Sustainable engineering of rammed earth construction. Material, design and performances optimization

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ABSTRACT Les bâtiments du futur doivent répondre à des exigences de plus en plus élevées en matière de performances énergétiques et de durabilité environnementale, pour l'ensemble des chaînes de production et construction. Cette question a suscité un vif intérêt vers l'utilisation de matériaux naturels comme la terre crue dans la construction, caractérisée par une intrinsèque disponibilité, durabilité et recyclabilité.

En Europe, la diffusion des technologies en terre crue a été entravée par l'absence de législation spécifique réglementant son utilisation à des fins portantes, en particulier dans les territoires à haut risque sismique.

La thèse a eu pour objectif la conception d'un type de construction modulaire renforcée en pisé, réalisée avec des matériaux naturels, peu coûteux ou de réemploi. Elle comprenait la conception de mélange de terre adaptée aux applications porteuses, la définition d'une technologie constructive pour les zones à haut risque sismique et l'évaluation des performances thermiques et énergétiques attendues au moyen de simulations numériques calibrées sur une campagne de caractérisation des matériaux. Les principaux résultats des travaux sont présentés et commentés.

Keywords raw earth, material characterization, seismic resistant design, thermal and energy performance

I. INTRODUCTION

In line with international and European directives, the construction sector today must respond to a series of new demands, being the most pressing those concerning the reduction of available resources, the containment of energy consumption and the abatement of CO_2 emissions (European Parliament, 2019). Construction based on the use of natural building materials have attracted international attention in response to the current energy crisis and the deterioration of natural resources due to their availability, lack of toxicity, recyclability, low energy incorporated in the manufacturing/production phase and good hygrothermal and acoustic performances.

In the context of new construction, solid rammed earth (from now on RE) building systems have undoubted environmental benefits compared to conventional technologies. Indeed, as shown by Ben-Alon et al. (2021), insulated RE walls system outperforms conventional construction solutions (insulated CMU), with embodied reductions of 78% for global climate change, 72% for energy demand, 90% for air acidification and 98% for air particulate pollution impacts. Furthermore, environmental impacts of uninsulated RE technologies are even lower, even if the expected heating and cooling loads are expected to be higher especially in continental climates (Ben-Alon et al. 2021). In Mediterranean and arid climates, characterized by a large thermal oscillation between day and night, RE walls have good thermal performances due to their high thermal mass, which stabilizes and balances the internal temperatures and humidity of the buildings, ensuring internal comfort conditions (Giuffrida et al., 2021). Several authors point out the importance of the adoption of climate-specific design choices for buildings (shape, size and location of windows) and bioclimatic strategies (cross night ventilation, rooves and windows shading elements) to decrease the energy demands for heating and cooling in several climates (Ben-Alon et al. 2023, Giuffrida et al. 2021). Recent contributions (Carrobé et al. 2021), concerning simulation studies on RE building characteristics and thermal performances reveal that RE walls used in temperate and arid climates manage to attain decrement factors of 0.14-0.23 and thermal amplitude variations from <1 °C to 2 °C; moreover, time lag is found to be ranging between 1 h and 14 h. Thermal comfort is estimated to be maintained within 73-81% of the time during summer. When considering heat and mass transfers, energy demands for heating and cooling are estimated to be in the range of 36-38 kW/m^2 (Losini et al. 2023) in arid climates.

Nonetheless, massive RE walls have poor seismic behavior. Indeed, the greater is the mass of walls, the higher are the induced seismic forces; this issue is moreover worsened by the weak RE response under compression forces, and the very low tensile strength, with a mechanical performance which is significantly influenced by hygrothermal conditions (Villacreses et al., 2021). This issue can be partially solved by the addition of fibers in the RE mixes, which creates a three-dimensional mesh which can enhance the tensile properties of the mixes while creating a ductile behavior of the walls (Jannat et al., 2020). Still, RE buildings are very vulnerable to earthquake excitations. Widely observed failure modes in previous earthquakes include the following mechanisms: brittle failures such as falling over due to out of plane actions, cracks at edges and at loading points where the load of the roof is transferred to the wall, loss of connectivity due to weak connections and propagation of cracks due to close distance between openings and corners (Correia et al., 2015). Several seismic resistant devices are proposed in the literature to mitigate vulnerability conditions of earthen structures (Giuffrida et al., 2021).

