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Stabilized rammed earth incorporating PCM: Optimization and improvement of thermal properties and Life Cycle Assessment

Susana Serrano[a], Camila Barreneche[a,b], Lídia Rincón[a], Dieter Boer[c], Luisa F. Cabeza[a*]

[a]GREA Innovació Concurrent, University of Lleida, Edifici CREA, Pere de Cabrera s/n, 25001, Lleida (Spain)

Tel: +34.973.00.35.77. Email: lcabeza@diei.udl.cat

[b]Departamento de Ciencia de Materiales e Ingeniería Metalúrgica, University of Barcelona, Martí i Franqués 1-11, 08028, Barcelona (Spain). Tel: +34.93.402.12.98. Email: c.barreneche@ub.edu

[c]Departament d'Enginyeria Mecànica, Universitat Rovira i Virgili, Av. Països Catalans, 26, 43007 Tarragona, Spain.

Abstract

In this paper PCM is added to three types of stabilized rammed. Mechanical and thermal characterization is carried out. To do so, the compressive strength is optimized and the final compositions obtained are used to formulate the materials which will be thermally characterized. The optimization process is done with a design of experiments (DoE) and a variance analysis (ANOVA). Finally, LCA is used to evaluate the environmental impact during the manufacturing phase, due to the addition of stabilizers and PCM in the rammed earth.

Keywords: Stabilized rammed earth; phase change material (PCM); optimization, life cycle assessment (LCA); thermal characterization

* Corresponding author. Tel.: +34-973-00-35-76; fax: +34-793-00-35-75.
E-mail address: lcabeza@diei.udl.cat.

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1. Introduction

The energy consumption for thermal comfort in buildings has grown recently due to the increase of users demand. Thermal energy storage can help to decrease the energy consumption in buildings. Thermal energy storage in buildings can be implemented by sensible heat or by latent heat (with the inclusion of PCM) to increase thermal inertia [1][2]. Phase change materials (PCM) have been studied for thermal storage in buildings during the past 30 years [2]. PCM placed on the building facade can be daily cycled. Thus, during the day the PCM absorbs heat and consequently is melted. Then, for the period of night the heat is discharged through the solidification process.

On the other hand, sustainable construction requires systems and materials that allow the integration of natural environment processes in construction, such as rammed earth. Earth is a widely available, sustainable and reusable material. More than a third of the planet uses earth as building material due to its low cost. Rammed earth is a traditional constructive technique which fell into disuse. For this reason, if we want to use this material again, it is necessary to regulate the use of rammed earth in buildings [3].

Venkatarama et.al.[4] studied the energy consumption in the manual process of constructing cement stabilized rammed earth walls and concluded that the compaction energy increases with the increase of the clay fraction in the soil mix, so, the clay fraction is an important parameter. On the other hand, the author remarks that the energy expenditure in the compaction process is a negligible quantity when compared to energy content of the cement. The selection of the stabilizer can increase the embodied energy of the rammed earth due to the extraction and production process of the stabilizer.

LCA is a tool for evaluating the environmental impact of a product through analyzing the corresponding life cycle phases from cradle to grave. In this case, LCA is mainly used to evaluate the environmental impact during the manufacturing and the dismantling phases. Zabalza et al. [5] conducted a state of the art regarding the use of LCA in the building sector. Menoufi et al. [6] conducted the LCA of seven experimental building with different constructive solutions (including different insulting materials and PCM), with the aim of pointing out the most sustainable constructive solution.

In this study PCM is added in rammed earth stabilized with three different materials. The compressive strength response is optimized with a design of experiments (DoE) and the final compositions obtained are thermally characterized. Finally, LCA is used to evaluate the environmental impact of the addition of stabilizers and PCM in the rammed earth.

The main objective of this paper is to develop a new stabilized rammed earth typology with improved thermal properties.

2. Materials and methodology

2.1. Materials

Different stabilizers are used to improve the mechanical properties of rammed earth composing three different rammed earth types. All rammed earth samples were composed by a matrix which is a mixture of clay (42.5%), sand (50%) and gravel (7.5%). The clay is commercialized by Ceràmica Almacelles S.A.. The sand is marketed by Nordvert of Grup Sorigué and its particle diameter is 1 > Ø > 3 mm. The sand has a particle size of 2 – 3 mm.

