Effect of human hair on thermal conductivity of mortars

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Abstract - This study aims to examine the potential for using Human Hair Fibers (HHF) to adjust the thermal properties of indoor spaces: HHF has a thermal conductivity of roughly 0.037 $W.m^{-1}. K^{-1}$, making it a good thermal insulator. This study examines the effect of 0% to 8% HHF by weight of cement on the compressive strength, open porosity, and thermal conductivity of mortars. It was found that the addition of HHF results in a decrease in thermal conductivity and compressive strength with an increase in porosity. Adding 8% HHF allows to obtain a lightweight mortar with 37% less thermal conductivity than the reference mortar at 28 days.

1. Introduction

The European market offers a wide range of thermal insulation materials [1]. Approximately 60% of the market is dominated by mineral and inorganic fibrous materials such as glass and stone wool, 30% by organic foamy materials (expanded polystyrene, extruded polystyrene, and polyurethane). In comparison, 10% are comprised of combined materials (wool-wool, gypsum-foam) and new technologies like nano cellular foams and transparent materials [2]. As a result, bio-based building materials are becoming increasingly relevant since they have very low or even positive environmental impacts (renewable resources, CO_2 storage, greenhouse gas emissions reduction, etc.) [3], [4]. Additionally, some of these materials have already been well established on the building market for many decades and possess excellent multi-physical properties (heat insulation, sound absorption, transmission loss) [5], [6].

Although thermal insulations are environmentally friendly, they are energy-intensive to produce and use non-renewable materials. Reducing the energy consumption of buildings is one of the most important challenges of the 20th century, especially considering climate change, fossil resource scarcity, and global energy demand [1]. Thus, sustainable thermal insulation materials derived from renewable resources and industrial waste are becoming increasingly popular. The first use of human hair fibers in concrete was in India, Pakistan, Syria, and other countries [7]. Several articles were written about the mechanical properties of concrete reinforced with HHF [8], but none discussed the thermal and microstructural properties of mortar reinforced with HHF. The effect of HHF introduction at different rates on the mechanical, porosity, and thermal properties of mortars was thus studied here.

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2. Materials and methods

2.1. Materials

For mortar preparation, cement, water, and sand are used. CEM I 52.5 N CE CP2 NF Portland cement, normalized sand with a particle size between 0.08 and 2 mm and a density of 1713 kg/m3 were used. There is a sand/cement mixture ratio of 3 and a water/cement mixture of 0.5. In the study, hair fibers predominantly measured 2 cm in length, representing the practical availability of hair clippings from a specific establishment (Fig. 1). Utilizing Scanning Electron Microscopy (SEM) analysis, the fibers' average diameter was determined to be 70 micrometers. The aspect ratio, a critical parameter for assessing reinforcement potential in mortars, was calculated to be approximately 286 based on the fibers' average length and diameter. HHF are incorporated as an additive to mortars (by weight of cement) in varying percentages, such as 0%, 1%, 1.5%, 2%, 2.5%, 3%, 4%, and 8%.

Fig. 1: Human hair fibers

2.2. Mixing design and specimen preparation

The formulation of mortar mixes follows the NF EN 196-1 standard protocol. First, HH fibers, cement, and water are mixed at a low speed (140 rpm) for 30 seconds. After that, the mix is sanded at a low speed for 30 seconds. It is then mixed for 30 seconds at high speed (285 rpm). In the final step, the components are mixed at high speed for 1 minute after scraping the mould for 90 seconds. Mortar cubes of 40x40x160mm size were fabricated to examine the compressive strength, the thermal conductivity and the open porosity.

2.3. Characterization methods

2.3.1. Mechanical characterization

The mortar specimens were tested for compressive strength at day 7 and 28 using CONTROLS PILOT4 C300KN. The loading speed for compression is 2400 N/s and 50 N/s according to NF P 18-455.

