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Effects of Thermal Bridges on the Thermal Performance of External Walls

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Abstract*: Cooling and heating become an important operational process in buildings. This process instates the consumption of energy to attain the desired conditions of comfort. This consists of adding or removing amounts of heat to or from the building depending on the surrounding climatic conditions. The created difference between internal and external conditions releases a heat flow from the hot environment to the colder environment. The flow and the amounts of heat traversing the building envelope depend on the capacity of the building envelope to obstruct the heat flow. Therefore, the thermal resistance of the building envelope is a crucial variable in the equation of energy-saving plans and sustainability strategies. The current research focuses on the thermal resistance of the external wall as a main part of the building envelope, it emphasizes the phenomena of thermal bridging in external walls. In thermodynamics, thermal bridges refer to a higher flow of heat transfer through a specific material, more conductive than its surroundings. Thermal bridges in building walls are usually caused by mortar joints used between insulated building blocks, solid blocks used as per the specifications of masonry works in the first line of blockwork and around openings, and by the concrete columns and beams within the building envelope. The present research investigates the effects of different thermal bridges on the performance of the external wall in terms of thermal transmittance and energy saving. The thermal resistance of external walls is calculated according to the combined method. The studied cases show that the ratios of different components of external walls depend on several parameters including the structural design and blockworks construction details. Mortar joints in blockworks are not regular; they vary roughly from 15 mm to 25 mm. The thermal bridging effect of mortar joints is simulated by reducing wall thermal resistance by a percentage that depends on the thickness of mortar joints between units of thermal blocks. The solid blocks used in the construction of external walls are used, due to some technical requirements, to make the first line of walls and around openings. They constitute an important thermal bridge also; in fact, they occupy an important fraction of the external wall reaching 8%. The third thermal bridge taken into consideration in this research is the exposed concrete within the building envelope. Despite the use of some solution applied to insulate exposed concrete, in all investigated cases and almost all cases, the concrete elements within the building envelope remain without thermal insulation. These percentages of thermal performance reduction due to different thermal bridges are obtained from a calculation of the thermal resistance of walls for different study cases using the combined method. The results show a huge drop in the thermal performance of external walls which results in a big loss of energy used to neutralize the transferred heat inside/outside the buildings through different thermal bridges.

***Keywords*: Thermal bridges, External wall, Energy-saving, Thermal insulation, Sustainability, Thermal resistance, Thermal transmittance, U value.**

1. Introduction

The severe climate change and global warming, due mainly to the increase in energy consumption, push to use more and more energy to compensate for the extra heat generated because of global warming. This vicious cycle of using more energy to neutralize the extra warming which is the consequence of energy consumption itself, continues unfortunately, and warns of worse consequences. CO2 levels have increased 25% since pre-industrial times because of human activities. According to estimates stated in “Global warming and energy demand” by T. Barker, P. Ekins, and N. Johnstone, the earth’s average surface temperature without the greenhouse effect would be −18 °C rather than +15 °C. Additionally, 60% of worldwide energy is consumed by the construction industry, 40% of which is consumed by buildings, and 70.4% of the energy consumed by buildings is by residential buildings. It is worth stating, in this context, that a big of the heat loss occurs through thermal bridges within the building envelope. A recent study done in the UAE by A. Al Amoodi and E. Azar, reports that over 59% of the total residential building energy consumption is due to HVAC. Therefore, residential buildings present a significant opportunity to decrease the effect of thermal bridges and energy consumption and thereby reduce the emission of greenhouse gases.

Historically, the oil crisis or oil shock in 1973 constituted the beginning of thinking to control the consumption of energy derived from fossil sources. Among the important topics that were on focus was thermal insulation because of its impact on energy consumption, and thinking began to create requirements related to the thermal insulation of buildings to reduce their energy consumption. The requirements and specifications for building insulation have become frequent, and the Kyoto Protocol of 1997 was an additional incentive to generalize the issue of insulation and control energy consumption at the global level. The issue of energy is still of great importance at the global level, and perhaps what it is witnessing in the current period of major fluctuations is clear evidence that energy is the most important element affecting the economies and policies of countries.

