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EFFECT OF SHEEP WOOL FIBRES ON THERMAL-INSULATION AND MECHANICAL PROPERTIES OF CEMENT MATRIX

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Abstract

The use of sheep wool as reinforcement of cement in order to produce mortar or plaster involves several advantages for environment and energy. Moreover, in several regions it is treated as a waste and, consequently, its employ is characterized by low cost. Aim of this paper is to evaluate the influence of wool fibres on thermal conductivity and mechanical properties of cement. The samples were prepared using wool fibres, obtained from a breed of Sicilian sheep, with three different length (i.e. 1 mm, 6 mm and 20 mm). Moreover, in order to evaluate the influence of fibre content, the samples were prepared by varying the fibres weight fraction up to maximum level. The thermal conductivity of samples was analyzed by using a heat flow meter, whereas the mechanical behavior was studied through compressive tests. In order to validate the thermal measurements, two theoretical models were applied. The results showed that wool fibres could be considered as a valid reinforcement in cementitious matrix to obtain mortars or plasters with both enhanced thermal insulation properties and good mechanical ones.

Keywords:

Wool fibres; Mechanical properties, Cement mortar; Thermal conductivity

1 INTRODUCTION

To reduce the environmental impact of operations on built environment (i.e. energy consumption and CO2 emissions) in several fields as the construction one, new technological solutions are proposed and new materials are investigated recently [Asprone 2011].

For instance, the use of natural fibres as reinforcement for cementitious or plastics matrix, substituting the synthetic ones, receives increase attention nowadays thanks to the specific properties, the price, the advantages for health and the recyclability.

Natural fibres can be classified according to their origins in ligno-cellulosic (from plants/vegetable), mineral (e.g. asbestos, which is hazardous for the health and basalt) and protein (from animals). These last fibres are grouped under the categories of hair (wool), fur (angora) and secretions (silk).

The use of such fibers in a cement matrix arose in response to two historical events, both associated with the replacement of asbestos in "fiber-cements". The first event dates back to World War II when asbestos was absorbed by the war industry as an insulating material in armored warships. The second event took place during the last decades of the last century when most developed countries prohibited the use of asbestos in building materials due to its carcinogenic properties.

Really, cellulose fibres are the most common used in several industrial applications as reinforcement for cementitious matrices. In scientific literature, several studies analyze the positive effect of vegetable fibres on the mechanical behavior of these innovative structures.

[Khorami 2011] studied the effect of three different cellulose fibres (i.e. bagasse, wheat and eucalyptus) on flexural properties of Fibre Cement Boards (FCB) showing that these properties enhanced considerably using bagasse fibres compare to the wheat and eucalyptus fibres. In particular, the best result was obtained with 4% by the weight (i.e. flexural strength was about 50% more than the control specimens).

[Li 2006] analyzed flexural properties of natural and chemically modified coir fibre reinforced cementitious composites reporting that flexural toughness of these cementitious composites increased by more than 10 times with coir fibre. [Tonoli 2010] showed the advantages of using hardwood short fibre pulp (i.e. eucalyptus) as alternative to softwood long fibre pulp (i.e. pinus) and polymer fibres, traditionally used in reinforcement of cement-based materials.

[Ramakrishna 2005] showed that the impact resistance of cement mortar slabs greatly increase (up to 18 times than that of the reference) by using a low percentage (up to 2.5% by weight) of different natural fibres (i.e. coir, sisal, jute and *hibiscus cannebinus*).

