properties suitable for secondary uses (e.g., landfill layering) but also demonstrate good potential for structural purposes. For instance, all the specimens meet the Italian code [28] minimum requirements of 28-day compressive strength (2.5 MPa) for load-bearing masonry applications.

Nonetheless, it is of paramount importance to perform further analyses to provide a better understanding of the physical and chemical properties of the mortars incorporating cellulose fibers. Indeed, this comprehension is essential for assessing their suitability as cost-effective and sustainable solutions for structural and non-structural applications.

3.2. Compressive Response of Small-Scale Masonry Walls

The compressive stress vs. vertical strain curves of the small-scale masonry walls are reported in Figure 8. Each specimen is labeled according to the following nomenclature: (i) type of element (MW—masonry wall); (ii) type of mortar (TM—traditional mortar; CM—mortar with 1% of cellulose fiber), and (iii) specimen number. Note that the compressive stress was computed as the ratio between the load and the loaded area of the specimens.

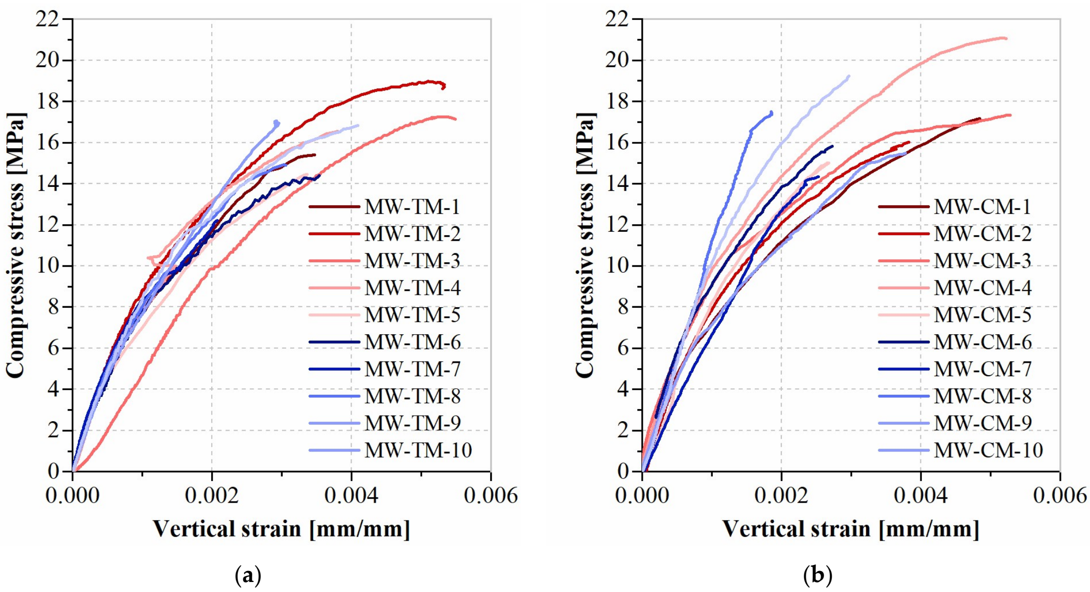


Figure 8. Compressive stress vs. vertical strain curves of masonry walls made with (**a**) traditional and (**b**) eco-friendly mortars.

As shown in Figure 8, all the specimens presented a relatively similar compressive behavior, regardless of the type of mortar considered. In general, the curves present an initial linear behavior (until reaching ~50% of the compressive strength), followed by a certain degree of non-linearity with increasing load levels. The change in the slope of the curve can be associated with microcracks caused by the incompatible elastic characteristics of the bricks and mortar. Once the compressive strength of the specimens was attained, previous cracks expanded, and new vertical cracks occurred along the lateral sides of the specimens (Figure 9).

Figure 9. Typical failure mode observed in the compression tests on masonry walls (example of failure mode observed in specimen MW-TM-1).

It is worth mentioning that the post-peak behavior of the curves is not reported in Figure 8. This is explained by the fact that for safety reasons, the instrumentation was removed after reaching the peak load.

Tables 3 and 4 present a summary of the results obtained with reference to the following parameters: failure load (P_{max}), compressive strength (σ_{max}), elastic modulus (E_m), vertical strain at peak load ($\varepsilon_{v,max}$), and characteristic compressive strength at 5% ($\sigma_{max,k}$). In accordance with EN 1052-1:1998 [26], the elastic modulus of the specimens was computed at one-third of the compressive strength (service load condition).

Table 3. Summary of results obtained in the compression tests of masonry walls made with traditional mortar.

Specimens	P_{max} [kN]	σ_{max} [MPa]	E_m [MPa]	$\varepsilon_{v,max}$ [mm/mm]	$\sigma_{max,k}$ [MPa]
TM-1	981.60	15.40	9854.49	0.0034	12.15
TM-2	1209.84	18.98	10,479.82	0.0054	
TM-3	1099.92	17.25	9748.23	0.0055	
TM-4	1055.28	16.55	9222.61	0.0038	
TM-5	925.44	14.52	8426.44	0.0033	
TM-6	917.64	14.39	8805.95	0.0035	
TM-7	779.16	12.22	11,824.18	0.0020	
TM-8	950.64	14.91	10,455.15	0.0030	
TM-9	1088.64	17.08	9146.66	0.0029	
TM-10	1072.56	16.82	9544.063	0.0040	
Average	1008.07	15.81	9751.04	0.0037	-
Dev.St	121.761	1.910	981.53	0.001	-
C.o.V.	0.121	0.121	0.103	0.28	-

Table 4. Summary of results obtained in the compression tests of masonry walls made with eco-friendly mortar.

