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Feasibility of Ecofriendly Mortars with Different Hemp Additions for Use in Building Sector

Daniel Ferrández *, Manuel Álvarez Dorado, Alicia Zaragoza-Benzal and Alberto Leal Matilla

Departamento de Tecnología de la Edificación, Universidad Politécnica de Madrid, Avda. Juan de Herrera, 6, 28040 Madrid, Spain; manuel.alvarezd@upm.es (M.Á.D.); alicia.zaragoza@upm.es (A.Z.-B.); alberto.leal.matilla@upm.es (A.L.M.)

* Correspondence: daniel.fvega@upm.es; Tel.: +91-0675363

Abstract: Cement mortars are commonly used in building works for the execution of enclosures and exterior rehabilitation of facades. The incorporation of plant-based additives enables the development of ecofriendly construction materials. In this work, a physical and mechanical characterisation of cement mortars with the incorporation of hemp in three morphologies (fibre, powder and pellet) was conducted. The results show how the additions of hemp powder and pellets with a partial replacement of natural aggregate reduce the final density of cement mortars and their thermal conductivity by more than 16% and 19%, respectively. On the other hand, the addition of hemp fibres reduces shrinkage during the setting of cement mortars, improving their flexural strength and increasing their durability. For this reason, it is possible to recommend the use of these mortars with the addition of natural hemp fibres without prior surface treatment to improve the physical-mechanical properties of these construction materials and extend their application field as ecofriendly materials for masonry work.

Keywords: ecofriendly materials; hemp; cement mortar; physico-mechanical characterization

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1. Introduction

The rehabilitation of the extensive building stock existing since the beginning of the last century represents a fantastic opportunity to implement actions aimed at sustainability and resilience in the construction sector [1]. These types of buildings have experienced a gradual ageing over the years and the action of multiple external climatic agents, so the maintenance and rehabilitation of this type of construction is an open task for building professionals today [2,3]. This research work shows the application possibilities of masonry mortars with the addition of hemp in different granulometries for their use in the building sector, especially in masonry work.

Because of the increasing demand for ecofriendly materials and the rising costs of synthetic reinforcement materials, the use of natural additions in composite applications has become an interesting alternative [4]. For this, natural fibres are characterised by the fact that they are renewable and cheaper compared to processed synthetic fibres [5]. In this way, these natural raw materials are positioned as a sustainable alternative in the production of construction materials. Their versatility and possibilities of use in masonry works interest researchers due to their enormous potential for application [6]. However, the properties of these natural additions are strongly dependent on external factors such as climatic conditions, and age, thus conditioning their chemical composition and their physical and mechanical properties [7]. Therefore, it is interesting to know the physical and mechanical properties of mortars with natural additives for use in masonry works, especially bast fibres (flax, hemp, jute or ramie), which are frequently used in construction [8].

There is evidence of the use of natural fibres obtained from plants and animals as reinforcement in masonry mortars from more than 5000 years ago in the Yellow River

Valley [9]. However, nowadays, they have become an environmentally friendly substitute for synthetic fibres with lower cost and excellent technical performance [10]. The physical properties of natural fibres are associated with their chemical composition and especially with the presence of cellulose, hemicelluloses and lignin, which are their basic components [11]. In cement-based materials, the incorporation of natural fibres has been shown to improve their fracture behaviour [12].

In addition, the fibre–matrix adhesion, durability and moisture resistance of these natural reinforcements are enhanced when chemical surface treatments are applied [13]. These curing processes have been extensively studied and involve alkaline, silane, acetylation, peroxide or permanganate treatments [14–16]. In this research, it was decided not to use any pre-treatment in the hemp additions incorporated. This was because it would make the final product more expensive and would increase its embodied energy.

Currently, there are many research studies that have focused on the use of natural fibres in the development of cement composites, including sisal [17,18], jute [19], flax [20], sugar palm [21], cereal straw [22], ramie [23], raffia [24], kenaf [25], abaca [26], coconut [27] and cotton [28], among others. These investigations have focused on the comparison of reference mortar series against other cement mortars with the addition of natural fibres, studying their properties. These studies test tensile strength [18,27], compressive strength [27,29], the modulus of elasticity [27] or specific fracture energy [30]. It is accepted that synthetic fibres have better physical/mechanical performance than natural fibres for use in building [31]. However, studies with natural fibres assume that these reinforcing materials are good at improving mechanical strength and avoiding brittle fracture of cement composites, as well as decreasing shrinkage, compared to traditional mortars [32].

Hemp fibres have been used to reinforce materials for more than 1000 years [33]. This traditional use is because hemp (Cannabis sativa) fibres are some of the strongest natural fibres in the world [34]. This plant has spread all over the world and currently has two subspecies, cannabis sativa and cannabis indica, the former being the most important industrially [35]. Hemp additions are used in manufacturing bio-composites, masonry mortars, and concrete and insulation materials in the construction industry due to their excellent performance [36]. In Figure 1, the basic structure of hemp composites is presented. The basic unit consists of cellulose polymeric chains aligned and gathered in microfibrils. These chains are joined by lignin, pectin and hemicellulose through hydrogen bonds [4]. In addition, hemicellulose is responsible for the biodegradation and thermal degradation of hemp compounds and moisture absorption. Lignin and pectin are thermally stable but also responsible for ultraviolet degradation [4]. In different studies, the composition percentages of these organic hemp compounds have been found to be cellulose (57–77%), hemicellulose (14–22.4%), lignin (3.7–13%), ash (0.8%) and wax (0.8%) [8,26,37,38].

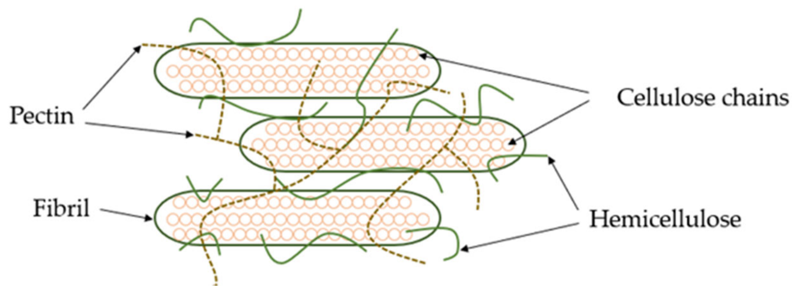


Figure 1. Hemp fibre architecture (our own elaboration based on Sedan et al., 2008, [4]).

