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Use of Wood Waste as Aggregate in Mortars: An Experimental Study

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Abstract. The construction sector is one of the largest and most active in the world economy, being responsible for consumption of huge amounts of natural resources. Natural sand and gravel are the most important resources in construction, they are mainly used as aggregates, and its extraction often causes environmental damages. Bearing these considerations in mind, the wood waste has been used as partial replacement of natural sand in concrete and mortars to reduce the environmental burden of natural sand extraction. The aim of this paper is to characterize the physical and mechanical properties of natural hydraulic lime-based mortars proportioned with different percentages of wood wastes (0% to 30%) as replacement of natural sand. Thus, several specimens of mortar proportioned with wood wastes have been subjected to different experimental procedures, such as: workability, mechanical strength, water absorption and thermal conductivity. Results obtained showed that the incorporation of wood waste causes a reduction of mechanical resistance mostly due to the increase in open porosity, but on the other hand the thermal conductivity presents an improvement up to 83%. The results obtained are quite acceptable and encouraging for the follow-up studies using wood wastes as fine aggregate in mortars and, simultaneously, to improve the energy efficiency of buildings since this waste material contributes to obtain mortars with improved thermal performance.

1. Introduction

The construction industry is one of the largest and most active sectors in the world economy, being responsible for almost 30% of the total CO_2 emissions produced by the global economics activities emissions and the consumption of huge amounts of natural resources [1]. Therefore, higher efficiency in the exploitation of natural resources and the recycling of waste has become one of the main priorities in Europe [2]. In addition, large scale building renovations are at the forefront of European Union energy policy, in order to reach its 2050 energy efficiency targets [3].

Bearing these considerations in mind, the aim of this study is twofold: to consider the possibility of adding wood wastes to rendering and/or plastering mortars to replace the traditional aggregates, and to develop new mortar with better thermal insulation performance in order to contribute to the reduction of energy consumption of the heating or cooling system in buildings. The wood industries generate a large amount of waste products from cutting, milling and drilling operations. For instance, during the wood sawing operations result in average 5–10% of waste by weight [4]. Currently most of these wood wastes are either used for heating or energy production with its burning, which raises other challenges related to the CO_2 generation. So far, a few research works have dealt with some type of wood waste, such as wood ash as a replacement for cement [5, 6] or in other studies [7, 8] wood chips (up to 8 mm of length) were incorporated in concrete. In general, the use of wood wastes as aggregates in cementitious materials revealed to be advantageous by obtaining lightweight materials as well as with improved thermal insulation performance [9-12].

Nevertheless, there is little knowledge of the effect of wood wastes on the performance of natural hydraulic lime (NHL) based mortars. In fact, only in the last decades has there been a growing interest in the use of NHL as a binder [13, 14] in mortars due to its beneficial properties (reduced modulus of elasticity and high permeability to water vapor, among others) and also due to its lower carbon footprint compared with Portland cement. In this context, it is intended to demonstrate in this study the effects of wood waste as aggregate on mechanical and physical properties of NHL-based mortars.

2. Experimental programme

2.1 Materials

The mortars were prepared with a natural hydraulic lime (NHL5) produced in Portugal according to EN459-1:2010 [15]. The Blaine fineness of the NHL was 9,400 cm^2/g. Three siliceous types of sands and wood wastes were used as aggregates in this study. The sands used were composed of coarse sand, medium sand and finer sand, which were mixed in volumetric percentages of 25%; 37.5% and 37.5%, respectively. The wood waste obtained from the wood cutting and drilling operations of pine wood was separated into three fractions and further mixed in such a proportion as to obtain a grain size distribution equivalent to the sand mixture.

The particle size distribution curves of the corresponding sand mixture and the mixture of three wood wastes are presented in Figure 1. The loose bulk density of each granular constituents determined according EN 1097-3:1998 [16], is the following: sand mixture = 1.612 g/cm^3; wood waste = 0.542 g/cm^3 and NHL = 0.869 g/cm^3. Polycarboxylate-based high-range water reducer (HRWR) produced by BASF was also used. The HRWR had a specific gravity, pH, chloride content, charge, and solid content of 1.05, 8, <0.10%, anionic, and 28–32%, respectively.

