Heat flow through materials in traditional and improved wall corner (plan) building junction

Improvement of Traditional Building Procedures in Dwellings towards an Energy-Efficient and Low-Carbon Architecture Practice in Mexico

Mejora en los procesos de construcción tradicional de las viviendas para una práctica de arquitectura energéticamente eficiente y baja en producción de carbono en México

Naoki Enrique Solano García
naoki@comunidad.unam.mx

ENSAYO

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Abstract

Brick-and-concrete based construction elements traditionally built for low-dense housing in Mexico were tested using energy modelling software to assess their thermal performance. Afterwards, an evaluation on physical properties of regionally available construction and insulating materials was made to propose alternative specification with reduced carbon and energy-efficient building envelopes.

Application of suggested improved building fabrics in this study intend to contribute to a reduction in energy demand in hot climate regions, where dwellings' electricity consumption escalates due to artificial cooling, while simultaneously considering fabric's specification, the level of craftmanship from local construction workers and the technologies available in the country.

Key words: architecture, energy efficiency, insulation, construction materials, building procedures

Resumen

Se efectuó una evaluación de desempeño térmico de elementos y especificaciones constructivas utilizados popularmente para viviendas de baja densidad en México mediante un software de modelado energético.

Asimismo, se evaluaron las propiedades termofísicas de materiales para construcción y aislamiento térmico disponibles en el país con el objetivo de proponer especificaciones constructivas alternativas con una reducida huella de carbono y mejorada eficiencia energética para envolvente arquitectónica.

La aplicación de los elementos constructivos mejorados en este estudio contribuye al análisis para la reducción de la demanda de energía en climas cálidos, derivada del uso de aire acondicionado, considerando el contexto de un país con una consolidada industria de la construcción basada en concreto y acero, al igual que mano de obra no especializada.

Palabras clave: arquitectura, eficiencia energética, aislamiento, materiales de construcción, procedimientos constructivos

Introduction

Mexico has a population of 129 million people and most of its territory has either tropical or arid climate. Most people live in areas where mechanical ventilation or cooling systems are needed in buildings, being the northern region the one with more associated electricity demand increases for this reason[1]. Each additional refrigeration ton requires enormous investments in electrical power infrastructure and, therefore, an inherent increase in operational carbon emissions. Moreover, dwellings in Mexico are built with little or no insulation strategies which have a direct impact in the amount of electricity consumed along buildings' life cycles. Air conditioning systems turn out less efficient due to the lack of an appropriate envelope that allows keeping indoor cool conditions for longer time. As Mexicans improve their economy and purchasing power conditions, an increase in cooling systems is expected to keep rising.

In the context of an increase on urban densification, reliance on exclusive wind or solar strategies – although highly beneficial and advisable – may not guarantee indoor comfort conditions if not combined with thermally-efficient building envelopes.

This does not mean that full insulation strategies are meant to be applied ubiquitously in all climates across the country. In some regions, applying full insulation strategies would be detrimental in terms of energy consumption as it would appear unnecessary. In such cases, a thermal mass strategy would be more beneficial in climates with important temperature variations from day to night time.

The study addressed, with a comparative methodology and applied design suggestions, only for full insulation strategies, based on the Passive House Standard. This study served as a supplementary benchmark in the development of a local urban energy-efficient and resilient architecture practice which is currently incipient in the country. The simplicity on the detail improvements on building fabrics depicted in this study were meant to foster adoption of sustainable design and construction measures among architects, designers and independent builders.

In sum, this study was composed mainly by reviews and correlations on physical properties and building fabric specifications being low-dense housing the main scope. It considers the level of craftmanship from local construction workers and the technologies available in the country.

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[1] (SENER 2015)

It is important to highlight that this study *did not intend to introduce Passive House* (PH) building standards into the Mexican context. The main goal is to address reduction of energy demands by making an energy-efficiency approach based on Passive House design considerations. This traduces into a different point of viewing buildings and their building procedures in emerging economies towards a sustainable and energy-efficient architecture practice in the context of climate change by acting locally and having global impact.

Passive House (PH) approach

The Passive House (PH) approach offers an integrated view of energy efficiency along with a thorough understanding on properties of construction materials and building physics, always ensuring a comfortable indoor environment for the user irrespective of the climate.

It is important to mention that this standard is meant to be complemented with mechanical cooling, heating or ventilation, as high levels of insulation might induce to an ambient of stacked inside air. However, this condition does not oppose to the possibility of natural ventilation from outside air through windows, especially in hot climates.

PH has advantages in terms of low energy consumption in buildings. Lower electricity bills and more sustainable use of energy through the years are just two of them. However, it is important to consider its implications. In fact, just by adding insulation layers to traditional building elements could lead to ineffective or counter-productive unwanted results if the whole implications are not correctly understood. The Passive House (PH) approach addresses this. It relies "on high levels of uninterrupted, all around insulation, airtight design, and heat gained from the sun through the windows (solar gains)" [2]. It is germane to point out that the PH approach is different from the 'passive solar design' approach, which in fact both can be mutually complemented. Table 1. summarizes the PH approach, makes a comparison with other energy requirements in UK and the current Mexican situation in the matter.

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[2] (Cotterell and Dadeby 2012, 17)

Table 1: Comparisons among different thermal requirements for buildings.

	Passive House (PH)	**UK regulations**	**Average of existing dwellings in Mexico**
Space heating demand	15 kW/h annum[3]	40 kWh/m^2 (Silver Level) 30 kWh/m^2 (Gold Level) [4]	Unavailable
Space cooling demand	Non-specified allowance.[3]	Not specified	Variable
Insulation (U-values)	≤ 0.15 W/m^{2}K	From 0.35 to 0.70 W/m^{2}K [4]	2.49 W/m^{2}K [5]
Windows	≤ 0.80 W/m^{2}K	1.4 W/m^{2}K [4]	Between 2.0 (wood) and 5.7 (aluminium) W/m^{2}K [6]
Airtightness	Maximum 0.6 ach[3]	< 10 m^3/h/m^2 @ 50 Pa [4] (2010 regulation) < 3 m^3/h/m^2 @ 50 Pa [7] (UK zero carbon)	Unknown. Probably between 9 and 12 m^3/h/m^2 @ 50 Pa [8]
Thermal comfort	20°C [3]	20°C	23°C [3]

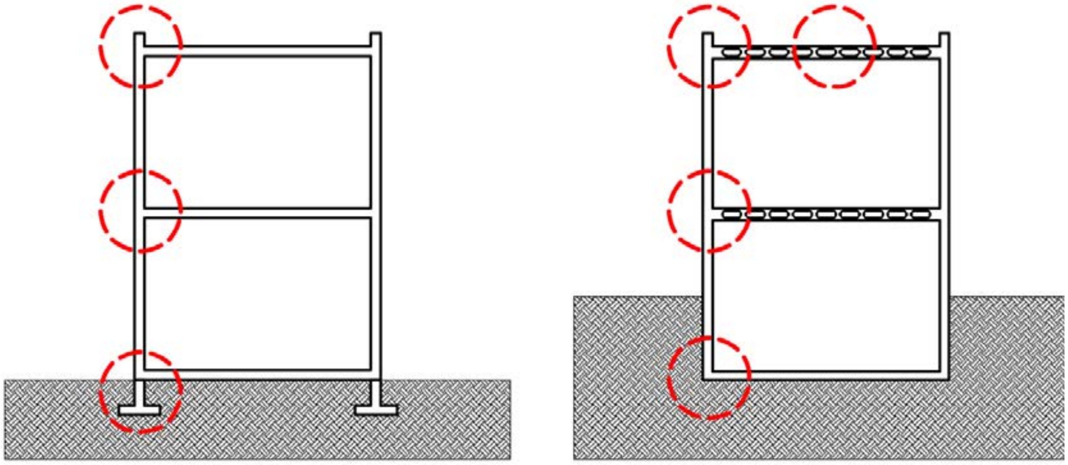

Figure 1: Location of thermal bridges in a regular dwelling, author's image

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3 (International Passive House Association 2014)
4 (Scottish Government 2015)
5 (Solano, Sustainability Line 2017)
6 (Kömmerling n.d.)
7 (Cotterell and Dadeby 2012)
8 (Gonzalez, et al. 2016)