Type 2 rammed earth is stabilized by two materials: straw commercialized by Forrajes Cominter S.L as physical stabilizer and lime ($Ca(OH)_2$) Cales Pachs® type CL-80 S (0 - 200 μ) is commercialized by Comercial Urgell S.A as physicochemical stabilizer.

Type 3 rammed earth is stabilized by straw as physical stabilizer again and alabaster powder commercialized by Alabaster Technology as physicochemical stabilizer.

Finally, Type 4 rammed earth is stabilized by two materials: pneumatic fibbers commercialized by GMN S.A. which is a residue from tires and as physicochemical stabilizer lime ($Ca(OH)_2$) was used.

The microencapsulated PCM used was Micronal® DS 5001 from BASF. The melting point of this PCM is 26 ºC (between 10-30 ºC). Micronal® DS 5001 has a latent heat capacity around 110 kJ/kg.

2.2. Methodology

To develop the new rammed earth with improved thermal properties a design of experiments (DoE) was carried out with Design Expert® software. The samples given by the DoE were evaluated through compressive strength tests. The optimums of these samples were then thermally analyzed.

2.2.1. Design of Experiments (DoE)

The DoE allows maximum information with minimum number of experiments. Furthermore, the main objective of the DoE is to deduce which components influence the mechanical properties of the new rammed earth.

The statistic design chosen to realize the DoE was Box-Behnken. The three factors chosen to be analysed were the content of straw or pneumatic fibbers (5–10 %), the amount of lime or alabaster (between 5 and 10%), and the percentage of Micronal® (0–10 %). The samples analysed and the order of the execution followed a random order to minimize systematic and accumulative errors on the results.

The objective of this DoE is to quantify the variation of mechanical properties of the measured rammed earth, according to the percentage used for each component.

2.2.2. Optimization process

The compressive strength was the mechanical property analyzed using an Incotecnic MUTC200 equipment and following the standard UNE-EN 196-1 [8]. The compressive strength was calculated following Equation (1) where R_c is the compressive strength, F_c is the maximum force at break point, and A is the area of the plates used in the assay, 1600 mm^2.

$$R_c = F_c / A \quad (1)$$

The dimensions of the samples were 40x40x160 mm [8]. The samples were made in the laboratory with a constant temperature, around 20-22ºC.

This mechanical response was optimized and the final composition obtained in the optimization process was used to formulate the final material which will be thermally characterized.

2.2.3. Thermal characterization

To perform the thermal characterization of optimum samples an equipment developed at the University of Lleida was used. This equipment was used to test the optima formulations through two experiments, the so-called Experiment 1 and 2 detailed in de Gracia et al [9].

The equipment used to perform the DSC analysis was a DSC-822e commercialized by Mettler Toledo. The crucibles used were aluminium crucibles of 100 µl under N_2 atmosphere flow of 80 ml/min. A dynamic method from 20 to 50 ºC and a 10 ºC/min heating rate were used to perform the thermal characterization by DSC. Specific capacity and melting enthalpy were measured.

3. Results and discussion

3.1. Optimization process

The compressive strength results of the samples analyzed following the DoE are listed in Table 1.

Based on the compressive strength results, the material with the best mechanical is rammed earth Type 3, while the worst ones is Type 4 rammed earth. Moreover, Type 2 and Type 3 models are statistically significant (p-value=0.0112 and p-value=0.0310, respectively), that is, differences between sample results have very low probability in being due to noise. For Type 4, the obtained model is not statistically significant; therefore the error in the model obtained would be bigger than the experimental error. For this reason, Type 4 is discarded and excluded from the thermal characterization.

