Brás, A, Goncalves, F and Faustino, P

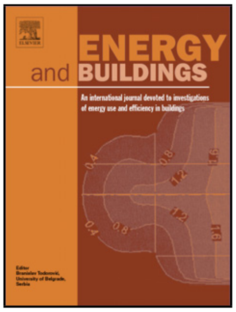
Cork-based mortars for thermal bridges correction in a dwelling: Thermal performance and cost evaluation

http://researchonline.ljmu.ac.uk/id/eprint/11653/

Article

Citation (please note it is advisable to refer to the publisher's version if you intend to cite from this work)

Brás, A, Goncalves, F and Faustino, P (2013) Cork-based mortars for thermal bridges correction in a dwelling: Thermal performance and cost evaluation. Energy and Buildings, 72. pp. 296-308. ISSN 0378-7788



Title: Cork-based mortars for thermal bridges correction in a dwelling. Thermal performance and cost evaluation

Author: Ana Brás Fábio Gonçalves Pedro Faustino

PII: S0378-7788(13)00837-2
DOI: http://dx.doi.org/doi:10.1016/j.enbuild.2013.12.022
Reference: ENB 4712

To appear in: *ENB*

Received date: 8-7-2013
Revised date: 24-10-2013
Accepted date: 12-12-2013

Please cite this article as: A.N.A. BRÁS, F.Á.B.I.O. GONÇALVES, P.E.D.R.O. FAUSTINO, Cork-based mortars for thermal bridges correction in a dwelling., *Energy and Buildings* (2013), http://dx.doi.org/10.1016/j.enbuild.2013.12.022

Cork-based mortars for thermal bridges correction in a dwelling. Thermal performance and cost evaluation

ANA BRÁS[1], FÁBIO GONÇALVES[1], PEDRO FAUSTINO[1,2]

[1] *Construction and Environment Section, ESTB – Polytechnic Institute of Setúbal, Portugal*

[2] *LEB – Designers and Consultants in Rehabilitation of Constructions, Lda., Portugal*

Corresponding author: Ana Margarida Armada Brás. Tel: +351212064660, Fax: +351 212 075 002, e-mail: ana.bras@estbarreiro.ips.pt

Abstract

The aim of the present work was to simulate the behaviour of cork-based mortars in the minimization of energy consumption and condensation effects in an existing dwelling from the 80's built in Lisbon, Portugal. Tests were carried out on hydraulic lime mortars and cement mortars with several proportions of cork as regards rheological characterization, thermal behaviour in and water vapour permeability. The first assessment of the behaviour of an existing dwelling showed that the power of heat dissipation in the dwellings' thermal bridges is of the same magnitude order than heat loss in roof and much higher than in vertical opaque envelopes or openings, which enhances the need to reduce thermal bridges in the building. The selection of the most adequate mortar was then carried out in view of several scenarios. The best solution corresponds to the correction of thermal bridges using a Hydraulic lime mortar with 70% of cork granulate (CH70). An economic evaluation was also done concerning electric energy cost and its annual growing rate in Portuguese residential buildings. The results show that the use of CH70 mortar for thermal bridge correction has a payback of 3 years when compared to the simple repair of the original external plaster.

Keywords: Cork granulates; Rendering cork-based mortars; Minimization of condensation effects; energy savings; existing dwelling thermal assessment; thermal bridges correction; global cost

1. Introduction

In the last decades, the energy consumption for heating in buildings has been reduced due to boundaries established by European regulations [1]. In Portugal this type of regulation was set in 1990, with the RCCTE (Regulation of the characteristics of thermal performance of buildings), which aimed to satisfy the thermal comfort conditions in buildings and to minimize pathological effects derived from the condensation surface [2; 3]. However, before the emergence of this regulation, there was lack of care concerning these issues, particularly with regard to correction of thermal bridges in buildings.

A thermal bridge is a building element where there is a significant change in the thermal resistance for the remaining surrounding due to the presence of materials with higher thermal conductivity and changes in thickness of vertical opaque envelope elements. Several studies show that thermal bridges are responsible for about 30% of heat losses in the winter period, increasing significantly the energy consumption for heating needs [4; 5; 6].

Other effect of thermal bridges is the cooling of the interior surfaces in these areas, resulting in higher condensations and the growth of moulds and fungi, generating a lack of air quality conditions [5; 7; 8]. This leads consequently to the production of allergens known to be associated with allergies and asthma and also other toxins and irritants that affect the respiratory health, which has a relevant impact on the occupant's health [9; 10]. Additionally, the presence of higher condensations and the growth of moulds lead to material degradation and other pathologies, increasing the need for maintenance and for more severe cases the need of rehabilitation. The prevention of this kind of problems is important, especially because there is a high number of buildings in Portugal that reveal such pathologies [7].

In order to test how each solution scenarios lead to the minimization of condensation problems in the thermal bridges, Glaser method may be used to evaluate any formation of condensation in the layers of the conjectured solutions. Condensation is defined according to the Glaser approach, which is a practical tool in building design, recommended by the DIN 4108 and EN ISO 13788 standards. Several works have focus on this subject [11].

The first one [11] describes an iterative technique for the definition of condensation across two-dimensional elements via the boundary element method (BEM). Using the Glaser approach, the vapour pressure is equalized to the vapour saturation pressure, and then the vapour equilibrium is redefined by means of the BEM solution until vapour pressure does not exceed vapour saturation pressure. This method provides an accurate identification of the condensation zone and its applicability was demonstrate by defining the condensation zone and the amount of liquid water generated on a T-shaped wall when subjected to different boundary conditions.

In [12] BEM method is applied to the curved wall models, identifying the zones where condensation occurs and quantifying the amount of liquid water generated. Previously to the application of BEM, the iterative process is first implemented and validated by applying it to the definition of condensation patterns across a hollow cylinder, for which the solution is calculated analytically.

Building rehabilitation becomes increasingly a necessity in Portugal, pushing this theme progressively towards sustainability. Currently there are good solutions targeted to the referred problems. However, these solutions require a high initial investment. The high energy consumption of buildings and the financial crisis are leading to the need of seeking solutions at an affordable cost, promoting energy rehabilitation [1; 13].

A good approach to achieve this goal could be the incorporation in traditional mortars of low-priced and thermal resistant materials, such as industrial by-products or other materials which are considered waste. Cork granulates are included in this group. Accordingly, Europe produces more than 80% of worlds cork and annually 68.000 to 85.000 tons of that production is considered waste due to granulates' small dimension or high density [14; 15; 16].

Cork is a natural, durable and renewable raw material, extracted from the oak *Quercus sober L.* which is common in Mediterranean area, with many uses as a composite material [17; 18; 19]. This material has the advantage of presenting low density due to its hollow cellular structure and high gas content, which assigns a low thermal conductivity, being thus a good material for thermal insulation [14; 17; 20; 21].

The approach of using this waste on traditional mortars might give a relevant contribution for its recycling and, furthermore, it will contribute to the decrease of initial costs, since the incorporation of cork granulates in mortars increases its yield.

2. Objectives and motivation

It was intended to develop specific rendering mortars able to be applied in thermal bridges to reduce condensation effects and heat transfer in buildings' vertical opaque envelopes. The purpose was to simulate the application of the best mortar compositions developed (from a thermal behaviour point of view) in a specific dwelling of the 1980 decade built in Lisbon, Portugal, where energy and condensation problems were assessed and observed.

In view of the previous, several hydraulic lime–cork mortars (HL5 and NHL5), for rendering application in thermal bridges, were developed and optimized. Different cork granulate dosages (from 0% to 80% in volume) were tested (as sand replacement by mass). The main challenge consists in developing a rendering mortar, with the maximum cork dosage as possible, while minimizing mortar thermal conductivity and cost changes.

Cork granulate is an industrial by-product and its use has environmental advantages. It is produced from scrap of cutting and trimming operations; some granules are subsequently used in the production of agglomerated products while others are though rejected. Hence, its cost is considerably lower compared with that of virgin cork. Thus, the aim of this work is also to transform this cork by-product into a highly value composite product.

The tests carried out on the studied mortars are listed below:

- Flow table test and rheological characterization
- Thermal conductivity
- Thermal behaviour in unsteady state
- Water vapour permeability

A comparison between the performance of referred NHL5 and HL5 – cork mortars – and a traditional cement mortar with or without cork aggregates was also made.

Afterwards, it was intended to assess the energy performance of an existing dwelling without thermal insulation. The purpose was to study how specific corrections of thermal bridges with the previous mortars lead to important energy savings and minimization of condensation effects.

Based on the original design stage of the existing dwelling, different scenarios were investigated in the thermal performance simulation in order to study how the specific corrections with the developed mortars may imply as regards energy consumption for heating. An economic evaluation was done taking into account the electric energy cost and its annual growing rate in Portuguese residential buildings. This analysis will enable to choose the best solution from a technical and economical point of view.