Another important characteristic of the PH approach is the absence, or minimisation, of thermal bridges. Thermal bridges occur when a material with relatively high conductivity interrupts or penetrates the insulation layer. In a building, thermal bridges are in construction junctions where building elements made of different materials meet (Figure 1)

Analysis on physical properties of materials

Construction and insulating materials have different properties and capabilities such as *density, thermal conductivity, specific heat capacity, vapour tightness, compressive stress, reaction to fire*, among others. These make a certain material to perform better for a function within the building fabric. Moreover, correlations among two or more properties can be found and it is very useful to consider them at the design stage – not only for structural or energy efficiency purposes but also – for good moisture management and airtightness. This also helps to choose the best materials and the order intended for application according to the requirements of the project. In terms of energy-efficiency, it might be thought that the most important characteristic of an insulating material is its thermal conductivity. However, there are other features that must be reviewed before considering a material suitable for a correct application.

Thermal conductivity

Materials with thermal conductivities less or equal than 0.10 W/mK are classified as insulating materials[9]. Additionally, they may be re-classified in excellent, very good, good and moderate insulating materials, according to their lambda value, as described in Table 2.

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[9] (Pfundstein, et al. 2008)

Table 2: Thermal conductivity values in different materials and classification[10]

	Material	Thermal conductivity (W/mK)	Classification
INSULATING MATERIALS	Polyisocyanurate foam (PIR)	0.028	<0.03 Excellent
	Polyurethane rigid foam (PUR)	0.028	
	Expanded polystyrene (EPS) (Unicel)	0.038	0.03 to 0.05 Very good
	Expanded polystyrene (EPS)	0.038	
	Extruded polystyrene (XPS)	0.039	
	Cellulose (Celbar)	0.04	
	Phenolic foam (PF)	0.04	
	Mineral rock wool	0.042	
	Mineral glass wool	0.044	
	Straw bale	0.045	
	Carpet (synthetic)	0.06	0.05 to 0.07 Good
	Wood fibre/cement panel	0.07	
	Pumice (tezontle, tepojal)	0.08	0.071 to 0.1 Moderate
	Cement-based adhesive	0.082	
	Reeds	0.09	
	Expanded clay	0.1	
NON-INSULATING MATERIALS	Insulating clay bricks (Tabimax)	0.12	Structural
	Timber (general)	0.12	
	Oriented Strand Board (OSB)	0.12	
	Plywood	0.12	
	Hardwood	0.18	
	Linoleum	0.19	
	Autoclaved aerated concrete (AAC)	0.24	Structural
	Gypsum plasterboard	0.25	
	Gypsum plaster	0.56	
	Concrete block, lightweight, 150 mm	0.66	Structural
	Cement render	0.72	
	Clay tile	0.85	
	Glass	0.96	
	Solid clay brick	1.2	Structural

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[10] Based on (Pfundstein, et al. 2008)

Density

Materials seem to have better insulating performance with lower densities. Findings suggest that the most favourable densities range between 20 and 100 kg/m^3. ‘At lower densities, the heat transmitted by radiation increases, and at higher densities the heat transmitted by conduction increases’[11]. In Table 3, highlighted materials match with lower densities, whereas structural materials showed high density values, thus having a greater mass.

Table 3: Densities of some insulating and construction materials,[12] [13]

	Material	**Density kg/m^3**
INSULATING MATERIALS SCOPE	Expanded polystyrene (EPS) (Unicel)	15
	Mineral glass wool	15
	Mineral rock wool	23
	Extruded polystyrene (XPS) (Foamular)	25
	Phenolic foam (PF)	30
	Polyurethane rigid foam (PUR)	30
	Cellulose (Celbar)	43
	Reeds	120
	Carpet (synthetic)	160
	Pumice (tezontle, tepojal)	175
	Expanded clay	260
	Cement-based adhesive	350
STRUCTURE MATERIALS SCOPE	Wood fibre/cement panel (Pamacon, Troldtekt)	350
	Sawn hardwood	510
	Plywood	540
	Timber (general)	variable
	Autoclaved aerated concrete (AAC)	750
	Insulating clay bricks (Tabimax)	1120
	Concrete block, lightweight, 150 mm	1760
	Solid clay brick	2000
	Reinforced concrete 20/25 MPa	2300
	Carbon steel	7800

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[11] (Pfundstein, et al. 2008, 9)

[12] Based on (Hammond and Jones 2008)

[13] Based on (Pfundstein, et al. 2008)

It is important to point out that inorganic synthetic materials, with lower densities, have a lower thermal conductivity value. Moreover, they tend to be stronger against moisture, mould growth and vermin.

Specific Heat Capacity (SHC)

The specific heat capacity describes the specific ability of a material to absorb heat depending on its mass[14]. Furthermore, it is very useful to use materials with high SHC as heat reservoirs in places where temperatures during the day are high and turn cold during the night. In this case, materials will release all stored heat during the day in due course. SHC values highlighted in Table 4 correspond mostly to organic based products having the biggest values. Structural materials used in this study (cement and clay based) do not have an outstanding SHC as widely argued among Mexican architects and designers.

Table 4: Specific heat capacity of some construction materials[15]

Material	Specific heat capacity J/kgK	Classification
Carbon steel	480	
Mineral rock wool	710	Insulating
Autoclaved aerated concrete (AAC)	750	Structural
Concrete block, lightweight, 150 mm	840	Structural
Reinforced concrete 20/25 MPa	840	Structural
Insulating clay bricks (Tabimax)	840	Structural
Solid clay brick	840	Structural
Pumice (tezontle, tepojal)	920	Insulating
Gypsum plaster	960	
Expanded polystyrene (EPS)	1000	Insulating
Extruded polystyrene (XPS)	1000	Insulating
Glass	1000	
Cellulose (Celbar)	1380	Insulating
Phenolic foam (PF)	1400	Insulating
Polyurethane rigid foam (PUR)	1470	Insulating
Wood fibre/cement panel	1890	Insulating
Straw bale	2100	Structural
Timber (general)	2100	
Sawn hardwood	2810	Structural

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[14] Heavy materials like bricks or concrete take longer to heat up, and if their specific heat capacity is higher, such materials can store more heat.

[15] Based on (Hammond and Jones 2008)

Vapour diffusion resistance (VDR)

All materials have a level of vapour permeability, or resistance, depending on the perspective. Materials with high diffusion resistance are 'vapour tight', meaning that do not allow the passing of water vapour through them. It is important to mention that vapour permeability is measured in several units which are relative to a given thickness per material, specified thickness or still air as showed in Table 5.

Table 5: UK, European and US vapour permeability values[16]

Vapour permeability value	Units	Symbol	Thickness/relative to
Vapour resistivity	MNs/gm	r-value	1 metre thickness
Vapour resistance	MNs/g	G-value	Specified thickness
Water vapour resistance factor	No unit	μ-value	Non-specified thickness
Equivalent air layer thickness	metres	Sd-value	Specified thickness, relative to air
Vapour permeability	Gr.HO2/hr/sqft/inHg	perm	Grains (Gr) of water vapour

Table 6 shows the vapour resistance value (G-value) of some materials according to their thickness and its water vapour resistance factor. The lower the figure, the more permeable the material. Highlighted values indicate the most vapour tight materials. It is important to point out that these have a low hygroscopicity level for having a closed-cell structure.

