Local Supply Chains and Circular Economy for Building Materials. The PLES Project in Sardinia

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Abstract. Sardinia is characterized by an economic and productive system of modest competitiveness. This connotation also distresses the construction sector, which is affected by historical problems related to insularity, employment difficulties, the lack of economic resources, as well as the contingent and more general economic-production crisis. This situation, associated with the high environmental impact connected to the construction industry, highlights the potential of innovative construction solutions based on the logic of the short supply chain, the circular economy, and the eco-balance. In that context the PLES (Local Products for Sustainable Buildings) project was carried out, with the aim of developing multilayer construction systems for walls and floors made of locally produced materials mainly of natural origin. This project, funded by the Sardinian public administration, was carried out through the collaboration between a research group and a cluster of companies operating in the Sardinian territory. This paper illustrates the objectives, activities and main results of the PLES project, which carried out a feasibility assessment of local supply chains start up for the production of building materials and eco-sustainable construction systems in Sardinia, highlighting both the critical issues and the positive repercussions.

Keywords: Building materials · Natural materials · Local supply chain · Energy efficiency · Eco-sustainable construction systems · Circular economy

1 Introduction

The construction sector is currently responsible on average for over 35% of the consumption of raw materials, soil, water, and energy and for over 30% of pollution and the production of waste. This situation requires a revision of the management models of the building stock, regarding both new and existing buildings. Focusing on the design and construction of new buildings, it should be emphasized that starting from 2021 all new buildings built in Italy will have to be "nearly Zero Energy Buildings" (nZEB) [1], namely buildings with almost zero energy needs [2–4]. This means significantly improving the energy performance of new buildings compared to the average of the

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national building stock [5]. In this context, the sustainability of building materials is of fundamental importance, and local supply chains take on a strategic role. In fact, the reduction of the environmental impact of a "green" building goes through the following factors:

- lower energy requirements than traditional buildings,
- lower water consumption compared to traditional buildings,
- lower environmental impact over the entire life cycle,
- best quality and indoor comfort.

These objectives can be achieved by means of the following strategies:

- increased use of natural ventilation,
- greater use of natural light and attention to passive solar gains,
- greater use of systems for low temperature heating and high temperature cooling, in other words systems that operate at a temperature close to that required with a low temperature difference,
- greater use of systems powered by renewable sources,
- greater use of *local and eco-sustainable materials.*

The resort to local short supply chains to produce building materials is particularly appropriate in contexts of isolated economies, such as those existing in island regions like Sardinia. Indeed, the situation of insularity increasingly encourages the implementation of self-sufficiency paths in the production and management of resources, to characterize the economy from the point of view of sustainability [6].

In this regard, it is worth underlining that the concept of sustainability involves both the environmental, the economic and the social aspects [7], therefore orienting the economy towards the track of sustainability suggests to implement solutions that enhance both the environmental, the economic and the social capitals.

The PLES project - Local Products for Sustainable Buildings - fits into this context. It is a project funded by the local authority Sardegna Ricerche [8], based on the synergy between the university and local companies for the achievement of a common goal. The PLES project fits into the general context of the bioeconomy and the circular economy, and in the specific context of sustainable construction. It is motivated by the need / opportunity to develop production processes based on the logic of short supply chain, circularity, and eco-balance, using eco-friendly, recyclable, locally available and energy-efficient construction materials. This need derives from considerations concerning various aspects, such as the need to renovate the construction sector in deep crisis, the condition of Sardinia's insularity, which requires self-sufficiency in terms of production and management of resources, the obligation to contain the impacts related to the construction sector.

This paper describes the PLES project in terms of objectives, activities and results achieved. The article is structured on 5 sections: after this introduction, Sect. 2 provides an overview of the project. Subsequently, Sect. 3 illustrates the main activities in which the project was divided, and Sect. 4 summarizes the results. Finally, Sect. 5 proposes some concluding remarks.