3. Material characteristics

For the mortars' formulation several materials were used namely: binders, a type of sand, a water reducer and a cork granulate, whose characteristics are presented herein:

- Binders: a natural hydraulic lime type NHL5, a hydraulic lime type HL5 and cement type CEM II B-L 32,5 N produced in Portugal by Secil with the characteristics presented in Tables 1 and 2.
- Sand: siliceous sand with grain size 0/1 (Figure 1).
- High range water reducer: modified polycarboxylates (PCE) (Table 3).
- Cork granulates: with grain size 0.5/2, supplied by Fabricor-Indústria, Preparação e Transformação de Cortiça, SA (Figure 1 and Table 4).

Table 1: Chemical and physical characteristics of NHL5 and HL5 provided by the manufacturer.

	NHL5	HL5	Standard
Physical Characteristics	Value	Value	
Density (g/cm^3)	2.7	2.8	
Fineness %	90 mm 15.0% 200mm 5.0%	90 mm 15.0% 200mm 5.0%	EN 459-1
Blaine (cm^2/g)	5780	5780	
Expandability alternative method (mm)	≤20	≤2.0	EN 459-1
Free Water (%)	≤2.0	≤2.0	EN 459-1
Air content (%)	≤5.0	≤5.0	EN 459-1
Setting time (h)	Start >1.0 End ≤15.0	Start >1.0 End ≤15.0	EN 459-1 EN 459-1
Mechanical Characteristics			
Mechanical Compressive strength at 7 days (MPa)	≥ 2.0	≥ 2.0	EN 459-1
Mechanical Compressive strength at 28 days (MPa)	≥ 5.0 and ≤15.00	≥ 5.0	EN 459-1
Chemical Characteristics			
Sulphates (SO_3) (%)	≤2.0	≤3.0	EN 459-1
Free Lime ($Ca(OH)_2$)(%)	≥ 15.00	≥ 4.00	EN 459-1

Table 2: Chemical and physical characteristics of CEM II B-L 32,5 N provided by the manufacturer.

Characteristics	CEM II/B-L 32,5N
Density (kg/m3)	3000

Blaine (cm²/g)		4520
Setting time (min)	start	128
	end	164
Expansibility (mm)		0.5
7 Days	Flexural strength (MPa)	5.80
	Compression strength (MPa)	31.10
28 Days	Flexural strength (MPa)	7.30
	Compression strength (MPa)	40.10
LOI (%)		13.60
Insoluble residue (%)		1.60
SiO_2 (%)		14.44
Al_2O_3 (%)		3.37
Fe_2O_3 (%)		2.50
CaO (%)		61.27
MgO (%)		0.96
Chloride content (%)		0.04
SO_3 (%)		2.35
Free lime (%)		0.91

Table 3: Technical and physical data provided by the manufacturer for the High Range Water Reducer (HRWR).

Technical data	
Form	Aqueous solution of modified polycarboxylate
Density (kg/dm³)	1.07 ± 0.02
pH-value	5.5 ± 1.0
Chloride content (%)	≤0.1
Solid content (%)	26.5 ± 1.3

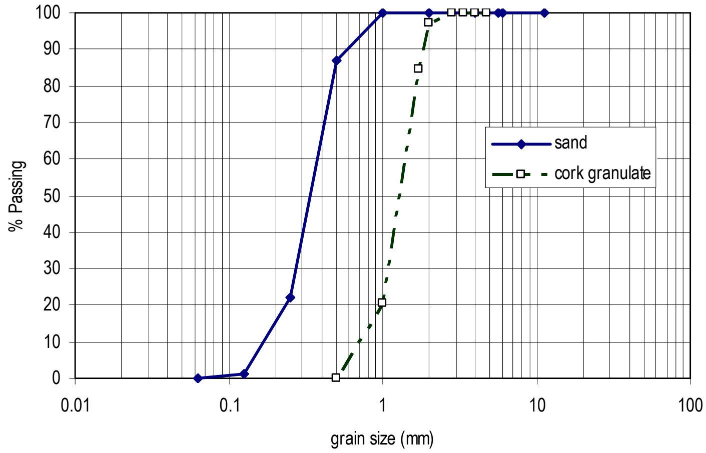


Figure 1: Grain size distribution for sand and cork aggregate type used in the cement based mortar.

Table 4: Loose bulk density of sand and cork granulates used in mortars preparation.

Loose bulk density(kg/m³)	Sand	Cork granulate

	1590.0	112.4

Several mortars were developed and tested. Those compositions are presented in the following tables (Table 5-7) (where w/b – water/binder ratio).

Table 5: Mortar compositions with HL5 – cork.

HL5-cork mortars	Identification	Percentage replacement (%)
CH=0% HRWR=1% w/b=0,6	CRef-HL5	0
CH=10% HRWR=1% w/b=0,6	CH10	10
CH=20% HRWR=1% w/b=0,6	CH20	20
CH=20% HRWR=2% w/b=0,6	CH20*	20
CH=40% HRWR=2% w/b=0,6	CH40	40
CH=50% HRWR=2% w/b=0,6	CH50	50
CH=50% HRWR=2% w/b=0,7	CH50*	50
CH=70% HRWR=2% w/b=0,7	CH70	70
CH=80% HRWR=2% w/b=0,7	CH80	80

Table 6: Mortar compositions with NHL5 – cork.

NHL5-cork mortars	Identification	Percentage replacement (%)
CNH=0% HRWR=1% w/b=0,6	CRef-NL5	0
CNH=10% HRWR=1% w/b=0,6	CNH10	10
CNH=20% HRWR=2% w/b=0,6	CNH20*	20
CNH=40% HRWR=2% w/b=0,6	CNH40	40
CNH=50% HRWR=2% w/b=0,7	CNH50*	50
CNH=70% HRWR=2% w/b=0,7	CNH70	70

Table 7: Mortar compositions with CEM II/B-L 32,5N – cork.

Cement-cork mortars	Identification	Percentage replacement (%)
CB HRWR= 0,3% w/b=0,6	CRef-CEM II	0
CC=10% HRWR= 0,3% w/b=0,6	CC10	10
CC=20% HRWR= 0,3% w/b=0,6	CC20	20
CC=40% HRWR= 0,3% w/b=0,6	CC40	40
CC=40% HRWR= 1% w/b=0,6	CC40*	40
CC=50% HRWR= 1% w/b=0,6	CC50	50
CC=50% HRWR= 2% w/b=0,6	CC50*	50
CC=70% HRWR= 2% w/b=0,6	CC70	70
CC=70% HRWR= 2% w/b=0,7	CC70*	70
CC=70% HRWR= 3% w/b=0,7	CC70**	70
CC=80% HRWR= 2% w/b=0,7	CC80	80
CC=80% HRWR= 2% w/b=0,75	CC80*	80

4. Experimental program

4.1. Flow table test

The flow table test is used to determine the “workability” of fresh mortar and in the present study the measurements were done following the description in ASTM C230. The spread was measured for all mortar compositions, for different resting times (Figures 2 - 4).

The consistence considered adequate for rendering mortars is, according to EN 1015-3:1999, 175 mm ± 10 mm, used as target in terms of water and HRWR quantity for each mortar. It was considered to correspond to workable rendering mortars. Based on this target value, some adjustments were adopted in selected mortar composition in terms of water/binder (w/b) ratio and/or HRWR percentage, as it can be seen at tables 5 to 7.

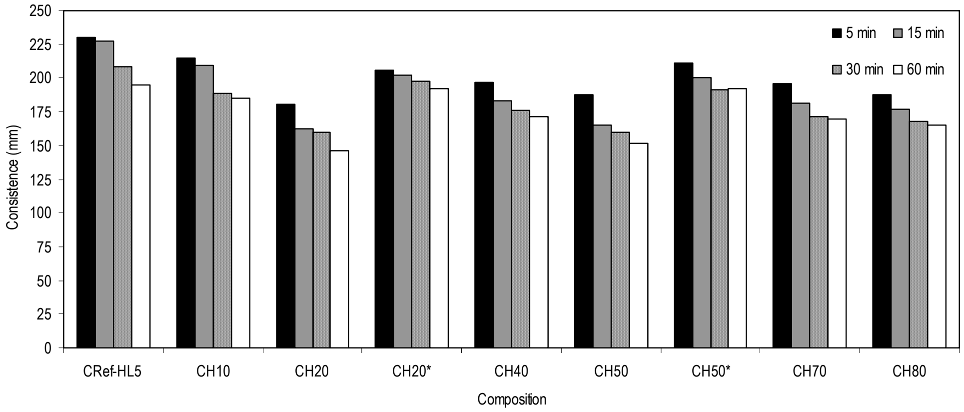


Figure 2: Consistency values obtained for the reference mortar (CRef-HL5) and for the mortars with cork granulate (CH) (from 10% to 80%). The results are presented for 5, 15, 30 and 60 minutes of resting time (after mortar preparation).