Table 6: Vapour diffusion resistance of some materials,[17] constant compressive stress (CCS)

Material	Vapour diffusion resistance μ	Vapour resistivity r-value MNs/gm	Thickness mm	Vapour resistance G-value MNs/g
Breather membranes	—	—	—	0.1-0.6
Reeds	2.00	10	20	0.2
Gypsum plasterboard	4.00	20	12	0.24
Mineral glass wool	1.00	5	100	0.5
Mineral rock wool	1.00	5	100	0.5
Gypsum plaster	10.00	50	15	0.75
Cellulose fibre	1.5	7.5	100	0.75

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[16] Refer to (Cotterell and Dadeby 2012, 152-153) for conversion methods among vapour permeability values and units.

[17] Based on (Cotterell and Dadeby 2012), (Pfundstein, et al. 2008), (Alev, Uus and Kalamees 2015)

Clay plaster	8.00	40	20	0.8
Insulating clay bricks	2.00	10	120	1.2
Pumice (tezontle, tepojal)	4.00	20	60	1.2
Brickwork	10.00	50	120	6.0
Polyurethane rigid foam (PUR)	30.00	150	50	7.5
Expanded polystyrene (EPS)	60.00	300	50	15
Phenolic foam (PF)	60.00	300	50	15
Extruded polystyrene (XPS)	80.00	400	50	20
Polythene sheet (vapor barrier)	—	—	—	250-7,500

This property is highly related to density and thermal conductivity in insulating materials. Materials with high ccs values tend to be used in applications where they are subject to compression loads, such as for industrial floors, rooftop terraces, green roofs and parking decks (Table 7). However, these applications correspond mostly to non-permanent punctual loads. Use of these insulation materials under foundation footings or slabs of a building may not be recommended.

Table 7: Constant compressive strength of two insulating materials[18]

Material	Constant compressive strength kPa
Extruded polystyrene (XPS)	50 to 250
Polyurethane rigid foam (PUR)	20 to 30

Airtightness

Airtight materials stop unwanted air leakage from the interior to the exterior, or vice versa in case of hot climates. Air leakages are linked to heat gains (in hot climates), or losses (in cold climates). It is advisable, that airtight materials are located towards the interior of the envelope as its easier to guarantee low rates of leaks. Table 8 indicates the most common.

[18] (Hammond y Jones 2011)

Table 8: Airtight and non-airtight materials[19]

Material	Airtight?
Steel	Yes
Cement-based adhesive	No
Cement render	No
Cement screed	No
Clay tile	No
Concrete block, lightweight	No
Reinforced concrete 20/25 MPa	Yes
Glass	Yes
Gypsum plaster	Yes
Cement mortar 1:4	No
Solid clay brick	No
Oriented Strand Board (OSB)	Yes*

Correlation between density and thermal conductivity

Thermal performance and density of a material are closely correlated. Low densities generally imply high porosity or high volume of voids. This leads to a decrease in thermal conductivity,[20] which is beneficial for its application in an efficient thermal envelope. In Graph 1[21], it can be appreciated that materials with densities ranging from 15 to 175 kg/cm^3 correspond to excellent and very good insulating materials.

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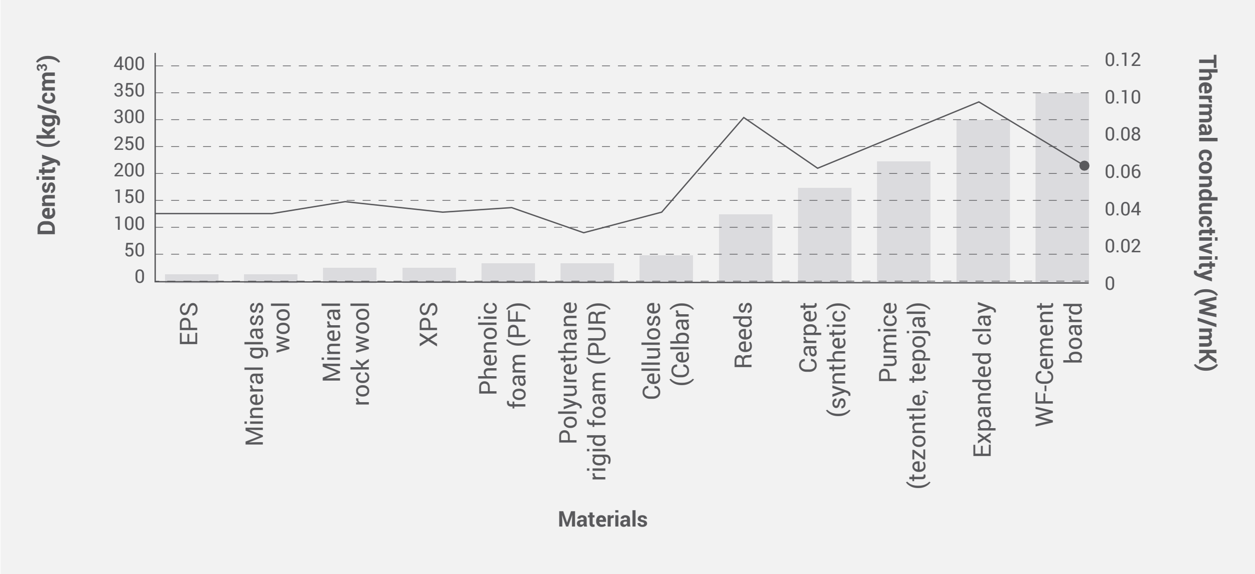
[19] According to Cotterell, Oriented Strand Board (OSB) is only airtight with 18 mm thickness or more.

[20] (Pfundstein, et al. 2008)

[21] Based on (Pfundstein, et al. 2008) and (Hammond y Jones 2011)



Graph 1: Correlation of density (bars) and thermal conductivity (lines) among different insulation materials

Furthermore, the gap between density and thermal conductivity increases when densities are lower. An extended range is found with the composite insulating material wood-fibre/cement panel which is denser, at which point the curve starts to invert. In this case, it is important to mention that at this point materials start having better performance in other functions rather than resisting heat conductivity.

Due to their frequent use in the industry, structural materials considered in this study have a relatively good thermal performance despite their elevated densities. Other materials worth considering – though their use is not widespread are autoclaved aerated concrete (AAC) bricks and insulating clay bricks (ICB). In this case, the curve and the bars in the graph in Graph 2[22] are stacked up.

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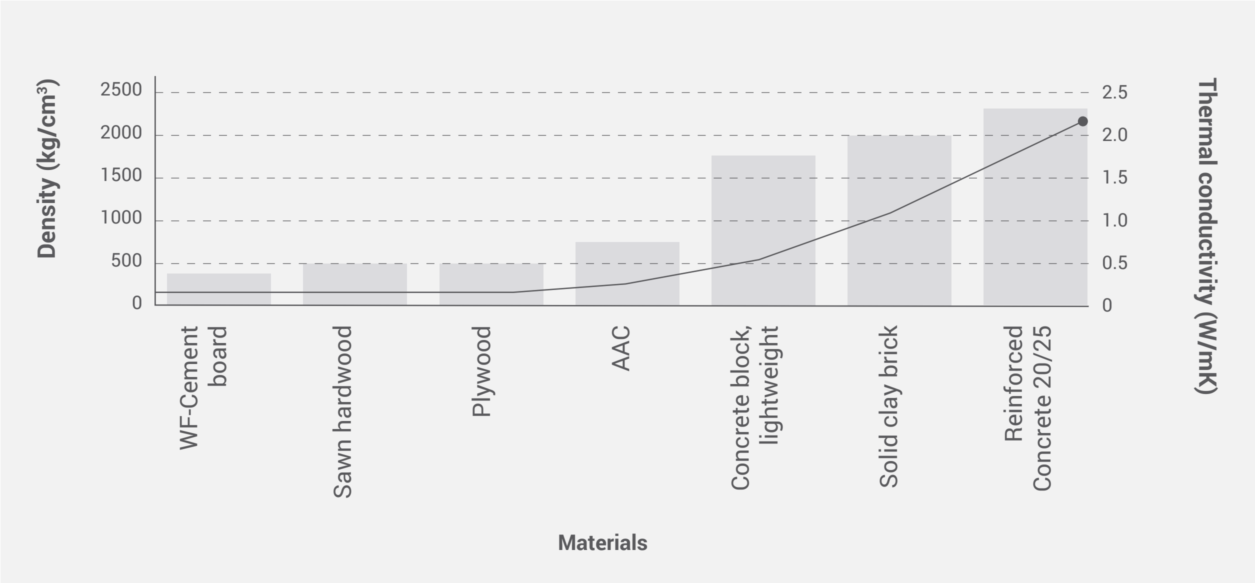
[22] Based on (Cotterell and Dadeby 2012), (Hammond y Jones 2011), (Pfundstein, et al. 2008)



