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Natural fibers reinforcement for earthen building components: Mechanical performances of a low quality sheep wool (“Valle del Belice” sheep)

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ABSTRACT

The paper proposes the use of Sheep wool fibers (SWF) deriving from the fleece of domestic sheep (“*Valle del Belice*” from Sicily) as reinforcement for rammed earth building components. Addition of natural fibers to the mix design of earth-based building materials allows to improve their tensile strength, ductility, impact resistance, toughness, and to reduce drying shrinkage. To this aim, an experimental campaign on more than 180 fibers has been carried out, determining the main mechanical properties of interest for their use as reinforcement. Since wool is highly hydrophilic, three different conditioning programs (wet, dry and an intermediate condition) were compared, in order to get useful information about the preservation of the mechanical properties in wet environments like those present in lime mixes. The dependency of the properties from the fibers’ diameter was investigated, and the results were statistically analyzed using a modified Weibull distribution as function of the fiber diameters, finding a strong correlation with the mechanical properties.

The use of natural fibers as reinforcement could enhance the environmental sustainability of the building components, especially when natural fibers are obtained from agricultural wastes deriving from sheep of low-quality wool not used in the textile industry and that must be disposed of in landfills.

1. Introduction

Earth constructions and earth-based building-components are becoming popular in the building sector due to their low environmental impact and sustainability. Among traditional building materials used throughout the centuries all over the world, raw earth has a prominent place. As stated from Guillaud et al., [1] one third of the world’s population lives in earthen dwellings; raw earth buildings are widespread from Latin America to Africa, from Central Europe to Middle East. Raw earth could be extracted and transformed directly in the building site, with significant reduction of environmental costs of transportation and related pollution. This is of relevant importance because improves the sustainability of the building sector, for building renovation or new constructions. Raw earth materials exhibit low tensile strength, so they have a reduced ability to respond to horizontal actions, like those occurring in seismic areas. For this reason, reinforcement fibers could be added to raw earth mix design to improve the tensile strength, ductility, impact resistance, toughness [2], and to control drying shrinkage and cracking resistance [3,4]. Synthetic or natural fibers are suitable for this use.

In literature, several studies concerning the use of natural fibers as substitute of synthetic ones in soil matrix composites have been published [5-7]. Natural fibers are replacing synthetic fibers because of their economic and environmental sustainability, and for some peculiarities of their mechanical performances like their high strength to weight ratios. In fact, natural fibers, in addition to environmental advantages like good availability, low cost, renewability, biodegradability, present a very low density, (i.e., natural fiber density is ranged between 1.2 and 1.6 [g/cm^3] lower than glass fiber density 2.4 [g/cm^3]) and generally are able to guarantee good mechanical properties to the composite, as tensile strength, stiffness, flexural strength, flexural modulus [8].

Natural fibers can be vegetable with a lignocellulose structure (e.g., jute, hemp, sisal, banana, coir, kenaf), or animal with a protein structure (e.g., hair or wool derived from animal). Plant’s fibers are basically composed by cellulose, hemicellulose, lignin, pectin, waxes, and water-soluble substances.

Lignin is the components that gives rigidity to the plant but reduces the adhesion of the fibers to clay or other kinds of matrices. The

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interaction between vegetable fibers and composite matrix has to be improved by chemical treatments [9], sometimes also necessary for reducing the hydrophilicity of the plant fibers. These treatments increase costs and complexity of the production process.

Animal fibers consist mainly of protein with a heterogeneous structure. Examples are silk fibers from silkworms, collagen fibers extracted from animal skins, wool fibers from sheep shearing, etc. Several studies demonstrated that among animal fibers, sheep wool suites well to building applications for both thermal and acoustic features [10], and if used as reinforcement for adobe clay or cement mix, also for its mechanical characteristics [11,12].

The possible use of sheep wool in combination with different matrices, as unfired clay adobe or cement mortar, for thermal and mechanical purposes has been investigated in several studies [13-16]

Statuto et al., [17] performed compression tests on adobe clay bricks reinforced with two kinds of natural fiber, sheep wool and wheat straw. The compressive strength of adobe bricks introducing sheep wool fibers was found considerably higher than compressive strength measured that of adobe clay reinforced with wheat straw.

The use of wool as reinforcement for mortar was investigated by Fantilli et al., [12] carrying out mechanical tests on small cement beams reinforced with untreated wool. They found that adding 10 g of untreated wool, corresponding to 1% in volume, the flexural strength increases of 18% and the fracture toughness of 300%. In addition, the researchers concluded that the results are strictly related to wool fibers length and to wool dosage within the samples [18].

When not used in the textile industry, sheep wool is an agricultural special waste produced by sheep breeding and contaminated with impurities, the type of impurity depending on the breed of sheep, the area in which the sheep are raised, and husbandry methods, with high disposal costs for breeders. Instead of being landfilled in a correct disposal way, often wool sheep is illegally disposed of with a strong environmental impact.

In Italy, according to data supply by BDN Zootechnical Register by the Ministry of Health, seven million sheep are destined to produce milk for cheese. Their wool is considered of low quality and sent to special landfills to be disposed of. Again, according to BDN data, each year more than 8,700 tons of “greasy wool” is produced. Sardinia (3,301,837), Sicily (906,069), Lazio (743,823), and Tuscany (422,734) are the regions with the largest number of sheep in Italy (Data provided by the BDN of the Zootechnical Registry established by the Ministry of Health at the CSN of the “G. Caporale” Institute of Teramo “IZS”).

Nevertheless, wool is a renewable, recyclable and environmentally friendly material, and the reuse of greasy wool could reduce both environmental pollution and energy consumption. By turning sheep wool in a new raw material, it is possible to produce innovative building materials and/or components fully complying with eco-friendly construction criteria and environmental certifications (e.g., BREEAM, LEED, DGNB, and Green Mark).

Mechanical behavior of natural fibers has been evaluated by considering its dependence on different parameters, i.e., fiber length, fiber weight ratio, fiber orientation, fabrication process, both considering single fiber or yarn. Tensile strength, stiffness, density, Young’s modulus, elongation at break of some of the most common reinforcement vegetal fibers are reported in Table 1 based on data from [8,19]. It can be observed that the values differ substantially among the different fibers, but that in any case they are comparable to those of synthetic fibers [20].

Due to their heterogeneous structure, the physical and mechanical behavior of natural fibers is difficult to predict [21]. Experimentally evaluated mechanical properties of natural fibers usually show very dispersed values, so that a statistical analysis is required in order to obtain valuable information for a successive mix design [22,23].