Specimens	P_{max} [kN]	σ_{max} [MPa]	E_m [MPa]	$\varepsilon_{v,max}$ [mm/mm]	$\sigma_{max,k}$ [MPa]
TMC-1	1113.48	17.47	8860.97	0.0048	12.91
TMC-2	1020.36	16.01	9121.02	0.0038	
TMC-3	1251.00	19.62	11,234.02	0.0052	
TMC-4	1344.84	21.10	11,203.07	0.0047	
TMC-5	964.08	15.12	9343.20	0.0026	
TMC-6	1007.88	15.81	12,409.26	0.0027	
TMC-7	916.56	14.38	6913.29	0.0025	
TMC-8	1117.56	17.53	11,037.57	0.0018	
TMC-9	987.66	15.49	9431.084	0.0037	
TMC-10	1239.48	19.44	10,670.48	0.0029	
AVG	1096.28	17.20	10,022.40	0.0035	-
Dev.St	142.260	2.232	1586.35	0.001	-
C.o.V.	0.130	0.130	0.15	0.32	-

Overall, it seems that changes in the mortar's compressive strength did not lead to significant variation in the load-bearing capacity of the masonry walls. As expected, the masonry made with the eco-friendly mortar presented slightly higher compressive strength compared to the specimens prepared with the traditional mortar (less than 10%). This result can be associated with the higher compressive strength of the former mortar type. Therefore, it can be concluded that for the specific geometry and material considered in this study, the influence of the cellulose fibers does not have a significant influence on the compressive behavior of the masonry, which is mainly governed by the compressive strength of the bricks.

The results obtained from the experimental tests were also used to assess the ability of an analytical formula available in the literature to predict the characteristic compressive strength of masonry, namely that provided by EN 1996-1-1:2022 [29]. In addition, the accuracy of the Italian code [28], which provides tabulated values to predict the characteristic compressive strength of masonry depending on the characteristic compressive strength of the bricks and type of mortar, was also evaluated. In accordance with EN 1996-1-1:2022 [29], the characteristic compressive strength of the masonry can be determined using the following equation:

$$\sigma_{max,k,\ EN} = K f_b^{\alpha} f_{cm}^{\beta} \quad (1)$$

where K is the shape factor, which depends on the type of bricks and mortar; f_b is the normalized compressive strength of the brick (obtained by converting the average compressive strength using EN 772-1:2011 [21]); f_{cm} is the compressive strength of the mortar; and α and β are constants. For the type of masonry studied herein, the values of K, α, and β were set as 0.55, 0.70, and 0.30, respectively. The values estimated using the formula given by EN 1996-1-1:2022 [29] ($\sigma_{max,k,EN}$), as well as those provided by the Italian code ($\sigma_{max,k,IC}$), are listed in Table 5 together with the average ($\sigma_{max,avg}$) and characteristic ($\sigma_{max,k}$) experimental values. The predictive value of the characteristic compressive strength of the masonry wall, obtained using a relationship proposed by the author ($\sigma_{max,k,prop}$), as explained ahead in the text, is also reported in Table 5.

Table 5. Experimental results vs. analytical estimates: compressive strength.

Specimens	$\sigma_{max,avg}$ [MPa]	$\sigma_{max,k}$ [MPa]	$\sigma_{max,k,EN}$ [MPa]	$\sigma_{max,k,prop}$ [MPa]	$\sigma_{max,k,IC}$ [MPa]
MW-TM	15.81	12.15	16.53	12.15	10.66
MW-CM	17.20	12.91	16.76		

Overall, it can be seen that the Italian code provided conservative predictions for both the MW-TM and MW-CM specimens, whereas the values obtained using the relationship provided by EN 1996-1-1:2022 [29] overestimate the experimental results: the values of $\sigma_{max,k,EN}$ were ~22% higher than the characteristic compressive strength obtained from the experiments. Therefore, an inverse analysis was performed in this study based on the formula given by EN 1996-1-1:2022 [29], with the objective of obtaining more accurate estimates of the experimental characteristic compressive strength of both the MW-TM and MW-CM masonry walls. In this context, the shape factors α and β were calibrated in order to achieve the minimal deviation from the experimental values. As shown in Table 5, by selecting a proper set of parameters (α = 0.65 and β = 0.24) for Equation (1), it is possible to obtain more accurate predictions ($\sigma_{max,k,prop}$) of the experimental results. However, given the limited number of test data available, further experimental studies are needed to refine the proposed model.