The following contribution aims at reviewing the main research steps, which led to the prototyping of a novel type of reinforced and modular RE construction made with natural, low-cost, or recycled materials. The contribution will focus on the main parts of the research. The first one is the study of a suitable RE material with enhanced mechanical, physical and thermal performances. The second one is the design procedure which led to the refinement of an innovative reinforced RE construction system. The last one is the assessment of the main thermal and energy performances of the designed technology when applied at a building scale.

II. METHODOLOGY

A. Material

The base material used in the experimental campaign is a soil quarried in Floridia, a city in the nearby of Syracuse (Sicily, Southern Italy), comprising 3 % of gravel, 70 % of sand, 17 % of silts and 10 % of clays. The particle size distribution has been obtained by means of sieving and sedimentation, according to ASTM D7928 – 17. The Atterberg limits of the soil fine fraction are LL=47.3%, PL=30.68% and PI=16.62%. The chosen soil thus presents an acceptable plastic index adapted to RE construction (Houben et Guillaud, 2006). Several mixes are designed on the base of previous experimental campaigns (Giuffrida et al., 2019), using the soil in combination with a local volcanic sand called “azolo” (with diameters below 4 mm), hydraulic lime, a filler derived from the sawing of marble and 20 mm long natural sisal fibers. Eight cubic-shaped samples for each mix design, with dimensions 150 * 150 * 150 mm, were manufactured. Samples were tested under unconfined compressive strength test (3 samples), capillary water absorption test (3 samples), moisture dependent thermal conductivity test (1 sample, 3 points of measure) and specific heat capacity assessment by means of DSC equipment. Sizes, manufacturing and curing processes were carried out in accordance with the New Zealand (2020) and Peruvian (2017) raw earth standards. The manufacturing protocol and testing methodology are described in Giuffrida et al. (2023).

B. Construction system

A design-simulation-validation approach, characterized by several design iterations, has been carried out for the prototyping and validation procedures useful to define the reinforced and modular constructive technique and building process. Particularly, the first design of the constructive system was carried out at the *Centro Tierra* of the *Pontificia Universidad Católica de Peru*, the main formulator of the Peruvian Standard on reinforced raw earth construction (NTE E 080). According to this standard, the construction system must use at least a solid 40 cm thick RE wall and the building characteristics (wall's height, spacings between loadbearing elements, voids width) must respect specific geometrical features. The first design solution involved the use of prefabricated RE panels (produced under controlled conditions to ensure a high-quality product) to be used together with a timber reinforcement frame (Schmidt 2016) to improve the overall strength. According to this system, the earthen masonry responds mainly to vertical loads, while the timber elements absorb the bending and shear stresses caused by any earthquakes, increasing the inertia of the cross-section. Moreover, an auxiliar horizontal surface reinforcement made by ropes was adopted to prevent from out of plane mechanisms (Blondet et al. 2013). This design was validated by a qualitative comparative dynamic test (Giuffrida et al., 2021).

The results of this test showed the effectiveness of the chosen seismic resistant design, but during model preparation, the need to simplify the constructive process forced us to abandon the idea of prefabricating the RE panels and to favor on-site built walls. This option was then pursued at University of Catania and in collaboration with Coop. Guglielmino (Sicily), by adopting a controlled premixed earth material and prefabricated reinforcing elements (timber posts and ring beams, rope reinforcement). In the final design solution for the constructive system, the reinforcing timber frame has a dual function: it works as a support element for the formworks during the construction phase, and it acts as a reinforcement for the walls in the event of an earthquake. This double function of the constructive system was validated by the construction of a prototype wall (Giuffrida et al., 2021). The structural performances of the proposed constructive system have been deduced from the literature (Blondet et al. 2017).

FIGURE 1. Different phases of the construction of the full-scale prototype.

C. *Thermal and Energy Performances*

The methodological approach adopted for the evaluation of the thermal and energy performances of the designed solution included:

- The design of a RE building model with geometrical and technological features based on the constructive system described in paragraph IIB.
- Dynamic thermal simulations on Design Builder software to compare the thermal and energy behaviors and the expected comfort provided by several uninsulated and insulated RE walls solutions.