Graph 2: Correlation of density (bars) and thermal conductivity (lines) among different non-insulating materials

Use of natural products for insulation

Cork appears to be a very efficient insulation material. However, from an ecological point of view, the overharvesting of the limited cork oak tree stocks could be in detriment of the environment. Cork grows slowly and the bark can be only removed approximately every nine years. Moreover. most of the organic insulation materials cannot be recycled or reused because of the flame retardant and stabiliser agents involved in their manufacture. Flame retardants such as boric salt is dangerous for groundwater, for example. Other materials such as polyester fibres were not considered into the study because their application is very limited or have not been sufficiently tested in the building industry to be applied in a secure and steady way. However, the main disadvantage for their mainstream adoption could lead to undesired depletion of resources product of unbalanced demand and regeneration capacities.

Strategies to achieve energy-efficiency

Design considerations

The following construction, insulating and finish materials were chosen to conform a series of prospective building fabric specifications (Table 9). Selection was made based on the interpretation of results obtained from an environmental analysis of materials and its physical properties.

Table 9: Selected building, insulation and finish materials considered for environmental assessment on improved building practices [23]

Structure materials	Insulation materials	Inside finish materials	Outside finish materials
WALLS			
Solid clay brick Concrete block, lightweight Insulating clay brick (ICB) Autoclaved Aerated Concrete (AAC) brick Reinforced concrete	Cellulose (blown) Mineral rock wool (board) Wood-fibre-cement panel	Gypsum board Gypsum plaster	Cement render No finish
ROOFS			
Reinforced concrete slab Reinforced concrete beam and vault slab (BVS)	XPS Wood-fibre-cement panel Pumice	Gypsum plaster	No finish Clay tile
GROUND FLOOR			
Reinforced concrete slab	Pumice XPS	Ceramic tile Linoleum Carpet	

Structural materials were chosen for two reasons: availability and outstanding thermal performance. The first ones relate as well to its universal adoption in the local building industry. Solid clay brick and lightweight concrete brick enter in this category. Both are economic, capillary open, act as 'reservoir cladding', have a relatively good SHC for heat storage, and can provide a good aspect even without outside render. The second reason relates with the thermal performance. AAC bricks and ICBs were considered for this reason. Despite their outstanding thermal performance among structural materials, they are expensive in the building market and require a more specialised workforce for its correct application. ICB is heavy and difficult to cut although it has the best thermal performance of all considered structure materials. AAC brick, despite being super lightweight – even more than lightweight concrete brick – is brittle. People might not adopt it so easily because of the careful transportation required and more expenses on site related from broken pieces due to uncareful handling.

Regarding structure roofing materials, reinforced concrete Beam and Vault System (vigueta y bovedilla) was chosen for its low cost and thermal performance although its environmental footprint is questionable due to the EPS formwork block used to form the vault. Reinforced concrete was chosen merely for being ubiquitous in the building industry and for its structural capacity.

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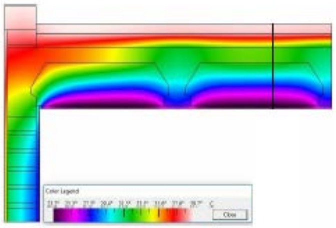
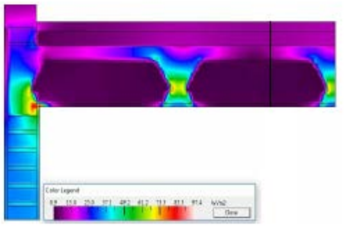
[23] (Solano, Sustainability Line 2017)

Sustainability Line



Isotherms (Lines of constant temperature)



Heat flux (Heats flow through materials)

J3-Wall W1 and Bean and vault R2

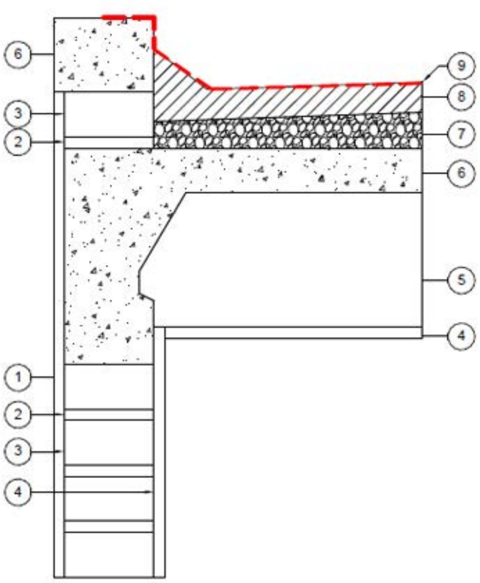


Figure 2: Thermal behavior of a Beam and Vault System Structure

Natural low embodied energy materials used for insulation are scarce in the country. However, cellulose fibres are readily available in the market and have low embodied energy because of its organic origin. Other natural materials such as reeds or straw bales were not considered because their supply form is not suitable for mainstream construction purposes. Pumice (known as piedra pomez, tezontle or tepojal), a natural mineral material, would perform two main roles: as a screed to provide an adequate slope in flat roofs, and as insulating material (See Figure 2[24])

As finish materials, gypsum plaster and cement render were chosen for inside and outside finishes. As seen before, gypsum plaster is airtight, and already a mainstream material in dwellings. Cement render performs very good on the outside for being a capillary break that blocks rainwater into the building fabric and is already adopted by builders as well. Finishes for floors were considered ceramic tiles, linoleum and carpet, which are the most common.

In a flat roof, the insulating materials must support the loads of the roof finishes (tiles, waterproofing membrane, screed, any gravel (pumice stone), wind and rain permanently and reliably. Load capacity should be considered if there are going to be constant traffic loads – as in a roof terrace – or for maintenance purposes only.

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[24] Results from (Solano, Sustainability Line 2017). Polystyrene formwork along with pumice stone used in roof cement screed performs thermally adequate. However, thermal bridges are still present in material junctions such as in concrete beams.

Insulation in walls must ensure prevention from slipping or moving out of position. This is done by adding fixing elements such as screws or structural studs.

Airtightness strategy

The achievement of low air leakage levels is an integral part of the PH approach. Success of the strategy depends on the continuity of the airtight layer throughout all the thermal envelope of the building. In most cases, careful installing of airtight layer by skilled workforce is required. Given the price increases in fuels and depletion of its sources, attention has been put in the amount of energy lost passing through thermal leaks in buildings. It is not surprising to see that making a building airtight is becoming a code requirement in other countries[25].

Air leakage levels should remain at least between 3 and 10 $m^3/h/m^2$ @ 50 Pa according to UK standards. However, there is no reliable study found on the matter applied for Mexican buildings. Moreover, current energy-efficiency building regulations in the country do not recognise this requirement as mandatory. However, a study made by Chilean researchers[26] showed that airtightness levels in Chilean homes range from 9 to 12 $m^3/h/m^2$ for concrete and brick masonry structures, which suggests that those values are probably applicable to Mexican dwellings given the fact that Mexico and Chile share similar building traditions. In such case, values for levels of airtightness are close to be acceptable in terms of today's UK regulations, but certainly far from the PH approach.