2 The PLES Project

The general objective of the PLES project, which also constitutes its scientific theme, was the development of constructive solutions for walls and floors consisting of multilayer packages that use sustainable materials, mainly of natural origin, and locally available. This objective was shared and pursued through the synergy between the research group and the companies belonging to the cluster supporting the project.

The project therefore had the objective of studying multilayered load-bearing elements including the insulating element, and which can be integrated with a finishing element capable of increasing the environmental acoustic comfort and adding aesthetic value to the panel. The multilayer package is made up as follows:

- structural elements:
  - Cross Laminated Timber (CLT) made of Sardinian Maritime Pine
  - masonry (clay bricks or concrete blocks)
- elements for thermal and acoustic insulation:
  - cork
  - sheep's wool
  - earth-based products
- finishing elements:
  - textile handicraft products
  - plasters of natural origin.

All the materials selected to make the multilayer packages are locally produced, and their choice was based on the following considerations.

The construction systems with CLT panels are having a rapid development throughout Europe thanks to their intrinsic advantages [9, 10]: naturalness, dimensional stability, the advanced degree of prefabrication at the production level, the rapidity of assembly, the remarkable properties of strength and stiffness. CLT elements are solid multi-layer load-bearing panels obtained by overlapping and gluing crossed layers of boards, which can be used both as walls and as floors. Recently, the first residential buildings with load-bearing structures in CLT were also built in Sardinia, however, using imported timber, in particular spruce from Austria or Germany, with a considerable increase in cost. A crucial point of the PLES project was the choice of using locally produced timber, namely Maritime Pine, contributing to the theme of sustainable development of zero-kilometer timber construction in Sardinia, using local resources. This in particular can enhance Sardinian forests, resulting in an increase in the forest area in order to guarantee the sustainability of the supply chain, with all the positive implications of environmental protection and ozone hole reduction, hydrogeological protection of a territory potentially at risk, and of development and economic impulse of traditionally depressed regional areas, as well as new life for the building market now in deep crisis [11, 12].

Cork, sheep's wool, earth, are also materials of natural origin, locally produced, and therefore consistent with the idea of biocompatibility and the production process in a short supply chain. These materials have interesting thermal and acoustic insulation characteristics - in particular the use of cork in construction is not new - however their systematic use is still penalized by the competition of materials manufactured on a large scale, which can therefore be placed on the market at a more competitive price. The definition of design criteria for the implementation of these materials in Sardinian timber-based walls or floors packages would give further impetus to the cork sector, to the emerging and innovative sectors of sheep's wool and earth as insulating materials, with the positive effects in terms of eco-sustainability and promotion in the employment and social sphere already highlighted for the Sardinian CLT panels.

The integration into the wall or floor construction systems of fine finishes, consisting of fine fabrics such as the traditional products of the island's textile craftsmanship, which can also bring a benefit in terms of noise reduction to the environment, expresses an innovative combination of traditional craftsmanship and technology, opening new scenarios in the field of design and technological research, with important repercussions in terms of development.

Alongside the wall and floor elements having the Sardinian CLT as a supporting structure, the study of the application of the insulating materials described above on traditional masonry elements (concrete and brick) was carried out too. Although these materials are obviously less sustainable than wood, this choice allows to better frame the performance of the timber-based packages in relation to the more traditional masonry elements, and to diversify the possibilities of using the innovative insulating materials.

The main activities in which the PLES project was articulated to achieve the intended objectives are illustrated in the next Sect. 3.

3 PLES Activities

The PLES project was developed through a series of activities:

1. Analysis of Production Processes;
2. Mechanical and Energetic Characterization of Materials;
3. Implementation of Models for Numerical Simulation;
4. Laboratory Tests on Manufactured Prototypes.