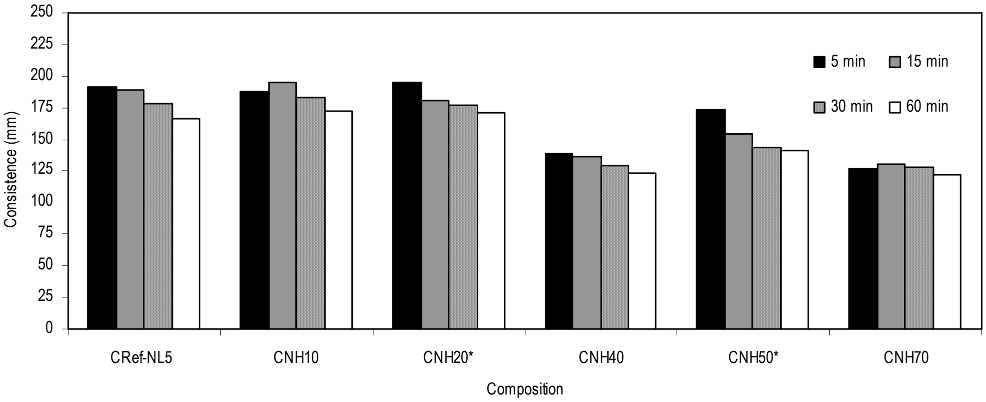


Figure 3: Consistency values obtained for the reference mortar (CRef-NHL5) and for the mortars with cork granulate (CNH) (from 10% to 80%). The results are presented for 5, 15, 30 and 60 minutes of resting time (after mortar preparation).

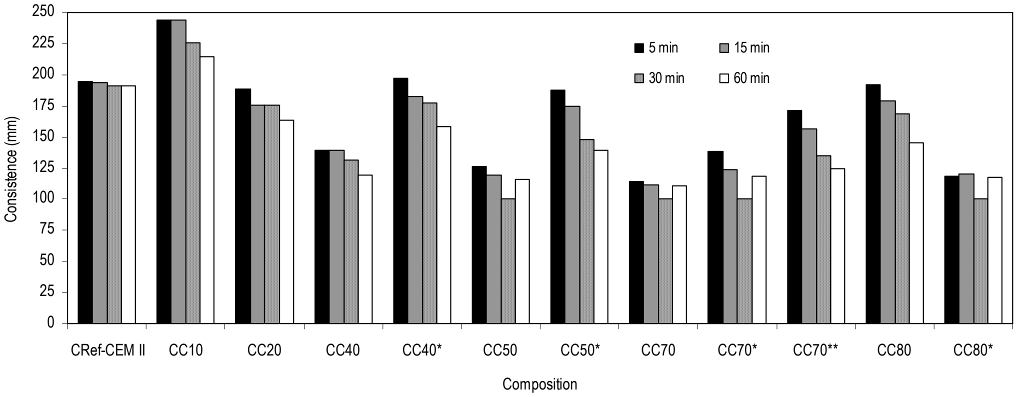


Figure 4: Consistency values obtained for the reference mortar (CRef-CEM II) and for the mortars with cork granulate (CC) (from 10% to 80%). The results are presented for 5, 15, 30 and 60 minutes of resting time (after mortar preparation).

The previous results show that HL5 mortars present less workability decrease than NHL5 or cement based mortars. Besides that, the workability decrease observed with an increasing cork dosage occurs due to the reduction on binder paste as long as cork amount is increasing. The higher water absorption capacity of cork granulates compared to the sand leads to a higher w/b demand with the increasing cork dosage in mortar composition. In order to minimize w/b ratio maintaining appropriate consistency, more HRWR was used. In order to minimize w/b ratio maintaining appropriate consistency, the HRWR was used in dosages up to 2 and 3%, since higher binder dosages may compromise the mortars due to segregation problems. In some cases, to get enhanced consistency and despite the higher use of HRWR, the w/b ratio was also increased.

According to Figure 2, it is possible to get good performance up to 80% of cork in HL5 based mortars. Figure 4 also shows the same trend, where 80% of cork volume can be incorporated in cement based mortars (CC80) if HRWR is well dosed (until 3% by cement mass). However, Figure 3 shows that 50% of cork in a NHL5 mortar is able to produce a good mixture from a fresh state point of view.

The consistency behaviour of HL5, NHL5 and cement based mortars for a resting time of 5 minutes and 30 minutes is presented in Figure 5 as a function of cork dosage.

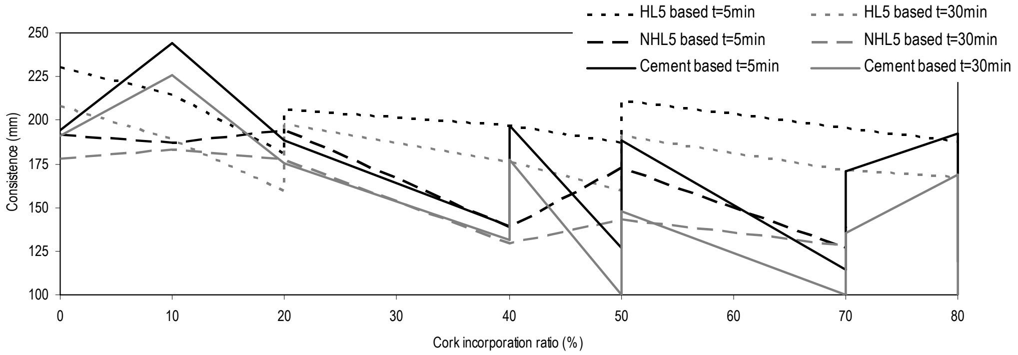


Figure 5: Consistency values for cork dosage (from 0% to 80%) to HL5, NHL5 and cement based mortars for a resting time of 5 min and 30 min after mix preparation.

The previous results show that HL5 based mortars present higher potential to incorporate higher cork percentages when compared to cement or NHL5.

Until 20% of cork dosage, all mortars present good workability even after 30 minutes of mix preparation. Between 20% and 70% of cork dosage, cement and NHL5 based mortars present similar behaviour if the same HRWR percentage is adopted. For cork incorporation higher then 70% only NHL5 mortar compositions are not able to be produced since its workability is significantly reduced.

4.2. Thermal conductivity

Thermal conductivity of the mortars was evaluated with a portable Isomet equipment (ISOMET – Heat Transfer Analyzer (model 2104) from Applled Precision) with a circular contact probe (0-2 W/(m.K) range) in laboratory environment with 23ºC and 55% RH. The probe is 6 cm diameter; and the dimension of all used specimens was 160x40x40 mm^3 (Figure 6).

Figure 6: Test Method for thermal conductivity

Heat flow through an object follows the model in eq. (1), where q is the heat flux (W), A is the area perpendicular to the heat flow (m^2), λ is the thermal conductivity of the section (W/mK), Δ t is the temperature drop across the object (K) and L is the thickness of the object (m). If the test is running with a constant energy input, then eq. (1) can be used.

$$q = \lambda A \frac{\Delta t}{L} \qquad (1)$$

The thermal conductivity (λ) measurements for all the designed mortar mixes with cork granulate are presented in Figure 7.

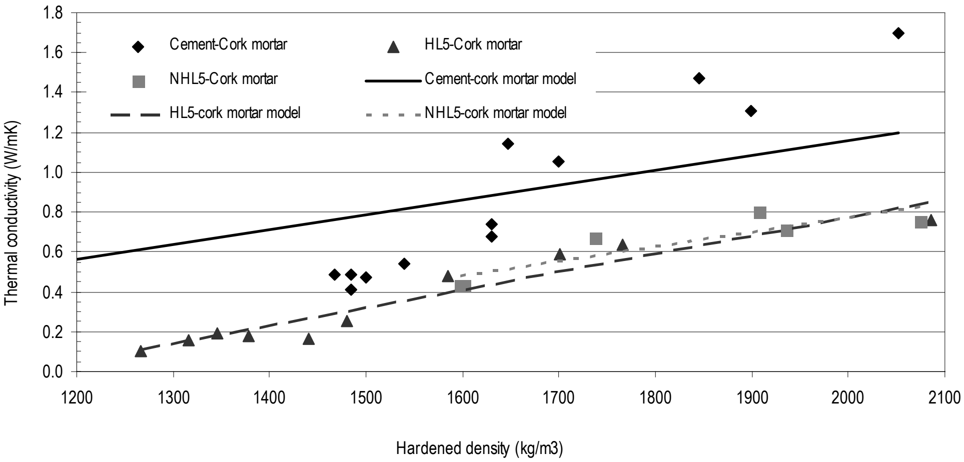


Figure 7: Relationship between the hardened density of mortars with cork incorporation (from 0% to 80%) and their thermal conductivity at 28d (for HL5, NHL5 and cement based).

For the mortars with cork granulate, an increasing cork dosage (which is related to a decreasing hardened density) leads to a linear decrease of thermal conductivity.