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The background of the current research, reviewed next, highlights the policies and the regulations issued by different authorities in the UAE concerning the thermal insulation of building envelope and specifically what concerns thermal bridging. Nevertheless, thermal bridges are mainly located in external walls, most of the conventional building systems do not care about them and do not consider their effects on the thermal resistance of the walls. However, some authorities imposed the elimination of thermal bridges, the implementation of the different proposed solutions faced difficulties and generated several problems.

The building envelope creates a thermal diaphragm separating the inside of buildings from the outside. Once a difference in temperature between the inside and outside is set, the heat starts moving toward a lower temperature zone to establish a temperature balance. The role of the air conditioning system is to neutralize the transferred heat inside the conditioned area. AC units act proportionally to the transferred quantity of heat so that a clear linear correlation between transferred heat and consumed energy for AC is proven. It comes then to evident interest in minimizing the flow of transferred heat. This is why the thermal transmittance of the building envelope is vital in this equation.

Thermal bridges are usually neglected by thermal insulation regulations and heat load calculation due to their supposed small magnitude in overall heat losses. The objective of this research is to perform a detailed analysis and calculation using the combined method to determine the thermal resistance of external walls based on actual measurements of mortar joints and all types of blockwork to quantify the magnitude of this thermal bridging effect. The calculation method, known as the Combined Method, is set out in BS EN ISO 6946.

2. Background

In 2003 Dubai Municipality issued an administrative resolution regarding thermal insulation of building envelope "Administrative Resolution No. (66) of 2003 Approving Regulations on the Technical Specifications for Thermal Insulation Systems and Control of Energy Consumption for Air-conditioned Buildings in the Emirate of Dubai". In Chapter One of the mentioned resolution which deals with Elements of Design, mentioned in its Section One "Building Design and Materials Selection" Article (7) the following:

In designing a building and selecting the materials forming its surfaces, the engineering principles aiming to reduce heat transmission from outside into the building shall be observed as follows:

A. External Walls and Roofs

Heat-resistant materials and thermal insulation materials locally available shall be used in the substances forming the roofs and external walls, such that the overall transmission coefficient- U does not exceed the following values:

Roof: U= 0.44 W/m^2.K. (0.078 Btu/h.W.°F)
Wall: U= 0.57 W/m^2.K. (0.100 Btu/h.ft2.°F)

In Chapter Three "General Guidelines", Article (12) Enhances the following:

The values of heat transmission coefficients set out in Article (7) hereof represent the maximum permitted limits. Such values should be preferably reduced by the use of the best thermal insulation methods or by the use of more heat-resistant materials.

Article (14): Thermal bridges in the buildings must be insulated as they represent passage for the flow of heat from outdoors into the building, such as the connection points between concrete beams and the external walls and the columns.

Moreover, the Dubai Building Code stated in its 2021 version in Section "E.5.2.3 Building envelope performance - E.5.2.3.1 Non-glazed elements" and K.7.2 Energy conservation - K.7.2.2 Building envelope performance - K.7.2.2.1 Non-glazed elements" that the average thermal transmittance of external wall should less than 0.57 W/m2K. It adds, however, "While the U-value for external walls can be achieved using aerated concrete blocks, the use of insulation for the entire building envelope is recommended".

Ministry Of Energy and Infrastructure issued also The National Green Building Regulation (NGBR). The mentioned regulation was the result of collaboration works and efforts of the following authorities and entities:

Department of Municipal and Transport	Fujairah Municipality
Department of Energy -Abu Dhabi	Sharjah Municipality
Dubai Municipality	Emirates Green Building Council
Dubai Electricity and Water Authority	Ajman Municipality
Ras Al Khaimah Municipality	Ministry of Industry and Advanced Technology
Umm Al Quwain Municipality	Sharjah Electricity, Water, Gas Authority

The NGBR includes in its chapter 1 "301 Chapter 1 – Energy Efficiency – 301.01 Building Envelope Performance - Requirements for Opaque Elements:

The average u-value of the external walls and roofs (that are exposed to ambient conditions) must not exceed the following thresholds:

Average external wall u-value ≤ 0.48 W/m²K, (this includes the block work and structural columns and beams).