Regarding hemp application in cement composites, there are several studies. Ruano et al. found that the addition of hemp fibres in cement mortars increased toughness, allowing beams to maintain the load for a wider displacement range [39]. Wambua et al. evaluated and compared the mechanical properties of polypropylene composites reinforced with sisal, hemp, jute and glass fibres, with the hemp fibre samples obtaining higher tensile strength [40]. Comak et al. conducted a study with diverse types of cement mortars incorporating hemp fibres with different morphologies, reaching the conclusion that the most significant improvement in physical and mechanical properties occurred for additions of 2–3% by volume and 12 mm fibres [41]. These hemp fibres exhibited a tensile strength around 690 MPa, a Young's modulus around 60 GPa and ultimate tensile strength near to 1.6% [42]. Moreover, as demonstrated by Poletanovic et al., the addition of hemp fibres in masonry mortars reduces their density by about 5%, although they increase the water absorption of these cementitious materials [43]. In any case, studies have been conducted to improve the properties of cement composites elaborated with recycled aggregates using hemp fibres, obtaining excellent mechanical properties results. These materials also improve with the alkali and acetyl treatment of the hemp fibres [44]. Likewise, other authors, such as Rosa et al. and Bourmaud et al., have shown how the use of hemp additions in the production of more sustainable composite materials reduces the cost during their production phases [45,46].

The aim of this research was to examine the behaviour of hemp additions in cement mortars' properties. To this end, this work proposed a novel study with the preparation of cement mortars with three differently shaped hemp additions: powder, fibre and pellet. Subsequently, their physical and mechanical properties were studied, with the aim of determining their application possibilities in masonry works.

2. Materials and Methods

This section presents the raw materials and dosages used to produce the cement mortars used in this work, as well as the experimental programme conducted for their physical and mechanical characterisation.

2.1. Materials

The following raw materials were used for the development of this research work: grey cement, natural sand, hemp in different forms and water.

The binder used was grey cement of the CEM II/B-L 32.5-N type. This is a material commonly used in building works, and which is becoming increasingly widespread in façade rehabilitation works for 20th century buildings, due to its excellent technical performance, ease of conservation and accessible cost [47]. This material, supplied by CEMEX (Madrid, Spain), has a real density of 3060 kg/m^3 determined according to the UNE 80103 standard [48]. Table 1 shows its elemental composition determined by X-ray fluorescence using a Bruker S2 Puma model (Billerica, MA, USA).

Table 1. X-ray fluorescence test (*) results for CEM II/B-L—32.5 N.

CaO	SiO_2	SO_3	Al_2O_3	Fe_2O_3	K_2O	TiO_2	MgO	SrO	NaO_2	MnO	P_2O_5
64.94	19.71	4.12	3.76	3.24	0.32	0.16	1.87	0.08	0.30	0.08	0.13

(*) Results expressed in mass percentage.

The type of aggregate used was natural river sand, supplied by the company Bricomart (Madrid, Spain). To better understand the properties of these sands used in the production of cement mortars, a physical characterisation was conducted, the results of which are shown in Table 2.

Table 2. Physical characterisation of the aggregates used.

Value Studied	Standard	Result
Fine Content (%)	UNE EN 933-1 [49]	2.03
Fineness Modulus (%)	UNE-EN 13139 [50]	4.13
Friability (%)	UNE-EN 146404 [51]	21.21
Bulk Density (kg/m^3)	UNE-EN 1097-3 [52]	1594
Dry Density (kg/m^3)	UNE-EN 1097-6 [53]	2516
Water Absorption (%)	UNE-EN 1097-6 [53]	0.98

All the values given in Table 2 agree with those obtained in previous research [54]. The fine particle content was close to 2%, defined as the amount of material passing through the 0.063 mm sieve in relation to the total sieved mass, which exceeds that usually obtained in standard sands. It was decided to use this type of commercial natural aggregate as it is the most common in rehabilitation works and would bring the study closer to a real case.

Figure 2 shows the granulometric curve obtained for the natural sands used in the production of the mortars. This granulometric curve was determined using the following series of sieves with standardised mesh sizes: 4.000–2.000–1.000–0.500–0.250–0.125–0.063–bottom (sizes in mm). The method described in the UNE-EN 933-1:2012 standard [49] for obtaining these curves consists of placing the series of sieves in decreasing order of mesh size, and then shaking the 1000 ± 0.005 g sample mechanically with the aid of a back-and-forth sieve shaker for 1 min, so that the aggregate is retained according to its size in the different sieves.

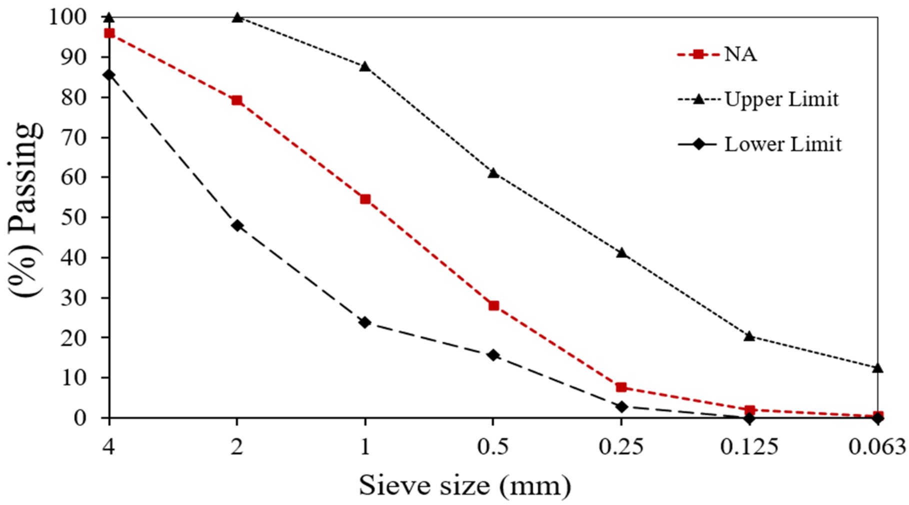


Figure 2. Size distribution curve compared to the limits of NBE FL-90 [55] adapted to sieve sizes established by UNE-EN 933-2 [56].