Concerning the elastic modulus, the masonry walls prepared using eco-friendly mortars exhibited slightly higher values compared to the specimens made with traditional mortars (10,022.40 MPa vs. 9751.04 MPa). The values of the elastic modulus determined in the experiments were then compared with the predictions given by both EN 1996-1-1:2022 [29] and the Italian code [28], which provide the following predictive equation:

$$E_{m,ana} = 1000\ \sigma_{max,k} \tag{2}$$

As shown in Table 6, the relationship given by EN 1996-1-1:2022 [29] and the Italian code [28] clearly overestimates the values observed in the experiments: the analytical predictions for the specimens MW-TM and MW-CM were, respectively, 1.24 and 1.28 times higher than the experimental results.

Table 6. Experimental results vs. analytical estimates: elastic modulus.

Specimens	E_m [MPa]	$E_m/\sigma_{max,k}$ [-]	$E_{m,ana}$ [MPa]
MW-TM	9751.04	802.55	12,150.00
MW-CM	10,022.40	776.29	12,910.00

Finally, as for the elastic modulus and the compressive strength, the deformation capacity of the masonry walls was relatively similar, regardless of the type of mortar considered: the average vertical strain was 0.0037 and 0.0040 for the MW-TM and MW-CM, respectively. It is worth mentioning that the assumptions made above refer to a limited number of test data, and further investigations are needed to confirm the trend results reported in this study.

4. Conclusions

The experimental investigations presented in this work provided a better understanding of the mechanical behavior of a mortar mixed with paper sludge-derived cellulose fibers. The experimental tests focused on assessing the influence of (i) varying fiber proportions and (ii) different practical preparation methods. At the same time, the potential use of this eco-friendly mortar in practical applications (small-scale masonry walls), such as those encountered in real-world scenarios, was also evaluated. This approach was defined with the dual objective of promoting the development of sustainable materials while maintaining adequate mechanical performance. Based on the results obtained, the following main conclusions can be drawn:

- Increasing the percentage of cellulose fibers in the mortar altered the post-crack behavior of the specimens. The traditional mortars (0% cellulose fibers) exhibited a sudden load decrease in strength at the end of the test, whereas the mortars containing 1% and 2% of cellulose fibers continued to deform after reaching the peak load. This behavior can be associated with the energy absorbed by the fibers and the capacity of the fibers to transfer tensile stresses between the two faces of the cracks, which improves the deformation capacity of the material.
- The cement-based mortar specimens made following an accurate preparation protocol (CM-I-1 and CM-I-2) exhibited relatively low variations in the flexural tensile strength compared to the traditional mortars (less than 5% of relative differences). This suggests a uniform fiber dispersion in the material. However, the compressive strength decreased by approximately 10%. This result is mainly attributed to the increased porosity of the material.
- The cement-based mortar specimens (CM-II-1 and CM-II-2) made without rigorous control of the preparation parameters presented a higher flexural tensile strength (compared to traditional mortar) when the fiber content was increased from 0% to 1%; this is mainly due to the fiber bridging effect. However, at 2% of fiber content, significant reductions occurred, likely due to non-uniform fiber dispersion. Concerning the compressive strength, a non-monotonic trend was observed with an increase in the percentage of the fiber content, with the CM-II-2 specimens showing reductions of 30% compared to the TM-II-0 specimens.
- Changes in the mortar's compressive strength did not significantly affect the load-bearing capacity of the masonry walls. The eco-friendly mortar slightly increased the wall's compressive strength (<10%) compared to the traditional mortar, primarily due to the higher compressive strength of the former. In general, the cellulose fibers did not significantly affect the masonry's compressive behavior, which was mainly influenced by the brick's compressive strength.
- The formula provided by EN 1996-1-1:2022 [29] resulted in non-accurate predictions of the compressive strength for masonry walls prepared using traditional and eco-friendly mortars. On the other hand, more accurate estimates were obtained when using the values given by the Italian code [28] and the relationship proposed by the authors. Concerning the elastic modulus predictions, both EN 1996-1-1:2022 [29] and the Italian code [28] overestimated the experimental results, regardless of the type of mortar used.

This study has provided valuable insights into (i) the mechanical performance of cement-based mortar incorporating cellulose fibers and (ii) the compressive behavior of masonry walls made using this eco-friendly material. However, several topics still need to be investigated. Some recommendations for further research are listed below:

- Experimental investigations are needed to define optimal cellulose fiber content that exploits both mechanical strength and durability while minimizing material costs.
- Microstructural analyses (SEM or computed tomography) should be performed to obtain a further understanding of the "macroscopic" behavior of the mortars incorporating cellulose fibers.
- More in-depth studies should focus on the environmental impact of these eco-friendly mortars, including life cycle assessments (LCA), with the aim of providing a better understanding of the sustainability benefits and drawbacks of these materials compared to traditional options.
- Experimental studies about the long-term durability of eco-friendly mortars are needed, including exposure to harsh environmental conditions and aging effects, with the aim of providing insights into structural performance and stability over extended service lifetimes.

Addressing these future research directions will not only contribute to a more comprehensive understanding of cement-based mortars prepared using cellulose fibers but will also help to develop standardized testing protocols and guidelines, which will help promote the widespread adoption of these materials as a sustainable and high-performance solution in the evolving construction industry.

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