3.1 Analysis of Production Processes

The starting point of the project consisted in the analysis of the production processes related to the materials and construction systems considered. This analysis was conducted with reference to the Life Cycle Assessment (LCA) model [13] and made it possible to highlight the consumption of energy, the primary and secondary resources, and the emissions and production of non-recyclable waste. In detail, the production cycles of the following products were considered:

- Cross Laminated Timber panel made of Sardinian Maritime Pine (Fig. 1);

- clay bricks for masonry;
- concrete blocks for masonry;
- sheep's wool insulating element;
- raw earth insulating element;
- finishing based on natural plasters;
- finishing with textile handicraft products.

Fig. 1. Production process for Sardinian Maritime Pine CLT panels manufacturing.

The impacts were assessed in terms of both economic, environmental, and social sustainability, and the main aspects associated with the production and marketing of the individual products were highlighted. This phase allowed on the one hand to highlight the main critical issues associated with the various production processes and to indicate possible solutions, on the other hand to propose the development of new materials and/or production processes and the optimization of the already existing ones. Of relevance within the project is the analysis of the supply chain relating to the production of glued laminated timber elements based on Sardinian wood. This activity made it possible to identify the optimal methods for: i) selecting the areas for the supply of the wood resource, ii) selecting and cutting the plants, iii) processing the logs into boards, iv) drying the boards, and to point out the costs and criticalities of the process [11, 14].

3.2 Mechanical and Energetic Characterization of Materials

During the project, an intense activity of experimental tests was carried out on the basic materials and components of the stratigraphies. Specific tests were carried out for the

physical-mechanical and thermoacoustic characterization of the products involved in the project and in general of similar products that the local companies intend to characterize, improve and / or promote.

The following tests were of paramount importance:

- tests for the characterization of Sardinian timber (Fig. 2),
- tests on various mix designs for lime-based plasters with natural and vegetable fibres such as wool, hemp, jute (Fig. 3),
- tests on panels in raw earth mixed with vegetable fibres such as hemp (Fig. 4).

Fig. 2. Non-destructive sonic testing on Sardinian Maritime Pine boards.

Fig. 3. Bending test (left) and compression test (right) on lime-plaster with natural fibres.

These products are completely innovative or handcrafted, therefore they are not equipped with technical data sheets that allow their marketing and use in construction. It is therefore necessary to acquire all the technical data useful for requesting the mandatory European certifications for placing them on the market.

In particular, the experimental tests have shown that Sardinian Maritime Pine is a medium-low quality material, especially compared to the woods of central Europe commonly used for the production of laminated timber, but its use in the form of CLT panels allows to obtain a final product with mechanical characteristics superior to those of the starting boards [15, 16].

Fig. 4. Compression test on raw hearth with hemp fibres.

3.3 Implementation of Models for Numerical Simulation

The project also involved the implementation of numerical models to simulate the mechanical and thermo-acoustic behavior of the multilayer packages and of the single constituent layers. This activity mainly consisted in the development and implementation, by means of calculation codes and commercial software, of numerical models for the simulation of the mechanical and thermo-acoustic performance, and the subsequent calibration according to the experimental results.

Particular attention was paid to modeling the mechanical behavior of the CLT panels (Fig. 5). This activity was carried out starting from the collection and study of the existing analytical models relating to the main mechanical characteristics of CLT, namely strengths and stiffnesses. These models were then compared with the experimental data resulting from the tests conducted on Sardinian Maritime Pine CLT elements. The comparison made it possible to adapt the existing models to the specific peculiarities of the local material, having quality generally lower than that of the Central European fir, the species on which most of the existing analytical models are calibrated.