While wool fibers as insulating materials are usually employed in long bundles, the length of reinforcing fibers is in the range of few centimeters, depending on the type of mix they are added to. It is well accepted that shorter fibers exhibit a greater tensile strength [24]. This is a general result, observed either with artificial and natural thin fibers, and generally attributed to the presence of flaws in the skeleton. Strength of fibers of different length can be predicted with the aid of Weibull distribution statistics, based on the theory of weakest link. The theory has proved valid for many types of natural fibers [25,26]: Shao et al., applied it to bamboo fibers [27] that was also investigated by Da Inacio et al., [28]. The latter group applied the methodology also to jute fibers [29]. Jute has been object of much attention, due to its suitability as reinforcing material [22,30,31].

Table 1
Mechanical properties of some common vegetable fibers.

Fiber	Density [gr/cm^3]	Tensile strength [MPa]	Young’s modulus [GPa]	Elongation at break [%]
Jute	1.23	325–770	37.5–55	2.5
Flax	1.38	700–1,000	60–70	2.3
Hemp	1.35	530–1,110	45	3.0
Ramie	1.44	915	23	3.7
Bamboo	1.50	575	27	2.0
Banana	1.35	721.5–910	29	2.0
Henequen	1.40	500	13.2	4.8
Pineapple	1.50	1,020–1,600	71	0.8
Kenaf	1.20	745–930	41	1.6
Coir	1.20	140.5–175	6	27.5
Sisal	1.20	460–855	15.5	8.0
Abaca	1.50	410–810	41	3.4
Cotton	1.21	250–500	6–10	7.0
Isora	1.20	550	–	5.5

Xia et al., [26] apply to jute fibers a modified Weibull distribution originally proposed by Zhang et al., for accounting for the relevant geometrical irregularities met in wool fibers [23].

The influence of fiber diameter (or, more generally, transversal dimensions) on the mechanical properties has also been widely recognized, although a general justification for it is still lacking, and the effect has been attributed to one or another physical property of the fiber.

An influence of effective diameter on mechanical properties of artificial fibers (PAN graphite fibers) was originally observed by Jones and Duncan, who attributed the effect to the sheath and core structure of the fibers, generated in the polymerization process [32]. They argued that a thin fiber contains a larger quantity of “sheath”, whilst a thick fiber contains a larger fraction of “core”. The dependency of the fiber strength on the diameter is due to the preferential orientation of the crystallites contained in the sheath. A similar explanation, related to the content of cellulose in the fiber, was used by Charlet et al., for interpreting the variation of Agatha flax fiber strength with the diameter and the position within the stem [33]. On the contrary, A. Shahzad attributes the diameter effect to the possibility that the number of flaws increases in the fiber with increasing diameter [34].

The hypothesis of the influence of flaws contained in the inner structures should lead to a modified form of the Weibull distribution for the tensile strength, as proposed in [23,26]. The weakest link assumption then should correspond to a brittle fracture of protein chains once the fibrils have stretched.

In this research work, an experimental campaign has been carried out with the aim of investigating a possible re-use of low-quality sheep wool. Tensile tests on almost 200 fibers were performed, and from the results the breaking tensile strength, the elongation strength and the stiffness properties have been evaluated. Also, a new correlation is proposed between fibers’ properties and fibers’ diameter, usually overlooked in previous investigations. The correlation between tensile properties of fibers and their water content was also analyzed, in consideration of the possible use of wool fibers in matrices that require water for curing.

The fibers investigated in this research work come from the shearing of “*Valle del Belice*” sheep, a domestic breed widespread in Sicily. This area of southern Italy is strongly characterized by the breeding of dairy sheep, whose fleece is not suitable for textile industry because constituted of thick and medium length fibers.

This study is the first to investigate the properties of a poor-quality wool, unsuitable for textile industry. In the past, "*Valle del Belice*" sheep wool was employed to make mattresses and pillows but currently they are only considered as a special waste with high disposal costs for farmers and the environment.

2. Materials and method

2.1. Sheep wool fiber

Sheep wool is an animal natural fiber composed of 60% animal protein fibers, 15% moisture, 10% fat, 10% sheep sweat and 5% impurities. In Table 2 is reported a typical chemical composition of wool [35].

Sheep wool has a semi-crystalline chemical structure, and is considered an α-keratin fiber, with a very complex multilayer structure. By a physical point of view SWF has a complex hierarchical structure with a predominantly α-helical conformation with microfibrils representing the crystalline part in the fiber structure, bounded by an amorphous matrix phase [36]. In agreement with several authors [15], SWF has an unique mechanical behaviour determined by its structural organization of the α-keratin fibers. The principal component of SWF is a core cellular component surrounded by an outside layer with cuticle cells. This core is constituted by cortical cells organized in an overlapping manner, following the direction of the fiber axis. These cortical cells are constituted by macrofibrils; each macrofibril being composed by several other microfibrils. Microfibrils are intermediate filaments proteins (α-keratin) bounded by keratin associated matrix proteins (KAPs) containing high levels of sulphur and tyrosine. Microfibrils are held together by intermolecular and intramolecular interactions such as hydrogen bonds, van der Waals interactions, salt linkages and disulphide bonds. The amorphous matrix is a matrix of globules connected to each other and with microfibrils by disulphide crosslinks. The formation of disulphide bonds gives the α-helical coils rigidity increasing the stiffness of the fiber. If these disulphide bonds are broken, wool fiber works like a spring, and its dimensional stability is compromised.

Tsobkallo et al., [37] analyzed the contribution of the microfibrils and the matrix to the deformation processes of the sheep wool fibers. In their study, they also compared different research works concerning the interpretation of the structural-mechanical properties relationship of wool α-keratin fibers. They distinguished three regions in the stress–-strain response: a Hookean region, a yield region, and a post-yield region. Hookean region is characterized by an almost linear increase in load whose slope is referred as Young's modulus of the material. In the yield region to a large elongation of the fiber corresponds a low increase in load. In the post yield-region the fiber stiffened again until the failure occurs.

All studies agree that Hookean region depends on stretching of the α-helix in the intermediate filaments, while the yield region derives from the unfolding of the α-helix. It is not clear in the post-yield region, the role of the fiber constituents. In literature almost all studies concern Merino Wool (Hookean region from 0 to 2% strain, yield region from 2 to 25–30%, a post-yield region beyond 30% strain) and are related to textile industry [38]. For this reason the interest was especially focused on the non-failure properties and less efforts have been spent on the breaking stress of wool [39]. Non-textile usage of wool is not yet developed but some studies are investigating its potentialities [40-42,49].