The aggregates used in this work had a continuous grain size, which was within the limits recommended by the regulations. It should be noted that a continuous particle size favours the workability of the mortar when fresh and improves the compactness and mechanical properties of the mortar when hardened [57].

Three different hemp morphologies were used as additives in the cement mortars produced: fibres, powder and pellets. Figure 3 shows the natural state of these three raw materials. These three types of additives have been carefully chosen to produce three diverse types of mortar. Firstly, a traditional cement mortar with a hemp-vegetable-fibre reinforcement, and secondly, two other diverse types: one replacing the aggregate fraction of 0.500 mm or less with hemp powder, and the other replacing the aggregate retained in the 2000–1000 mm sieves with hemp pellets.

The hemp additions were previously washed with water in a way equivalent to what was done in the studies of Ruano et al. and Ferreira et al., to eliminate residues that had adhered to them during the production process [13–39], and then dried in an oven at a temperature of 70 ± 1 °C for a period of 24 h. The hemp fibres were sieved prior to use to obtain two distinct series of fibres, with lengths between 8.0 and 12.0 mm (Figure 3a). The powder had a particle size of less than 2.0 mm (Figure 3b). The pellet hemp shown in Figure 3c had an average diameter of 4.0 mm and a length between 1.0 and 2.0 cm.

(a) (b) (c)

Figure 3. Additives used: (**a**) natural hemp fibre of length 8–12 mm, (**b**) shredded hemp powder of length less than 2 mm, (**c**) pellet hemp of average diameter 4 mm.

Finally, the water used for the mixing of the mortars was tap water from the Canal de Isabel II (Madrid, Spain). This is drinking water fit for human consumption and suitable for use in mortars and concretes [58], which has been successfully used in previous studies [59]. Among its main characteristics are its soft hardness (25 mg $CaCO_3$/L) and neutral pH between 7 and 8 [60] recommended to avoid setting alterations.

2.2. Mortars Elaboration

For the preparation of the mortars studied in this research, the dosages by weight shown in Table 3 were used. It should be noted that all the mixes prepared were following the recommendations of the UNE-EN 196-1 standard [61], using an IBERTEST IB32-040V01 planetary mixer and always following the same techniques and methods.

Table 3. Dosages used to produce mortars.

Mortar	Cement (g)	Water (g)	Sand (g)	Hemp Additions (g)			Consistency (mm) UNE-EN 1015-2:2007 [62]
				Fibre	Powder	Pellet	
Reference	450	248	1350	—	—	—	174
Fibre	450	248	1350	20	—	—	177
Powder	450	248	900	—	30	—	178
Pellet	450	320	450	—	—	90	169

The samples prepared with these dosages were cured in a humid chamber in conditions of 95 ± 2% relative humidity and a temperature of 22 ± 1 °C for 28 days, to obtain a correct setting and hardening of the mortars. On the other hand, the water content of the dosages was experimentally fixed until a plastic consistency of the mortar was obtained, corresponding to a cake diameter obtained on the shaking table of 175 ± 10 mm according to the recommendations of the UNE-EN 1015-2:2007 standard [62].

To determine the crystalline phases in the hardened mortars, a mineralogical analysis was conducted. The results are shown in Table 4, obtained using Chung's method and Bruker's EVA software.

Table 4. Relative percentage of each crystalline phase in the processed mortars. Semi-quantitative analysis.

Quartz	Potassium Feldspar	Plagioclase	Phyllosilicates	Calcite	Dolomite	Gypsum	Belite	Portlandite	Ettringite
52	15	12	7	5	1	2	2	3	3

Table 4 shows the high quartz content of the mortars due to the siliceous nature of the sands used. This type of aggregate has been shown to be suitable and to have a positive effect on the mechanical properties of hardened mortars [63].

2.3. Experimental Program

The experimental programme developed in this research consisted of a physical and mechanical characterisation of the diverse types of mortar produced, with the aim of analysing the suitability of these cladding and bonding materials for their application in masonry work related to building renovation. In this regard, the tests proposed, and their application regulations, were as follows:

The actual density of hardened mortar was according to standard UNE EN-80103: 2013 [48]. A pycnometer was used for this test. The process consisted of finely grinding the sample of each type of mortar and depositing it in a Le Chatelier flask, avoiding the formation of pores. Subsequently, the real volume of the sample was obtained by difference of weights, the density being the result of applying the equation:

$$\delta = \frac{m_{Dry}}{V_{Real}} \tag{1}$$

where m_{Dry} is the mass of the specimen previously dried (70 °C for 24 h) and V_{Real} is the actual volume obtained according to the method described.

The thermal conductivity coefficient was obtained using the UNE-EN ISO 8990:1997 standard as a reference [64]. For this test, a Hot-Box was used, as shown in Figure 4, equipped with thermocouples and a datalogger for the accumulation of temperature data. The test was performed using 24 × 24 × 3 cm^3 mortar plates placed on one side of the Hot-Box, and an internal heat source was applied and after 24 h, when the heat flux (Φ) could be assumed to be stationary, the thermal conductivity was measured and the Fourier equation was applied:

$$\Phi = \frac{Q}{t} = \frac{\lambda}{e} \cdot S \cdot (T_{Int} - T_{Ext}) \tag{2}$$

where λ is the calculated thermal conductivity coefficient, e is the thickness of the sample, S is the surface of the plate and $(T_{Int} - T_{Ext})$ is the difference between the inside and outside temperature of the Hot-Box.