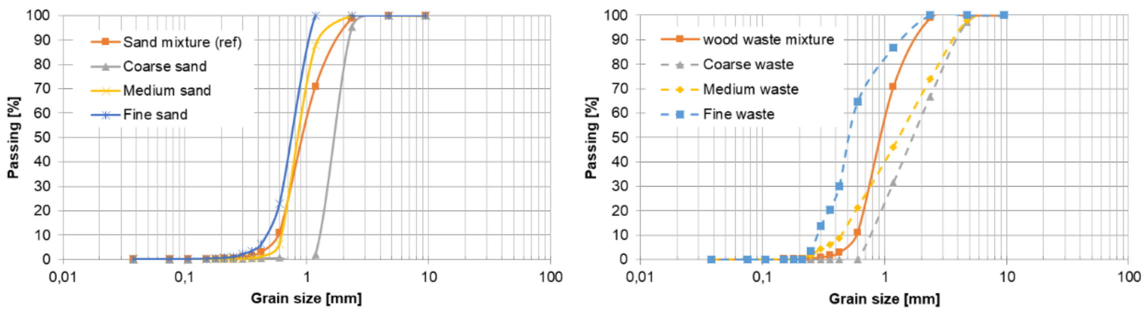

Figure 1. Particle size distribution curves

2.2 Mortar compositions and samples preparation

Mortar mixture proportions namely the percentage of wood waste as sand replacement and the dosages of HRWR and water/NHL ratios are reported in Table 1. The water/NHL ratios were determined depending on the percentage of waste used and in order to obtain mortars with flow consistency around of 150 mm, which was carried out based on the European Standard EN 1015-3:1999 [17]. It should be noted that the HRWR was used to minimize the need to excessively increase the amount of water as a caused by the presence of the wood waste. All mortars had NHL to sand ratio fixed and kept equal to 1:3 (by volume). Four wood waste percentages as sand replacement were used: such as 0%, 10%, 20%, 30%. The mortar mix compositions, namely the water/NHL ratio, the dosage of HRWR and percentage of waste as sand replacement by mass are presented in Table 1.

Table 1. Mortar mixture proportions.

Sand replacement percentage	water/NHL ratio (-)	HRWR percentage
0	0.80	0.9
10	0.93	0.9
20	1.36	0.9
30	1.66	0.9

The preparation of the mortars and specimens was based on EN 1015-2:1998/A1:2006 [18] but adapted as follows: the dry NHL and sand (with or without wood waste) was hand mixed to assure homogenization of all dry materials. Then, the dry mixture was introduced into the mechanical mixer container and 80% of the water were added and mixed during 90 s. After that the remaining water with the HRWR is added; after 150 s the mixer was stopped to scrape the container borders and turned on for another 30 s to complete the mixture. Each mortar composition was cast into metallic prismatic moulds with 40 x 40 x 160 (mm) filled by two layers and mechanically compacted with the mechanical mortar compacter device. In addition, circular disc specimens with diameter and thickness of 95 mm and 20 mm, respectively, were made with the purpose of thermal conductivity measurements. The fresh molded specimens were placed in controlled curing conditions, namely at temperature of 20±3 ºC and relative humidity of 65±5%. After the three first days the specimens were demolded and maintained under the same hygrothermal conditions up to 28 days of age.

2.3 Mechanical strength

The strength tests were done following standard EN 1015-11:1999 [19]. Flexural and compressive strengths were obtained using a universal traction machine Zwick Z050 with a 2-kN load cell and a deformation rate of 0.2 mm/min for flexural strength was adopted, while for compressive test a load cell of 50 kN and deformation rate of 0.7 mm/min was used. Before the mechanical and flexural tests, the mortars' dynamic modulus of elasticity was carried out according to the EN 14146:2004 [20], using a ZEUS Resonance Meter equipment.

2.4 Open porosity and density

Open porosity was measured by total saturation with water of five specimens of each mortar under vacuum and hydrostatic weighting based on EN 1936:2007 [21]. Samples were dried and placed under vacuum for 24 h, then maintained under vacuum but immersed in water for another 24 h, and finally left for 24 h immersed at ambient pressure. After this procedure, the specimens were hydrostatically and saturated weighed. In order to better understand the previous results, the fresh density was measured after mixing by following ASTM C138 [22].