Cork granulate can decrease the conductivity of conventional cement mortar in 75%. In HL5 based mortars the incorporation of cork can reduce thermal conductivity to 20% of the original value (CRef-HL5) while in NHL5 based mortars, since it s only possible to incorporate cork until 70%, the conductibility is reduced until 50% of the reference value (CRef-NHL5).

Generally, the best performance results, from a thermal properties point of view, are those obtained by HL5 based mortars, where conductivity values are easily bellow 0.20 W/m.K.

4.3. Thermal behaviour in unsteady state

Based on the previous results of workability and thermal conductivity, five different mortars were selected due to their best performance: CRef-HL5, CRef-CEMII, CC70, CH50 and CH70.

The unsteady behaviour of mortars was tested using an innovative experimental procedure (Figure 8).

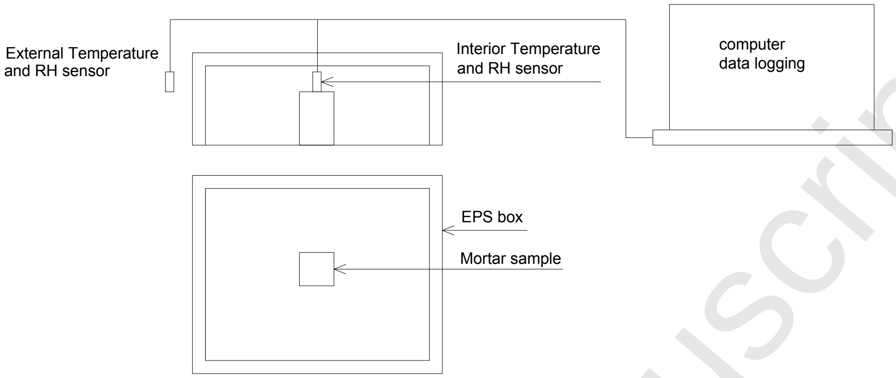


Figure 8: Test Method for unsteady state thermal behaviour

In order to understand the mortars´ behaviour in terms of unsteady state, a transient heat flow rate was imposed at all the surfaces of a prismatic mortar using preheating in a climatic chamber at (35±2) ºC. Before running any test, the specimens were conditioned in the mentioned climatic chamber, in a controlled environment with a set-point temperature of 35±2 ºC and 50±5 % RH, until constant mass was reached.

The tests were carried out in a controlled laboratory environment at 18ºC. After conditioned at 35ºC, each tested mortar was placed inside a box (EPS box with 20x20x15cm) in order to avoid the influence of the instantaneous external environmental conditions in the test. Inside each box a temperature and RH sensor was placed through the use of a probe at the surface, enabling monitoring hygrothermal variation each 5 minutes. During the test, the temperature of the mortar starts to decrease with time. For each mortar composition tested (CRef-HL5, CRef-CEMII, CC70, CH50 and CH70) three samples were tested, to check dispersion and have more reliable data, during 2 hours and data was recorded at the surface of each sample until mortar temperature reached laboratory temperature.

Measurements of temperature variation with time (as function of the mass of each tested mortar) were calculated. The purpose was to detect the behaviour of each mortar when subjected to thermal variations that simulate what happens in summer conditions (18 ºC - 35 ºC). Results are presented as temperature variation, taking into account the weight of each tested mortars.

The unsteady behaviour of CRef-HL5, CRef-CEMII, CC70, CH50 and CH70 mortars was tested using this experimental procedure and the results are presented in Figures 9 and 10. Figure 9 presents the temperature variation per kg of mortar against time for those mortars. Figure 10 presents the non-dimensional temperature variation values (taking as reference the CRef-CEM II mortar) for CRef-HL5, CRef-CEMII, CC70, CH50 and CH70.

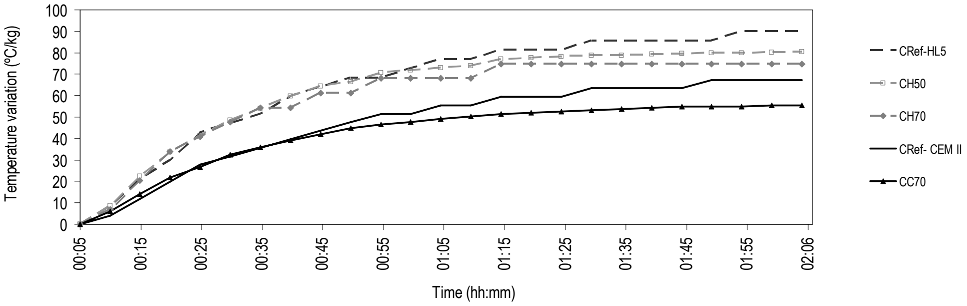


Figure 9: Temperature variation per kg of mortar against time for CRef-HL5, CRef-CEMII, CC70, CH50 and CH70.

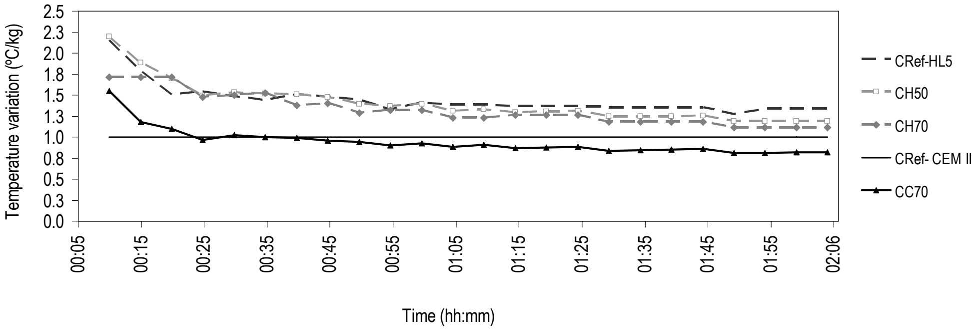


Figure 10: Normalized mortars temperature variation against time for CRef-HL5, CRef-CEM II, CC70, CH50 and CH70, taking as a reference the CRef-CEM II.

The previous mortars were subjected to thermal variations that simulate what happens in summer conditions (18ºC-35ºC). For the same initial temperature conditions, Figure 9 shows that the incorporation of cork in mortars composition leads to a reduction of temperature variation, when compared to the reference mortar (CEMII or HL5). Probably, it means that cork mortars enable the retention of heat when compared to reference mortars, such as CRef-HL5 or CRef-CEMII.

CC70 mortar is the one that tends to present less temperature variation, meaning that at the unsteady state, mortars with cork promote the reduction of heat transfer through the system, which is probably related to a higher thermal delay. In fact, [22] shows that the heat transfer through a system incorporating natural cork exhibits higher thermal delay than the extruded polystyrene (XPS), which proves the relevance of this study.

Figure 10 shows de thermal variation of each tested mortar when compared to the CRef-CEM II mortar. It is shown that a mortar with HL5 probably presents less thermal delay than the one promoted by cement. Figure 10 also evidences the influence of cork in mortars. A normalized value less than one corresponds to less thermal variation with time when compared to a reference cement mortar. Thus, it means that the thermal delay promoted by CH50 and CH70 mortars can not achieve the one promoted by CC70 mortars.

4.4. Water vapour permeability

The water vapour permeability of the hardened mortars was performed in accordance with European Norm EN 1015-19 (1998). For each type of mortar 3 specimens were used, consisting on a mortar disk 10 mm thick previously subjected to a curing period of 28 days. Each disk was attached to a metal capsule (set). The capsule contains water in its interior and 1 cm of air between the specimen and the water in order to create a high humid environment inside the capsule. Then the sets were placed in a climatic chamber with a temperature of 20±5 ºC and 50±5 % RH. Results are presented in Figure 11. A comparison with air is made by determining the thickness of diffusion air layer equivalent (Sd) to 10 mm of mortar.

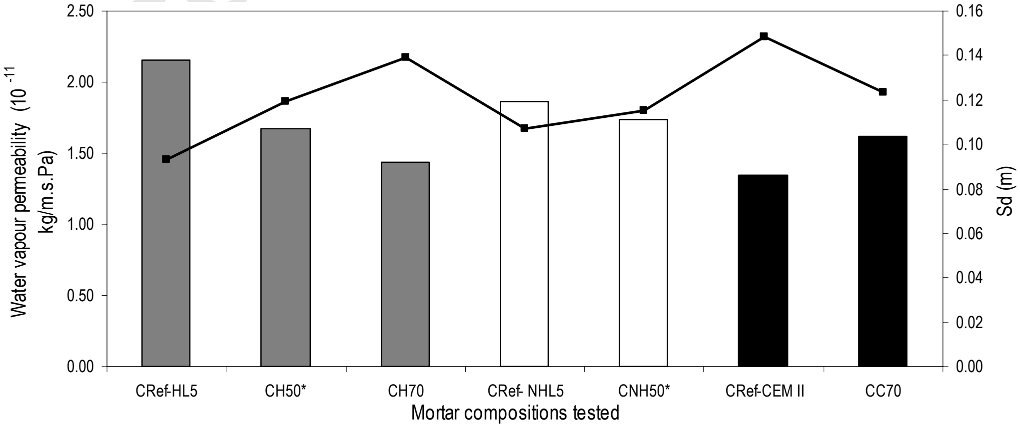


Figure 11: Water vapour permeability (bars) and thickness of diffusion air layer equivalent (black line) for CRef-HL5, CH50, CH70, CRef-NHL5, CNH50*, CRef-CEM II and CC70.