[Asprone 2011] developed a composite material, made by a pozzolanic mortar reinforced by a hemp fibre grid with a latex coating, to be potentially used in retrofitting application of civil structures. The results showed that the hemp fibre grid can provide a significant improvement of the flexural behavior of the pozzolanic mortar and the durability of the hemp fibres in the pozzolanic mortar environment greatly improved by using latex coating. [Claramunt 2011] showed the beneficial effects that the previous hornification of the vegetable fibers (i.e. softwood kraft pulp and cotton linters) have on the mechanical performance and durability of cement mortar composites. [Di Bella 2014] compared mechanical and durability properties of lime plaster reinforced with synthetic fibres (i.e. polypropylene) with those of plasters reinforced with two kinds of natural fibres: i.e. sisal and kenaf fibres. In particular, the decrease of mechanical properties due to freeze/thaw cycles is comparable under flexural load condition for all plasters analyzed in this work, while the decrease of compressive strength, shown by plasters reinforced with sisal fibres, is lower than other ones. Moreover, thanks to their higher hydrophilicity, the plasters reinforced with natural fibres present low weight loss after ageing time in salt spray environment than ones with polypropylene.

Compared to cellulose fibres, other ones (mineral and protein) are less used as reinforcement of inorganic matrices. At the best of our knowledge, several scientific studies about mineral fibres and no about protein ones are available in literature. For instance, [Jiang 2010] analyzed the effect of basalt fibres on drying shrinkage, mechanical properties and bond performance of cement mortars. They showed that by adding of basalt fibres it reduced markedly dry shrinkage of mortar especially at early ages. Moreover, mortar with basalt fibres showed a greater compressive and flexural strength at early hydration period, but a little less strength at the age of 28 days than mortar without fibres. [Kabay 2014] showed that an improved flexural strength, fracture energy and abrasion resistance can be obtained by using basalt fibres even at low contents. However, inclusion of basalt fibres in concrete resulted in a decrease of compressive strength. [Jiang 2014] analyzed the effects of the volume fraction and length of basalt fibres on the mechanical properties of fibre reinforced concrete. In addition, these results show that adding basalt fibres significantly improves tensile strength, flexural strength and toughness index, whereas the compressive strength shows no obvious increase.

The use of wool as reinforcement of cement in order to produce mortar or plaster involves several advantages (i.e. the recovery of a material that in several regions is considered a waste, the environmental and energetic sustainability in production, the locally application and the low cost of production and use).

In Sicily, there are about 730000 sheep, reared for the production of milk and meat. Their wool is considered a special waste. The shear, which occurs at least once a year, produces about 3 kg of wool per sheep for an annual production of about 2.2 million kg. To encourage the breeding of sheep would allow increased production of wool by reducing disposal costs.

Properly carded and washed with natural soaps and anti-moth products, in order to avoid rot and bacterial attacks, it can be processed individually or mixed with other natural or synthetic fibres (i.e. polyester or hemp) to achieve good thermal insulation/acoustic properties of panels. The wool fibres are regenerated, breathable, hygroscopic and recyclable.

It is water-repellent and at the same time is able to absorb moisture. Then, it can repel water in liquid form, but it also can absorb water vapor up to 33% of its weight without appearing wet, favoring a natural regulation of humidity within the housing and reducing the risk of condensation with subsequent damage to the structure.

The wool is resistant to high enough temperatures without decomposing. At 250 °C begins to be damaged, it flashes if the surrounding environment reaches 600 °C, in this case it does not emit toxic gases. Indeed, a panel of sheep wool with adequate porosity has the ability to absorb toxic gases (oxides of nitrogen and sulphur) and formaldehyde without they become toxic deposits inside the panels, but turning them into neutral substances that reinforce the fibre itself.

The objective of the present paper is to study the mechanical behavior and thermal conductivity of a cement mortar reinforced with wool fibres at three different fibre contents (i.e. 13%, 23% and 46% by wt. of cement) and using three fibre lengths (i.e. 1 mm, 6 mm and 20 mm).

2 EXPERIMENTAL SETUP

2.1 Materials and Manufacturing

The wool, obtained by a breed of Sicilian sheep, were supplied by “Istituto Zooprofilattico” of Palermo. In order to prepare the fibres, the following procedure was realised:

- Washing and drying: the wool was washed with running water at 30 °C in order to remove both impurities such as dust and dirt and other substances that acts as waterproofing. Then, the wool was dried in air for a week. The final product is a fell, compact and felted.
- Fibre cut: the wool was cut in short fibres, using a cutting mill supplied by Retsch, mod. SM 100 Comfort, in order to promote the mixing between matrix and fibres. In order to evaluate the influence of the fibre sizes, three different lengths were investigated; i.e. 1 mm, 6 mm and 20 mm (Fig. 1).