The water absorption coefficient was obtained by capillarity according to UNE-EN 1015-18: 2003 [65]. Capillarity is one of the most frequent mechanisms of water penetration in porous materials, and one of the main causes of the deterioration of building materials due to humidity. These lesions arise because of the attraction between water and the surface that forms the pore network of the mortar in accordance with Jurin's Law. This test was conducted using RILEM half specimens that had been previously flexure evaluated and dried (70 °C for 24 h). The specimens were then immersed in water on the flexural-fracture side, up to a height of one centimetre, for 90 min, calculating the capillary absorption coefficient according to the expression:

$$\mathrm{C} = 0.1 \cdot (M2 - M1) \tag{3}$$

where C is the capillary absorption coefficient measured in kg/(m^{2}min$^{0.5}$), M1 is the weight of the sample after 10 min of testing and M2 is the weight at 90 min.

Shore D surface hardness was obtained following the procedure adapted from UNE-EN 13279-2: 2014 [66]. This is a property of relevance for façade cladding that determines the material's resistance to scratching on its surface. This was performed using a Shore D durometer and measuring five times on two opposite sides of the standardised RILEM specimens measuring 40 × 40 × 160 mm^3.

Open porosity was determined according to UNE-EN 1936:2007 [67]. This property is defined as the ratio between the accessible volume of pores and the apparent volume of the material, in relation to the compactness and compressive strength of the mortar. This property is calculated as:

$$POR_{open} = \frac{W_{sat} - W_0}{W_{sat} - W_{imm}} \cdot 100 \tag{4}$$

where W_{sat} is the saturated weight of the sample. To obtain W_{sat} each sample was completely immersed in water for two hours and then weighed until the difference between two consecutive weighings was less than 0.1%. W_0 is the initial weight of the sample previously dried in an oven for 24 h at a temperature of 70 °C and W_{imm} is the immersed saturated weight obtained with the aid of a histrostatic balance. This test was conducted on standardised RILEM specimens.

The total water absorption coefficient, according to the recommendations of the UNE-EN 14617-1:2013 standard [68], was obtained according to the equation:

$$Total_{Absorption} = \frac{W_{sat} - W_0}{W_0} \cdot 100 \tag{5}$$

where W_{sat} is the saturated weight of the sample and W_0 is the initial weight of the previously dried sample, determined in the same way as in the open porosity. Mortar slabs of $15 \times 15 \times 2$ cm^3 were used for this test.

Determination of the surface permeability was by means of the Karsten pipe test, according to the recommendations of the RILEM method for measuring water absorption under low pressure. The pipe method test (Test nº II. 4) [69] makes it possible to recreate the conditions of rain and 90 km/h winds and is recommended for determining the effect of pipe additions on the permeability of the enclosures, which is necessary for subsequent cleaning and maintenance work that may affect their durability [70]. Mortar slabs measuring $24 \times 24 \times 3$ cm^3 were used for this test.

Determination of the dynamic Young's modulus was carried out by ultrasound ($\mathrm{MOE_{us}}$). For the determination of this parameter, IBERTEST equipment was used, using 55 kHz receiver–transmitter contact probes. This $\mathrm{MOE_{us}}$ was determined by first calculating the longitudinal transmission velocity of the mortar sample (v_{us}), according to the equation:

$$v_{us} = \frac{L}{t_{us}} \tag{6}$$

where L is the normalised sample length RILEM (16 cm) and t_{us} is the time for wave propagation measured with the ultrasound equipment. Subsequently, the $\mathrm{MOE_{us}}$ is determined according to the expression:

$$MOE_{us} = \frac{\rho \cdot (1+\mu) \cdot (1-2\mu) \cdot {v_{us}}^2}{(1-\mu)} \tag{7}$$

where ρ is the density of the mortar evaluated and μ the Poisson's coefficient (which can be estimated at 0.2–0.3).

Determination of the mechanical flexural and compressive strength of the mortars was according to UNE-EN 1015-11:2000/A1:2007 [71]. Firstly, standardised RILEM prismatic specimens measuring $4 \times 4 \times 16$ cm^3 were evaluated in simple bending, and then the two half-dimensions obtained after the bending test were evaluated in compression. To conduct these tests, six samples of each type of mortar of 28 days of age were used with an AUTETEST 200-10SW hydraulic press. The equations to determine the flexural strength (σ_f) and compressive strength (σ_c) are:

$$\sigma_f = \frac{M_f}{\mathrm{W}} = \frac{3 \cdot P \cdot l}{2 \cdot a \cdot b^2} \tag{8}$$

$$\sigma_c = \frac{P}{1600} \tag{9}$$

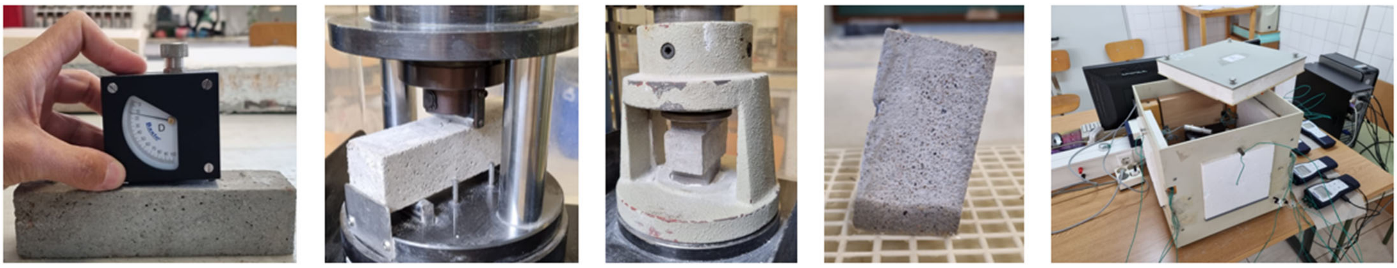
where P is the applied point load, l is the support spacing (approximately 10 cm) and a and b are, respectively, the width and height of the cross-section of the specimen.

Adhesion strength was determined according to UNE-EN 1015-2 [72]. This is a mechanical property referring to the mortar's ability to withstand normal stresses on its surface without detaching as a coating. This property depends on multiple parameters in addition to the material used, such as [73] the mortar–substrate interface, humidity and cleanliness of the substrate, and the method of application and curing. This test was conducted by applying a one-centimetre-thick layer of mortar on a previously moistened ceramic scraper measuring 40 × 50 × 5 cm^3. Once the mortar sample had been hardened and cured in a humid chamber for 28 days, metal discs of 50 mm diameter were glued on its surface, separated at least another 50 mm from each other. Tension was then applied until breakage in the direction normal to the disc, separating it from the application surface, and thus determining the bond strength.

