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EXPERIMENTAL DEVELOPMENT OF CLAY BRICKS REINFORCED WITH AGRICULTURAL BY-PRODUCTS

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SUMMARY

The valorisation of agricultural co-products, by-products and wastes may play a significant role in the framework of the concept of bio-economy, which is referred to the transition from a linear to a circular economy, based on the exploitation of by-products and transformation of residues from waste to new resources. After contributing to the restoration of the level of organic matter in the soil, these biomasses could be indeed valorised in different ways, *e.g.*, as added-value components in other industrial sectors (nutraceutical, cosmetic, *etc.*), as alternative fuel in energy plants, or in the construction sector, in which they could be incorporated in some building elements with the aim to increase their technical performance.

In order to verify the possibility of employing two among the most diffused agricultural by-products (*i.e.*, wheat straw and sheep wool), some experimental bricks realized with clay mixed with these vegetal and animal fibres were prepared. These bricks (so-called "*adobe*") were tested in their mechanical properties, in order to highlight the differences between the two types of bricks and to evaluate the possibility to use them as building elements in bio-architecture. The results of the mechanical tests showed that the compression strength of the adobe bricks prepared with sheep wool was significantly higher than those incorporating wheat straw, while these latter have exhibited a shrinkage lower than adobe bricks realized without any additive fibre.

Key words: agricultural wastes, wheat straw, sheep wool, adobe bricks, bio-architecture

INTRODUCTION

The diffusion of green technologies is gaining wider spaces thanks to their contribution to the reduction of carbon emissions into the atmosphere generated by traditional fossil material (petroleum, gas, or coal), in the general context of an enhanced environmental protection. The increasing attention to environmental topics has pushed the political and scientific world to develop new strategies able to reduce the environmental impact and to promote a sustainable development through the exploitation of agricultural by-products, co-products and wastes, in order to reduce the waste generation and the use of non-renewable resources. In this framework, the concept of bio-economy - considered as a circular economy that presupposes the re-use of by-products arising from production processes - is suitable in order to obtain new products through ideally processes called "*zero-waste*" and to create new by-product markets. The use of by-products and residues from agriculture, forestry and agro-industry should anyway be always evaluated and planned with care, so as to avoid an excessive removal of organic matter from the agricultural soil, reducing its fertility on the long term, with negative effects on agricultural and/or natural ecosystems.

In the agro-industrial sector - such as wineries, olive oil mills, cheese factories, *etc.* - a large quantity of secondary products could be available, and they can be used to generate "clean" energy such as biogas and bio-methane. Arising from particular organic waste, some high-value products - such as dietary supplements, cosmetics or pharmaceuticals of great interest for experimentation in green and sustainable chemistry - can so be obtained. Organic waste can also be reused in the aquaculture sector, in particular for sustainable production of fish feed. The scientific community has found good results in the formulation of alternate feed from organic by-products as well (Ayadi et al., 2012).

Moreover, agricultural co-products, by-products and waste may play a significant role in bio-architecture, since they could be valorised also in the construction sector, when incorporated in clay bricks with the aim to increase their technical performance, so contributing to improve traditional building components through the addition of natural elements. Sustainability can only be possible when construction uses renewable materials or materials recycled from construction wastes (Serrano et al., 2016). Mostly within the Mediterranean area, spontaneous architecture still constitutes indeed a visible witness about the role that the rural constructions have historically played in connection with the surrounding environment, joining the agricultural production needed for human nutrition with the control and care of extra-urban land (Picuno, 2012). In some Southern Italian regions - *e.g.* Apulia and Basilicata - extraordinary examples of earthen rural building realized with clay bricks (Fig. 1) are widespread all over the rural landscape (Statuto and Picuno, 2017, Statuto et al., 2017).

Figure 1. Earthen vernacular rural building in Basilicata Region.