2.3.2. Dry density and porosity

Mortars density was calculated from dry sample mass and sample size measurements. Additionally, mercury injection is used to determine open porosity and pore size distribution. Measurement of mortar porosity is carried out using the Micrometrics Autopore IV 9520 Porosimeter. The penetrometer is filled with low-pressure mercury after removing all air (0.1 MPa). As the pressure increases, the mercury is able to reach smaller pores. After that, samples are placed in a hydraulic fluid under high pressure (up to 414 MPa).

2.3.3. Thermal conductivity

Thermal conductivity measurements were conducted using the Hot Disk probe. In this method, a Kapton sensor is used as a source of heat and temperature sensors. Most often, the probe is sandwiched between two identical samples. Prior to the experiment, the following parameters must be optimized: probe size, experiment duration, sample size, and probe power [9]. For each hair percentage, the sensor was placed between the mortars and three values were taken. Hair fibers of a specified apparent density were placed in between the probe, and a series of measurements were subsequently conducted to ascertain their thermal conductivity, in both a compacted and uncompacted state.

3. Results and discussion

3.1.1. Compressive strength

The results of the compressive tests are plotted in Fig. 2. Each point represents the average of three tests. As compared to the reference mortar, mortar reinforced with HH fibers had a much lower compressive strength. A compressive strength of 36.4 MP, 29.1 MPa and 14.9 MPa (day 28) can be achieved for 0%, 1% and 8% HHF. The addition of 8% HHF reduces compressive strength by 49%. A decrease in mechanical strength can be attributed to an increase in porosity caused by the incorporation of HHF particles into the matrix and poor HHF adhesion to the matrix. Aspect ratio, fiber content, and fiber treatment influence the mechanical properties of mortars [10]. It has also been observed that a high concentration of human hair in mortars causes balling and lumping of fibers, which would adversely affect the mechanical properties of the studied mortars. The compressive strength of mortars is reduced when HH fibers are added, but the materials produced have enough mechanical strength to be used in structural applications, for example, prefabricated blocks for load bearing walls with improved thermal insulation properties [9].