The evolution of shrinkage in the diverse types of mortar produced was measured from the demoulding of the samples up to the age of 150 days. This test was conducted on specimens measuring 2.5 × 2.5 × 28.7 cm^3 and following the recommendations of the UNE 8011289 standard [74].

Determination of the durability of mortars against repeated freeze–thaw cycles was according to the recommendations of standard UNE-EN 12371:2011 [75]. This test was conducted on standardised RILEM specimens measuring 4 × 4 × 16 cm^3. A series of three specimens was used and they were subjected to freeze–thaw cycles, while another series of three specimens was used as a reference without cycles. The cycles, 25 in total, consisted of immersing the specimens in water for 18 h at 20 °C and then freezing them for 6 h at a temperature of −12 °C. Subsequently, the loss of flexural strength and mass variation in the aged specimens were evaluated by durability cycling.

Finally, Figure 4 shows images of the tests and equipment used to obtain the results, as described in the methodology.



(a) (b) (c) (d) (e)

Figure 4. Tests conducted, (**a**) Shore D surface hardness; (**b**) flexural strength; (**c**) compressive strength; (**d**) water absorption coefficient by capillary action; (**e**) Hot-Box to obtain thermal conductivity of the mortars.

3. Results and Discussion

This section presents the results obtained for the physical and mechanical characterisation of the mortars studied in this research.

3.1. Physical Characterisation of Mortars

This physical characterisation included the thermal conductivity, real density, total water absorption, capillary water absorption, open porosity and surface permeability tests.

Firstly, Figure 5 shows the results obtained for the thermal conductivity of the mortars and their real density, two properties that are closely related to each other, as has been proven in previous studies [76]. It should be noted that a reduction in the coefficient of thermal conductivity of mortars leads to an increase in the final thermal resistance of the enclosure where the cladding is applied and an improvement in its energy efficiency.

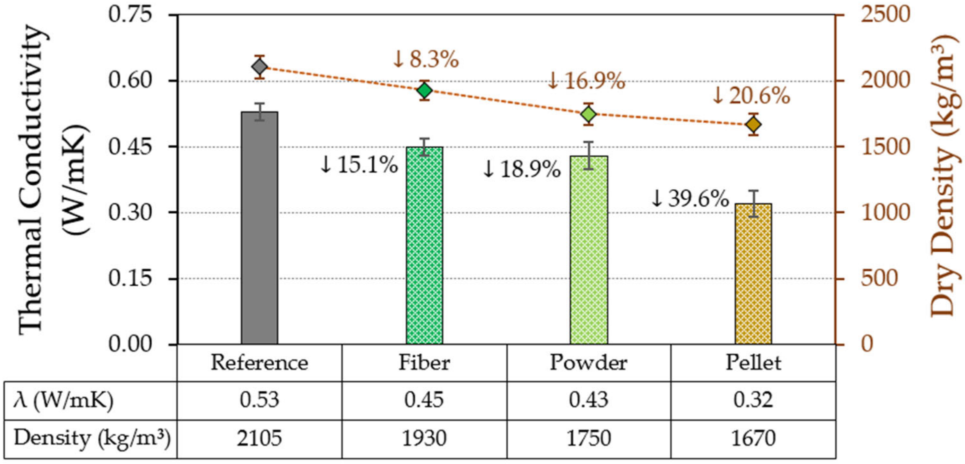


Figure 5. Coefficient of thermal conductivity of the mortars and actual density of the processed mortars.

Figure 5 shows how all the types of hemp added to the cement mortars reduced their thermal conductivity coefficient and their real density. In this regard, the addition of hemp pellets as a substitute for the aggregate fraction larger than 1000 mm allowed an average reduction in the thermal conductivity of the material of 39.6%, which was 20.6% lighter than traditional mortar. In the same way, the other two additions used contributed to an improvement in the thermal resistance of the mortars and lightened the final weight of the hardened material. These results are in line with those obtained by other researchers who have worked with palm [77], coconut [78] or sisal [79] fibres, which studies showed a positive relationship between the incorporation of vegetal additions and a decrease in thermal conductivity in cementitious materials.

Table 5 shows the results obtained for the physical properties of the mortars that show their behaviour under the action of water: total water absorption, open porosity and the coefficient of water absorption by capillarity. These physical properties are related to the possible pathologies caused by dampness in the mortars and their final compressive strength.

Table 5. Coefficient of capillary water absorption, open porosity and total water absorption of the processed mortars.

Sample	Capillarity Absorption (kg/m^{2}min$^{0.5}$)	Open Porosity (%)	Total Water Absorption (%)
Reference	0.54 ± 0.03	18.3 ± 2.1	31.7 ± 1.5
Fibre	0.57 ± 0.05	19.1 ± 1.1	34.1 ± 1.4
Powder	0.65 ± 0.06	22.5 ± 0.9	38.3 ± 0.5
Pellet	0.72 ± 0.05	27.4 ± 1.2	43.3 ± 0.8

It is well known that capillary moisture can rise through stone walls, not only from the inside of the cladding, but also through the facing mortar. For this reason, it is not advisable to use exceptionally fine aggregates in the mortar, as this hinders capillary rise [80]. In Table 5, a higher water absorption coefficient per unit area is observed for mortars with hemp additions, which is due to their higher porosity and water absorption capacity. However, the nature of the UNE-EN 1015-18 test only allows the mass of water absorbed by capillarity to be elucidated, without indicating the final height reached by the water. In this regard, previous studies have shown that in traditional mortars with a more compact structure and a finer pore size, water is able to reach higher levels than in mortars with a larger pore volume and greater water absorption capacity [81]. In any case, the mortars with hemp additions used are more suitable for cladding work on facades that are not very exposed to water. In agreement with the results obtained for density, the mortars with hemp additions in pellets showed a higher open porosity and total water absorption.

Continuing with the water action evaluations, Figure 6 shows the results obtained for the surface permeability test on facing mortars. This test is especially relevant for estimating the penetration of rainwater in mortars placed on site or during cleaning work in the maintenance of a façade.