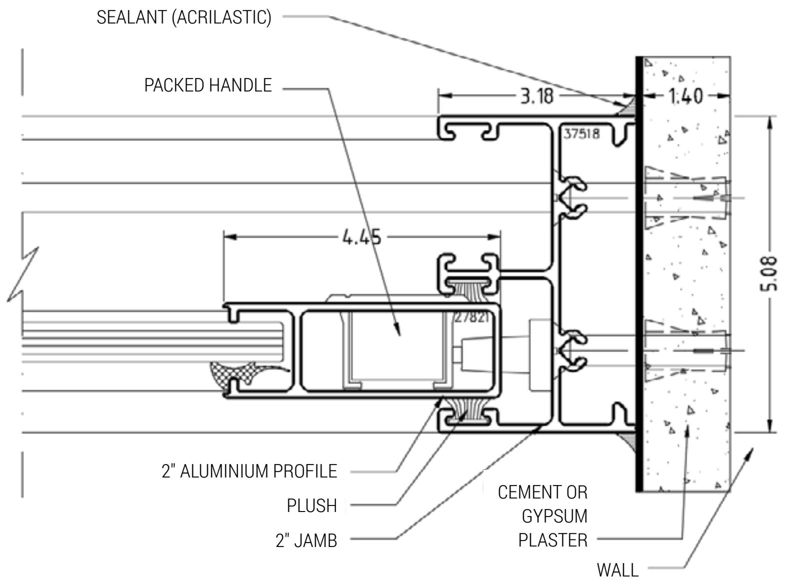

Figure 3: Typical aluminium window with no thermal break. Measures in centimetres (general) and inches (profiles)

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[25] (International Passive House Association 2014)

[26] (Gonzalez, et al. 2016)

As Gonzalez points out, those values are result of discontinuities between construction components. Nevertheless, it is unknown in which building fabric conditions Gonzalez's study was conducted. Presence of gypsum plaster in all walls and ceilings should be enough to achieve low rates of leaks[27]. Windows and doors to outside could probably be the cause for the major air leaks. In Mexico, most of them are made of aluminium profiles which, besides allowing high rates of heat flow, are poorly attached to wall jambs, as seen in Figure 3.[28]

Aiming for figures lower than 3 m3/h/m2 could significantly impede heated volumes of air to enter the building. Fortunately, Mexican dwellings frequently use two materials that are easy to make leak-free and are tolerant of poor workmanship: concrete and gypsum. It is a good common practice in Mexico to cover all walls and ceilings with gypsum plaster (Figure 4[29])

The challenge relies in attaching windows and doors with no air leaks. The strategy to achieve this is very simple, by means of a parge coat. According to Cotterell & Dadeby, two thin gypsum plaster frame layers (known in Mexico as *emboquillado*) in appropriate order should be more than enough to avoid leakage through the exposed masonry of the wall. First, a thin gypsum plaster layer is applied, prior installing window. Then, once window has been installed, a sticking sealing tape is applied all around the frame followed by a second plaster layer. Tape should remain embedded into the last gypsum plaster coat to create a continuous airtight layer between the wall and the window. For best results, it is highly desirable to *change from aluminium to timber window frames* because aluminium ones do not have airtight or thermal breaks as seen before. Timber frames, in the other hand, are more airtight and have a lower thermal conductivity due to the total mass of the frame (Figure 5).[30] Also, they tend to be more robust plus having a lower embodied carbon.

Figure 4: Walls and ceilings covered with gypsum plaster.

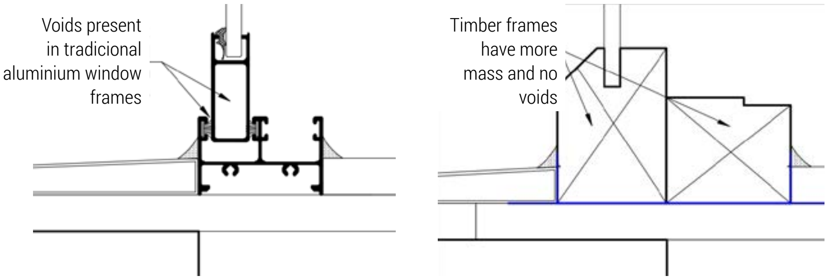

Figure 5: Difference between aluminium profile windows and timber windows

[27] (Cotterell and Dadeby 2012, 130)

[28] Adapted from (Vazquez 2013)

[29] (Solano, Conjunto Puerto México (building) 2015)

[30] Based on (Vazquez 2013), (Cotterell and Dadeby 2012)

Certainly, switching to double glazed windows made of PVC frames would be the most desirable option, although right now are very expensive in the market.

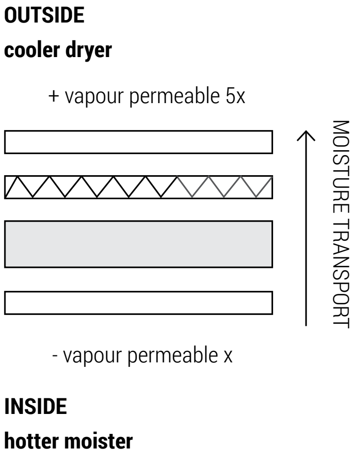

Figure 6: Recommended moisture management in cool climates.

Moisture management strategy

Water has many ways of impacting the building being the main agent that most ruins them. This aspect is highly related with the latter section. Not ensuring low levels of air leaks can provoke unwanted condensation in the building fabrics. An understanding on moisture transportation processes is required to avoid unwanted results that could damage the fabric or affect indoor comfort conditions. Today, most buildings manage moisture presence through the same building fabrics, which allow air to pass through elements and naturally dry out when moist. However, after insulating the building envelope, increasing airtightness, and expecting higher differences in interior and exterior temperatures, different indoor conditions are created. If the thermal mass of the building is isolated due to the addition of insulation lining the internal surfaces, there may be an adverse effect on internal temperatures and comfort conditions[31].

Masonry walls do not have detrimental impact with cyclical wetting and drying, which will continue to happen in improved specification, if insulating, inside and outside finishes do not trap moisture in-between. According to Cotterell and Dadeby, a useful rule of thumb is to allow moisture to move from the inside to the outside of the envelope using successively more vapour-permeable materials (Figure 6).[32]

In the case of Mexican dwellings, this would be done differently because brickwork has a higher G-value (vapour resistance) – which is around 6.0 MNs/g – compared with adjacent materials in both directions; and it is located at the centre of the building assembly. Surrounding natural insulation (cellulose) and finish materials have a lower G-value – between 0.24 and 1.5 MNs/g – which means that they allow drying more easily than the structure core. This may not suppose a problem in most regions of the country where relative humidity (RH) levels are ranged between 30 and 60 per cent, at most of the times. Bricks will still be absorbing moisture and releasing it in due course as they do in the traditional building practice. Finish materials would do the same towards the inside and the outside, respectively. However, regions of the country with permanent high levels of RH on the outside, such as in the coast, could have interstitial condensation in the cool part of the natural insulation layer (cellulose) as the moisture direction would be from outside to inside.