Table 2
Typical Chemical composition of raw sheep wool.

Chemical Composition of Raw Sheep Wool			
Keratin	33%	Carbon	50%
		Hydrogen	12%
		Oxygen	10%
		Nitrogen	25%
		Sulphur	3%
Dirt	26%		
Suint	28%		
Fat	12%		
Mineral water	1%		

2.2. Experimental programme

2.2.1. Physical properties

A sample of fibers (around 180) was randomly selected among the raw material (i.e., "*Valle del Belice*" SWF), choosing fibers having roughly the same initial length (comprised between 160 and 220 mm). Each fiber, previously washed with cold water and natural soap, was dried in environment condition (T = 20° C – RHU = 50%) for 1 week, and trimmed to 150 mm. The fiber diameter was measured with a Zeiss Microscope, (software LAS Core, LEICA application suite Version 3.70), taking the average of 3 measures along the length. The coefficient of variation of the fiber diameter (CV_D) along the longitudinal axis is negligible (lower than the 10%), its variation ranged between 4 and 6 μm. Then the fibers were weighted on a precision balance Sartorius - model CP124S to obtain the density of each sample (Fig. 1, a - b). Fig. 2 presents a Scanning Electron Microscope (SEM) image of the wool fiber.

2.2.2. Mechanical properties

The mechanical tests were carried out on single wool fiber, following the prescription of ASTM D 2256 – 10. The experimental campaign concentrated on one-gauge length only, close to the one likely to be used in the reinforcement of rammed earth prototypes. For practical reasons, a gauge length of 50 mm was selected, and kept constant. The tensile apparatus sketched in Fig. 3 was designed for the tensile tests. The wool fiber was glued at the ends of the gauge length between two cork clamps. The fiber assembly was placed horizontally in the apparatus to avoid the effects of gravity. One edge of the fiber was rigidly fixed to the testing apparatus, the other edge was free to slide on a Teflon sheet placed on the other side of the apparatus. The free end was connected to the loading device, applied using direct weight.

The mounting of single fiber in the tensile testing machine has been done with great care to avoid damage of the fiber, misalignment of the load, and to prevent premature failure and errors in measurement.

The selected fibers were subdivided in 3 groups of about 60 fibers each having roughly the same diameter distribution. Each group was subjected to a different conditioning program:

- 1st condition: wet condition. Fibers were immersed for ten minutes in distilled water (ten minute was found to be a sufficient time for wool to reach saturation).
- 2nd condition: controlled environment. SWF were immersed in distilled water for ten minutes, then were left to dry for 24 h in ambient with controlled temperature and humidity, 20° C and HR 50% respectively.
- 3rd condition: oven-dried condition. Fibers were put in oven at 80° C for thirty minutes. After this time the fibers reached constant mass.

These different test conditions were selected because of the high hygroscopicity of wool. Wool can absorb large quantities of water, and experimental test results could be affected by this characteristic.

Load and elongation were directly measured during the test. The nominal stress was obtained dividing the load for the area of the initial cross section, assumed circular and using the average value of the diameter.

Wool is a viscoelastic anisotropic material, whose tensile properties depend on the speed of application of the load [43]. In our experiments the load was slowly applied with a rate of about 2 10^{-2}N/min. Each test

Fig. 1. SWF diameter (a) and mass evaluation (b).

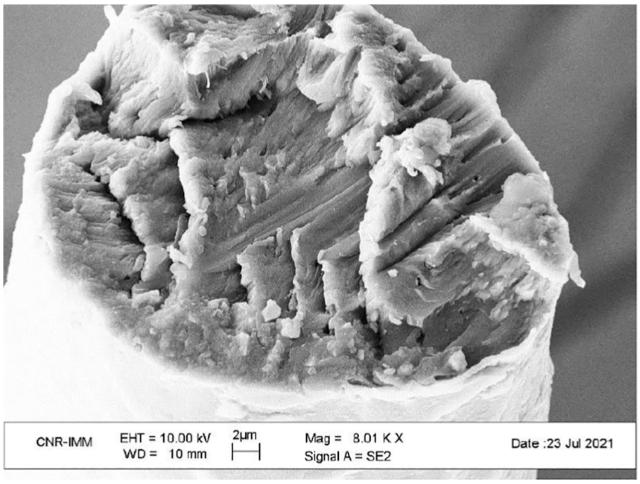

Fig. 2. SEM image of the transversal section of Valle del Belice wool fiber.

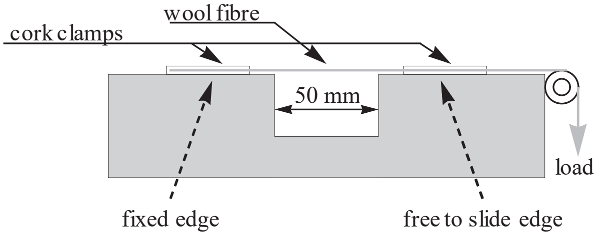

Fig. 3. Schematic representation of the load testing apparatus.

lasted, therefore, from 15 to 25 min.

The load was monotonically increased up to failure. Each test was recorded by photo images that were subsequently elaborated to get the load-elongation curve. The fiber's failure stress and strain, an estimation of the yield strength and strain and the secant initial stiffness modulus were determined from the experiment. A typical stress–strain plot is shown in Fig. 4.

Four phases can be distinguished: an almost initial linear range can be recognized, from which the secant stiffness modulus can be determined. Conventionally, this was defined as the secant modulus at 60% of the yield load. Then occurs a non-linear phase, until the stress–strain curve presents a yield, after which a plateau is reached, where the stress gradient sensibly decreases. At the end of this plateau the elongation can reach a value one order of magnitude greater than the one corresponding to the yield stress. The stress and strain at the end of the plateau have been labelled σ_p, ϵ_p, respectively. Finally, the stress presents a sharp hardening; however, the last phase is not always present. Usually, breakage occurs early during this final stage.

3. Results and discussion

3.1. Diameter and density measurements

Fig. 5 shows the distribution of the values of the diameters measured for the whole population of fibers. Although most of them fall near 70 µm, the dispersion is considerable, and motivates the investigation relative to the influence of the cross-section dimension on the mechanical properties.