Cement based mortars are less permeable to water vapour than the reference mortar made of HL5 or NHL5. For water vapour, a reduced permeability is a negative factor in a mortar, since it does not allow a proper drying of the water that penetrates in it and impairs the elimination of water vapour that occurs within buildings.

The incorporation of cork granulates in HL5 based mortars leads to a decrease of permeability (it decreases 22% if 50% of cork is introduced and 33% in the case of CH70). The effect of cork in water vapour permeability of NHL5 based mortars is not so significant, where for CNH50* the decrease is only of 7% when compared to CRef-NHL5.

Nevertheless, those values are higher than the ones presented by CRef-CEM II, where the incorporation of 70% of cork leads to an increase of water vapour permeability in 20%, with benefits for a rendering mortar.

According to EN 998-1, a mortar to be used with thermal behaviour should present a water vapour permeability higher than 1.29×10^{-11} kg/m.s.Pa. Based on this, it can be considered that all tested mortars herein presented have sufficient permeability to perform well as a rendering mortar.

4.5. Flexural and compressive strength

Together with the previous tests, mortar strength determination was made. In order to determine mechanical characteristics of the formulated mortar, a testing campaign was undertaken and all 3 specimens of each mortar composition were submitted to flexural and compressive strength tests following standard EN 1015-11. These tests were performed at 28 days and the results are presented in Table 8.

Table 8: Flexural and compressive strength of the tested hardened mortars at 28 days.

Identification	Flexural strength (MPa)	Compressive strength (MPa)
CRef-HL5	1.14	2.99
CH50	0.45	0.70
CH50*	0.29	0.36
CH70	0.28	0.42
CRef-NL5	1.54	3.23
CNH50*	0.55	1.04
CRef-CEM II	5.2	24.4
CC70**	1.8	4.5
CC70	2.5	6.4

5. Analysis

5.1. Mortar analysis and selection of the best compositions for thermal rehabilitation

It was intended to study the performance of the previous mortars when applied in the corrections of thermal bridges of an existing dwelling built in the 80’s (Figure 12). Thus, in order to select the best mortar compositions it was take into account the requirements of rendering mortars defined in NP EN 998-1: Specification for mortar for masonry. Part 1: Rendering and plastering mortar (Table 9).

Table 9: Requirements of rendering mortars with thermal behaviour according to NP EN 998-1.

Compressive strenght (MPa)	Water absorption coefficient due to capillary action (kg/m².min$^{0.5}$)	Water vapour permeability (kg/m.s.Pa)	Thermal conductivity (W/m.ºC)
≥ 0,4	≤ 0,40	$\geq 1{,}29\times10^{-11}$	≤ 0,20

Mortar mixes CRef-HL5, CH50, CH70, CRef-NHL5, CNH50*, CRef-CEM II and CC70 present compressive strength values higher than 0.4 MPa. In fact, HL5 based mortars and cement based mortars are the ones that fulfil the water absorption coefficient due to capillary action requirement. None of the NHL5 based mortars fulfil the national requirements concerning water absorption coefficient due to capillary action, which enhances the need to develop this specific property.

Based on the previous results concerning fresh and hardened state (see Point 4), it was decided to simulate what was the contribution of each mortar in the minimization of condensation effects in an existing dwelling with these problems. Based on limited financial resources for the rehabilitation works, the goal was the outside removal of rendering mortars from the thermal bridges and the replacement with new optimized mortars.

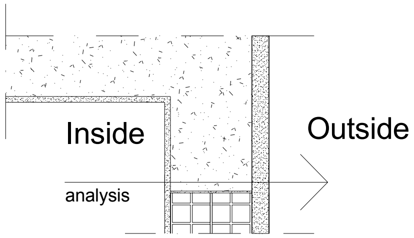


Figure 12: Detail of the thermal bridge zone.

5.2. Assessment of the energy performance of an existing dwelling – original situation

The previous mortars where developed with the intention to be applied in the correction of thermal bridges of an existing dwelling from the 80's built in Lisbon, Portugal. The original building is compact with two floors above ground level and the exterior vertical opaque envelope of the dwelling was made of a single brick wall without thermal insulation inside, with an external plaster similar to CRef-CEM II mortar.

This construction technique for the building envelops has proved to be the cause of great thermal loss and condensation. Figure 13 presents the plant of the first floor of the analysed typology. Figure 14 presents the condensation effects in the first floor of the dwelling and Figure 15 shows one detail of the single brick wall and the thermal bridge near the terrace.

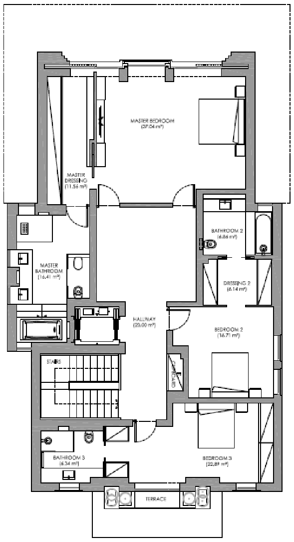


Figure 13: Example of the first floor of the dwelling (adapted from [23]).

Figure 14: Example of the condensation effects at the first floor of the dwelling.

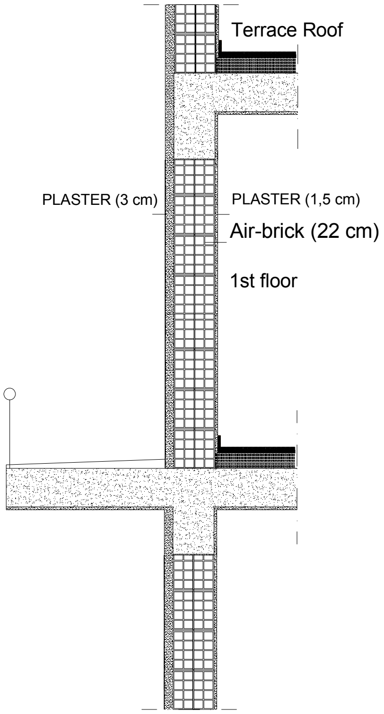


Figure 15: Detail of the single brick wall and the thermal bridge near the terrace.

The main structural details of the dwelling that were used for simulation studies are summarized in Table 10. Vertical opaque envelopes and support frames represent more than 30% of the total construction area (Table 11), which underlies a detailed analysis concerning energy evaluation of building vertical opaque envelopes.

Table 10: Structural details of the dwelling.

Structural element	Characteristics	Thermal characteristics
Support frame	Reinforced concrete (RC)	Without thermal insulation in RC wall
Envelope	Brick walls	No thermal insulation
Terrace Roof	Reinforced concrete (RC)	No thermal insulation
Openings	Extruded aluminium system with double glazing	Extruded aluminium system: double glazing 6 (16) 6
Floor on ground	Reinforced concrete (RC)	No thermal insulation

Table 11: Area of each structural element of the dwelling.

Structural element	Areas (m^2)
Envelope	212
Terrace Roof	177
Openings	178
Usable area (m^2)	512

The analysis of the specific energy consumption for heating of the dwelling was carried out according to the Portuguese Legislation [2]. For residential buildings with an area not greater than 1000 m^2 the DL 80/2006 (RCCTE) is applied. This regulation is applied to the new, rented or refurbished residential buildings, stipulating a maximum consumption of heating energy in winter (Ni), cooling energy in summer (Nv), energy for heating sanitary waters (Na) and primary energy, as a conversion of the last three parameters in kgoe (Nt). This methodology is based in the EN ISO 13790 and its summarized description could be found in [24].

This analysis aims at:

- ✓ Correlating particular structural and engineering situations to the high/ low consumptions of the building;
- ✓ Identifying possible improvements to energy management.

The following figure (Figure 16) presents the heat losses for the dwelling in the winter season.