Table 1. Formulations of the DoE and results of mechanical characterization (compressive strength)

Run	Matrix mixture (%)	Physical stabilizer (%)	Physicochemical stabilizer (%)	Micronal ® (%)	Type 2 (N/mm^2)	Type 3 (N/mm^2)	Type 4 (N/mm^2)
1	80.00	7.50	7.50	5.00	2.6006	4.0888	1.9127
2	80.00	7.50	7.50	5.00	3.0593	3.0038	1.5827
3	80.00	7.50	7.50	5.00	2.5316	4.0825	1.7794
4	80.00	7.50	7.50	5.00	2.3293	3.2642	1.6815
5	75.00	10.00	10.00	5.00	3.0465	3.7549	1.9457
6	77.50	7.50	5.00	10.00	2.8370	3.7904	1.5659
7	72.50	7.50	10.00	10.00	3.3792	2.8459	1.4949
8	72.50	10.00	7.50	10.00	2.7347	3.3085	1.6236
9	82.50	7.50	10.00	0.00	3.1904	4.8732	1.8378
10	80.00	10.00	5.00	5.00	3.1295	4.0603	1.1631
11	77.50	5.00	7.50	10.00	2.5710	1.9008	1.3738
12	87.50	5.00	7.50	0.00	1.9105	3.4534	1.4229
13	80.00	7.50	7.50	5.00	2.5959	4.0017	1.1733
14	82.50	10.00	7.50	0.00	2.4665	4.1769	1.1664
15	87.50	7.50	5.00	0.00	1.8128	4.0614	1.3534
16	80.00	5.00	10.00	5.00	2.3971	2.6645	1.6844
17	85.00	5.00	5.00	5.00	2.4305	4.3186	1.5117

The equations defining the optimum formulations which will be thermally analysed are given by equation (2) (for Type 2 and (3) for Type 3:

$$\sigma_2\ (N/mm^2) = 0.92885 + 0.10341 * (\%Straw) + 0.09017 * (\%Lime) + 0.053543 * (\%PCM) \quad (2)$$

$$\sigma_3\ (N/mm^2) = 3.88896 + 0.14816 * (\%Straw) - 0.10462 * (\%Alabaster) - 0.11798 * (\%PCM) \quad (3)$$

The addition of PCM into the rammed earth materials does not change significantly the mechanical properties under compressive strength, which is smaller for Type 2 material.

Taking into account equation (2) (, higher percentage of stabiliser give higher rammed earth compressive strength properties within the ranges studied. For Type 3 rammed earth, taking into account equation (3), increasing the alabaster and PCM percentages, decrease the compressive strength properties.

The thermal properties study of the rammed earth was performed using seven formulations. Six of them are optimum formulations and the other one is the matrix without stabilizers or PCM. The optimum formulations were selected using equations (2) and (3): the PCM percentage was fixed (0%, 5% and 10%) and the compressive resistance was defined as the maximum value. The compositions of the optimum samples thermally analysed are shown in Table 2. The compressive strength values expected for each formulation are also listed in Table 2.

Table 2. Composition and expected compressive strength of samples thermally analyzed

	Sample	Matrix mixture (%)	Physical stabilizer (%)	Physico-chemical stabilizer (%)	PCM (%)	R_c (N/mm^2)
	Matrix	100.00	0.00	0.00	0.00	3.47
Type 2	Opt. 2.1	70.17	9.99	9.84	10.00	3.38
	Opt. 2.2	75.00	10.00	10.00	5.00	3.13
	Opt. 2.3	80.00	10.00	10.00	0.00	2.86
Type 3	Opt. 3.1	75.00	10.00	5.00	10.00	3.66
	Opt. 3.2	80.00	10.00	5.00	5.00	4.26
	Opt. 3.3	85.00	10.00	5.00	0.00	4.85

3.2. Thermal characterization

3.2.1. Thermal transmittance (U-value)

The results listed in Table 3 show that the U-value of the optimums decreases when the rammed earth matrix is doped with more microencapsulated PCM.

On the other hand, the Matrix mixture (composed by sand, gravel and clay) and the Optimum 3.3 have the highest thermal transmittance.