Fig. 1: Fibre length: a) 20 mm; b) 6 mm; c) 1 mm

The wool fibres were added to a commercial Portland cement 32.5 R type CEM II/ A-L 32.5 R in according to EN-197/1 [2000], with varying the fibre content as a function of the size. In particular, three different percentages (i.e. 13%; 23% and 46%) were identified as the maximum reachable value for each fibre length (i.e. respectively, 20 mm; 6 mm and 1 mm). In Tab. 1 it is reported the composition of all samples. The composites will be identified with the sample code LXXCY, were XX identifies the fibre length and Y indicates the fibre weight content (1 for 13 wt%, 2 for 23 wt% and 3 for 46 wt%). For instance, L20C1 indicates the composite incorporating 13 wt% of fibre with length 20 mm. Some samples were realised also using a not washed fibres (NW in the sample code) in order to verify the effect of the impurities' presence. It is evident that shorter fibres allowed to reach higher content of fibres.

Tab.1: Composition of the composites.

Sample ID	Fibre length [mm]	Washing	Fibre content [%]
L20C1	20	X	13
L20C1NW	20		13
L6C1	6	X	13
L6C2	6	X	23
L6C2NW	6		23
L1C1	1	x	13
L1C2	1	x	23
L1C3	1	x	46

The mixture (i.e. cement, water and wool fibers) was blended manually for 10 min, followed by mixing in a mechanical mixer for 10 min to secure good homogeneity. The samples were realised within a formwork, having the sizes identified by specific, and they were aged for 28 days.

Compression tests were carried out, in according to ASTM C39/C39M [2014], by using a Zwick-Roell Universal Testing Machine (UTM), equipped with a load cell of 600 kN. Five samples for each structure were tested at room temperature.

3 THEORETICAL MODELS

In addition to experimental measurements of thermal conductivity, two combinations of the series and parallel models were applied [Wang 2006], [Taoukil 2012].

The composite structure is constituted by two phases, a matrix (i.e. cement) and an insulating material (i.e. sheep wool) having volume fractions (1-θ) and θ, respectively. When the two phases are thermally in parallel in the direction of heat flow, the effective thermal conductivity λ_p of the sample is given by:

$$\lambda_p = \theta\lambda_i + (1-\theta)\lambda_m \tag{1}$$

where λ_m is the thermal conductivity of the matrix, λ_i the thermal conductivity of the insulating material.

When the two phases are thermally in series in the direction of heat flow, the effective thermal conductivity λ_s is given by:

$$\lambda_s = 1/\left(\frac{\theta}{\lambda_i} + \frac{(1-\theta)}{\lambda_m}\right) \tag{2}$$

For an intermediate distribution of phases, [Willy and Southwick 1954] proposed in their model a weighted arithmetic mean:

$$\lambda_{WS} = F\lambda_p + (1-F)\lambda_s \tag{3}$$

Whereas, [Chaudhary and Bhandari 1968] proposed in their model a weighted geometric mean:

$$\lambda_{CB} = \lambda_p^F \lambda_s^{(1-F)} \tag{4}$$

F is a numerical correlation factor and can be defined as the fraction of the material oriented in the direction of heat flow.

4 RESULTS AND DISCUSSION

4.1 Thermal conductivity testing

The results of the thermal conductivity testing with varying the wool content and, for each percentage, the fibre length, are shown in Fig.2.