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[31] (Guillott and Spataru 2010)

[32] Based on (Cotterell and Dadeby 2012, 129)

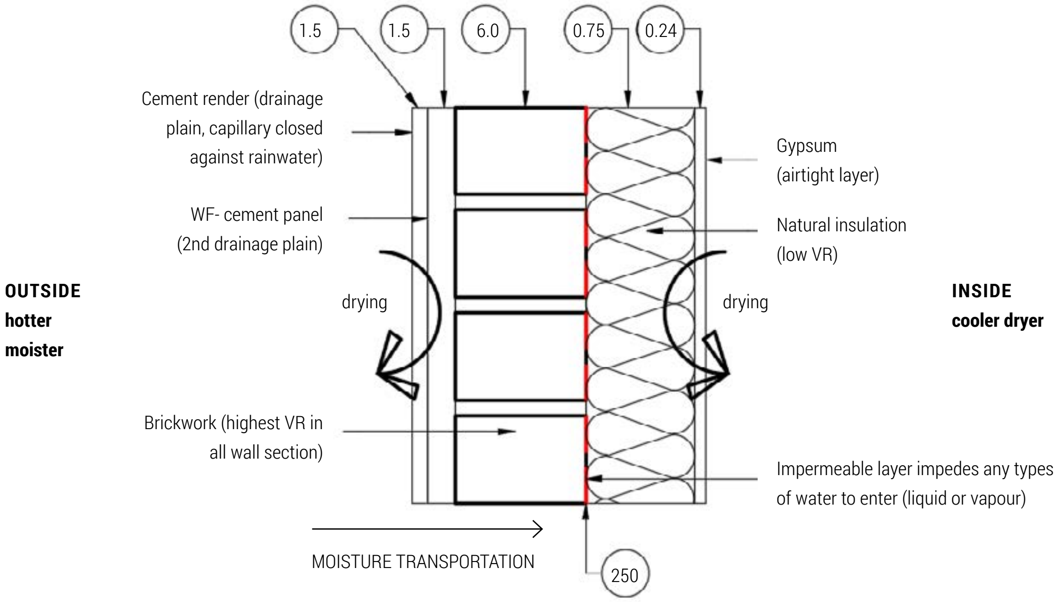

Figure 7: Recommended moisture management for hot-humid climates. G-values are in circles

Regulation *NOM-020-ENER-2011*[33] establishes that in such cases a vapour control layer should be added. Furthermore, the regulation lists a series of cities and regions where vapour control layers are mandatory. Cites such as Manzanillo, Puerto Vallarta, Acapulco, Cancun, Mazatlan and Veracruz are included in this list. In this moisture condition, a water permeable membrane should be placed adjacent to the brick towards the interior to stop any type of water (liquid or vapour) to reach the natural insulation layer which could be affected in its performance if wet (Figure 7[34]).

Interstitial condensation happens when the temperature difference between the outside and inside temperatures is significant and water vapour condenses on the cooler surfaces (Figure 8[35]).

In hot climates, where mechanical cooling is used, indoor conditions are cooler and dryer than outside, which could feel uncomfortable to some. Low moisture content of dry indoor air can be increased by keeping plants or having clothes to dry indoors, as well as normal cooking and bathing activities. Moreover, clay plasters could help to better manage dry indoor conditions due to its hygroscopicity.[36] Hygroscopic materials act as water vapour 'amplifiers' by absorbing moisture and releasing it.

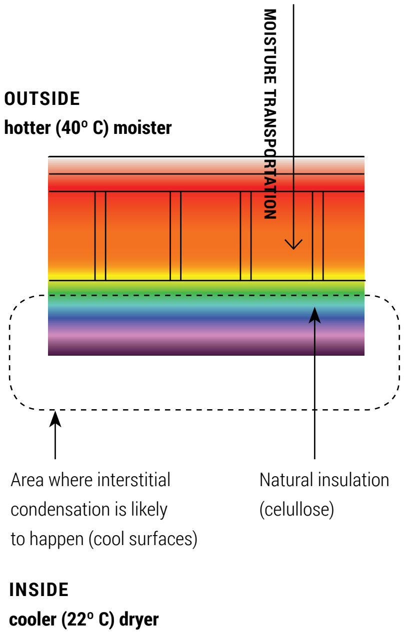

Figure 8: Area of interstitial condensation risk

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[33] (Diario Oficial de la Federación 2011)

[34] Results form (Solano, Sustainability Line 2017)

[35] Results from (Solano, Sustainability Line 2017)

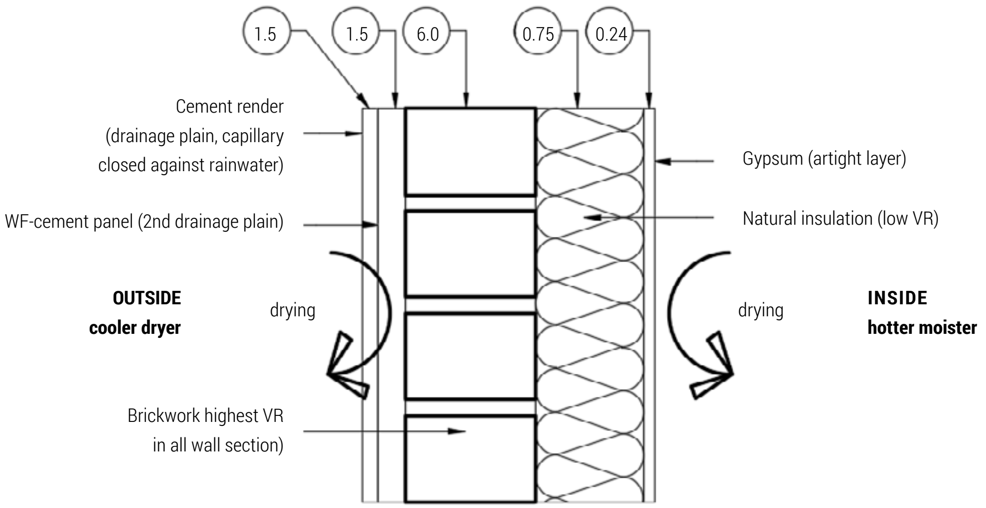
[36] (Brown y DeKay 2001)

Clay plasters could absorb moisture from fabric materials and then release it keeping dry conditions in the fabric and increasing moist conditions in indoor environment. In the inverse scenario, where internal conditions are a lot moister and hotter than external conditions - as in cool climates in the UK – breathable membranes should be in the outside part of the wall. However, in Mexican cool climates such as in the mountains a breather membrane could be unnecessary. Cement render will act in a similar way allowing core materials to dry towards the outside and effectively serving as waterproof against rainwater. As seen in Figure 9[37], most of the materials in the proposed building fabric have a low vapour resistance (VR), which allow to manage moisture through its thickness.

Anti-thermal bridge strategy

The most efficient way of ensuring substantial minimisation of thermal bridges is by designing consistent layers in the envelope in a way that high conductive materials (structure, finishes, etc) do not interfere with the insulation layer. It is highly desirable that insulation materials meet only with other insulation materials in building junctions. The same logic is suggested for the other construction elements whenever possible. With this strategy, insulation layer is continuous through all the envelope. The next figures compare heat fluxes of traditional and improved building practices for some junctions.

Figure 9: Recommended moisture management for cool dry climates. G-values (vapour resistance values) are in circles



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[37] Results from (Solano, Sustainability Line 2017)

These images are representative of the minimisation of thermal bridging after insulation and anti-thermal bridge strategies are applied (Figure 10[38], Figure 11[39], Figure 12[40]). Isotherms and heat flux schemes are very useful for identifying hot or cold areas in the design and predict thermal degradation or condensation.As seen above, materials that have less resistivity to heat flow appear 'isolated' after insulation measures. Areas depicted in green, yellow, cyan and red are representative of materials that allow easier heat flows through the envelope. In the other hand, zones in blue depict materials that do not allow easy heat flow. Still, there are some thermal bridges that should be accounted for when calculating total heating and cooling loads, but these are minimised.