It is clear that almost all legislative parts like municipalities are aware of the importance of the thermal insulation of external walls, however, the implementation of the regulation in this regard remains facing difficulties due to inefficient thermal insulation systems available for external walls. The main problem defecting the insulation of external walls is the thermal bridging. Despite a few solutions imposed to insulate exposed concrete within the building envelope, the issue persists mainly because of the important side effects of the proposed solutions.

Despite the solutions proposed in the last years, thermal bridging persists and represents a considerable issue affecting the thermal performance of external walls. A new system THERMOCOAT has been invented in order to remedy this building's pathology.

Despite the efficiency of the invented system THERMOCOAT and its reward by the Ministry of Energy and Infrastructure in 2023, the implementation of the mentioned system faces considerable resistance to take place as an efficient solution for thermal bridging phenomena and to improve the thermal insulation of external walls. While many thermal analysis and studies have been elaborated to put in evidence the importance of the proposed solution, these efforts are still not enough to enable THERMOCOAT as a solution for thermal bridging of external walls.

The current research accentuates the mentioned efforts by putting in evidence the huge effects of thermal bridging on the thermal performance of building envelope. The study of different actual cases shows that the precalculated transmission coefficients do not correspond to physical reality which mistakes the calculation of heat losses. All necessary calculations are performed based on the actual structural design and the actual joints of masonry units as well as their thermal transmittance coefficients. Wrong assumptions, over simplifications, and neglecting the presence of thermal bridges can lead to significant underestimation of actual heat flows through the external walls.

3. Thermal Analysis and Calculation of Study Cases

A. Description of the Method

The used method to calculate the thermal transmittance and thermal resistance is the Combined Method set out in BS EN ISO 6946. It involves the calculation of the upper limit of thermal resistance of the element and the lower limit of thermal resistance. Any inhomogeneous layer is to be treated as a bridged layer when using this calculation method. The standard calculates the U-value of the component from the arithmetic mean of these two limits. The actual value always lies between the two mentioned limits. The upper limit of the thermal resistance is calculated by combining in parallel the total resistances of all possible heat-flow paths. In the study cases, there are four paths according to the wall core composition. The first path regards the solid blocks, the second is of mortar joints of blockwork units, the third path is of the concrete elements within the external wall, and finally the thermal block path. The latter constitutes the core of the conventional thermal insulation of external walls. The lower limit of the thermal resistance assumes the principle of isothermal surfaces. It is calculated by combining in parallel the resistances of the heat flow paths of each layer separately and then summing the resistances of all layers of the plane-building element.

B. Heat Exchange of Buildings

The amount of energy that's consumed for heating and cooling buildings depends significantly on geographic location, house size, construction type, and the materials used for construction. In fact, the heat flow through the envelope of the buildings is mainly ruled by the difference of indoor and outdoor temperature, the thickness and area of the envelope and the type of materials constituting the envelope.

1) Essential Concepts

- Heat always moves from warmer areas to colder areas. In winter, we heat the interior of a home, so the direction of heat flow is from inside to outside. In summer when it's hotter outdoors, the direction is reversed.
- The greater the temperature difference, the faster heat flows. If it's 70°F inside and 75°F outside, there's not much energy moving through the enclosure, and the difference is not very noticeable. But, if it's 70°F inside and 0°F outside, there is a lot of heat flow, and the difference is immediately noticeable.
- Air contains moisture vapor. The warmer the air is; the more moisture it can hold. The moisture in the air condenses inside the wall, causes damage, and affects consequently the building's durability.
- The building envelope (roof, walls, foundation, windows, and doors) controls tightly the amount of heat exchange with the external environment.

The importance of the thermal insulation of buildings becomes a crucial aspect that needs more attention by designers and building construction companies.

C. Thermal Bridges

The term "thermal bridges" refers to weak points in the building envelope that allow heat to pass through more easily. They occur where materials that are better conductors of heat are allowed to form a 'bridge' between the inner and outer face of a construction.

A thermal bridge has a higher thermal conductivity than the surrounding material, allowing heat to flow more easily through that section. This can result in heat loss in the winter and heat gain in the summer, making the building less energy efficient and potentially causing discomfort for the occupants. Additionally, thermal bridges can lead to condensation and mold growth, which can cause damage to the building and health problems for the occupants.