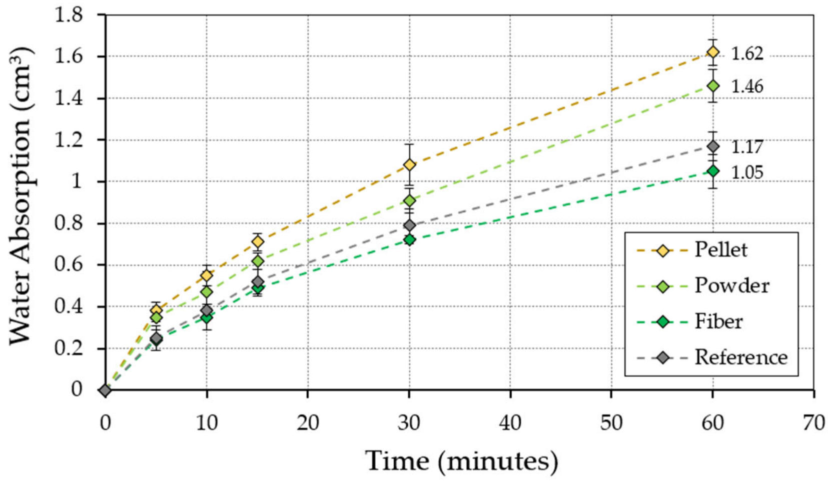


Figure 6. Surface permeability test results using the Karsten tube test.

In Figure 6, it can be seen how the mortars with added hemp in pellets presented a higher permeability under the action of water. This result is a consequence of the disintegration of these pellets during the mixing process and the higher pore volume resulting in the hardened mortar samples. The best results in this test were obtained by the samples of mortar with added hemp fibres, which suggests the suitability of this coating material for application in climatic areas exposed to rainwater.

Thus, in terms of water resistance, mortars with hemp fibre were the best performers, positioning themselves as the best solution for use in the rehabilitation of external façade cladding [82]. On the other hand, mortars with the addition of hemp in pellet and powder form are more suitable for use as filling mortars under screeds and slope formation.

3.2. Mechanical Characterisation of Mortars

This section presents the results obtained for the mechanical characterisation of the mortars: flexural and compressive strength, bonding strength, Shore D surface hardness and dynamic Young's modulus using ultrasound.

Firstly, in Figure 7, the results obtained for the flexural and compressive mechanical tests conducted on standard RILEM specimens measuring 40 × 40 × 160 mm^3 are presented.

The addition of hemp fibres produces the expected effect of improving the flexural behaviour of cementitious mortars. A similar effect was observed by Poletanovic et al. where they obtained significant improvements in flexural strength by adding NaOH-treated natural hemp fibres to cementitious materials [43]. However, for compressive strength, there was a slight decrease (7.9%) compared to traditional mortar. This effect was observed by Candamano et al. and was attributed to the lower workability of the samples and their higher heterogeneity [5]. On the other hand, the incorporation of hemp powder as a replacement for the aggregate fraction below 0.500 mm, and hemp pellets as a replacement for the 1000 and 2000 mm aggregate, leads to a decrease in mechanical strength. This effect was also expected because of the lower compactness of these mortars and lower density, the aggregates being a key contributor to the mechanical strengths in masonry mortars [83]. In view of these results, it can be observed that all the samples exceeded the minimum compressive strength of 7.5 N/mm^2 for masonry mortars recommended in the UNE-EN

998-2 standard [84]. In this sense, it can be inferred that the dosages elaborated in this study are viable for application in masonry works and the execution of masonry walls and wet partition walls.

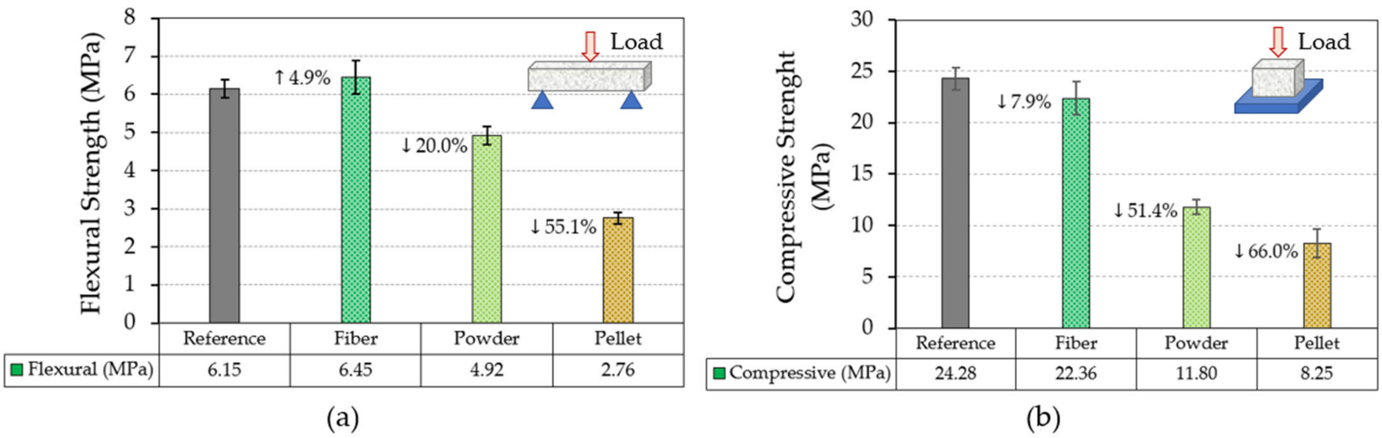


Figure 7. Results of mechanical tests on mortars: (**a**) mechanical resistance to bending; (**b**) mechanical resistance to compression.

Figure 8 shows images obtained for each of the mortar dosages elaborated for this research. These images were taken on the fractured face in bending with the aid of a USB digital microscope using 20× magnification.