Table 3. Steady state conditions and U-value in Experiment 1

		Matrix	Opt.2.1	Opt.2.2	Opt.2.3	Opt.3.1	Opt.3.2	Opt.3.3
Tenv.top	[ºC]	23.24	22.97	22.79	22.44	23.03	22.98	23.12
Tsample_top	[ºC]	31.34	29.99	30.17	29.24	29.71	29.84	29.81
Tsample_center	[ºC]	31.84	32.71	31.85	31.16	32.42	32.10	32.57
Tsample_down	[ºC]	34.94	34.41	34.79	33.15	33.69	33.81	33.48
Tenv_down	[ºC]	42.98	43.85	42.20	42.35	43.08	42.87	43.14
$\dot{q}_{top} / A$	[W/m^2]	90.00	78.25	87.14	87.62	86.76	87.77	89.81
$\dot{q}_{bottom} / A$	[W/m^2]	92.00	94.17	90.21	88.77	90.56	93.27	96.15
U-value	[W/m^2·K]	25.33	19.51	19.19	22.58	21.23	22.81	25.33
κ	[W/m·K]	0.51	0.39	0.38	0.45	0.42	0.46	0.50

Moreover, the thermal conductivity was calculated by (4) where *U-value* is the thermal transmittance and *S* is the thickness sample (0.02 m). Therefore, taking into account the results shown in Table 3, the thermal conductivity decreases when PCM is added to the formulation. This is due to the same reason as U-value: the PCM microcapsules are polymeric shells and this is a low-thermal conductivity material.

$$\kappa = \frac{\text{U - value}}{\text{S}} \tag{4}$$

3.2.2. Total accumulated heat (q_{acc})

Cp was analyzed performing the Experiment 2 with the University of Lleida device. The results are listed in Table 4. The results of the total heat accumulated (q_{acc}) by the samples are also included in this table.

Table 4. Heat storage capacity and total heat accumulated during Experiment 2

		Matrix	Opt.2.1	Opt.2.2	Opt.2.3	Opt.3.1	Opt.3.2	Opt.3.3
$T_{initial}$	[ºC]	20.48	20.64	21.38	18.44	21.70	19.08	20.31
T_{final}	[ºC]	42.16	40.93	42.10	40.30	42.33	41.23	43.46
ΔT_{sample}	[ºC]	21.68	20.29	18.72	21.86	20.63	22.15	23.15
q_{TOT}	[J]	29958	33008	31908	31025	30905	30405	30326
Cp_{sample}	[J/kg·ºC]	874.9	956.6	939.0	820.7	952.3	915.0	850.7
Thickness	[m]	0.02	0.02	0.02	0.02	0.02	0.02	0.02

De Gracia et al. [9] state that the measuring error of the University of Lleida device is 8%, therefore, all samples analyzed have results with differences with this 8% except Opt.2.1 which has slightly higher accumulated heat.

The power of heat accumulation over time, obtained with samples Matrix (without PCM) and Opt.2.1 (with 10% PCM) performed during Experiment 2, is visualized in Figure 1. These powers of accumulation are calculated subtracting the heat flux entering minus the heat flux leaving the samples from both surfaces. The area under the curve is the heat accumulated by the samples. The difference of areas between both curves is due to the PCM effect.

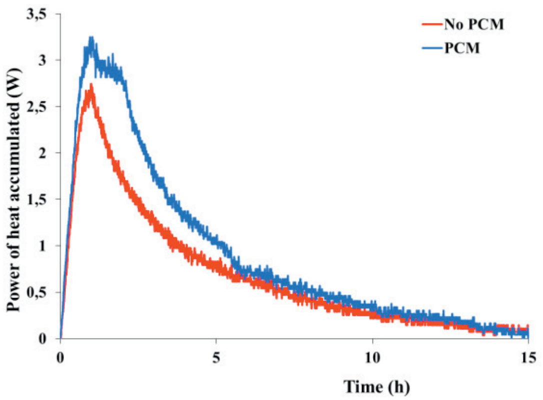

Fig. 1. Power of heat accumulation during Experiment 2

Moreover, the Cp values of the samples analyzed are increased by the addition of PCM in the samples. The rammed earth sample without PCM or stabilizers has a Cp of 874.9 J/kg·ºC. However, samples with 5% wt of PCM has a Cp of 939 J/kg·ºC and 915 J/kg·ºC and samples with 10% wt of PCM has a Cp of 956.6 J/kg·ºC and 952.3 J/kg·ºC.

To verify the results obtained with the University of Lleida device, a DSC analysis was carried out. The temperature range used was approximately the same than in the University of Lleida device. The results are shown in Table 5.

The DSC results differ between 0.4% and 13% relative to the results of the homemade device from University of Lleida.