2.5 Water absorption by capillarity

The water absorption test was performed based on EN 1015-18: 2002 [23]. For each mortar, a sample of three specimens (40 x 40 x 160 mm^3) previously subjected to a curing period of 28 days and laterally waterproofed was used. Before the tests all the specimens were placed in an oven at 60 ºC for a minimum of 48 h for mass stabilization. The specimens were vertically placed in a watertight box with a water depth of 2 mm, which was kept constant. The box was covered to maintain constant hygrothermal conditions. The grout specimens were weighed after 5, 10, 15, and 30 min and at each hour during the first 6 h of testing, and then weighed every 24 h. The capillary water absorption coefficient was determined by the angular coefficient of the linear part of the capillary absorption curve.

2.6 Thermal conductivity

Thermal conductivity of the mortars was evaluated with a portable Isomet equipment with circular contact probes API210412 working in a range of 0.04 to 2.00 W/(m.K). The probe is placed on the sample and a heat flow through the specimen that follows the model in Eq.1,

$$q = \lambda A \frac{\Delta t}{L} \tag{1}$$

Where q is the heat flux, A is the area perpendicular to the heat flow, λ is the thermal conductivity of the section (W/(m.K)), Δt is the temperature drop across the specimen and L is the thickness of the specimen.

3. Results and discussions

3.1 Consistency and fresh density

As previously mentioned, the consistency determined using the flow table test was used as target to gauge the appropriate water dosage for each mortar. The consistency and fresh density values are presented in Figure 2. The fresh density of mortar was found to decrease with the increase of the wood waste content. The effects of wood waste on density are mainly caused by the lower density of wood and higher content of incorporated air due to the shape of the wood particles. The fresh densities of mortars proportioned with wood waste content of 10%, 20% and 30% were reduced to 20.4%, 21.0%, and 25.8%, respectively, compared with those of the plain mortar.

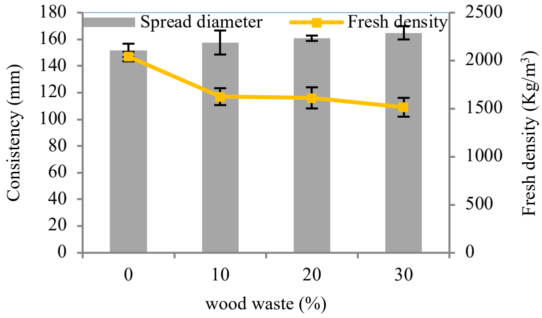

Figure 2. Consistency and fresh density as a function of wood wastes content.

During the mixing of mortars, it was clear that mortars' workability is reduced with the increased dosage of waste due to the water absorption capacity of wood wastes. The higher water absorption capacity of wood waste particles compared to the sand leads to a higher water/NHL ratio with the increasing waste dosage, as can be seen in Figure 3.

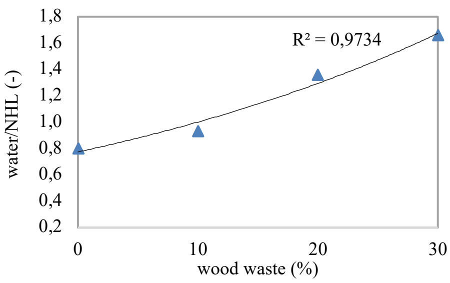

Figure 3. Water/binder ratio as a function of wood wastes content.

Based on the flow table test results and on the relationship between the waste dosage and water/NHL ratio (Figure 3), it was proposed the following equation (Eq.2) to predict the water/NHL ratio needed to obtain a mortar with proper consistency for rendering purpose. It should be noted, however, that this equation is valid for the type and dosage of HRWR used in this study.

$$water/NHL\ ratio = 0.7743 \cdot e^{0.0257.P} \tag{2}$$

Where P is the wood waste content as sand replacement in %.

3.2 Mechanical parameters

The results of compressive and flexural strengths parameters are presented in Figure 4. The substitution of sand with wood wastes caused a reduction in both compressive and flexural strengths of about 90%. The reason could be the lower density of wood waste than sand and due the shape of waste particles (which are flat and thin) that caused a less compact microstructure (see Figure 5).