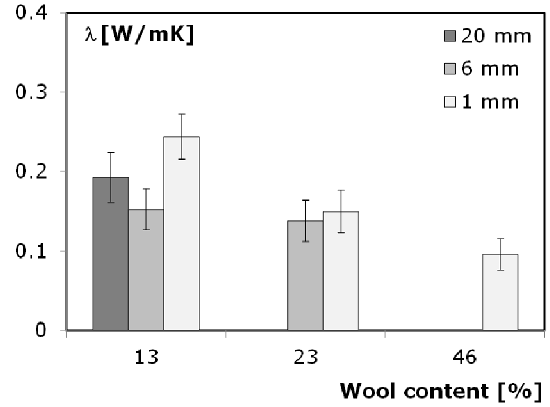

Fig. 2: Thermal conductivity analysis

This graph shows that:

- For a content of 13%, it is possible compare the effect of all fibre lengths. In particular, a conductivity equal to 0.193 W/mK represents the lower limit for a sample reinforced with 20 mm long wool fibres. This value is lower than commercial thermal insulating mortars for masonry (i.e. 0.279 W/mK). The samples L6C1 show the better properties (0.153 W/mK). Whereas, the samples L1C1 have the worst behavior. The wool adding in the cement involves an improvement of its thermal properties. It is worth noting that too long fibres have two limits, related, respectively, to technology and performance. There are a number of physical fibre properties that affects both slump and workability: i.e. type/configuration, quantity, length, proportions of the plain mix, admixtures or additives incorporated in the mix. In particular, longer fibres reduce the workability to a greater degree than shorter ones and, consequently, it is much needed to limit the quantity of fibre in order to guarantee a homogeneous distribution in the matrix. Moreover, the fibres interact among them creating a network, as a mat, that is characterized by lower thermal properties than a compact layer, constituted by shorter fibres (i.e. 6 mm). The presence of fibres with a 1 mm length allows to reduce the conductivity due to a better dispersion in the matrix, but the content is still too low and this fibres behave mainly as a filler. The samples L6C1 present the better properties due to the content allows to create a more efficient layer of wool within the matrix.

- For a content of 23%, the thermal conductivity reach similar values for both the samples, L6C2 and L1C2. The error bars are overlapped. The first ones are characterized by their lower limit of wool content, in the second the fibres are not only a filler but the quantity allows them to constitute an insulating structure within the cement.For a content of 46%, the lower limit of wool content for a fibre length of 1 mm is reached. In this case the mean conductivity is equal to 0.096 W/mK, similar to values of commercial plaster (i.e. 0.086 W/mK).

Moreover, analyzing the behavior of all L1 samples, it is possible to observe that the conductivity decreases by increasing the wool quantity. In fact, higher contents of fibres allow to create a more powerful thermal reinforcement.

In Fig. 3 are reported the results for the samples L20C1 and L6C2, with and without the step of washing. Although, the washed wool is characterized by a thermal conductivity lower than the not washed wool, as shown with a preliminary analysis on the fibre (respectively, 0.035 W/mK against 0.050 W/mK), the samples reinforced with not washed wool present a lower mean conductivity (i.e. -24% for L20C1 and -31% for L6C2) . The impurities of the not washed wool induce the formation of air bubble (λ = 0.026 W/mK) within the sample. Although, the entrapped air represents a defect that influences negatively other properties (i.e. mechanical), it improves the thermal conductivity.

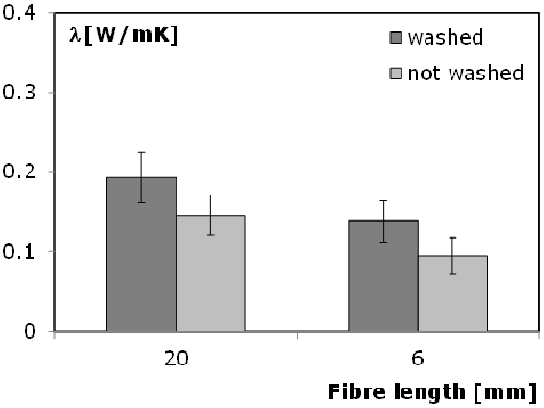

Fig. 3: Comparison between washed and not washed samples.