The building model consists of a rectangular-shaped box, with three rooms facing South and two rooms facing East and West. All the load-bearing RE walls are 40 cm thick, while the partitions are made of lightweight materials. The stratigraphy of the designed walls, roof and solid ground floor and the characteristics of the materials are shown in Giuffrida et al. (2021). The net internal height of the walls is 3.00 m, the total envelope area is 825.9 m^2, while the gross volume is 261.4 m^3. The shape factor is 3.16, and the net usable area is 58.92 m^2.

The dynamic thermal behavior of the representative RE building was analyzed using Design Builder software, version 6.0, which is based on the Energy Plus calculation engine. In this simulation study, the effect of moisture storage and transport on the heat flux and consequently on the overall thermal behavior of the building has not been considered given the lack of experimental data (the study was conducted during 2020 COVID-19 outbreak). In the Design Builder reference residential building model, all rooms are accounted as occupied zones. Occupants, electrical devices, cooking, and lighting systems constitute the internal loads with power densities reported in Giuffrida et al. (2021). A constant air exchange of 0.5 V/h is set for outside air infiltration. Meteorological data from the Energy Plus Weather (EPW) file for the city of Catania (Italy) updated to 2019 were used as meteorological input. The simulations aimed at identifying the best RE wall design solutions, their energy consumptions when using HVAC systems and the expected comfort in free-running conditions (EN 16798-1/2019).

II. RESULTS

A. *Material*

The results of the overall experimental campaign are described elsewhere (Giuffrida et al. 2023). For the sake of brevity, we herein show the best mixture’s properties, which is the one composed by the soil, the filler (marble sawing waste) and sisal fibers. Results are summarized in Table 1, where it is possible to appreciate that the resistance exceed the limits of 1.3 MPa and 1.0 prescribed by the New Zealand and the Peruvian Standard. This fiber-reinforced mix have the highest compressive strength (6.9 MPa) and one of the highest Young Modulus (264 MPa) between all the tested mixes. Results concerning the material behavior in terms of capillary rising water revealed that using marble sawing waste enables a decrease of water absorption until the 6.9%, deeming with the prescriptions set out in HBE 195-2002. As regards thermal conductivity, at a constant temperature of 20°C, thermal conductivity increases when the relative humidity increases. Thermal conductivity for the chosen mix design ranges between 0.508 and 0.588 W/mK. Specific heat capacity is consistent for all the examined mixes and for the chosen mix is 1000 J/kg K, which entails good inertial properties.

In Giuffrida et al. (2023) it is included a comparison of the obtained thermal conductivity and compressive strength values with other RE materials results found in the literature.

TABLE 1. **Results of RE material characterization**

Mix	**Dry density**	**Compr. strength**	**Young Mod.**	**Water absorp.**	**λ_{dry}**	**$\lambda_{30\%RH}$**	**$\lambda_{50\%RH}$**	**$\lambda_{70\%RH}$**	**c**
	[kg/m³]	[MPa]	[MPa]	[%]	[W/mK]	[W/mK]	[W/mK]	[W/mK]	[J/kg K]
MFRE	1989	6.69	264	6.9	0.508	0.540	0.582	0.588	1000

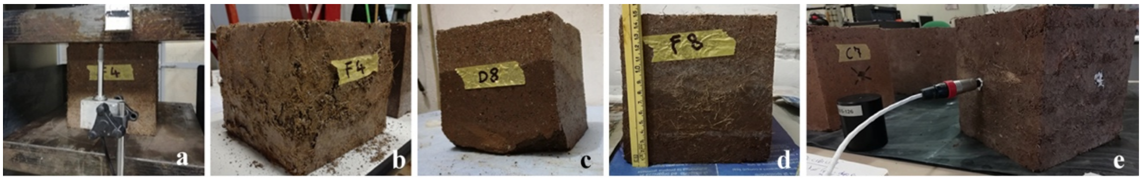

FIGURE 2. Compressive strength (a-b); water capillary absorption (c-d); thermal conductivity (e) tests for RE materials.

B. Thermal and Energy Performances

As abovementioned, an accurate dynamic thermal analysis was performed on a representative RE building in Mediterranean climate, to evaluate and compare the thermal behavior of an uninsulated and several biobased insulated RE envelope solutions in free-running conditions.