Table 5. Results of DSC analysis

		Matrix	Opt.2.1	Opt.2.2	Opt.2.3	Opt.3.1	Opt.3.2	Opt.3.3
$T_{initial}$	[ºC]	20.42	20.65	21.32	18.42	21.59	19.00	20.33
T_{final}	[ºC]	42.35	40.91	42.26	40.27	42.54	41.19	43.57
Cp	[J/kg·ºC]	846.5	1027.2	942.6	836.5	1098.9	934.5	862.07
T_{mPCM}	[ºC]	-	28	27	-	23.93	27.96	-
Hm	[kJ/kg]	-	2.57	1.45	-	2.99	1.15	-

4. Life Cycle Analysis

Life Cycle Assessment (LCA) is an objective process for evaluating the environmental loads associated to a product, process or activity by identifying and quantifying the use of mass and energy and the discharges to the environment [10]. LCA accounts for all energy inputs and outputs of a building during its entire life cycle, including manufacturing, use, and demolition phases.

In this LCA, the environmental impacts are measured with the Eco indicator impact point given by Eco Indicator 99 (EI99), extracted from the database EcoInvent 2009[11]. According to EcoInvent database, Life Cycle Inventory of the building materials is detailed for the manufacturing phase. EI99 divides the impact into 10 impact categories that are further grouped into three different damage categories. They are (1) Eco system quality, which includes Acidification & eutrophication, Ecotoxicity, and Land occupation, (2) Human health, which includes Carcinogenics, Climate change, Ionizing radiation, Ozone layer depletion and Respiratory effects, and (3) Resources, which includes Fossil fuels and Mineral extraction. Finally, these three damage categories are aggregated into a single indicator.

The LCA has considered the manufacturing phase of the optimums. The impact points for each damage category are shown in Figure 2.

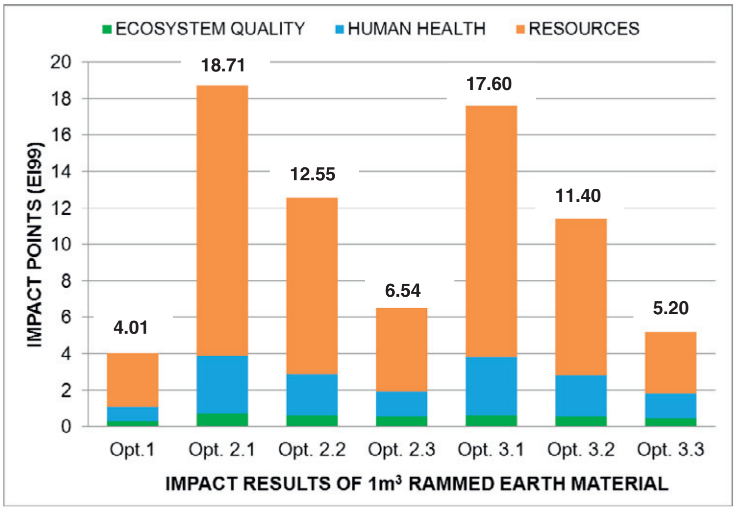

Fig. 2. Impact points (EI99) of the manufacturing phase.

In summary, the optimums with 10% of PCM have higher impact points. The value of impact points increases 1.30-1.63 times with the addition of stabilizers (Opt.2.3 and Opt.3.3). With the addition of stabilizers and 5% of PCM (Opt.2.2 and Opt.3.2), increases 2.84-3.13 times compared with the Opt.1. The addition of 10% of PCM and stabilizers (Opt.2.1 and Opt.3.1) increases the impact points 4.39-4.66 times.

In all cases, the addition of lime has a higher impact than the addition of alabaster.

5. Conclusions

Stabilized rammed earth improved with PCM in different proportions has been first optimized and then thermally analyzed in this paper. Finally, the environmental impact due to the addition of PCM has been evaluated by using Life Cycle Assessment considering the manufacturing phase of the material.

One design of experiments (DoE) was used in order to optimize the formulations of enhanced rammed earth material by adding three different stabilizers and PCM. The formulations were characterized applying compressive strength test. The results of these analyses have been collected in this paper. The thermal properties of the optimum formulations were characterized by a device developed by the University of Lleida and a DSC analysis. The thermal transmittance, the effective thermal conductivity, the total capacity to store energy, and the specific heat of the samples with 5% and 10% of PCM were analyzed as well as of the sample which contains neither stabilizers nor PCM.