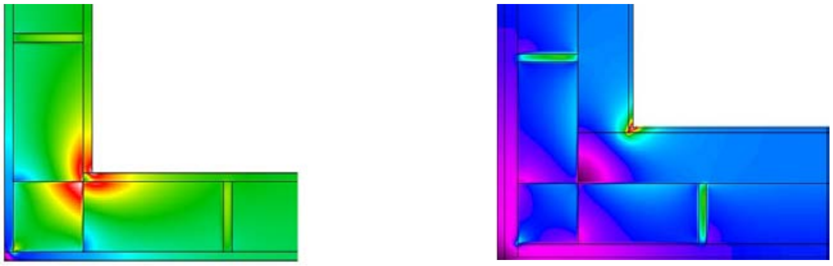

Figure 10: Heat flow through materials in traditional and improved wall corner (plan) building junction

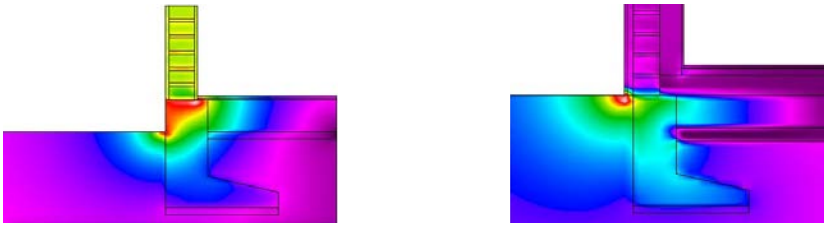

Figure 11: Heat flow through materials in traditional and improved wall / foundation building junction

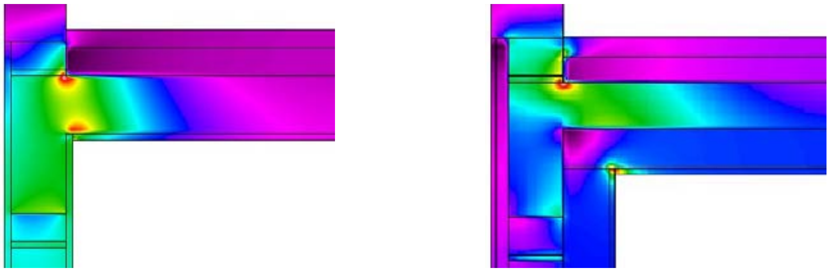

Figure 12: Heat flow through materials in traditional and improved wall / roof corner building junction

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[38] Results from (Solano, Sustainability Line 2017) using THERM Software

[39] Results from (Solano, Sustainability Line 2017) using THERM Software

[40] Results from (Solano, Sustainability Line 2017) using THERM Software

Sequencing in building procedures

Construction detailing in energy-efficient buildings requires a change in normal work sequencing. Site team need to be informed very clearly about the transitions in the different materials and have at least the general notion of what an energy-efficient envelope implies. Sequencing notes in specifications could be very useful. Attention to detail and strict supervision are critical in this endeavour.

In Mexico, it is very common to make after-built adjustments and repairs. This is mainly due to a lack of supervision or underqualified staff on-site. To tackle this, Cotterell and Dadeby suggest appointing supervisors who are exclusively attentive on critical issues, such as airtightness, to ensure materials are in the correct order. The main disadvantage would be the increase in building costs. Building at an airtight standard is not overly complex or difficult to learn, though. Adequate communication, preparation and meetings to make clear the basics of the intended goal could really boost construction quality. Finding robust construction solutions in the design stage is the key. Over complicated solutions could be a clear disadvantage towards an energy-efficient architecture practice because building procedures are more dependent on practical attainable application ease rather than overly specific complicated (or small) detailing. Moreover, electrical and water fixtures should consider insulation strategies as well to achieve more efficiency.

Results

In the following Graph 3, it can be appreciated the significant thermal improvement of main traditional building elements. Improved fabrics depicted in this graph are the ones that resulted in low EE and low U-values in the thermal and environmental assessment. In the case of walls, thermal improvement was close to almost 9 times compared with traditional practice. In the case of ground floor slabs, improvement was of almost 10 times. In the other hand, traditional reinforced concrete beam-and-vault roof practice had an outstanding U-value since the beginning. Still, its U-value improved almost two times after suggested fabric improvements.

Graph 3: Results on improved building elements and enhanced U-Values compared with current building practices [41]

	Structure material	Insulating material	Thickness mm	U-value W/m^{2}K	Mass kg
WALLS	Solid clay brick	Cellulose (blown), WF/ cement board	295	0.306	298.36
		Mineral rock wool, WF/ cement board	297	0.327	304.15
		EPS, WF/cement board	302	0.292	309.44
	Concrete block, lightweight	Cellulose (blown), WF/ cement board	270	0.338	268.01
		Mineral rock wool, WF/ cement board	297	0.322	282.55
		EPS, WF/cement board	289	0.304	283.29
	Insulating clay brick	Cellulose (blown), WF/ cement board	270	0.299	210.41
		Mineral rock wool, WF/ cement board	297	0.288	224.95
		EPS, WF/cement board	276	0.304	225.50
	Autoclave aerated concrete (AAC) block	Cellulose (blown), WF/ cement board	290	0.314	197.86
		Mineral rock wool, WF/ cement board	307	0.304	204.28
		EPS, WF/cement board	296	0.317	212.95
	Reinforced concrete wall	XPS	293	0.286	365.00
		XPS, mineral rock wool	305	0.284	363.25
		XPS, WF/cement board	342	0.277	399.05
ROOFS	Reinforced concrete roof	XPS, WF/cement board, pumice	328	0.311	364.60
		XPS, WF/cement board, pumice	353	0.298	396.60
		XPS, pumice	304	0.302	343.53
	Beam and vault roof system (EPS)	XPS, WF/cement board, pumice	455	0.255	232.36
		XPS, WF/cement board, pumice	455	0.296	264.27
		XPS, pumice	405	0.319	214.86
SLABS	Reinforced concrete slab	XPS, pumice	344	0.299	442.48
		XPS, pumice	377	0.272	485.55
		XPS, pumice	377	0.264	475.15

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[41] All fabrics are in the around 30 cms of thickness and a U-value of 0.3 W/m^{2}K. In every case, a gypsum plaster for internal finish and cement render as external finish was considered, except for underground elements (13-16, 18,19,21-24).

Conclusions

This study explored sustainable design alternatives that have impact on operational carbon used for cooling in Mexican dwellings, especially for regions of the country where energy consumption escalates in hot seasons of the year. It is unreal to expect energy savings by adopting half measures, as currently done in the country. Strategies should be applied having a thorough understanding on properties of materials and building physics to adequately propose efficient thermal envelopes with real impact on decrease of energy consumption, and improved indoor environment conditions. Specific features on the site and climate are to be considered as well.

Traditionally built construction elements appeared to manage moisture through the same building fabric in an efficient way, although its thermal properties are seriously compromised because of this. If not addressed, poor performance of buildings will tend to increase energy consumption.

Construction energy-efficient buildings imply a series of practical on-site challenges. Tight supervision, knowledge of concepts and attention to the detail are integral. Training and informing on-site staff about the basic principles explaining its implications could really make a positive result.

Refurbishment of the present building stock is another important challenge. Existing buildings will have, at some point, to adjust to energy regulations or simply, new sustainable uses. Design should consider future implications to make sure that they will not tend to overheat in the future. In new buildings, designers have the liberty of planning beforehand moisture, airtightness and insulation strategies suitable for a low energy building. In a refurbishment, knowledge on the pre-existing condition of the building is sometimes unknown. Sometimes, it is necessary to cut through the walls to investigate the current condition of the building looking for evidence that would allow to make the correct decisions. Life-cycle analyses in new and refurbished buildings that consider capital, maintenance and operational costs of buildings are fundamental to achieve a resilient, sustainable and responsible architecture practice. In the long term, sustainability has always a positive aftermath, either in environmental or financial dimensions.