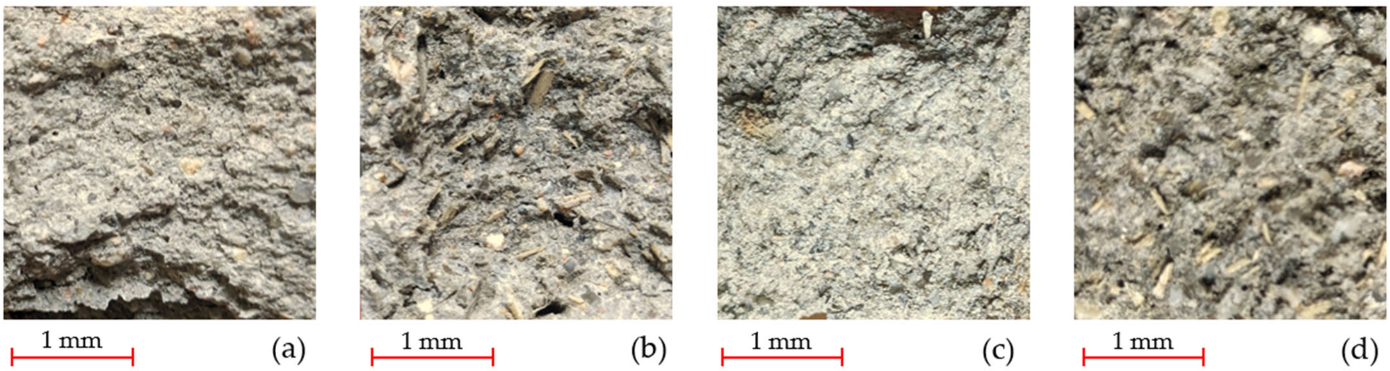


Figure 8. Cement mortar matrix. (**a**) Reference mortar; (**b**) mortar with addition of fibres; (**c**) mortar with addition of hemp powder and replacement of aggregate ≤0.500 mm; (**d**) mortar with addition of pellets and replacement of aggregate ≥1.000 mm.

In Figure 8a, the compactness of the traditional reference mortars can be observed, which has a positive effect on their compressive strength. On the other hand, Figure 8b shows that the hemp fibres have shown good fibre–matrix adhesion, improving the flexural strength of the traditional mortars. Nevertheless, and in agreement with the studies conducted by Ruano et al., when examining the failure surface it could be seen that most fibres were pulled out [39]. Figure 8c shows the perfect integration of the hemp powder as a substitute for the fine fraction (less than 0.500 mm) of the aggregate. Finally, in Figure 8d, it can be seen how the hemp pellets disintegrate during the mixing process, to be homogeneously integrated into the cement matrix in replacement of the aggregate larger than 1000 mm. This results in a lower mechanical strength of the mortars having the addition of pellet hemp, in accordance with their higher porosity and lower density.

This mechanical characterisation was complemented with the adhesion, surface hardness and dynamic Young's modulus tests shown in Table 6.

Table 6. Adhesion strength, Shore D surface hardness and dynamic Young's modulus by ultrasound (MOE_{us}).

Sample	Bonding Strength (MPa)	Shore D Surface Hardness	MOEus (MPa)
Reference	0.53 ± 0.04	86 ± 3	17,833 ± 301
Fibre	0.45 ± 0.02	81 ± 5	10,314 ± 215
Powder	0.41 ± 0.05	74 ± 2	7486 ± 216
Pellet	0.34 ± 0.03	62 ± 4	4031 ± 287

Firstly, Table 6 shows that all the mortars analysed in this research have a bond strength higher than 0.30 N/mm^2, the minimum established by the UNE-EN 988-1 standard for use as a coating material [85]. However, the different hemp additions have a negative impact on the adhesion of the mortars, with the dosage with the addition of hemp pellets showing the worst results. As has been shown in other studies [73], the bond strength of mortars is essential to improve the structural behaviour of masonry walls subjected to lateral loads, and it is difficult to find an optimal dosage of mortar with hemp that improves the mechanical behaviour of traditional mortar. Regarding surface hardness, this is a property of great relevance for facing mortars that will be exposed to areas of high urban traffic and heavy wear [86]. It can be observed how mortars with hemp additions presented a lower surface hardness, with the most significant reduction being in the dosage with pellets (28%↓), which is due to the replacement of the natural aggregate by these materials of vegetable origin in the hardened composites. Finally, the dynamic Young's modulus, determined with the help of the ultrasonic technique, allowed us to obtain an indirect measure of the mechanical strength of the mortars, which agreed with the results obtained for compression in Figure 7. The lower ultrasonic propagation velocity and lower MOE_{us} of the mortars with the addition of hemp pellets and powder was a consequence of their lower density and more porous structure [87].

3.3. Durability Tests

In the durability tests, this research studied the shrinkage of the elaborated materials, determined up to the age of 150 days, as well as the behaviour against freeze–thaw cycles of the elaborated mortars.

Firstly, Figure 9 shows the shrinkage curves for each type of mortar used in this research.

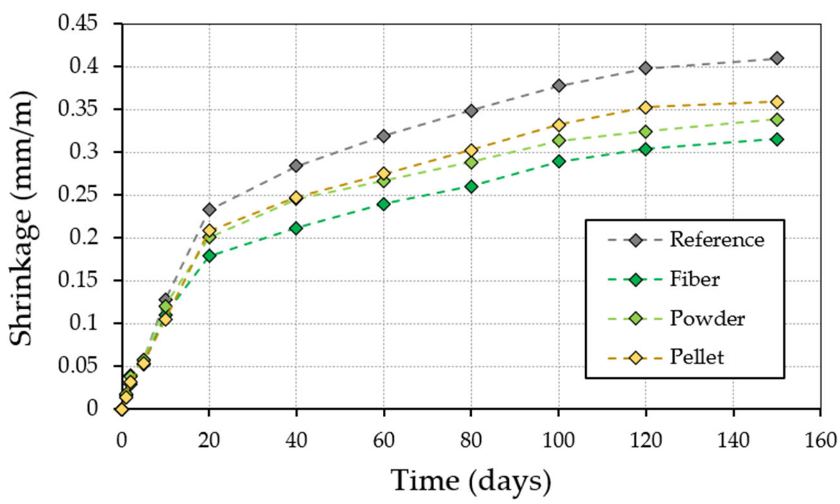


Figure 9. Evolution of shrinkage in mortars as a function of time.