The following Figures 3 and 4 show two graphs for two representative periods of 2019: the warmest summer week (28 July–1 August) and the coldest winter (7–11 December) week. In both figures, dry bulb outdoor temperature (T_o), indoor and outdoor surface temperatures (respectively T_{si} and T_{so}), and average indoor air temperatures (T_a) profiles are depicted. These profiles refer to the uninsulated RE configuration (using only bioclimatic strategies as roof overhangs and night cross ventilation) and to an insulated one (using the abovementioned bioclimatic strategies and an exterior lime hemp insulation layer on the RE wall). All the simulations are run under free-running conditions (in the absence of an HVAC system). As can be seen from Figure 3, given a profile of outdoor temperature (T_o) and outdoor surface temperature ($T_{so,uninsulated} = T_{so,insulated}$), the indoor surface temperature profile of the insulated case ($T_{si,ins}$) is on average 1.77 °C lower than the uninsulated case ($T_{si,un}$) throughout the period considered. Moreover, the indoor air temperature values in the insulated case ($T_{a,ins}$) are always below 30 °C and on average 2 °C lower than those in the uninsulated case ($T_{a,un}$). For the insulated solution the decrement factor value is 0.0057 and the time lag is 24 h, slightly worst compared to the uninsulated solution which shows a decrement factor of 0,0034 and a time lag of 26h.

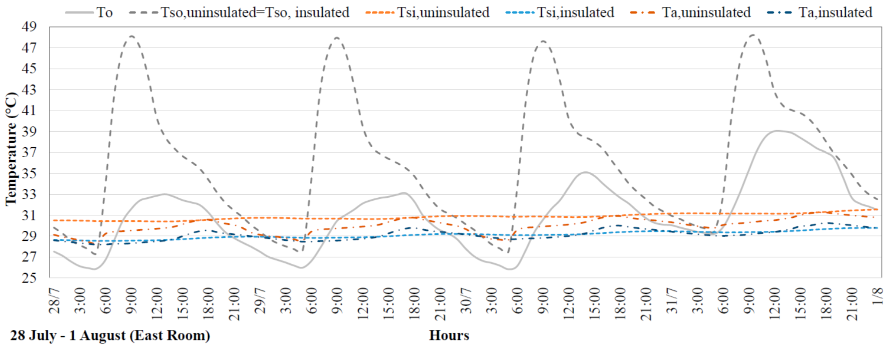

FIGURE 3. **Thermal performance of the uninsulated and insulated RE wall (summer)**

Observing the graph in Figure 4 allows us to make interesting considerations. Given the profiles of outdoor temperature (T_o) and outdoor surface temperature ($T_{so,uninsulated} = T_{so,insulated}$), the profile of indoor surface temperatures in the insulated case ($T_{si,ins}$) is almost always above the profile of indoor surface temperatures in the uninsulated case ($T_{si,un}$). The minimum values of indoor surface temperatures in the insulated case are on average 0.78 °C higher than those in the uninsulated case. Moreover, minimum values of indoor air temperature in the insulated case ($T_{a,ins}$), which are on average 0.87 °C higher than in the uninsulated case ($T_{a,un}$) and always above 17 °C.

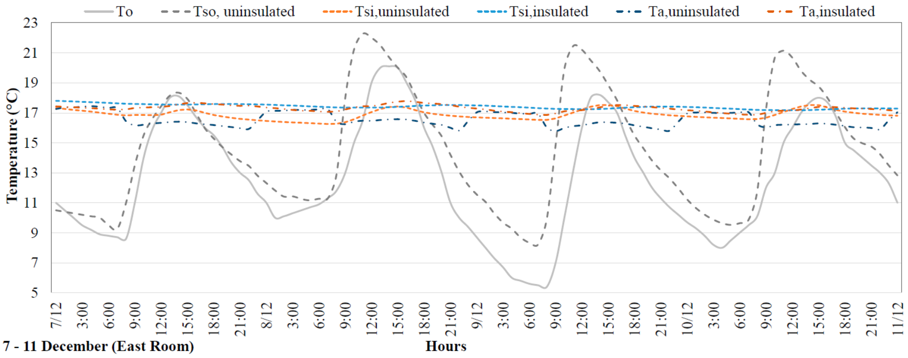

FIGURE 4. **Thermal performance of the uninsulated and insulated RE wall (winter)**