The increasing demand for processes with reduced environmental impacts and lower energy consumption also involves the building sector in which "sustainable" buildings are increasingly required (Picuno, 2017; Statuto and Picuno, 2016). The most recent trend is to use natural and/or recycled materials as substitutes for traditional material used in constructions, in order to combine a good energy performance while reducing the environmental impact and protecting human health as well (Sica et al., 2015). Currently re-evaluated by bio-architecture is the *"earth material"* that, together with wood and stone, is one of the most common building materials in the world, thanks to its ecological and recyclable properties. The use of earth material has very interesting consequences on the current perception of the rural landscape - the colour of the building being similar to its surroundings - as well on the agricultural environment, since this material doesn't represent a waste because it would be, at the end of its useful life, incorporated in the same context (Picuno, 2016).

Today about 30% and 50% of the world's population lives in earth structures, especially in some regions of Africa, Asia and Latin America, while in Europe they are still a niche product of the construction industry (Parisi et al., 2015).

One of the most interesting element of earthen construction is the use of sun-dried earth bricks – made of raw clay soil mixed with barley or wheat straw (so-called ''*adobe*'') – as a walling material (Picuno, 2016). The main applied raw materials are coarse sand, argillaceous earth and lime. The natural earth mixtures are often corrected by the addition of fibres, to control cracking while adobes are drying in the sun. Especially in rural building, the use of earth material, in particular clay, is diffused thanks to its good mechanical properties and to the low presence of high-cost crude grains, that are mixed with vegetable fibres and water for the realization of adobe bricks used as walling material (Liberatore et al., 2006).

Adobe is a construction material that presents several attractive characteristics. It is low-cost, locally available, recyclable, adapted to a large variety of soils, presents good thermal and acoustic properties, and it is associated to simple constructive methods that require reduced energy consumption (Millogo et al., 2014; Silveira et al., 2012). To improve the mechanical strength, impermeability and the durability of locally produced adobe, in general, small amounts of hydrated lime or natural fibres are added to the soil matrix.

With the aim to examine the mechanical properties of adobe bricks realized with natural material locally available in the Mediterranean area, in the present paper the results of mechanical tests on adobe bricks prepared with different natural fibres, are presented.

MATERIAL AND METHODS

The experimental tests were performed in the Laboratory for Testing Materials of the SAFE School of the University of Basilicata (Potenza – Italy). Two different types of blocks of clay, manually mixed with sheep wool in one case, and with wheat straw in a second case, were tested to define their mechanical properties.

Sheep's wool has been widely used in the construction field as an insulating material (Corscadden et al., 2014; Zach et al., 2014), thanks to the well-known thermal and acoustic insulation properties of this by-product arising from sheep breeding, whereas no studies have been carried out on the possible use of sheep wool inside the matrix of building elements. The choice of wool was suggested by the widespread sheep breeds in the rural areas examined, which are characterized by a low-quality wool by-product, having short fibres, which are not suitable for the textile industry and a low average selling price (around 0.6 € kg^{-1} - year 2017). This price is not even enough to pay the costs necessary for the care and well-being of animals; just as a reference, in the same year 2017 the price to shear a sheep is about 1.60 € kg^{-1} of wool.

Concerning wheat straw, the possibilities of its use as an additive for reinforcing clay bricks have been analysed during some previous studies (Picuno, 2016), in which the mechanical behaviour of some bricks made using straw as reinforcing material has been investigated, expressing the relevant results in terms of their mechanical properties.

In the present research, adobe bricks of cubic shape (150 mm edge) were prepared with local materials, in particular the clay and the wool were find in the municipality of Acerenza, located in the north-east part of Basilicata Region, and three typologies of specimens were prepared:

– Clay bricks (only clay) (typology: "C");
– Clay bricks mixed with 3% by weight of sheep wool (typology: "W");
– Clay bricks mixed with 3% by weight of wheat straw (typology: "S").

Prior to the dough, the clay was sifted to obtain particles not exceeding 4.75 mm (Fig. 2) while the straw and wool fibres were weighed before the preparation of the dough (Fig. 3a and 3b).

Figure 2. Clay material during the sifting process.