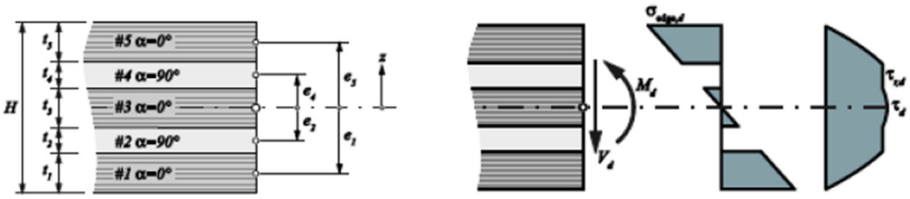


Fig. 5. 5-layer CLT panel subjected to bending action: stress distribution [17].

The simulation of the energetic and acoustic behavior of the building materials and components was based on experimental data relating to measurements of the thermal conductivity of the materials, of the permeability to water vapor and of the soundproofing and sound-absorbing power. Some data were measured with equipment that perform

tests according to standardized international procedures, such as thermal conductivity, while other quantities, such as the sound absorption of some materials, were estimated based on measurements performed on-site. In some cases, moreover, to have all the data necessary to simulate the thermo-energetic and acoustic behavior of the prototypes, reference was made to technical standards databases or to scientific literature. Figures 6 and 7 show respectively a thermo-hygrometric simulation and an acoustic simulation of a stratigraphy.

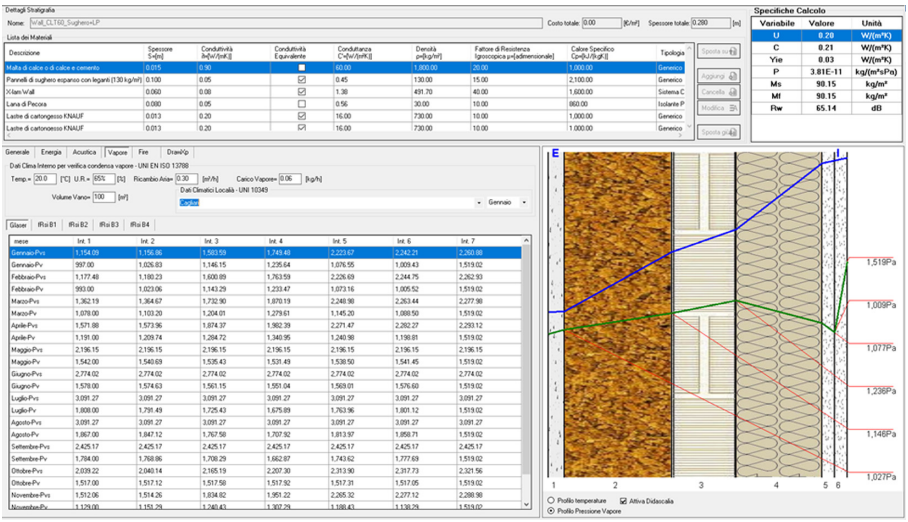


Fig. 6. Thermo-hygrometric simulation of a stratigraphy.

3.4 Laboratory Tests on Manufactured Prototypes

The last experimental activity carried out within the project involved the manufacturing of stratigraphy prototypes and the implementation of laboratory tests for the characterization of their mechanical and thermo-acoustic performance.

In particular, thermal and mechanical tests were carried out on Sardinian Maritime Pine CLT panels (Figs. 8 and 9) to obtain the main quantities, such as strength, stiffness and thermal conductivity, to define their performance, and acoustic tests on masonry (Fig. 10), CLT-based walls, and panels covered by handicraft fine fabric (Fig. 11) to define the soundproofing power of the stratigraphies.

The mechanical and energetic properties of the tested materials and construction systems were collected and implemented according to the procedures provided for compatibility with the BIM (Building Information Modeling) protocol [18]. Through this kind of coding, now indispensable for the advanced management of projects, a database has been created with the aim of promoting the marketing of the local products, and their use by designers and customers [19].

The main results achieved by the PLES project through the activities previously described are summarized in the next Sect. 4.