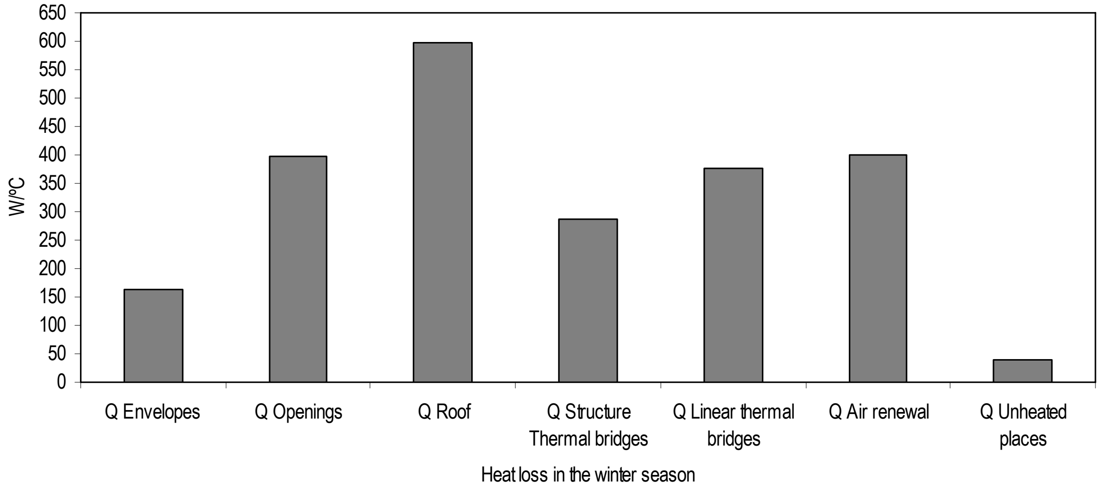


Figure16: Heat losses in the dwelling – original condition (winter season).

Legend:
Envelopes – external walls
Structure thermal bridges – plane components of the thermal bridges, that takes into account the U-value (W/m^2K) of the constructive solution
Linear thermal bridges – takes into account the extra heat losses along a unit length of a thermal bridge, at a unit temperature difference and in a unit time. It is measured in W/mK, where the length of the edge takes an important role (corner, joint, column, window perimeter).

In the heating phase (Figure 16), it is shown that the power of heat dissipation (Q) in the dwellings' thermal bridges (where the sum of heat loss is equal to 660 W/ºC) is of the same magnitude order than the heat loss in the roof and much higher than in vertical opaque envelopes or openings. This situation is partially responsible for the condensation phenomenon found inside the building (Figure 14), namely in thermal bridges, where the indoor RH was equal to 80% and the indoor temperature during the winter season was only of 16ºC, even if heating devices where used inside.

The previous evidences and the fact that it was intended to optimize financial resources for the thermal building rehabilitation, lead to the analysis of different scenarios in order to look into what possible building changes on field may imply as regards energy consumption (for heating and cooling).

5.3. Assessment of the energy performance of an existing dwelling – thermal bridges correction

It was intended to study how specific corrections of the thermal bridges with the previous developed mortars lead to important energy savings and minimization of condensation effects.

The scenarios tested (Table 12) correspond to the removal of rendering mortars from the thermal bridges and the replacement with new optimized mortars (Cref-HL5, CH50, CH70, CNH50* and CC70 – scenarios 1 to 5). Scenario 6 corresponds to the removal of the external plaster (made of a mortar type Cref-CEM II) and replacement by CH70.

Table 12: Thermal analysis scenarios adopted for the dwelling.

Scenario	Situation
0	Original situation (Cref-CEM II): repair of the existing external plaster
1	Thermal bridge correction: Cref-HL5
2	Thermal bridge correction: CH50*
3	Thermal bridge correction: CH70

4	Thermal bridge correction: CNH50*
5	Thermal bridge correction: CC70
6	New external plaster in all area of the vertical envelops: CH70

The results of the simulation concerning the energy consumption variation for heating (kWh/m^2.year) when different scenarios were tested in the existing dwelling are presented in Figure 17.

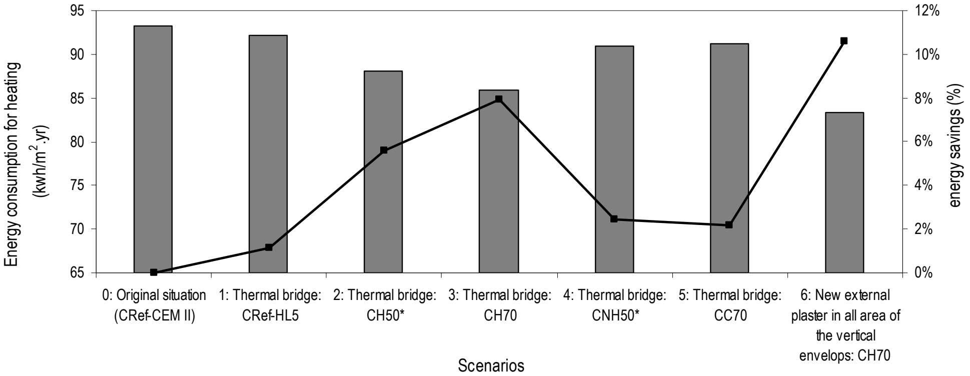


Figure17: Energy consumption for heating (bars) for the 6 scenarios tested for the building thermal improvement.

It is shown that scenario 3 leads to the best solution – correction of thermal bridge by using a Hydraulic lime mortar with 70% of cork granulate (CH70). When compared to the original situation, scenario 3 leads to an energy saving of 8%, which is much higher than the savings promoted by scenario 4 or 5. Scenario 6, which corresponds to the replacement of all original external plaster by CH70, means only 11% of energy savings for such an expensive intervention, which enhances the importance of the correction of thermal bridges.

In order to test how each one of the previous scenarios lead to the minimization of condensation problems in the thermal bridges, a preliminary thermo-hygrometric assessment was carried out according to the Glaser method (based on ISO 13788), to evaluate any formation of condensation in the layers of the conjectured solutions (Figure 17). This analysis was made using the average hygro-thermal conditions inside the building (RH=80% and T=16ºC).

ISO 13788 describes calculation methods to avoid the occurrence of eventual moulds or problems due to condensation and to determine the interstitial condensation because of water vapour diffusion. The following main problems of the building physics are dealt with:

1. The internal surface temperature of a building component below which a mould can take place.
2. The interstitial condensation due to the water vapour diffusion by comparing the condensation rate in winter to the evaporation rate in summer.

The method establishes the annual moisture balance and calculates the maximum amount of the accumulated moisture due to the interstitial condensation. However, since it was not possible to obtain the annual data of accumulated moisture, the calculation was made using the RH and Temperature average values from January, a month where condensation problems were found in the building.

Equation 2 was adopted to calculate the temperature in each material transition zone (internal surface temperatures) from the thermal bridge (T_{zone_i} (ºC)), knowing the U-value, the average temperature inside the building (Ti (ºC)), the average temperature outside (Te (ºC)) and the thermal resistance of all materials from the thermal bridge (R_{zone_i} (m^2 ºC/W)).
Equation 3 enables the calculation of the saturated vapour pressure $Psat_{zone\_i}$ (Pa) for each zone in the thermal bridge.

The analysis is based on the calculation using eq. 2 and 3 starting from the inside to the outside of the building. Table 13 presents the results for the scenarios 0 to 5.

$$U \cdot (T_i - T_e) = \left(T_i - T_{zone\_i}\right) \cdot \frac{1}{\sum_{i=o}^{n} R_{zone\_i}} \quad (2)$$

$$Psat_{zone\_i} = 610.5e^{\frac{17.26T_{zone\_i}}{237.7+T_{zone\_i}}} \tag{3}$$

Table 13: Results for the internal surface temperature and saturated vapour pressure for the thermal bridge when its correction is according to scenarios 0 to 5 (based on ISO 13788).

Scenarios		Constructive solution at the thermal bridge (see Figure 12)	T_{zone_i} (ºC) (eq. 2)	Saturation Pressure $Psat_{zone\_i}$ (Pa) (eq.3)	SUM Sd (m)	Vapour Pressure (Pa)
Inside			16.0			
	CRef-CEM II (scenario 0)	Surface of the internal plaster	12.2	1418.8	0.0	1451.3
		Internal plaster	11.9	1394.7	0.2	
		Concrete structure	8.7	1123.9	7.2	
		External mortar	8.2	1085.0	7.6	950.5
Outside			7.0			
Inside			16.0			
	CRef-HL5 (scenario 1)	Surface of the internal plaster	12.4	1442.6	0.0	1451.3
		Internal plaster	12.2	1419.9	0.2	
		Concrete structure	9.2	1161.4	7.2	
		External mortar	8.1	1079.3	7.5	950.5
Outside			7.0			
Inside			16.0			
	CH50* (scenario 2)	Surface of the internal plaster	13.4	1541.0	0.0	1451.3
		Internal plaster	13.3	1523.7	0.2	
		Concrete structure	11.1	1321.5	7.2	
		External mortar	7.8	1056.7	7.6	950.5
Outside			7.0			
Inside			16.0			
	CH70 (scenario 3)	Surface of the internal plaster	14.0	1594.6	0.0	1451.3
		Internal plaster	13.8	1580.4	0.2	
		Concrete structure	12.1	1412.4	7.2	
		External mortar	7.6	1045.1	7.6	950.5
Outside			7.0			
Inside			16.0			
	CNH50* (scenario 4)	Surface of the internal plaster	12.7	1471.6	0.0	1451.3
		Internal plaster	12.5	1450.3	0.2	
		Concrete structure	9.8	1207.5	7.2	
		External mortar	8.0	1072.5	7.5	950.5
Outside			7.0			
Inside			16.0			
	CC70 (scenario 5)	Surface of the internal plaster	12.7	1464.924456	0.0	1451.3
		Internal plaster	12.4	1443.349106	0.2	
		Concrete structure	9.6	1196.87242	7.2	
		External mortar	8.0	1074.01166	7.6	950.5
Outside			7.0			

After the calculation, a cross-section of the building element is drawn with the thickness of each layer equivalent to its water vapour diffusion-equivalent to the air layer thickness Sd. Figure 18 presents the results for the thermal bridge studied for the 6 different scenarios tested. Straight lines are drawn joining the saturation vapour pressures at each interface between materials. Together with the previous line, a vapour pressure line is also drawn (Real P line). If Real P line values are equal or higher than saturated vapour pressure (Sat P), interstitial condensation at one or more than one interface may occur.