The comparison between experimental data and Willy and Southwick model is reported in Fig.3a. It is evident a correlation. In fact, the mean values of thermal conductivity are within a region identified by the equation (3) solved for F=0.25 (i.e. bottom line) and F=0.35 (i.e. top line) [Bhattacharya 2002]. The deviation from the top line is due to effect of fibre length that influences the choice of the factor F

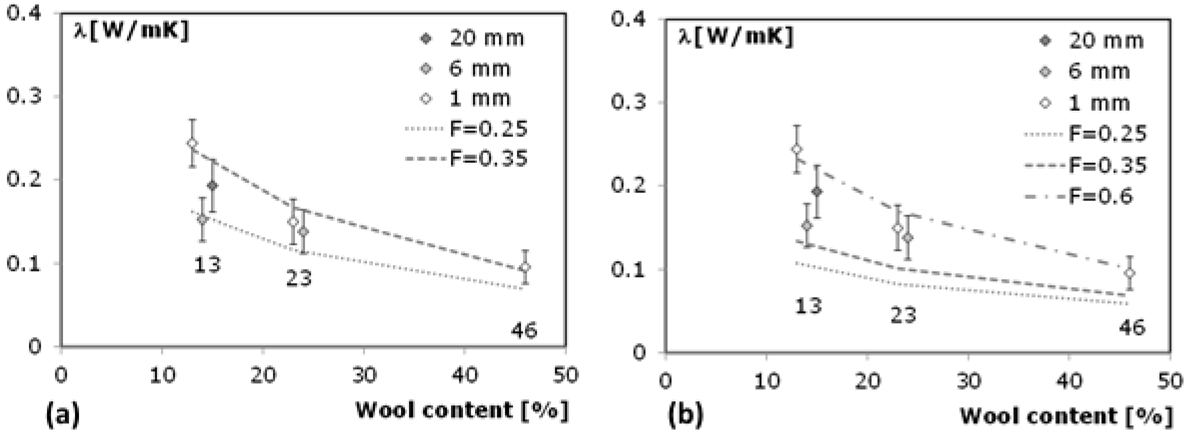

Fig.4: Comparison between experimental data and theoretical models: a) Willy and Southwick; b) Chaudhary and Bhandari.

The comparison between experimental data and Chaudhary and Bhandari model is reported in Figure 4b. In this case, the correlation is less evident. This different behaviour, than other cited studies (i.e. [Taoukil 2012]), is due to:

- The percentage of fibres that it is possible include in the cement (i.e. 55%, 70% and 87% in volume for 13%, 23% and 46% in weight, respectively). In fact, for intermediate values, the two models are not comparable. Whereas, their difference decreases for low percentage.
- The difference of thermal conductivity between wool (i.e. 0.035 W/mK) and cement (i.e. 1.2 W/mK). This is another factor that influences the overlapping between the two models.

4.2 Mechanical testing

The results of compressive tests with varying the wool content and, for each percentage, the fibre length are reported in Fig. 5. In particular, the values of failure stress are reported.

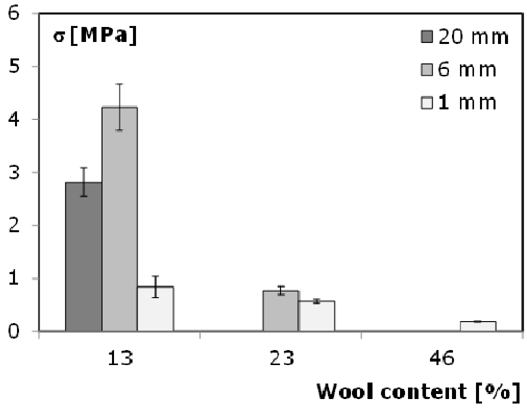

Fig. 5: Mechanical analysis.