Main results of acoustic simulation

Rw	40.8 dB
Front mass	110 kg/m²
ΔRw	1.0 dB
Ln,eq,w	0.0 dB
ΔLnw	0.0 dB

Stratigraphy

n. layer	Layer type	Layer name - description	S [cm]	s' [MN/m³]	Mf [kg/m²]	λ [W/mK]
1	Generic	Lime or lime and cement mortar	1.5	0.0	27.0	0.900
2	Generic	Expanded cork panels with binders (130 kg/m³)	10.0	0.0	13.0	0.045
3	Building System	X-lam Wall	10.0	0.0	49.2	0.138
4	Wall Insulation	Sheep wool	8.0	0.0	2.4	0.045
5	Generic	Plasterboard slab KNAUF	1.3	0.0	9.1	0.200
6	Generic	Plasterboard slab KNAUF	1.3	0.0	9.1	0.200

Fig. 7. Acoustic simulation of a stratigraphy.

Fig. 8. Conductivity measurements on CLT panels.

Fig. 9. Bending test on CLT panels.

Fig. 10. Acoustic measurements on clay-brick masonry.

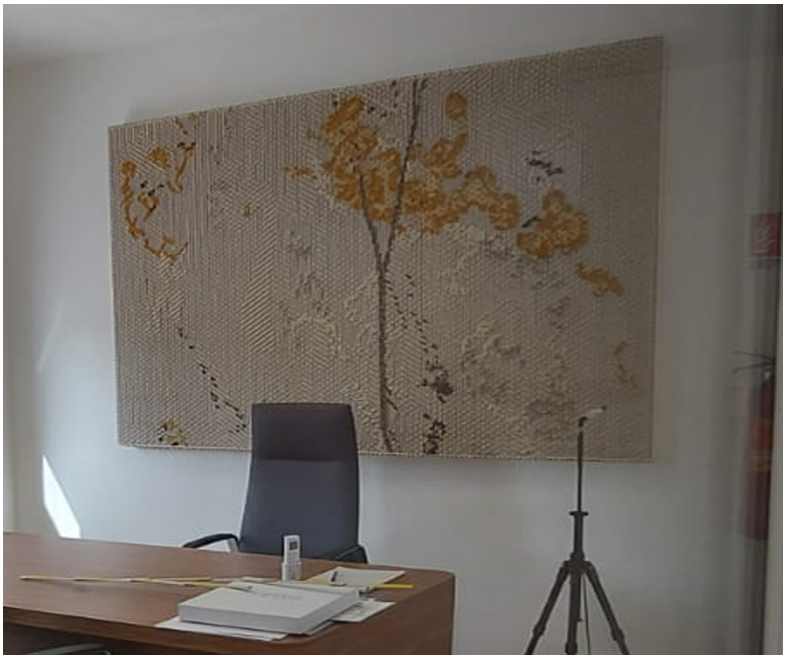


Fig. 11. Acoustic measurements on textile panel.