For each typology (C, W, S), n. 2 specimens were manually made (Fig. 4a and 4b); therefore, they were placed to dry under the sun in a hot and ventilated place for nine weeks during summer. After the drying period, the dimensions of the blocks were measured in order to calculate the percentage of shrinkage for the three different analysed typologies.

Figure 3a. weighing of straw.

Figure 3b. weighing of sheep wool.

The compression tests (Fig. 5) were performed by using a computerized universal testing machine Galdabini PMA-10 type (Galdabini S.p.A., Italy), by placing the adobe bricks between the rigid steel plates of the testing machine and testing them in terms of unconfined compression strength through displacement-controlled axial tests. A uniform load was applied without shocks, continuously increasing until failure, with the moving head of the testing machine travelling at a rate of 1 mm min^{-1}. The breaking load was considered as the maximum load reached during the test.

Figure 4a. dough prepared with clay and straw.

Figure 4b. dough prepared with clay and wool.

Figure 5. Compression test on an adobe bricks.

RESULTS AND DISCUSSION

In Table 1 the results of compression tests on the three different types of adobe bricks are reported in terms of average value for each one of the different typologies which were analysed. The results showed that the compression strength of the adobe bricks prepared with sheep wool was significantly higher than those incorporating wheat straw, while these latter have exhibited a shrinkage lower than adobe bricks realized without any additive fibres. Probably, the greatest resistance to breaking the clay bricks with wool is due own to the structure of the fibres: the scales that cover the filaments make it rough and, at the same time, the interstices among scales increase the surface of contact with clay, making the adobe more compact and durable.

Table 1. Average compressive strength of the adobe bricks experimentally tested.

Adobe brick typology	Maximum compressive strength σmax (N mm^{-2})	Shrinkage (%)
C	2.05	7.3
W	4.32	6.7
S	1.86	2

The results showed that the compression strength of the adobe bricks prepared with sheep wool (W) has been significantly higher than those incorporating wheat straw (S), while these latter have exhibited a shrinkage lower than adobe bricks realized without any additive fiber (C).

Figure 6 reports a diagram stroke/load for one of the tested adobe bricks prepared with clay and sheep wool. From the analysis of this figure, it can be noticed that the behaviour of this material during the compression test appears as quasi-elastic in the first phase, followed by the definitive failure of the cubic specimen.

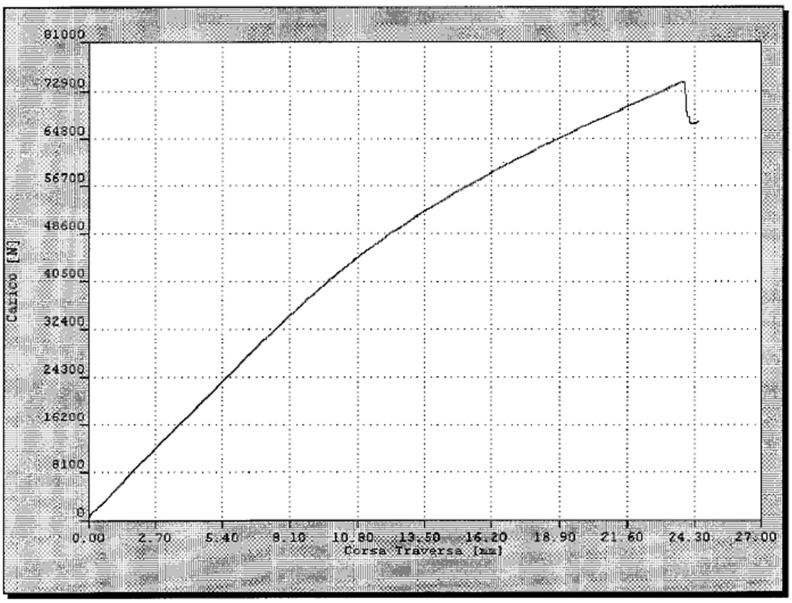

Figure 6. Stroke/load diagram for the compression test on a cubic-shape adobe brick.