This graph shows that:

- For a content of 13%, the samples L6C1 are characterised by the better properties. The samples L1C1 show the lower values of stress. Whereas, the samples L20C1 have an intermediate behaviour. This phenomenon is due to the effect of the length of fibres and their quantity. The fibres having a length of 20 mm have saturated the matrix and this induces residual tension in the material after the manufacturing phase. Moreover, the more tangled structure of the wool network represents a further element promoting the formation of cracks. The fibres having a length of 1 mm can be considered only a filler that do not improve the mechanical properties of the matrix. Vice versa, the fibres having a length of 6 mm play a role as reinforcement for the cement. The typical failure modes are shown in Fig. 6.
- It is worth noting that the samples L20C1 are characterised by a catastrophic conical flaking (Fig. 6 a). The presence of 6 mm fibres avoid this sudden damage (Fig. 6b). Finally, the samples L1C1 are characterised by several deep longitudinal cracks (Fig. 6c).
- For a content of 23.28% and 46%, the behaviour of the samples is really worse. The fibres have not a function of reinforcement but it promote the cracking of the samples, as observed in Fig. 7.

Moreover, analyzing the behavior of all L1 samples, it is possible to observe that the stress drastically decreases by increasing the wool quantity. This occurs also for the samples L6, considering the two contents (i.e. 13% and 23%).

The results for the samples L20C1 and L6C2, with and without the step of washing, are shown in Fig. 8. The samples with washed wool are characterised by better properties. The presence of impurities, as previously described, induces the formation of bubble of air that promotes the propagation of cracks in the samples.

Fig. 6: Failure modes: a) L20C1; b) L6C1; c) L1C1.

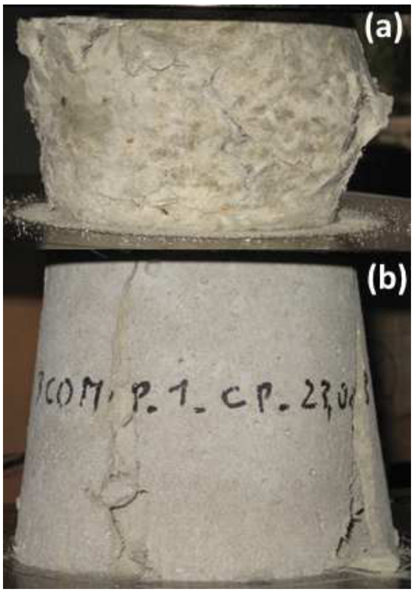

Fig. 7: Failure modes: a) L6C2; b) L1C2.

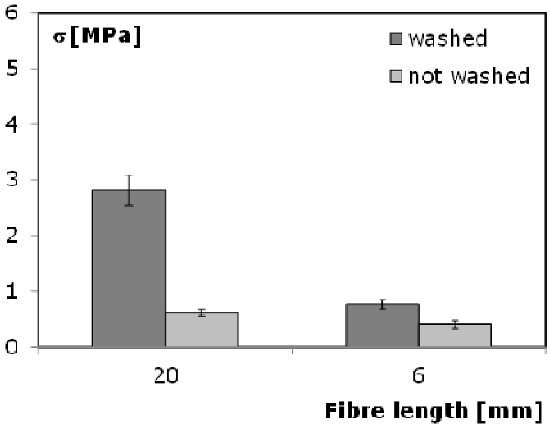

Fig. 8: Comparison between washed and not washed samples.

5 CONCLUSIONS

In several regions, as Sicily, the sheep wool represents a waste that can be recovered and used in the buildings as reinforcement of mortars or plasters.

From the present study, it is possible to draw out that:

- thermal conductivity of the samples reinforced with wool decreases, by increasing the content of fibre;
- shorter fibres (i.e. 6 mm against 20 mm and 1 mm against 6 mm) promote the formation of a compact insulating layer with the cement that reduces further thermal conductivity.
- not washed wool fibres induce the formation of bubble air in the matrix with a consequent reduction of conductivity.
- mechanical properties are reduced by the presence of both fibres too long that saturate the matrix because of residual tension and fibres too short that have only a role as filler.
- the better mechanical properties are conferred by fibres of 6 mm with a percentage of 13%.

Finally, exists a correlation between the experimental measurements of thermal conductivity and the Willy and Southwick model.

These results evidence the goodness of wool as insulator material within cement mortars. Nevertheless, it is worth noting that it is needed to find a compromise with the mechanical resistance in order to identify the better ratio length/content (e.g. length equal to 6 mm and weight content to 13%, in the investigated case).

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