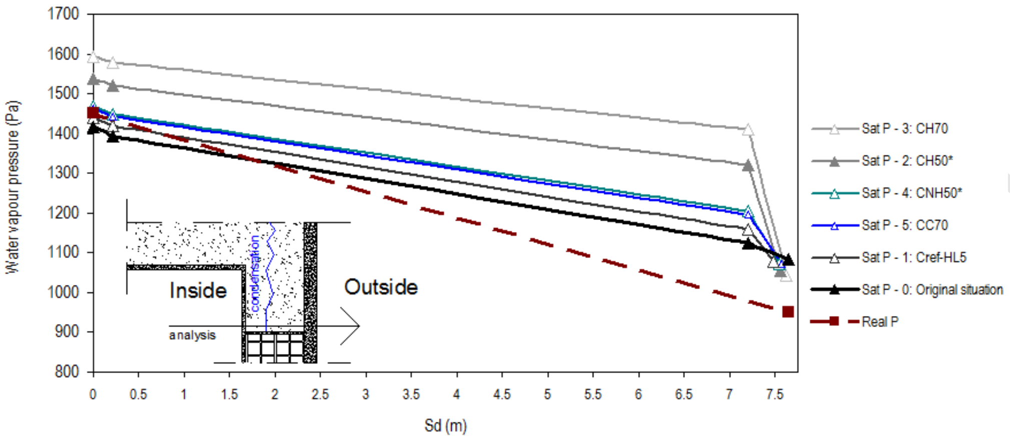


Figure 18: Glaser diagram for the thermal bridge studied for the 6 different scenarios tested.

As a result of this analysis, for the average hygro-thermal values used in this calculation, it is shown that the original situation leads to condensation phenomenon. Scenario 1 was rejected since interstitial condensation was found at the supported frame interface (Figure 18). Scenario 4 and 5 (CNH50* and CC70) correspond to the minimum conditions in order to avoid condensation at the surface of the thermal bridge (at least using the same thickness of plaster materials as in the original situation).
The comparison between the ''as built'' condition (scenario 0) and the five alternative solutions hypothesized shows that it is preferable to place the CH70 based mortar on the outside surface of the thermal bridge (scenario 3). Thus, it seems that the use of HL5 based mortars with incorporation of cork granulate dosages are an effective choice (scenarios 2 and 3).

6. Economic evaluation of the case study – scenarios analysis concerning thermal performance

Increasing energy efficiency in buildings implies lower spending by consumers in the annual energy bill. However, the effectiveness of the economic benefit only occurs when the initial investment cost is exceeded by the cost that results by the accumulated energy consumption for buildings' heating or cooling.

Taking into account the previous tested scenarios, an economic evaluation was made concerning the electric energy cost and its annual growing rate in Portuguese residential buildings. This analysis will enable to choose the best solution from a technical and economical point of view, taking into account the initial investment costs, the maintenance and energy costs for heating (operational cost). Based on this, it was admitted the following expression for the global cost:

$$C_{g,n} = C_0 + C_{man,n} + C_{\exp,n} \qquad (4)$$

Where: Cg,n – Global cost in the year n (in €/m²); C_0 – Initial cost in €/m²; $C_{man,n}$ – Maintenance cost (in €/m²); $C_{exp,n}$ – Operational cost in €/m².

The initial cost was estimated using the construction materials prices data and the necessary manpower to remove the existing external plaster by a new optimized mortar, using the original thickness (Table 14).

Table 14: Initial cost of an intervention on field concerning the best analysed scenarios.

Scenario	Situation	Initial cost (€/(m².cm))
0	Original situation (CRef-CEM II): repair of the existing external plaster	27.1
2	Thermal bridge: CH50*	37.1

3	Thermal bridge: CH70	37.3
4	Thermal bridge: CNH50*	37.1
5	Thermal bridge: CC70	37.3

The maintenance cost adopted took into account the necessary cleaning work, small repair operations and application of a new wall painting each 7 years (C_{man} = 5.8 €). Since these prices are a function of the inflation rate, the prediction of maintenance cost is a function of that.

The methodology adopted for the determination of the energy costs for heating (operational cost) is based on the Portuguese legislation [2] that concerns the heat loss in the heating season:

$$Q_{ext} = 0.024 \times U \times A \times GD \qquad (5)$$

Where:
Q_{ext} = heat loss in the thermal bridge (kWh); U= is the U-value (Wm²ºC); A= thermal bridge area (m²) and GD = degree day (ºC.days)

In the Portuguese households the current main source of energy is electricity, representing about 42.6% of the total energy consumption [25]. Firewood is the second main source of energy, representing about 24.2% of the energy used in Portuguese households. The continuous growing of electricity consumption in Portuguese residential buildings leads to a major role of this energy source in the domestic sector, which is directly related with the increasing use of equipments using this type of energy but also with the use of electricity for heating. That can explain why electricity registered the greatest consumption evolution when compared with all other energy sources [1; 26].

According to a survey on energy consumption made in Portugal [25], almost 80% of residential buildings in Portugal use electrical heater in the heating period and the electricity cost rate increases 4% / year. Thus, the operational cost should be a function not only of the electricity cost (0.17€ / kWh (according to EDP - electrical company, taking into account taxes), but also of the electricity cost rate.

Accordingly, the global cost should assume the following equation:

$$C_{gx} = C_0 + \sum_{x=1}^{n} (C_{manx}(1+\alpha)^x + U \times GD \times 0.024 \times C_{ex} \times (1+\alpha')^x) \times (1+i)^x \qquad (6)$$

Where: α = inflation rate (2.77% in 2013); α' = electricity cost rate per year (4%); *i* = Discount rate (for this private investment, it was used the Euribor rate at 365 days =1.335%).

For this specific dwelling located in Lisbon, from technical point of view scenarios 2, 3, 4 and 5 are the ones able to be applied in thermal bridges corrections without leading to condensation phenomenon. Thus, the prediction of the global cost was made taking into account the previous data (Figure 19).

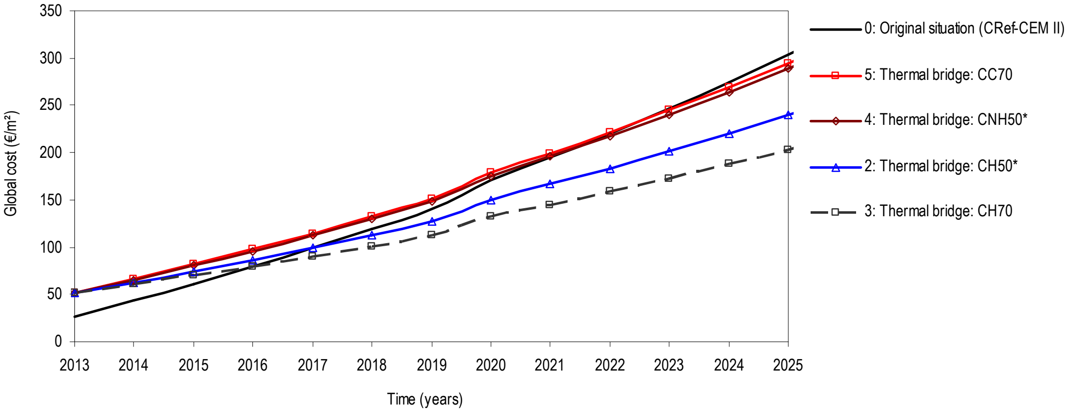


Figure 19: Prediction of the global cost evolution using specific mortar (scenarios 0, 2, 3, 4 and 5) for thermal bridges correction.