The indoor thermal comfort of the building was evaluated according to the adaptive comfort model. The operative temperature (T_{op}), calculated under freerunning conditions for the entire year and for all investigated cases, was used as the reference parameter for assessing the indoor thermal comfort. The hourly variations in T_{op} during the selected period (28 July to 2 August) are depicted in Figure 5 as well as the range of the comfort temperatures for categories I, II, and III. The uninsulated scenario falls within the limits of normal comfort expectations for more than the 80% of the analyzed time without use of HVAC system. Compared to this scenario, the insulated solution using an exterior layer of 10 cm thick lime hemp insulation, enables a further reduction in discomfort hours in summer conditions of around 20%, with comfort conditions maintained for more than the 95% of the analyzed time.

Furthermore, when using a HVAC system, the use of an insulation layer have a good influence in the reduction of total energy demand for cooling and heating with respect to the uninsulated case (which was equal to 75 KWh/m^2) by the 45%.

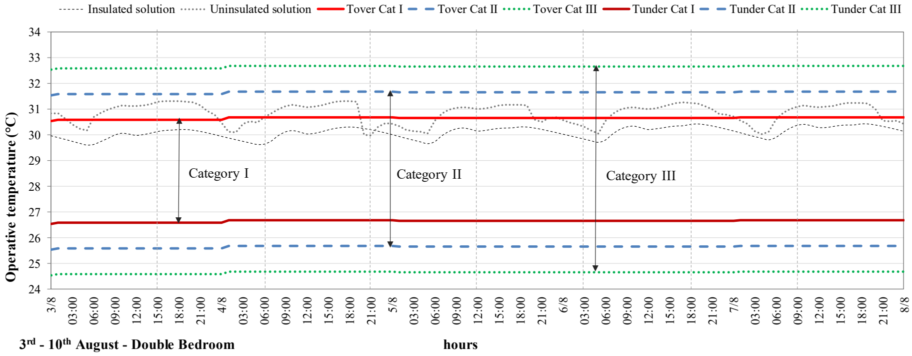

FIGURE 5. Adaptive comfort model for uninsulated and insulated RE buildings

III. CONCLUSIONS

This contribution focused on the main research steps which led to the prototyping of a novel type of reinforced and modular RE construction technology made with natural, low-cost or recycled materials.

According to the circular economy approach, this study focused on combined stabilization methods for RE material by using natural, recyclable materials, and by-products from other production chains to improve different material properties. Natural sisal fibers were adopted to improve the mechanical strengths, thus enhancing the ductility of materials, while marble sawing waste was used to reduce the issue of capillary water absorption. Experimental activities proved that the stabilization strategiy using fibers and marble sawing waste allowed reaching:

- Compressive strength up to 6.69 MPa by adopting sisal fibers in the mixes; use of marble sawing waste does not significantly alter the mechanical properties of the samples.
- Young's modulus values of 260 MPa.
- Low capillary absorption water values, equal to 6.9%.
- Moisture dependent thermal conductivity values between 0.508 W/mK and 0.588 W/mK.
- Specific heat capacity around 1000 J/ kg K.

Both the material composition and the designed reinforced RE constructive system are the object of the Italian Patent N. 102021000006644.

The thermal performance validation herein presented showed the feasibility of using massive RE walls in Mediterranean climates to ensure adequate indoor conditions in summer conditions. In particular, the analysis showed that during summer, the RE material used for the envelope behaves as a thermal flywheel and remarkably dampens the incoming heat wave, keeping the curve of the inner surface temperature almost constant compared to the outdoor one. In the uninsulated scenario, indoor air temperature is maintained below 30 °C, but this value can be further reduced by about 1 °C by the addition of a layer of bio-based insulation. The use of thermal insulation improves winter performances by maintaining an average indoor air temperature of 17 °C with an increase of 0.87 °C compared to the uninsulated case. Moreover, indoor thermal comfort is maintained for the 95% of time.

These results are important for the future generation of raw earth materials and buildings because they conjugate the environmental sustainability of bio-based building technologies with the reduction of waste from architecture, engineering and construction sector. This aim is pursued by using locally available materials and inexpensive technologies, with low environmental and economic costs, with consequent positive effects for the environment and local economies.

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