Fig. 6 shows that there is a marked dependence of the density on the fiber diameter: the larger the diameter, the smaller is the density. The tendency curve that interpolates the data points is compatible with a core and fibril internal structure of the fiber. The SWF average density is 0.94 [gr/cm^3] lower than synthetic fibers' density (e.g., for glass fiber it is 2.5 [gr/cm^3]), and lower than average wool density found in literature that is 1.3 [gr/cm^3].

3.2. Mechanical properties

The following mechanical properties have been evaluated from each test:

- Secant Stiffness Modulus.
- Stress and strain at the yield (estimated as intersection between linearized trends in the initial phase and in the plateau region).
- Elongation at break.
- Stress at break.

Average values μ_i and standard deviations σ_i for these quantities, together with the fiber diameter, are reported in Table 3, separately for the three testing conditions and for the whole population.

Results are quite dispersed, as typically happens with natural materials. For instance, measured breakage tensile stress ranged between 222.37 [MPa] and 68.18 [MPa] for saturated fibers (1st test condition), between 261.50 [MPa] and 74,01 [MPa] for the 2nd test condition and between 252.65 [MPa] and 52.53 [MPa] for the 3rd test condition.

However, the dispersion of the results is compatible with the nature of the material, and it allows to characterize its mechanical behavior with reasonable confidence.

From the average values reported in Table 3 it can be observed that the three different test conditions do not significantly affect the results; in any case the best performances appear to be obtained for the samples

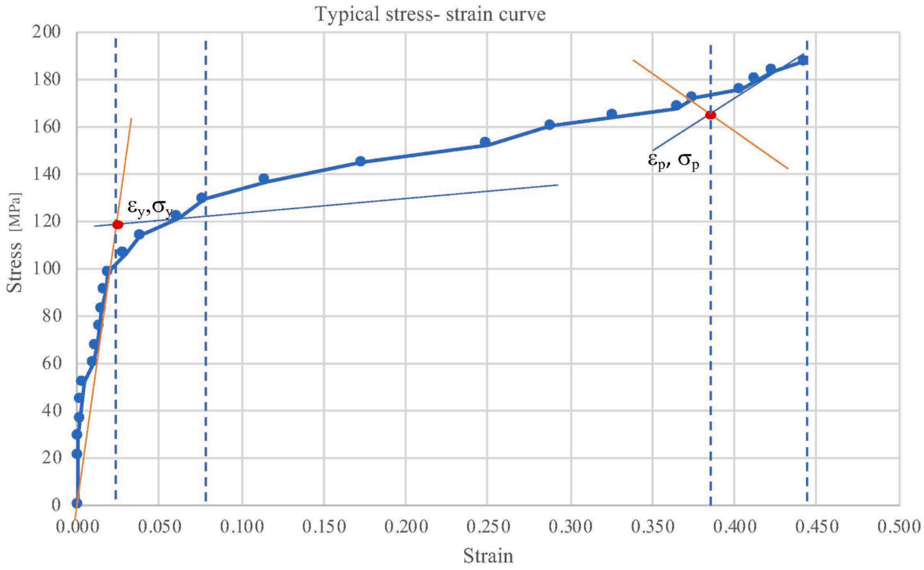

Fig. 4. Typical result of a tensile test. Fiber with 2nd conditioning setting. Vertical dashed lines indicate the transition of phase as reported in the text (first, second, third and fourth phase).

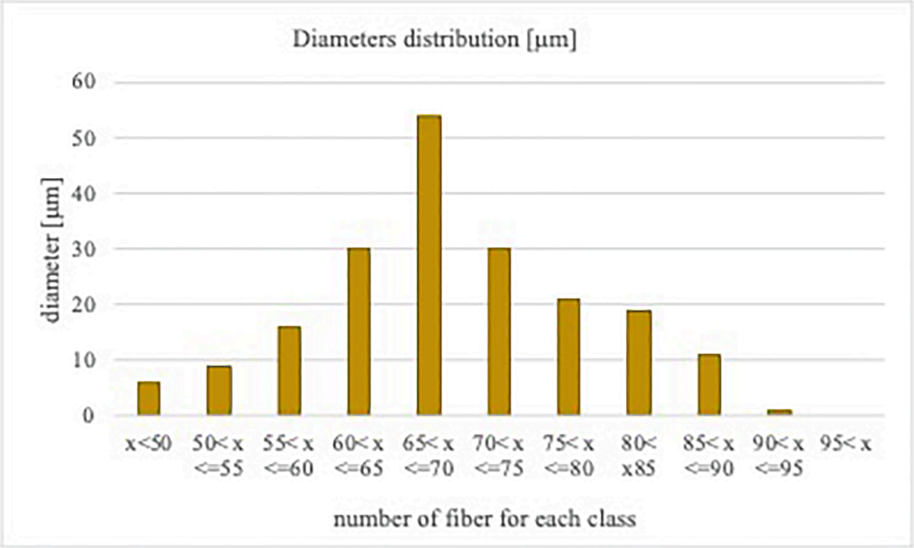

Fig. 5. Distribution of fiber diameters in the sample.

with a controlled content of moisture (condition 2), which is a valuable information because this is close to the real condition of fibers inside a mixture.

From the values reported in Table 3 can be built average trilateral stress–strain curves for the three testing conditions, joining the couples $(\sigma_{y}–\varepsilon_{y})$, at yield, plateau stress and corresponding elongation $(\sigma_{p}–\varepsilon_{p})$, at the end of the plateau region, and failure stress and strain $(\sigma_{r}–\varepsilon_{r})$. The resulting plots are reported in Fig. 7. This representation confirms that the thermal and hygrometric conditioning do not significantly affect the results.

By comparing our results with a typical wool tensile stress–strain curve obtained on Merino sheep, some differences can be observed. The initial linear elastic region extends up to 3–7% for "*Valle del Belice*" SWF, while the Hookean region for Merino wool usually does not exceed 2%. The yield region extends below 30% of strain in both cases. Then fracture occurs in "*Valle del Belice*" SWF between 40% and 45% of strain while the extension can reach 50% – 60% for Merino wool fibers [44]. Consequently, also the breaking stress is larger for Merino wool.

The average value of the mechanical strength found in our experiments (137.31 MPa) is similar to those reported by Cheung et al., [45], ranging from 120 MPa to 174 MPa, but lower than the mechanical strength of wool suitable for textile industry (e.g., Merino wool, Romney wool), that is around 250 MPa [46].

Elongation at break, ranging between 45% and 50%, is comparable with literature data and higher than for other natural fibers.

The results obtained, especially those relating to strength, elongation, and density, confirm the suitability of these fibers to be used as reinforcement in raw earth materials.