The results show that the use of CH70 mortar (scenario 3) for thermal bridge correction has a payback of 3 years (2016) when compared to the simple repair of the original external plaster (scenario 0). The use of 50% of cork granulate instead of 70% of cork in HL5 based mortar has a payback 4 years after the intervention. Scenarios 4 and 5 do not present benefits from a payback point of view since their behaviour is quite similar to scenario 0, especially after 2020.

Ten years after the intervention, the use of scenario 3 leads to much more economic savings than other solution: Scenario 3: 75€/m^2; Scenario 2: 45€/m^2; Scenario 4: 6.5€/m^2 and Scenario 5: 2.0€/m^2.

7. Conclusions

In order to study the thermal behaviour of a typical Lisbon dwelling of the 80’s, several hydraulic lime - cork mortars (HL5 and NHL5) and cement–cork mortars (CEM II/B-L 32,5N) for rendering application in building thermal bridges were developed and optimized. Different cork granulate dosages (from 0% to 80%) were tested (as sand replacement by mass) until the maximum possible cork dosage while minimizing mortar thermal conductivity and cost changes.

Subsequent to the analysis of different testing properties, the following conclusions can be drawn:

- Fresh state properties show that it is possible to get good performance up to 70% of cork either in hydraulic lime or cement based mortars.
- From a thermal point of view, for the same initial temperature conditions, it is shown that the incorporation of cork in mortar compositions leads to a reduction of temperature variation, which is probably related to a higher thermal delay. It is also shown that cork-based mortars with hydraulic lime present less thermal delay than those with cement.
- The incorporation of cork granulates in hydraulic lime mortars leads to a decrease of permeability while for cement based mortars, the presence of cork leads to an increase of water vapour permeability.

In order to select the best mortar compositions it was carried out a simulation of what was the contribution of each selected mortar composition in the minimization of condensation effects in an existing dwelling from the 80’s built in Lisbon, Portugal.

It is shown that the power of heat dissipation in the dwellings’ thermal bridges is of the same magnitude order than heat loss in roof and much higher than in vertical opaque envelopes or openings, which enhances the need to reduce thermal bridges in the building.

Based on the original design stage of the existing dwelling, 7 different scenarios were investigated in the thermal performance simulation in order to study how the specific corrections with the developed mortars may imply as regards energy consumption for heating:

- scenario 0: repair of the original external plaster;
- scenarios 1 to 5: Thermal bridge correction with different rendering cork-mortars
- scenario 6: New external plaster in all area of the vertical envelops with hydraulic lime cork-mortar.

When compared to the original situation, scenario 3 leads to an energy saving of 8%, which is much higher than the savings promoted by scenario 4 or 5. Scenario 6 which corresponds to an expensive intervention by replacement of all original external plaster by CH70 only means 11% of energy savings. From a condensation phenomenon point of view, the comparison between the ‘‘as built’’ condition (scenario 0) and the five alternative solutions hypothesized show that it is preferable to place the CH70 based mortar on the outside surface of the thermal bridge (scenario 3).

An economic evaluation was made concerning the electric energy cost and its annual growing rate in Portuguese residential buildings. The results show that the use of CH70 mortar (scenario 3) for thermal bridge correction has a payback of 3 years (2016) when compared to the simple repair of the original external plaster (scenario 0). The use of 50% of cork granulate instead of 70% of cork in HL5 based mortar has a payback 4 years after the intervention.

Acknowledgments

The authors of this paper wish to acknowledge the support of Eng. Márcio Leal who contributed with the cement based mortars preparation.

References

[1] J. Sousa, Background of Portuguese Domestic Energy Consumption at European Level (http://ceur-ws.org/Vol-923/paper07.pdf). FEUP, 2007, Porto, Portugal.

[2] Portuguese Legislation. Decree-law 80/2006 — Regulamento das Características de Comportamento Térmico dos Edifícios (RCCTE), 2006.

[3] A. Andaloro, R. Salomone, G. Ioppolo, L. Andaloro, Energy certification of buildings: A comparative analysis of progress towards implementation in European countries, Energy Policy 38 (2010) pp.5840-5866.

[4] EST (2008) Enhanced Construction Details: Introduction and use. Edition, London, UK, Energy Saving Trust. 2008.

[5] G. Evola, G. Margani, L. Marletta, Energy and cost evaluation of thermal bridge correction in Mediterranean climate, Energy and Buildings 40 (2008) 2083–2089.

[6] T. Theodosiou, A. Papadopoulos, The impact of thermal bridges on the energy demand of buildings with double brick wall constructions, Energy and Buildings 43 (2011) 2385–2393.

[7] Abreu, I. A.; Lopes, J. – Energetic Rehabilitation in Buildings - Cost-Effective Solutions to Minimise Thermal Bridging. Department of Construction and Planning, Polytechnic Institute of Bragança. Portugal.

[8] A. Tadeu, I. Simões, N. Simões, J. Prata, Simulation of dynamic linear thermal bridges using a boundary element method model in the frequency domain. Energy and Buildings, 43(12) (2011), pp. 3685-3695.

[9] Reducing Home Heating and Cooling Costs – Energy Information Administration, July 1994.

[10] Guidelines for indoor air quality: dampness and mould. WHO/Europe, 2009.

[11] N. Simões, F. Branco, A. Tadeu. Definition of Two-Dimensional Condensation via BEM, Using the Glaser Method Approach, EABE - Engineering Analysis with Boundary Elements Journal, Vol. 26, n.º 6 (2002), pp. 527-536.

[12] A. Tadeu, N. Simões, F. Branco, Steady-state moisture diffusion in curved walls, in the absence of condensate flow, via the BEM: A practical civil engineering approach (Glaser Method). Journal of Building and Environment, Vol. 38 (2003), pp. 677-688.

[13] A. Andaloro, R. Salomone, G. Ioppolo; L. Andaloro, Energy certification of buildings: A comparative analysis of progress towards implementation in European countries, Energy Policy 38 (2010) pp.5840-5866.

[14] Silva, S.P.; Sabino M.A.; Fernandes E.M.; Correlo V.M.; Boesel L.F.; Reis R.L. - *Cork: properties, capabilities and applications.* Int Mater Rev 2005; 50(6): pp.345–65.

[15] S.R. Karade, M. Irle, K. Maher, Influence of granule properties and concentration on cork-cement compatibility. Holz als Roh- und Werkstoff 2006;64: 281–6.

[16] T.J.F. Fonseca, B.R. Parresol. A new model for cork weight estimation in Northern Portugal with methodology for construction of confidence intervals. Forest Ecol Manage 2001;152:131–9.

[17] L. Gil, Cork composites: A Review. Materials (2009), 2(3): 776-789.

[18] F. Hernández-Olivares, M.R. Bollati; M. del Rio, B. Parga-Landa, Development of cork-gypsum composites for building applications. Constr Build Mater (1999);13:179–86.

[19] S. Lucas, V.M., Ferreira, Selecting insulating building materials through an assessment tool. Portugal SB10: Sustainable Building Affordable to All (6), Case studies.

[20] N. Simoes, A. Moreira, F.G. Branco, Effect of natural and expanded granulated cork on strength and thermal behaviour of concrete. XXXV IAHS World

[21] D.K. Panesar; B. Shindman, The mechanical, transport and thermal properties of mortar and concrete containing waste cork, Cement & Concrete Composites 34 (2012) 982–992.

[22] I. Simões, N. Simões, A. Tadeu, Thermal delay simulation in multilayer systems using analytical solutions, Energy and Buildings 49 (2012), 631–639

[23] www.thekeysatquinta.com/The_Keys-BelAir.pdf

[24] J. Ferreira, M. Pinheiro, In search of better energy performance in the Portuguese buildings—The case of the Portuguese regulation, Energy Policy, Volume 39, Issue 12, December 2011, pp. 7666-7683

[25] Inquérito ao Consumo de Energia no sector doméstico 2010. (Survey on Energy Consumption, in Portuguese). National Institute of Statistics and General Directorate for Energy and Geology: Lisbon. 2011.

[26] ADENE – Agência para a Energia, Energy Efficiency Policies and Measures in Portugal, ODYSSEE- MURE 2010 - Monitoring of EU and national energy efficiency targets, ADENE, November 2012.

Cork-based mortars for thermal bridges correction in a dwelling. Thermal performance and cost evaluation

ANA BRÁS[1], FÁBIO GONÇALVES[1], PEDRO FAUSTINO[1,2]

[1] *Construction and Environment Section, ESTB – Polytechnic Institute of Setúbal, Portugal*

[2] *LEB – Designers and Consultants in Rehabilitation of Constructions, Lda., Portugal*

HIGHLIGHTS

Minimization of energy consumption and condensation effects in a dwelling from the 80's ► Contribution of cork-based mortars for thermal bridge correction ► Development of specific rendering mortars (cement and hydraulic lime–cork. ► Based on the original design stage of the existing dwelling, different scenarios were investigated. ► The influence of electric energy cost and its annual growing rate in Portuguese buildings. ► This analysis will enable to choose the best solution from a technical and economical point of view.