Through the analysis of the data obtained from the mechanical properties characterization of the material, it can be concluded that Type 3 rammed earth have the best results in compressive strength test, then Type 2. The worst results are the compressive strength of rammed earth Type 4 which was discarded.

The results show that, Type 2 rammed earth, increasing the percentage of straw and lime, used as physical and physicochemical stabilizer, the compressive strength of the material is improved (within the percentages range studied in this paper). Furthermore, increasing the percentage of PCM improves slightly the compressive strength. On the other hand, with Type 3 rammed earth, the results show that increasing the percentage of straw and decreasing the amount of alabaster and PCM, the compressive strength of the material is improved.

The optimum formulations obtained from DoE model equations were thermally analyzed. The thermal transmittance decreases when PCM is added (from 22.58-25.33 $W/m^2{\cdot}K$ to 19.51-21.23 $W/m^2{\cdot}K$) and the thermal conductivity decreases clearly when PCM is added to the formulation. This is because the PCM microcapsules are made with polymeric material which is a low-conductivity material.

Moreover, the total heat accumulated by the samples under study was quantified. Opt. 2.1 (10% PCM) accumulates 10.2% more heat than the Matrix, and Opt. 3.1 (10% PCM), 3.2%. The optimums with straw and lime as stabilizers can accumulate more heat than the optimums with alabaster and straw.

Furthermore, *Cp* values were calculated with the experimental data obtained in this last experiment, concluding that the *Cp* increased when PCM was added. This is because the samples studied can accumulate sensible heat and latent heat from the PCM. These results are compared with the DSC analysis and have an error of 0.3-13%.

Finally, the LCA shows that incorporating microencapsulated PCM in the rammed earth increases up to 4.5 times the impact points of the material. For this reason, macroencapsulated PCM is recommended to improve the LCA results. The addition of stabilizers also increases around 1.5 time the impact points of the material, but the use of alabaster has 1.26 times less impact points than the lime.

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References

[1] Cabeza L.F, Castellón C, Nogués M, Medrano M, Leppers R, Zubillaga O. Use of microencapsulated PCM in concrete walls for energy savings. *Energy and Buildings* 2007; **39**:113-119.

[2] Cabeza L.F, Castell A, Barreneche C, de Gracia A, Fernández A.I. Materials used as PCM in thermal energy storage in buildings: A review. *Renewable and Sustainable Energy Reviews* 2011; **15**:1675-1695.

[3] Barbeta i Solà, G., "Mejora de la tierra estabilizada en el desarrollo de una arquitectura sostenible hacia el siglo XXI", PhD Thesis, 2002.

[4] Venkatarama Reddy B.V, Prasanna Kumar P. Embodied energy in cement stabilised rammed earth walls. *Energy and Buildings* 2010; **42 (3)**: 380-385.

[5] Zabalza I, Aranda A, Scarpellini S. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. *Building Environment* 2009; **44**:2510–2520.

[6] Menoufi K, Catell A, Navarro L, Pérez L, Boer D, Cabeza L.F. Evaluation of the environmental impact of experimental cubicles using Life Cycle Assessment: A highlight on the manufacturing phase. *Applied Energy* 2012; **92**:534–544.

[7] Romero R, Zunica L. Estadística, diseño de experimento y modelos de regresión. Valencia: Universidad Politécnica de Valencia ed., Spain; 1993.

[8] UNE-EN 196-1:2005. Métodos de ensayo de cementos. Parte 1. Determinación de resistencias mecánicas.

[9] de Gracia A, Barreneche C, Farid M.M, Cabeza L.F. New equipment for testing steady and transient thermal performance of multilayered building envelopes with PCM. *Energy and Buildings* 2011; **43**:3704–3709.

[10] Papadoppoulos A.M, Giama E. Environmental performance evaluation of thermal insulation materials and its impact on the building. *Building Environment* 2007; **42**:2178–2187.

[11] The Ecoinvent Center. A competence centre of ETH; PSI; Empa & ART. http://www.ecoinvent.ch/. Ecoinvent data v2.1.