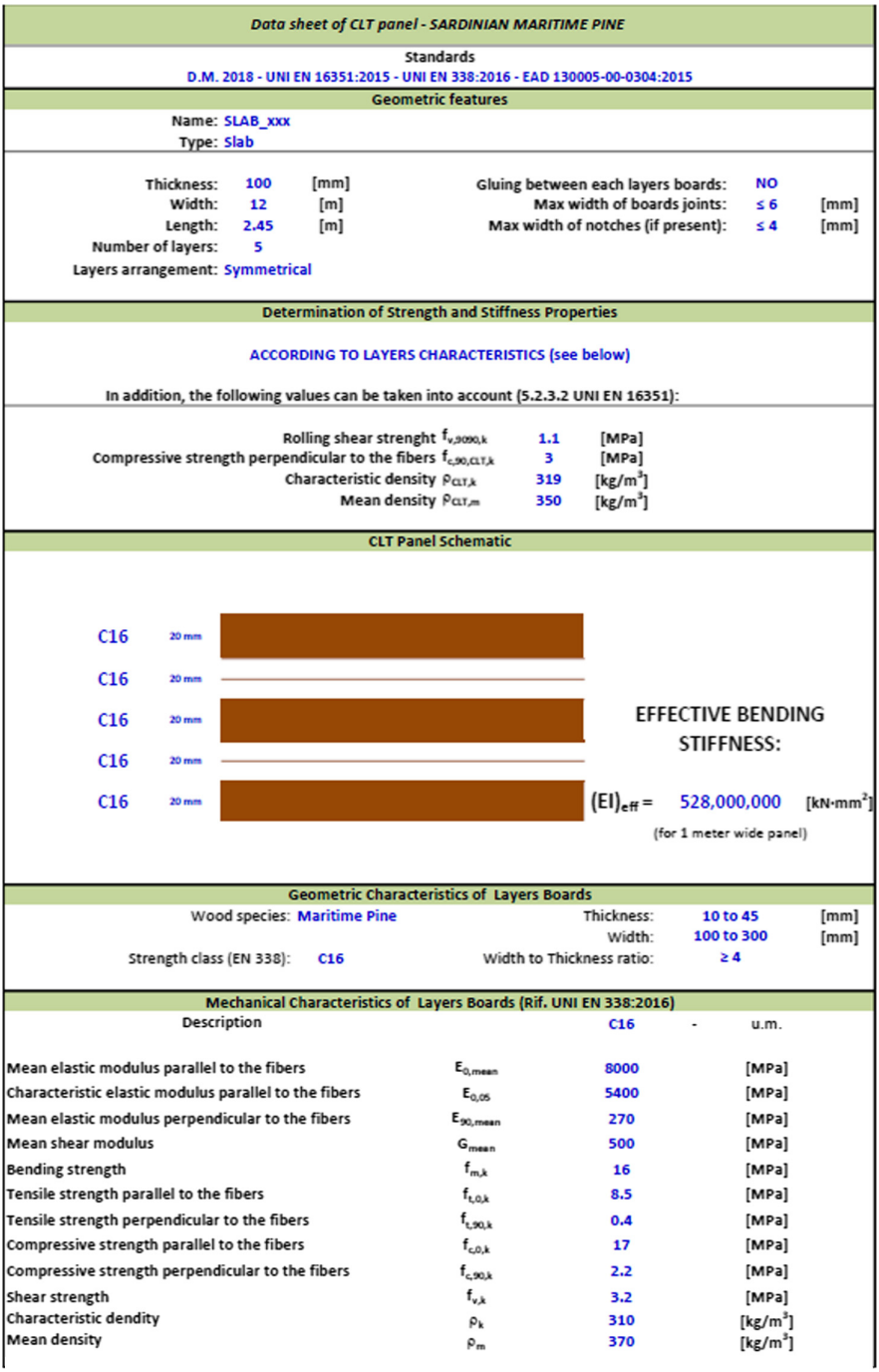
4 PLES Results

The PLES project aimed to strengthen the Sardinian business system from a sustainable perspective through the enhancement of technologies and the implementation of innovative ideas and processes, in order to increase the competitiveness of regional companies in a global context through greater flows of technologies, skills, people. In this perspective, the main results achieved are the following:

- boost to the development of the Sardinian wood supply chain for structural use;
- support for the diversification of the production and destination of traditional materials such as sheep's wool, raw earth, cork;
- impulse to the development of the production sector of derivatives from vegetable fibres and of fabrics to be used in the construction sector;
- increased competitiveness and innovativeness of the artisan enterprises potentially interested;
- development of new production processes;
- optimization of existing production processes, also through the application of innovative tools and technologies.