The content of wood waste showed equal effect on compressive strength as that observed for flexural strength. However, it is quite evident that the addition of wood waste punished compressive strength more than flexural strength, as can be noted that the flexural strength values remain practically constant after 10% of waste content (Figure 4). This behaviour is consistent with results found in the literature [40] and it can be justified by the fibrous structure of the wood wastes which helps the mortar to resist tensile stresses, being the type of functional requirement that matters most in a plaster and rendering mortars. Nevertheless, it can be seen that the greatest reduction in mechanical performance occurs with the introduction of wood wastes up to 10%, while for dosages higher than 10% reduction in mechanical properties is not as pronounced. It should be noted, however, that the compressive strength in plasters or renders is not a parameter of high importance since in normal conditions they are not subject to this type of action

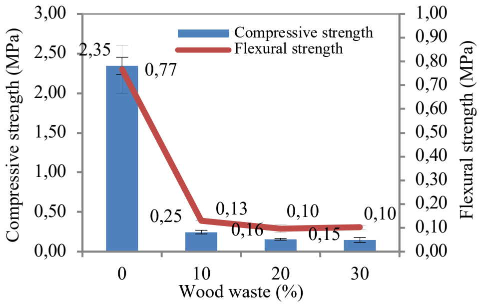

Figure 4. Compressive and flexural strengths as a function of wood wastes content.

The values of open porosity and density measured after 28 days of curing are shown in figure5. Considering that mortars are considered as lightweight mortars if their density is less than 1800 Kg/m^3, from the data in Figure 5 it can be noted that this density value is achieved even in the smallest content of wood waste. This result is fully consistent with the data reported by Corinaldesi et al [24] who reached density values under 1800Kg/m^3 if at least 5% of wood waste was used.

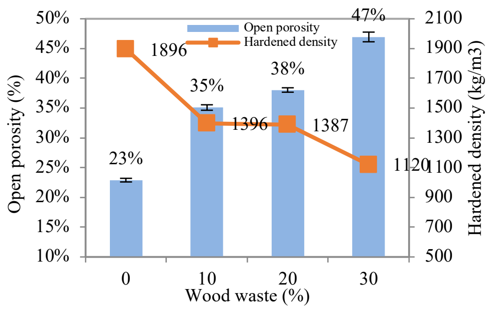

Figure 5. Evolution of dry density and open porosity as a function of wood wastes content.

Since all the mortars were formulated with similar consistency, as result of changing the waste content its mixing water quantity varies. For this reason, differences in the microstructure can be notable. A previous study has shown [25] that the porous structure of wood aggregates is not affected by their introduction into the cementitious matrix. In this sense, the open porosity of the matrix mainly depends on other factors, such as: particles size of aggregates, water dosage, temperature, state of sample moisture and mode of samples preparation [26, 27].

From Figure 6 can be observed the values of dynamic modulus of elasticity, the measured values reveal that the introduction of wood waste in the mortar causes a significant reduction in the dynamic modulus of elasticity compared to the reference mortar, most likely due to the microstructure of the wood. However, the values do not change much for waste content above 10%. However, by comparing the obtained results with those reported in the literature [24] for similar mortar formulations an elasticity module in the range of 6-11MPa was reported and it is clear that the values obtained are not in the same range of the literature values. However, this difference is mainly due to the fact that this study uses NHL which this mechanically different when compared to the Portland cement used in other works.

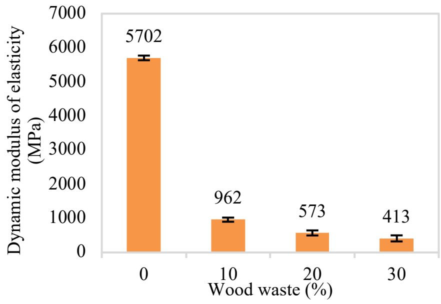

Figure 6. Evolution of dynamic modulus of elasticity as a function of wood wastes content.

3.3 Water action behaviour

The water behaviour of mortars was studied by water absorption by capillary test and drying test. The results of capillary water absorption coefficient are presented in Figure 7. It can be noted a linear decrease of water capillary absorption coefficient until 20% of wood wastes dosage as a replacement of sand. Therefore, for dosages between 20% and 30% there is an increase of this property reaching the highest value for the dosage of 30%. In fact, a larger amount of waste in the mortar is responsible for the existence of macro-pores in mortar microstructure, which reduces the capillarity waster absorption coefficient. On the other hand, a higher amount of wood waste in the mortar (above 20%) causes an increase in water absorption because the hygroscopicity of the wood overlaps with the effect of increasing the size of the capillary pores.