3.3. Influence of the diameter on the mechanical properties

The mechanical properties of fibers, especially their strength, are well known to be strongly influenced by the fiber length. The size effect can be effectively estimated with well-established methods [20]. This factor is absent in the present experimental program, since all the fibers had the same gauge length. However, it has also been reported that the

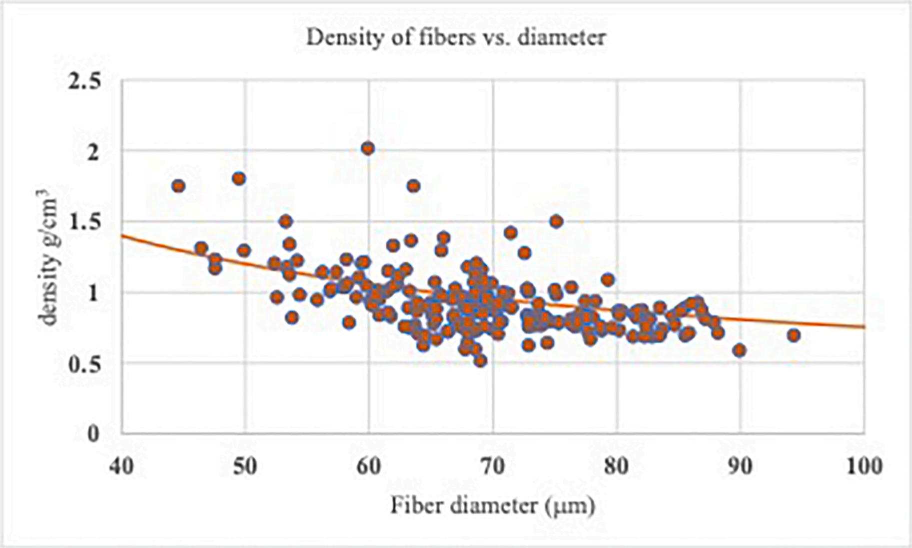

Fig. 6. Correlation between fibers density and fibers diameter.

Table 3
Mechanical test results. Average values and standard deviation.

	σ at break [MPa]		Elongation at break [%]		σ at yield [MPa]		ε at yield		E_s [MPa]	
	μ	σ	μ	σ	μ	σ	μ	σ	μ	σ
Saturated specimens	134.57	34.10	42.00	0.11	75.37	21.92	0.04	0.02	2057.06	584.53
Normal conditioning	144.02	41.61	43.00	0.11	84.70	23.31	0.05	0.02	1903.59	621.32
Dry specimens	133.65	47.22	43.00	0.19	85.97	33.59	0.07	0.03	1367.38	381.40
Entire population	137.31	41.37	42.00	0.14	81.44	27.15	0.05	0.02	1739.41	755.44

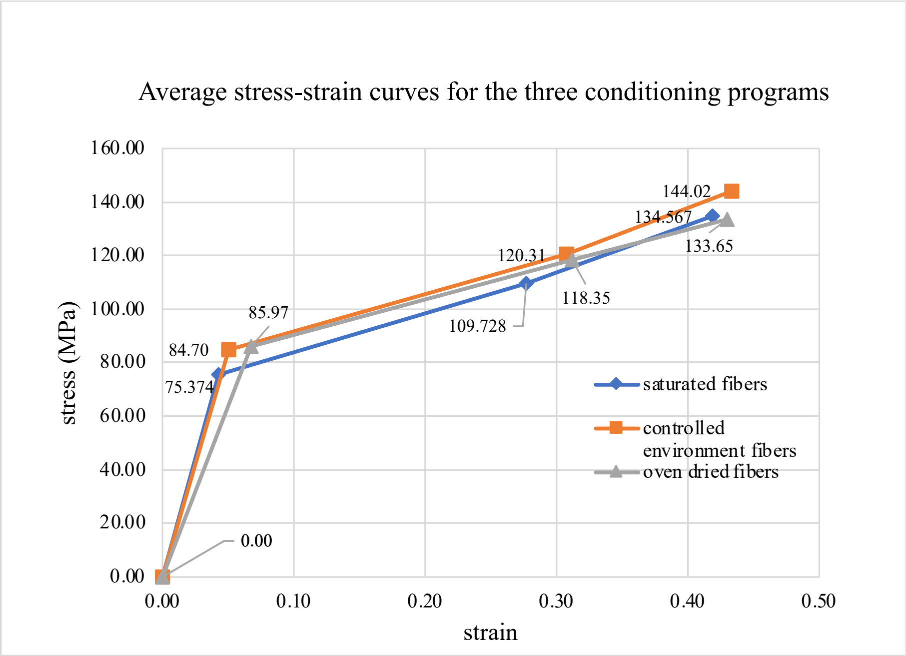

Fig. 7. schematic representation of the stress- strain curve ([N/mm^2], [%]) under 3 different test conditions.

mechanical properties of natural fibers change according to the fiber's diameter. In this section we aim to investigate to some deeper extent this phenomenon, that can be of some interest for optimizing the use of SWF as reinforcement material.

Plots of Fig. 8 show the tensile strength of the three groups of fibers as function of the fiber diameter. There is a clear tendency of the breakage stress to decrease with the diameter, for all the conditioning settings, although the data present some dispersion, especially for small