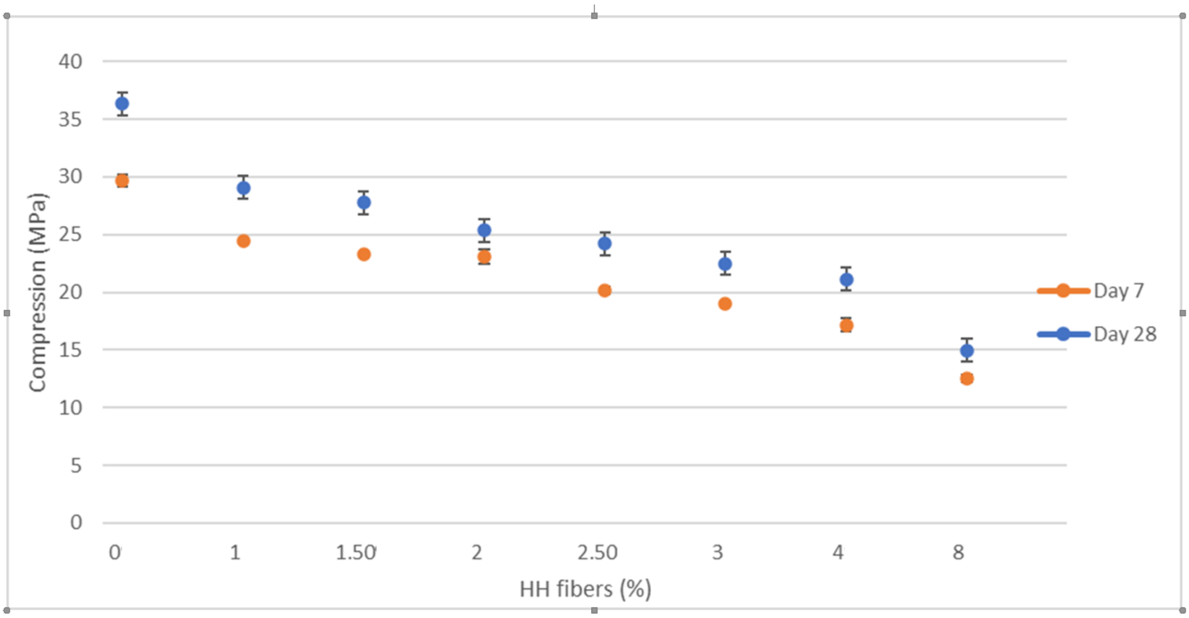

Fig. 2: The influence of adding HHF on the Compressive strength

3.1.2. Porosity

As can be seen in Fig. 3, pores range in diameter between 3.6 nm and 429 µm. Furthermore, the pores increased in areas with pores between 100 nm and 10 µm and greater than 10 µm with the addition of hair fibers. The porosity of all mortars varied between 14.1 % and 23.2% when 8% HHF was added. The analysis reveals that the mortar exhibits a considerable number of macropores and large capillaries, which potentially contribute to reduced thermal conductivity. However, the presence of such pores in mortars is unfavorable, as it adversely impacts their mechanical strength. The primary cause for this reduction in mechanical properties is the presence of macropores, resulting from the addition of human hair fibers (HHF) to the cement paste and the transition zones formed between the cement paste and fibers. Consequently, it is crucial to balance thermal conductivity reduction and maintain adequate mechanical strength in mortars to achieve optimal performance. This can be attained by selecting suitable materials and adjusting mixing proportions during the mortar preparation process. Several studies have reported findings counter to the positive influence of fibers on the microstructural properties of mortars and concrete. For instance, Gencel et al. (2011) discovered that fiber addition could increase porosity and subsequently decrease mechanical strength [11]. Similarly, Yan et al. (2016) noted that incorporating bamboo fibers resulted in a compressive strength decrease of approximately 10% to 15% due to increased porosity [12]. Researchers have ascribed these trends to factors such as fiber-matrix compatibility issues, increased porosity, and the hydrophilic nature of natural fibers, leading to weaker interfaces between fibers and the mortar matrix [13]–[15].