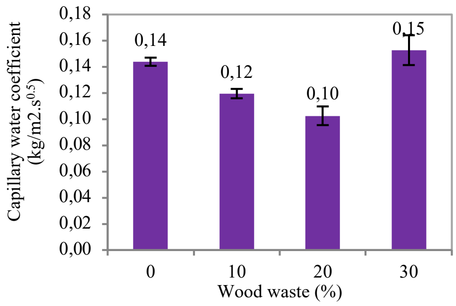

Figure 7. Evolution of water absorption coefficient as a function of wood wastes content.

Regarding the drying test results (Figure 8), the drying index presents an increase in its value with the increase of the dosage of waste. Such behaviour can be explained by the larger capillary pores that allow greater overall dying of the mortars. Comparing the drying rate of these mortars with those found in the literature [28], it can be said that the mortars in this study have higher drying index.

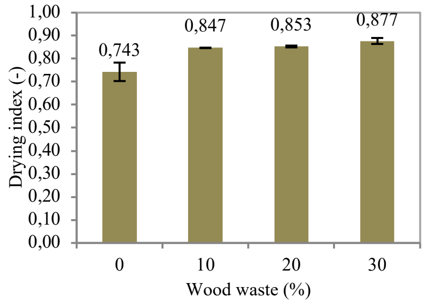

Figure 8. Drying index and drying rate as a function of wood wastes content.

3.4 Thermal conductivity

As can be seen in Figure 9, thermal conductivity decreased with wood waste content. The results showed that the mortar containing 10% wood waste is characterized by a thermal conductivity value of 0.37 W/m.K, sensibly lower (about 60%) than that measured for the mortar without any waste of 0.97 W/m.K. This performance can be explained both by the wood waste being less heat conducting compared to sand and the lower mortar compactness resulting from higher waste content. The findings from this research thus agree with those reported in the literature. Belhadj et al. [12] stated remarkably reduced thermal conductivity due to the addition of wood shavings, as well as Corinaldesi et al. [24] showed that the thermal conductivity of the cementitious pastes with sawdust was 25% lower than reference mixture.

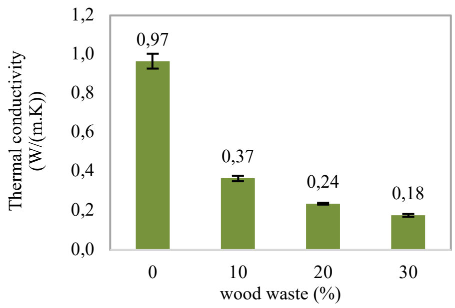

Figure 9. Evolution of thermal conductivity as a function of wood wastes content.

It should be noted that the mortar with 30% of wood waste has a value of thermal conductivity less than 0.2 (W/(m.K)) corresponding to category T2 of the main parameter of classification of thermal mortars according to standard EN 998-1: 2016 [29].

4. Conclusions

This research focuses on the analysis of wood waste as natural sand replacement on natural hydraulic lime mortars. Hence, batches with different percentages of sand replacement ranging from 0% to 30% were tested. The main conclusions are summarized as follows:

- Mortars containing wood wastes showed an increase in water demand. HRWR has been used to reduce the amount of mixing water. It was proposed an equation to predict the water/NHL ratio needed to obtain a mortar with proper consistency.
- Wood waste addition produced less evident detrimental effects on flexural strength than compressive strength, most likely due to the microstructure of the wood.
- The introduction of wood waste in the mortar causes a significant reduction in the dynamic modulus of elasticity compared to the reference mortar. However, the values do not change much for waste content above 10%.

- The addition of wood waste seems to show positive influence on lowering both water absorption (up to 20% of addition) and thermal conductivity, which resulted 80% lower through the replacement of 30% of the sand by wood residues.
- Based on such performance, the mortars made with wood waste can be considered very suitable for plasters. The conclusions made in this study therefore pertain to this particular experimental and materials range.

Hence, this research develops the implementation of a waste to be used in construction based on the definition of a mortar using wood waste as aggregate. This wood wastes usage provides also an improvement in the sustainability of these mortars, as they use a great volume of waste (in alternatively to natural sand) and simultaneously improve the energy efficiency of buildings because as demonstrated this waste contributes to obtain mortars with reduced thermal conductivity.

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