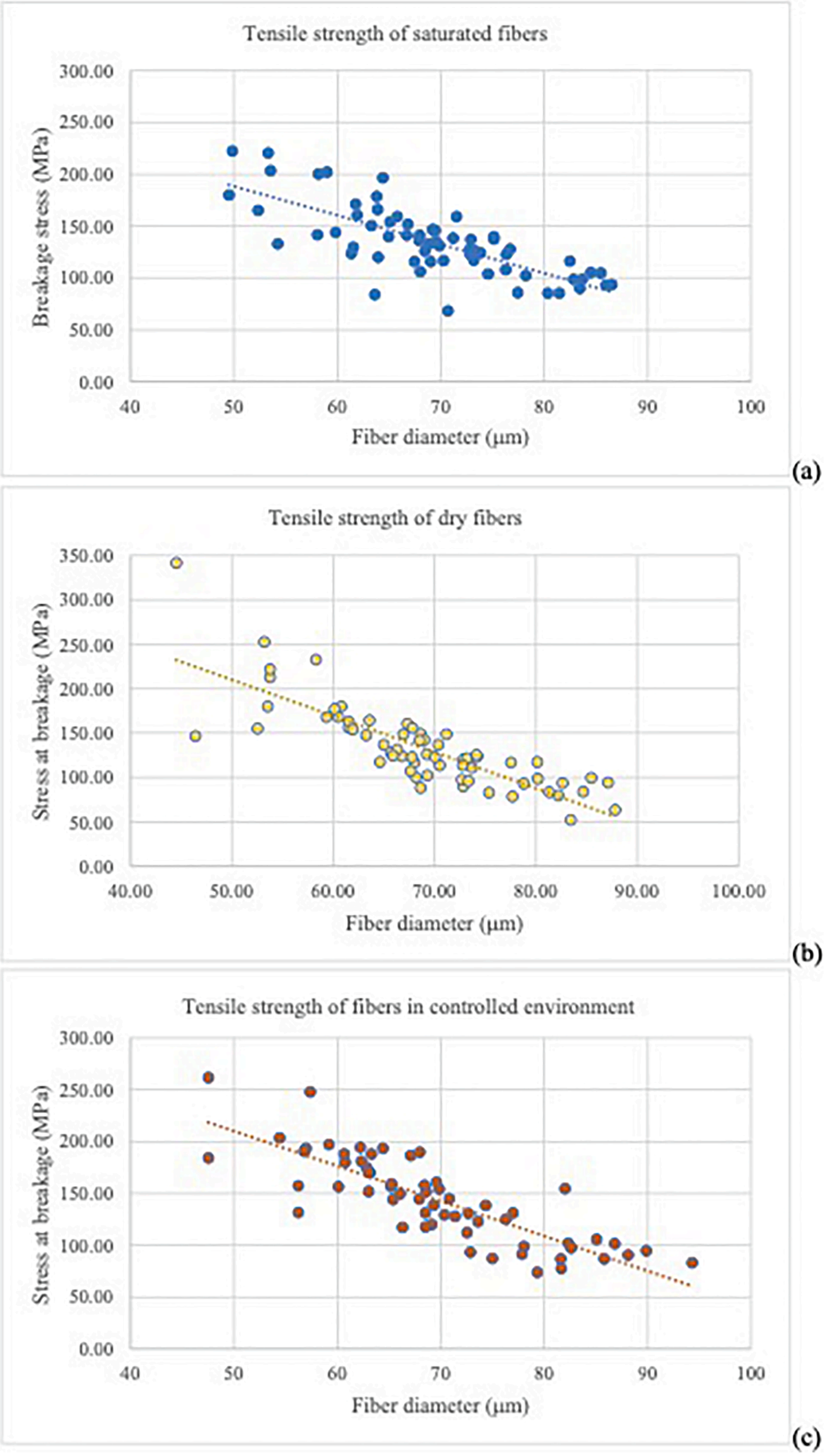

Fig. 8. correlation between breakage tensile stress and diameter, (a) 1st condition, (b) 2nd second condition, (c) 3rd condition.

diameters.

Superposing the data, as noticed in section 3.2, there is little difference in the results obtained for the tensile strength between the three groups (Fig. 9).

A similar dependency has been found for the other mechanical properties. The plots of Fig. 10 shows that there is a direct correlation between the secant stiffness modulus (E_s) and the tensile strength (σ_r), in spite of the considerable dispersion. Consequently, an analogous correlation exists between the secant Hookean stiffness modulus and the fiber diameter (the greater the diameter the lower the stiffness).

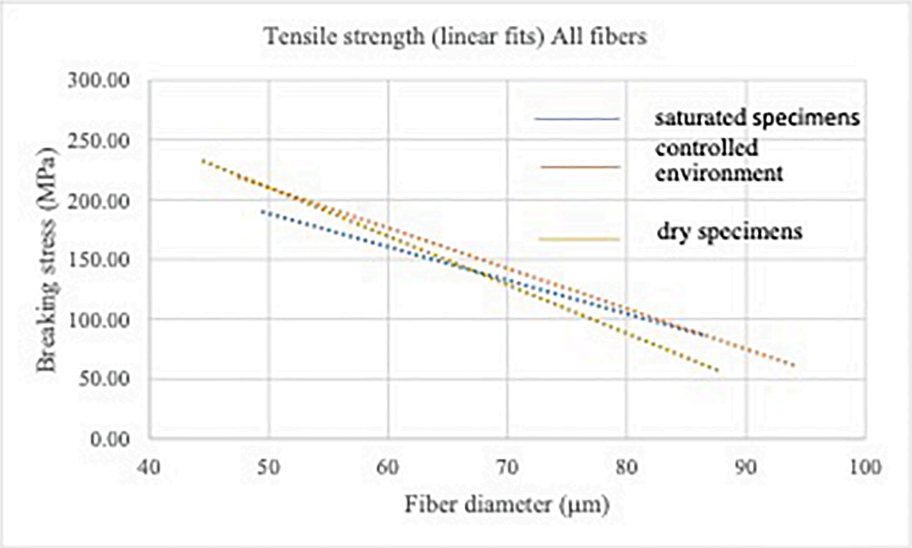

Fig. 9. Correlation lines between diameter and tensile strength under the 3 test conditions.

3.4. Statistical analysis of test results

The correlation between the mechanical properties and the fiber's diameter is interpreted using a statistical analysis based on Weibull distribution theory.

Several factors influence natural fiber tensile behavior, such as fibers' heterogeneities, chemical structure, and failure mechanism. For this reason, statistical analysis is necessary to define reliable properties of strength and stiffness of sheep wool fiber. Weibull probability distribution function is a suitable tool for the interpretation of the experimental results of specimens affected by size effects. Weibull model was conceived to correct size dependence of unidimensional structure subjected to tensile load; it considers the unidimensional structure as a chain constituted by different rings, each one having different strength, and predicts the probability of rupture of the weakest ring. Probability of rupture of the weakest rings is the probability P ($X \leq x$) that this rings fails for a force less or at least equal to × [47]. In literature was already demonstrated that this numerical model is suitable for predicting the correlation between strength and gauge length of the fiber for natural fibers including sheep wool [23]. In this paper, a modified Weibull distribution model is proposed for considering the dependence of strength from diameter.