Moreover, the future may be in vernacular expressions. Materials with presence in vernacular Mexican typologies such as reeds, straw bales, palm tree and claystone are difficult to be adopted as mainstream insulating and construction materials at this point because their physical properties have not been widely researched. Moreover, lack of adoption depends as well on lack of steady and consistent features when using them. Raw materials cannot be used in their natural form because they need previous treatment due to safety and hygiene reasons. Some of them could potentially absorb high quantities of moisture, which is undesirable for any building material. They should be waterproof (to avoid moist storage), anti-flammable, ensure a good level of hygiene, and unattractive to vermin and mould growth. Claystone and mudstones, which are combined with natural products such as straw, reeds or even manure are, in principle, a promising vernacular expression that could serve as an excellent energy-efficient thermal envelope and thus should be further investigated. In sum, an energy-efficient building may not be designed with expensive technology, high-impact, inorganic synthetic materials.

Mainstream adoption of natural construction and insulating materials has many ecological advantages such as massive carbon sequestration but should be done in a responsible way. An increased demand for natural based products could lead to a greater depletion of tropical rainforests. Mexico is particularly vulnerable in this sense as it has a timber industry with incipient or no forest conscience. In the other hand, a timber industry where forest areas are managed and increased to reach demand will turn into effective carbon emission locks, as currently happens in countries with sustainable forest development such as Sweden.

There are no universally applicable solutions or approaches. It was realised that attempting to make unique or 'fit-all' details could in fact lead to irresponsible building practices.

The suggested improvements in this study are meant to serve as a reference point to illustrate how energy efficiency in buildings could be approached. Every case should be carefully addressed according to climate, site conditions, needs, available materials, technology, budget and workforce, as in any project.

Reducing the carbon footprint of new and refurbished buildings can start taking very simple measures such as: considering regionally available materials, avoiding over-ordering materials, re-using and recycling wherever possible are just some of them. And they could potentially bring down capital costs in construction.

It is important that architects and designers are aware of the manufacture and transportation processes involved in the materials that are considered in the design. But most important of all, build once and well to avoid after-occupancy corrective measures to the building.

Some architects are reluctant to energy efficiency measures arguing that it is not their responsibility to address those issues. However, the architect's role is ensuring comfortable inside conditions to the user, considering their needs and reality with the resources which are available. The challenge relies in adapting and responding to the depletion of our natural resources. Denial of the problem, frequently tied with a state of comfort, is impeding our built environment to adapt to the environmental challenges.

References

ALEV, Ullar, Andres Uus, and Targo Kalamees . “Comparison of Mineral Wool, Cellulose and Reed Mat for Interior Thermal Insulation of Log Walls.” 25 09 2015. file:///C:/Users/Naoki/Downloads/Fail_Comparison%20of%20Mineral%20Wool,%20Cellulose%20and%20Reed%20Mat%20for%20Interior%20Thermal%20Insulation%20of%20Log%20Walls%20(1).pdf (accessed 08 10, 2017).

BROWN, G.Z., y Mark DeKay. *Sun, Wind & Light: Architectural Design Strategies.* Second edition. New York: John Wiley & Sons, Inc., 2001.

CIRCULAR Ecology. *Embodied energy and carbon - The ICE database.* 2017. http://www.circularecology.com/embodied-energy-and-carbon-footprint-database.html#.wxy9d4g1_IU (accessed 07 29, 2017).

COTTERELL, Janet, and Adam Dadeby. *The Passivhaus Handbook: A practical guide to constructing and retroffiting buildings for ultra-low energy performance*. Plymouth: Green Books, 2012.

DIARIO Oficial de la Federación. “NOM-020-ENER-2011, Eficiencia energética en edificaciones.- Envolvente de edificios para uso habitacional.” 09 08 2011. http://dof.gob.mx/nota_detalle.php?codigo=5203931&fecha=09/08/2011 (accessed 05 05, 2017).

FERREIRO, Héctor, Victor Fuentes, Salvador Gutierrez, Mario Hernandez, and Nicte Olivares . Manual for *Solar Architecture*. 1st edition. Mexico: Trillas, 1991.

GELLERT, R. “Natural fibre and fibre composite materials for insulation in buildings.” *In Materials for energy efficiency and thermal comfort in buildings*, edited by Matthew Hall, 229-252. Nottingham: Woodhead Publishing Limited, 2010.

GONZALEZ, Alex, Carolina Recart, Rodrigo Espinoza, and Ariel Bobadilla. “Simple Tool to Evaluate Airtightness in Chilean Homes.” Switzerland: MDPI, 2016.

GUILLOTT, T, and C Spataru. “Materials for energy efficiency and thermal comfrort in the refurbishment of existing buildings.” *In Materials for Energy Efficiency and Thermal Comfort in Buildings*, edited by Matthew Hall, 649-674. Oxford: CRC Press, 2010.

HALL, Matthew, L Gellert, and A Peacock. *Materials for Energy Efficiency and Thermal Comfort in Buildings*. Nottingham: Woodhead Publishing Limited, 2010.

HAMMOND, Geoffrey P, and Craig Jones. “*Embodied energy and carbon in construction materials*.” In Proceedings of the Institution of Civil Engineers - Energy, 87-98. Bath: ICE Publishing, 2008.

HAMMOND, Geoffrey, y Craig Jones. *Embodied Carbon: The Inventory of Carbon and Energy (ICE).* 2011. file:///C:/Users/Naoki/Downloads/embodied-carbon-the-inventory-of-carbon-and-energy-ice%20(sample).pdf (último acceso: 08 de 08 de 2011).

INTERNATIONAL Passive House Association. “Active for more confort: Passive House .” 2014. https://passivehouse-international.org/upload/download_complete_PH_Brochure.pdf (accessed 02 05, 2017).

KÖMMERLING. “Thermal conductivity according to profile fabric.” n.d. http://www.kommerling.com.mx/aislamiento-termico.php (accessed 08 02, 2017).

MURGUÍA, Miguel, and Diana Mateos. *Detalles de arquitectur*a. Third. Mexico: Pax Mexico, 1997.

PFUNDSTEIN, Margit, Roland Gellert, Martin Spitzner, and Alexander Rudolphi. *Insulating Materials: Principles, Materials, Applications*. First. Munich: Detail Practice, 2008.

SCOTTISH Government. *Maximum U-values for building elements of the insulation envelope*. 2015. http://www.gov.scot/Topics/Built-Environment/Building/

Building-standards/publications/pubtech/th2015domcomp (accessed 08 18, 2017).

SEGOVIA, Jose Antonio. *Tipos de cimentaciones recomendadas para el D.F.* 2013. http://www.smig.org.mx/peritos-profesionales-en-geotecnia.php accessed 08 11, 2017).

SENER. "Prospectiva del sector energético 2015-2029." 2015. https://www.gob.mx/cms/uploads/attachment/file/44328/Prospectiva_del_Sector_Electrico.pdf (accessed 06 12, 2017).

SOLANO, Naoki. "Conjunto Puerto México (building)." Mexico City, 2015. —. *Sustainability Line*. Dundee: University of Dundee, 2017.

VAZQUEZ, Cesar. "Documentos de Arquitectura: Detalles de ventanas de canceleria de aluminio de fijos y corredizas de 2" incluye sus perfiles y detalles especificados." 24 02 2013. http://documentos.arq.com.mx/Detalles/111548.html (accessed 08 02, 2017).

Naoki Enrique Solano García
naoki@comunidad.unam.mx

Investigador de Carrera en el Centro de Investigaciones en Arquitectura, Urbanismo y Paisaje de la Facultad de Arquitectura de la UNAM. Es arquitecto por la Facultad de Arquitectura de la UNAM (2012) y cuenta con estudios de Maestría en Ciencias de Diseño y Construcción de Edificios de Cero Emisiones y Baja Energía, por la Universidad de Dundee, habiendo ganado una Beca Chevening para la realización de estudios de posgrado en el Reino Unido (2017). Su línea de investigación se centra en la eficiencia energética de envolvente arquitectónica.