From a technical-practical point of view, the project has made it possible:

- to determine the mechanical performance of Sardinian Maritime Pine CLT panels and consequently to implement technical data sheets containing their mechanical properties, which can be used to encourage production and use of this innovative material (Fig. 12);



Data sheet of CLT panel - SARDINIAN MARITIME PINE

Standards

D.M. 2018 - UNI EN 16351:2015 - UNI EN 338:2016 - EAD 130005-00-0304:2015

Geometric features

Name: SLAB_xxx
Type: Slab

Thickness:	100	[mm]	Gluing between each layers boards:	NO	
Width:	12	[m]	Max width of boards joints:	≤ 6	[mm]
Length:	2.45	[m]	Max width of notches (if present):	≤ 4	[mm]
Number of layers:	5				
Layers arrangement:	Symmetrical				

Determination of Strength and Stiffness Properties

ACCORDING TO LAYERS CHARACTERISTICS (see below)

In addition, the following values can be taken into account (5.2.3.2 UNI EN 16351):

Rolling shear strenght	$f_{v,90/90,k}$	1.1	[MPa]
Compressive strength perpendicular to the fibers	$f_{c,90,CLT,k}$	3	[MPa]
Characteristic density	$\rho_{CLT,k}$	319	[kg/m^3]
Mean density	$\rho_{CLT,m}$	350	[kg/m^3]

CLT Panel Schematic

C16 20 mm
C16 20 mm
C16 20 mm
C16 20 mm
C16 20 mm

EFFECTIVE BENDING STIFFNESS:

$(EI)_{eff}$ = 528,000,000 [kN·mm^2]

(for 1 meter wide panel)

Geometric Characteristics of Layers Boards

Wood species:	Maritime Pine	Thickness:	10 to 45	[mm]
		Width:	100 to 300	[mm]
Strength class (EN 338):	C16	Width to Thickness ratio:	≥ 4	

Mechanical Characteristics of Layers Boards (Rif. UNI EN 338:2016)

Description		C16	-	u.m.
Mean elastic modulus parallel to the fibers	$E_{0,mean}$	8000		[MPa]
Characteristic elastic modulus parallel to the fibers	$E_{0,05}$	5400		[MPa]
Mean elastic modulus perpendicular to the fibers	$E_{90,mean}$	270		[MPa]
Mean shear modulus	G_{mean}	500		[MPa]
Bending strength	$f_{m,k}$	16		[MPa]
Tensile strength parallel to the fibers	$f_{t,0,k}$	8.5		[MPa]
Tensile strength perpendicular to the fibers	$f_{t,90,k}$	0.4		[MPa]
Compressive strength parallel to the fibers	$f_{c,0,k}$	17		[MPa]
Compressive strength perpendicular to the fibers	$f_{c,90,k}$	2.2		[MPa]
Shear strength	$f_{v,k}$	3.2		[MPa]
Characteristic dendity	ρ_k	310		[kg/m^3]
Mean density	ρ_m	370		[kg/m^3]

Fig. 12. Sardinian Maritime Pine CLT panel – Data sheet.

- to design and manufacture some prototypes of stratigraphy (Fig. 13) based on natural, local, innovative materials, to study their mechanical and thermo-acoustic behavior and to prepare the relative technical data sheets.

Fig. 13. Stratigraphy made of (from inside to outside): fine fabrics, wood panel, sheep's wool, 3-layer CLT, cork, natural plaster.

All the activities, contents, results and products of the PLES project have been implemented on a freely accessible dedicated website [19], in order to provide a solid basis for the implementation in Sardinia of local supply chains for the production of eco-sustainable building materials.

5 Conclusions

The PLES (Local Products for Sustainable Buildings) project was aimed at developing construction solutions for walls and floors consisting of multilayer packages that use sustainable materials, mainly of natural origin, and locally available. This objective was pursued through the synergy between the university and a group of companies operating in the Sardinian territory.

The project's activities demonstrated the structural-energetic effectiveness of the analysed stratigraphies, highlighting their suitability to meet the performance requirements for walls and floors, and pointing out the possibility of using high-performance, low environmental impact and locally produced construction systems in Sardinian building sector.