The average compressive strength values of the three types of bricks resulted higher than the minimum value of 1 N mm^{-2} required for building materials (Vega et al., 2011). The average values of compression strength of the fibrous reinforced blocks appear to be quite interesting, particularly in the case of adobe bricks reinforced with sheep wool, which have proved to have an interesting mechanical strength, better than those reinforced with straw. From the results obtained through the present experimental tests it can be concluded that further analysis should be performed, aimed to the definition of optimal mixture of soil with natural fibres.

The result obtained from blocks prepared with clay only (C) have shown a slightly better compression resistance than those mixed with straw (S). This aspect appeared quite surprising, since it is expected that the presence of fibres would have played a significant role in the compressive strength of the soil (Sharma et al., 2015), giving a general increase of the mechanical properties of the composite material. This result in our experiment could be probably due to the good mechanical properties of the clay that was used.

Table 2 shows the mean compression strength values of clay blocks realized with straw during similar researches already performed on some blocks of the same type produced in the Materials Testing Laboratory of the University of Basilicata under previous Master/Doctoral thesis (Lista, 2015; Bochicchio, 2017). In the first case the natural materials came from a different area (Municipality of Senise - southeast part of Basilicata Region).

Table 2. Comparison of average compression strength values (N mm^{-2}) of bricks made with clay and straw in previous studies (Lista, 2015) and the new ones (Bochicchio, 2017).

Analized bricks	Maximum compressive strength σmax (N mm^{-2})	Shrinkage (%)
Clay bricks with straw (Lista,2015)	0.92	5
Clay bricks with straw (Bochicchio,2017)	1.86	2

As it is possible to notice from table 2, the average compressive strength in case of bricks realized in the year 2017 is about the double of that one of bricks made in 2015. This result seems again probably connected to the better mechanical characteristics of the clay itself. To collect more data to improve the knowledge of mechanical behaviour of adobe, future studies are needed to understand the interaction between fibres and clay (Silveira et al., 2013).

CONCLUSIONS

The recovery and reuse of by-products arising from the agricultural sector is a good solution to preserve non-renewable raw materials and mitigate the emissions into the atmosphere. Through the use of "green" processes and reuse of by-products, co-products and wastes it is possible to reduce the amount of waste and to solve some problems concerning the disposal. This practice of reuse is applicable to several productive sectors, including the bio-building sector, with the aim to achieve low-impact structures on the environment, to preserve human health and to reach good energy performance. The reuse of agricultural by-products in bio-architecture could be applied especially in the rural building sector. The role of rural building is indeed fundamental for enabling practices aimed to reduce resources consumption, combat environmental degradation and create better living environments, preserving at the same time architectural and historical assets. Since a suitable restoration and functional requalification of the farm building obtained through the use of traditional construction material may contribute to the sustainability of the rural environment, the use of adobe bricks would be a very interesting option, since it is a environmentally-friendly construction material that presents several attractive characteristics, being low cost, locally available, recyclable, adapted to a large variety of soils, presenting good thermal and acoustic properties, and it is associated to simple constructive methods that require reduced energy consumption.

The experimental tests presented in the present paper confirm the general results available in the scientific literature about adobe material, with some possible improvements of its mechanical characteristics. The addition of natural fibres, in particular in the case of sheep wool, has been revealed as an interesting option, able to improve the compression strength of the adobe bricks; other mechanical parameters would probably benefit from this reinforcement as well. Furthermore, considering that non-sold wool must be disposed of as a special waste, with heavy economic and management burdens for the farmer, its valorisation would lead both to the reduction of woollen volumes - characterized by a low quality, so not suitable for the textile industry - and the reduction of environmental damage, due to the illicit disposal by some farmers and to the wrong management of waste water resulting from their washing.

Future analysis appears thence necessary, mainly focused on the role that natural fibres could perform when mixed into the earthen mixture of adobe bricks, that could be better explored through the study at microscopic level of the adhesion of the fibres to the clay matrix and the consequent effects on the general mechanical properties of the reinforced earth construction.

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