The positive effect of hemp additions in reducing shrinkage in masonry mortars can be seen in Figure 9. All samples showed similar behaviour. The powder additions replacing the fine fraction of the aggregate (<0.500 mm) reduced the shrinkage of the mortars to a greater extent than in the case of the samples with pellet additions replacing the fraction larger than 1.000 mm. This result agrees with other studies where it has been observed that the fine fraction contributes to a greater extent to increase shrinkage in masonry mortars [88]. On the other hand, and as has been observed by other researchers working with natural fibres, the addition of hemp fibres was postulated as the best addition to reduce shrinkage during the setting process [89,90].

Finally, Figure 10 shows the results obtained for the flexural strength of samples subjected to accelerated ageing cycles, in comparison with the values obtained for a reference series of each mortar. Additionally, the loss of mass experienced by the mortar samples subjected to freeze–thaw cycles after the end of the proposed durability cycles is included in the graph.

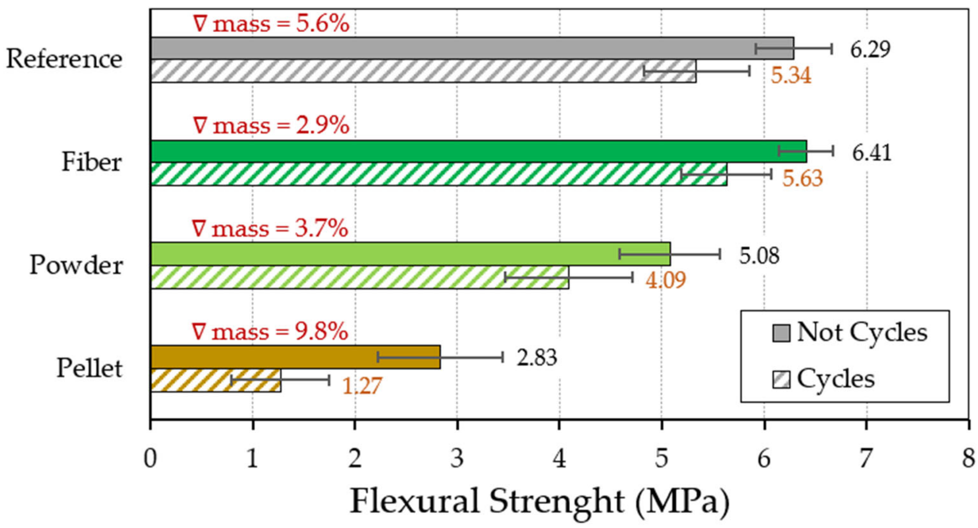


Figure 10. Accelerated ageing test. Bending test results and mass loss in samples with and without freeze–thaw cycles.

As porous materials, cement mortars have a high capacity to retain water that can deteriorate these materials when exposed to an aggressive environment [91]. Every year, governments invest a great deal of human and material resources to repair damage in façades caused by freeze–thaw cycles, so their study, both theoretical and practical, is valuable for understanding the possibilities of applying mortars in façade rehabilitation works [92]. Analysing the results shown in Figure 10 for this accelerated ageing test, it can be seen how the mortars with the addition of hemp fibre improved the mechanical flexural strength of the material subjected to cycles and maintained its dimensional stability to a greater extent. In this sense, mortars with the addition of natural hemp fibre showed excellent durability against the external action of frost, in agreement with other studies where natural fibres were used and their application was validated in this type of climatic conditions [93]. Mortars with the addition of hemp powder had significantly decreased (24%↓) mechanical strength with respect to the traditional aged mortar, although they obtained a lower mass loss. Finally, mortars with the addition of pellets to replace the aggregate over 1000 mm were the mortars with the worst resistance and the worst dimensional stability, and their exposure in environments susceptible to low temperatures and adverse freezing conditions is not recommended.

4. Conclusions

In this research, the effect of the incorporation of different hemp additions on the physical and mechanical properties of masonry mortars was studied. Cement mortars have been commonly used as a coating material for plastering and rendering in masonry works, especially since the second half of the 20th century [94]. In this sense, there are currently a multitude of masonry works in both new and refurbished buildings involving this type of binder material, and it is important to know its most relevant properties.

The most relevant conclusions drawn from this research were as follows:

- Hemp fibre is positioned as the best morphology to be added in the manufacture of masonry mortars. It was proven that cement mortars with hemp fibre have greater resistance to bending, less shrinkage and greater durability against freeze–thaw cycles compared to traditional mortars. In this sense, this type of mortar has better technical performance for use in construction works.
- On the other hand, mortars with the addition of powder and pellets do not present an optimum performance for use as a cladding material in buildings. Their mechanical properties, durability and water absorption capacity make it difficult to use them in outdoor environments subject to weather conditions. However, this type of mortar makes it possible to reduce the consumption of natural aggregates in construction and to obtain a lower density and thermal conductivity coefficient. For all the above reasons, it is considered appropriate to recommend the use of this type of material for filling floor screeds and for use in masonry works without major requirements.

The positive effect of these mortars in reducing thermal conductivity is in line with the Sustainable Development Goals for improving the energy efficiency of cities (Goal 11: Sustainable Cities and Societies [95]). This advantage, together with the use of plant-based materials that have a lower environmental impact, suggests the use of these ecofriendly cement mortars as a cladding material for building works. However, there is still a long way to go, and it would be necessary to improve the mechanical properties of these materials for their use in structural masonry walls. In any case, as a cladding material, they have a good potential for application as they have an acceptable surface hardness of more than 60 Shore D units in all the cases analysed, and, above all, a reduction in shrinkage during the setting process. This last point is of vital importance for the use of these mortars in climates with abrupt daily temperature changes, as it avoids the appearance of surface cracks that deteriorate the mortar and may cause subsequent pathologies in the materials.

In any case, this work focused on the study of natural hemp additions without previous surface treatments for use in buildings. In future research, it could be interesting to compare the effect of these untreated additions with other hemp cured with NaOH or seawater, as well as to study their viability for use with other binders to produce masonry mortars.

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