In addition, the project made it possible to evaluate the feasibility of implementing local supply chains in Sardinia to produce materials/building elements for sustainable construction and green building.

Of particular importance is the definition of the performance of load-bearing panels in Sardinian CLT, whose local production would allow the activation of a specific supply chain, with important positive effects in environmental, economic, and social terms.

The results of the PLES project can be considered as a basic platform on which to build effective and shared paths aimed at the implementation of these supply chains for sustainable building materials, with the involvement of all potentially interested parties in the Sardinian territory.

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References

1. Directive 2010/31/ EU of the European Parliament
2. Kurnitski, J., et al.: How to define nearly net zero energy buildings nZEB. REHVA J. 6–12 (2012)
3. Wu, W., Harrison, M.S.: Residential net-zero energy buildings: Review and perspective. Renew. Sustain. Energy Rev. **142**, 110859 (2021)
4. Aelenei, L., et al.: Design issues for net zero-energy buildings. Open House Int. **38**(3), 7–14 (2013)
5. Gupta, A., Deshmukh, S.K.: Energy efficient construction materials. Key Eng. Mater. **678**, 35–49 (2016)
6. Clean energy for EU islands, https://ec.europa.eu/energy/topics/markets-and-consumers/clean-energy-eu-islands_en, last accessed 2021/06/18
7. Brundtland, G.H.: Our Common Future: Report of the World Commission on Environment and Development. UN-Dokument A/42/427, Geneva (1987)
8. Sardegna Ricerche, https://www.sardegnaricerche.it/en/, last accessed 2021/06/18
9. Brandner, R., Flatscher, G., Ringhofer, A., Schickhofer, G., Thiel, A.: Cross laminated timber (CLT): overview and development. Eur. J. Wood Wood Prod. **74**(3), 331–351 (2016). https://doi.org/10.1007/s00107-015-0999-5
10. Espinoza, O., Rodriguez Trujillo, V., Laguarda Mallo, M.F., Buehlmann, U.: Cross-laminated timber: status and research needs in Europe. BioResources **11**(1), 281–295 (2016)
11. Concu, G.: Sustainability of the timber supply chain on the island of sardinia. In: Gervasi, O., et al. (eds.) ICCSA 2020. LNCS, vol. 12255, pp. 353–367. Springer, Cham (2020). https://doi.org/10.1007/978-3-030-58820-5_27
12. Fragiacomo, M., Riu, R., Scotti, R.: Can structural timber foster short procurement chains within mediterranean forests? A research case in Sardinia. South-east Eur. For. **6**(1), 107–117 (2015)
13. Guinée, J.B., et al.: Life cycle assessment: past, present, and future. Environ. Sci. Technol. **45**(1), 90–96 (2011)
14. Concu, G.: Introductory Chapter: Timber and Sustainability in Construction. In: Concu, G. (eds) Timber Buildings and Sustainability, InTech (2019)
15. Concu, G.: Prediction of maritime pine boards modulus of elasticity by means of sonic testing on green timber. Appl. Sci. **11**(4), 1748 (2021)
16. Concu, G., De Nicolo, B., Fragiacomo, M., Trulli, N., Valdes, M.: Grading of maritime pine from Sardinia (Italy) for use in cross-laminated timber. Proc. Inst. Civil Eng. – Constr. Mater. **171**(1), 11–21 (2018). https://doi.org/10.1680/jcoma.16.00043
17. EN-1995:2008-06 Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings. European Standard, European Committee for standardization

18. Mastino, C.C., Concu, G., Baccoli, R., Frattolillo, A., Di Bella, A.: Methods for acoustic classification in buildings: an example of application of bim procedures on wooden buildings. In: Proceedings of 48th International Congress and Exhibition on Noise Control Engineering, June 16–19, 2019, Madrid, Spain (2019)
19. The PLES project. https://sites.unica.it/ples/. Accessed 18 June 2021