Weibull distribution based on the weakest link theory for the failure strength σ_f states that the probability P of failure of a fiber of volume V is

$$P = 1 - Exp\left[1 - \frac{V}{V_0}\left(\frac{\sigma_f}{\sigma_{f0}}\right)^m\right] \tag{1}$$

where V_0 is the volume of a link segment, the exponent m is the Weibull modulus and σ_{f0} is a scale parameter. The value P is estimated using the probability index

$$P = \frac{i}{N+1} \tag{1}$$

where N is the total number of data points, and i is the rank of the generic data point. The two-parameters Weibull distribution was modified by Watson and Smith [48] and Gutans and Tamuzs [40] introducing an additional parameter, in order to account for discrepancies with the experimental data. The original proposal introduces an exponent on the ratio L/L_0 assuming fibers of constant cross-section. Following this idea, in the case of fibers with different diameter we assume as probability distribution:

$$P = 1 - Exp\left[1 - \left(\frac{V}{V_0}\right)^{\bar{\gamma}}\left(\frac{\sigma_f}{\sigma_{f0}}\right)^m\right] \tag{2}$$

that, for the case of fibers of same gauge length, and diameter d, reduces to

$$P = 1 - Exp\left[1 - \left(\frac{d}{d_0}\right)^{\gamma}\left(\frac{\sigma_f}{\sigma_{f0}}\right)^m\right] \tag{3}$$

From the proposed probability distribution is possible to relate the expected strength of two fibers of diameters d_1, d_2:

$$\mu_{\sigma,2} = \mu_{s,1}\left(\frac{d_2}{d_1}\right)^{-\gamma/m} \tag{4}$$

The experimental tensile strength values obtained on 180 SWF of different diameters were statistically analyzed by Weibull distribution. Formula (4) can be manipulated to give:

$$Ln(1 - Ln(1-P)) = \gamma Ln(d) + mLn(\sigma_f) - \gamma Ln(d_0) - mLn(\sigma_{f0}) \tag{5}$$

Therefore, a plot of $Ln(1 - Ln(1 - P))$ vs. $Ln(\sigma_f), Ln(d)$ should lie on a plane, the coefficients of the equation of the plane allowing to identify the constants m, γ, $Ln(d_0^{\gamma}\sigma_{f0}^m)$.

Fig. 11 shows that the data points can effectively be interpolated by a plane, whose equation yields the values

$$m = 1.27852\gamma = -0.22606Ln\left(d_0^{\gamma}\sigma_{f0}^m\right) = -4.68762$$

The correlation is quite good, the coefficient of determination being $R^2 = 0.94413$. Only some points relative to the largest diameters fall slightly outside of the plane.

The probability density distribution of equation (4) is represented in Fig. 12 as a 3D plot as function of the breaking strength and of the diameter. The data points are superposed to the plot, and closely follow the distribution function.

4. Discussion of the results

The values found for the strength, elongation at break, initial stiffness, are close to those reported in the literature for SWF. Compared to the properties of vegetable fibers most commonly used for reinforcement, the strength is lower, but the elongation at break is much larger. Similarly, wool fibers are less stiff than most vegetable fibers. These results suggest that the use of SWF as reinforcement in raw earth-based

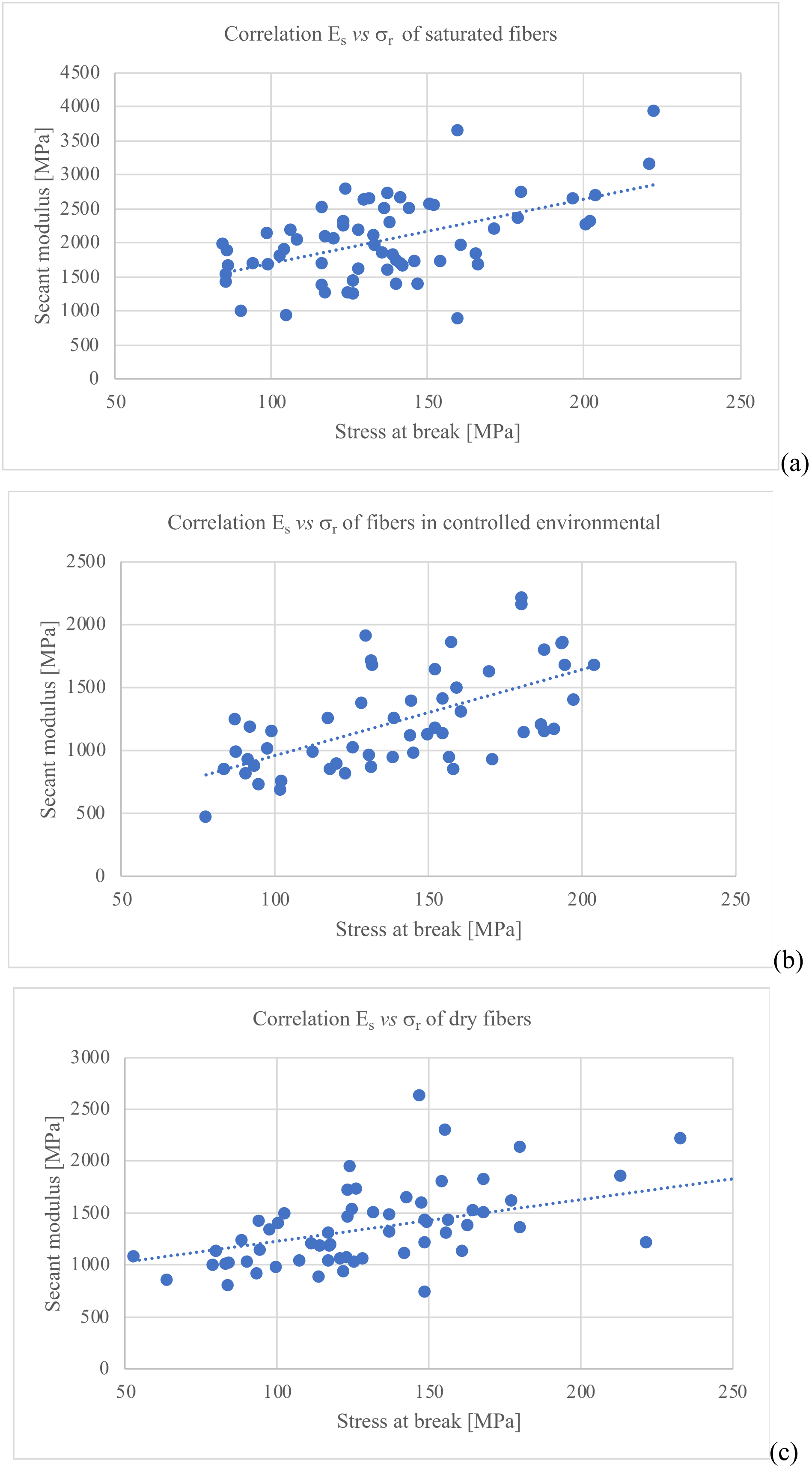

Fig. 10. correlation between secant stiffness modulus (Es) and breakage tensile strength (σ_r), (a) 1st condition, (b) 2nd second condition, (c) 3rd condition.