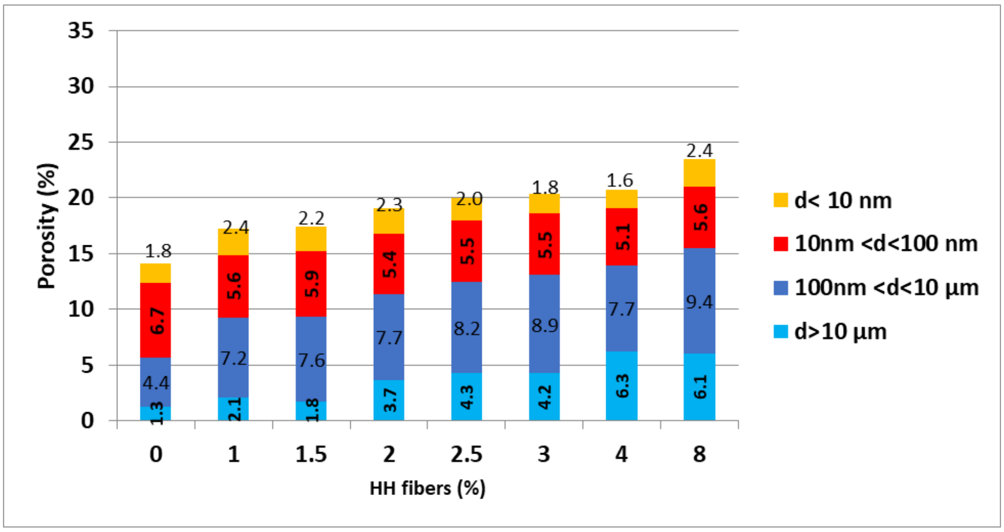

Fig. 3 : Variation of the pores volume of mortars in different pore range

3.1.3. Thermal conductivity and density

Table 1 shows the thermal conductivity of mortars with different amounts of HH fibers. The results showed that the thermal conductivity of the mortars with HHF (1.72–1.2 $W.m^{-1}·K^{-1}$) was lower than the reference mix (1.89 $W.m^{-1}·K^{-1}$). Thermal conductivity decreased by approximately 37% when adding 8% HH fibers. There is a direct correlation between thermal conductivity and density of bio-aggregate based building materials, as well as with formulation factors (binder, aggregates, and binder-aggregate ratios) and water content [16]. Therefore, the decreasing thermal conductivity values mainly resulted from the HH fibers used in mortars, which had a porous structure and low thermal conductivity (0.037 $W.m^{-1}·K^{-1}$). It should be noted that the mentioned thermal conductivity value was measured at an apparent density of 506 ± 9 kg/m^3 (with compaction). The low thermal conductivity of HH fibers is a key factor in reducing the overall thermal conductivity of the mortars. This is because the porous nature of HH fibers hinders the transfer of heat through the material, resulting in a decreased rate of thermal energy transmission. It can also be observed that the thermal conductivity results follow the same trend as the bulk density results, which indicates that the thermal conductivity decreases as mortar bulk density decreases. The thermal conductivity of the mortars with HH fibers mixes was consequently found to be reduced from 1.72 to 1.20 $W.m^{-1}·K^{-1}$ with the corresponding bulk density of 2101–1945 kg/m^3.

Table 1 : Properties of produced HHF mortars

HH fibers (%)	Density ($Kg.m^{-3}$)	Thermal Conductivity ($W.m^{-1}.K^{-1}$)	Compressive Strength (MPa)	Porosity (%)
0	2211 ± 1.1	1.89 ± 0.1	36.4 ± 2.3	14.11 ± 0.5
1	2101 ± 0.2	1.72 ± 0.1	29.1 ± 3.7	17.23 ± 0.2
1.5	2090 ± 0.3	1.63 ± 0.1	27.8 ± 2.9	17.44 ± 0.1
2	2068 ± 0.2	1.57 ± 0.1	25.3 ± 5.5	19.05 ± 0.1

2.5	2063 ± 0.2	1.52 ± 0.1	24.2 ± 3.8	20.01 ± 2.6
3	2045 ± 0.1	1.47 ± 0.1	22.5 ± 1.1	20.40 ± 1.3
4	2020 ± 0.1	1.41 ± 0.1	21.1 ± 5.2	20.71 ± 0.8
8	1945 ± 0.2	1.20 ± 0.1	14.9 ± 2.3	23.46 ± 1.3

4. Conclusion and perspectives

This study evaluated cement-based mortars containing HH fiber wastes' thermal, microstructural, and mechanical properties. It is possible to achieve a good balance between the thermal and mechanical performances of mortars by using HH fibers at an optimum content. Furthermore, the addition of HH fibers decreased the thermal conductivity of the composites studied by up to 37% when 8% HH fibers were added to mortars. Based on these experimental results, the following conclusions were drawn:

- The compressive and bending strength were consistent with the density and porosity, indicating that adding more HH fiber will decrease its mechanical strength.
- When HH fibers are added, the MIP tests reveal pores larger than 10 µm. Therefore, MIP results showed a gradual increase in porosity with HH fiber addition.
- Human hair fiber reinforcement improves the insulation properties of mortar by reducing thermal conductivity. The results reveal that 8 wt% HHF with a thermal conductivity of 1.2 $W.m^{-1}.K^{-1}$ allows to obtain good thermal insulation with sufficient mechanical strength of some structural applications.

The promising outcomes of the study suggest the need for additional research into the recycling of human hair for use in cementitious materials. Future investigations should consider several factors, such as the HHF treatment, including washing and drying before incorporation into mortar, or the use of superplasticizer to improve their dispersion, mortar flowability, and fiber/binder adhesion. Another aspect to explore is the impact of varying lengths of HHF on the mechanical strength of the material. The hygroscopic properties of HHF mortars should also be examined, as well as their environmental impact through a life cycle analysis. The incorporation of human hair waste-based mortars in construction practices presents a promising avenue for enhancing insulation in buildings while simultaneously mitigating the environmental impact associated with human hair waste.

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