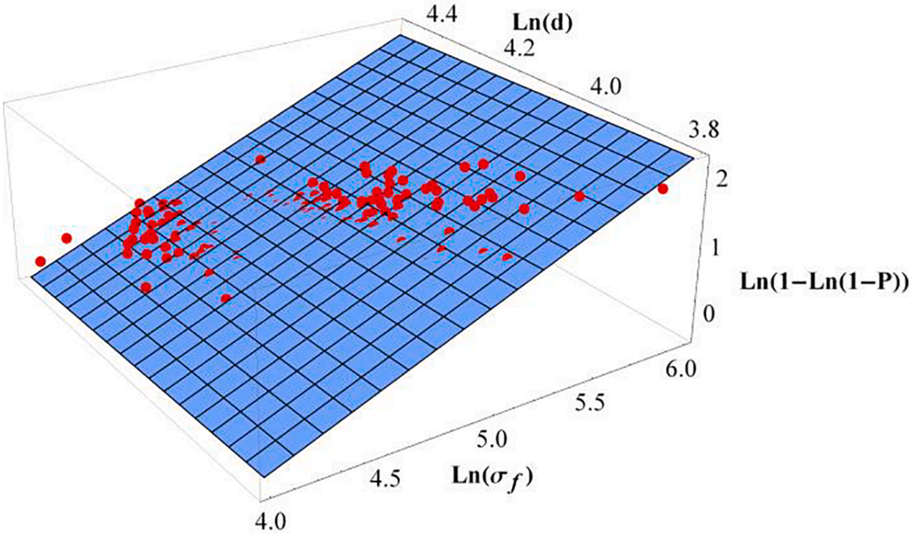

Fig. 11. Interpolation of fibers' strength vs. fibers diameter.

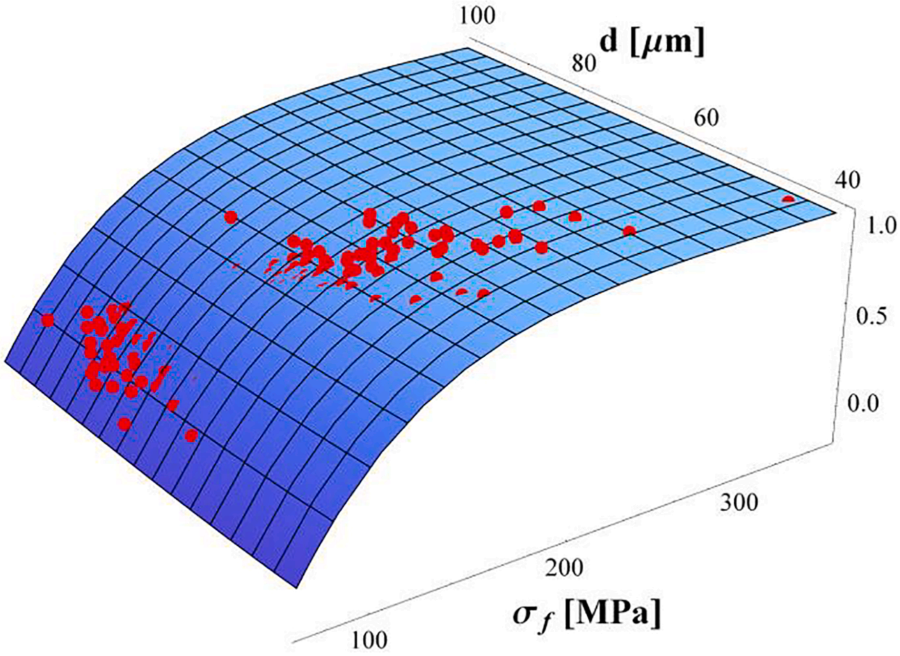

Fig. 12. Distribution function of the of fibers' strength vs. fibers diameter.

composites can increase their ductility and fracture energy, which is one of the main limitations in the use of those materials. Indeed, preliminary tests (that will be reported as part of a forthcoming investigation), confirm that the addition of wool fibers to raw earth mixes, together with a moderate increase in the flexural strength, allow to greatly increase the ductility of the composite.

As demonstrated, the dispersion of the results is mainly due to their dependence on the fibers' diameter. The distribution of stress at break (but also of the stress at yield) are very well fitted by Weibull statistics, suggesting that the model of distributed flaws can account for the found dependency of the fiber strength on the fiber diameter. Breakage can be due to the rupture of weak bonds connecting the layers of helicoidal fibrils, whose density is non uniform on the wool fiber, due to their hierarchical structure.

Deeper investigation is needed from a micromechanical point of view, to validate this hypothesis.

5. Conclusions

In this study, for the first time physical and mechanical characterization of *Valle del Belice* wool fibers was carried out with the aim of a possible use of this agricultural special waste as strengthening system for rammed earth building components.

Tensile tests were performed on selected fibers that had undergone three different conditioning programs:

- wet condition,
- controlled environment,
- oven-dried condition.

The three groups of specimens yielded very similar results. This means that the fibers can be used in composites that need water for curing, like raw earth composites.

The results found for the fibers' strength, elongation at break and stiffness compare well to those reported in literature for other types of wool, although somewhat smaller than those obtained with high quality Merino wool; they are:

- average strength of 137.31 MPa.
- initial secant modulus of 1.74 GPa.

These values confirm the suitability of these fibers as a reinforcement material for raw earth mixtures.

As normally occurs with natural fibers, the measured mechanical and physical properties result quite dispersed, however some trends clearly emerge. In this work fibers of the same gauge length were tested, so that the correlation between mechanical properties and fibers diameter was investigated. A statistical analysis was proposed by using a modified Weibull distribution and a very good correlation was found for the breaking stress and initial stiffness. An accurate selection of fibers' diameter can then help to reach a reasonable uniformity of the mechanical properties, necessary for employing the fibers in the construction process.

In conclusion, the results appear to encourage the possibility of the use of greasy wool in the building sector. This practice could decrease environmental pollution by reducing a huge amount of waste related to low-quality wool from dairy sheep also bringing benefits to the breeders.

CRediT authorship contribution statement

M.C.M. Parlato: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **M. Cuomo:** Conceptualization, Methodology, Formal analysis, Data curation, Writing – review & editing, Supervision. **S.M.C. Porto:** Visualization, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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