Thermal bridges are generally located at the connection points of different parts of the building. In the study cases, three main thermal bridges break the insulation of external walls commonly made of thermal blocks. In France, Total Energies estimates that thermal bridges cause more than 40% of heat losses.

The following table presents the thermal characteristics of bridged and bridging materials.

1) Thermal Bridges of Masonry Mortar Joints

They represent a significant fraction of the blockworks area depending on the thickness of mortar joints. As per the investigations undertaken on sites, the thickness of these joints vary between 15mm to 25 mm. Accurate calculation of the joints area have been done however the BRE as the UK's leading centre of expertise on the built environment, construction, sustainability, energy, fire and many associated issues precise in this context that it is needed to include mortar joints in the calculation for both inner and outer leaves of walls by treating the masonry leaf as a bridged layer. The joints may be disregarded, however, if the difference in thermal resistance between bridging material and the bridged material is less than 0.1 m2K/W. For normal mortar this means that the joints can be disregarded when the thermal conductivity of the masonry units is greater than 0.5 W/m·K and the thickness of the blocks

Table 1
Thermal characteristic of wall materials

Material	Thk. [m]	l [W/mK]	r [Kg/mc]	R [m2K/W]
Cement mortar	0.200	0.94	1900	0.213
Cement mortar	0.250	0.94	1900	0.266
Cement mortar	0.300	0.94	1900	0.319
Solid block	0.200	1.27	2240	0.157
Solid block	0.250	1.27	2240	0.196
Hollow block 200	0.200	1.17	1900	0.171
Thermal block 200-60	0.200	0.10	1350	2.083
Thermal block 250-60	0.250	0.12	1390	2.033
Thermal block 250-110	0.250	0.08	1220	3.086
Thermal block 300-75	0.300	0.14	1700	2.113
Thermal block 300-160	0.300	0.07	792	4.615
Reinforced concrete	0.200	1.85	2400	0.108
Reinforced concrete	0.250	1.85	2400	0.135
Reinforced concrete	0.300	1.85	2400	0.162
Polystyrene - Extruded	0.060	0.03	35	1.935
Polystyrene - Extruded	0.075	0.03	35	2.419
Polystyrene - Extruded	0.100	0.03	35	3.226

or bricks is not more than 105 mm; that applies to almost all brickwork, and to most walls built with dense masonry units. Otherwise include the mortar joints in the calculation. The fraction of mortar is as follows:

- for blocks of face area 440 × 215 mm with 10 mm joints, fraction = 0.067
- for other cases the fraction is calculated as follows:

later.

$$1-\frac{(\textbf{block length}\times\textbf{block height})}{(\textbf{block length}+\textbf{joint thickness})\times(\textbf{block height}+\textbf{joint thickness})}+0.001$$

In which the term 0.001 allows for half blocks at corners etc.

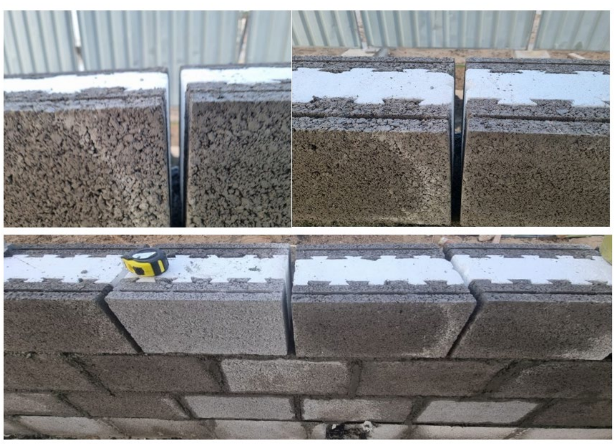

Fig. 1. Mortar joints of thermal blocks

According to the investigations undertaken in different projects, the thickness of masonry mortar joints varies between 15 mm to 25 mm. In some cases, a thickness of 30 mm is reached.

Fig. 2. External wall made of thermal blocks under construction

As per the BRE formula presented previously the fraction is calculated as follows:

1st case:

- Height of masonry unit (thermal block): 200 mm
- Length of masonry unit (thermal block): 400 mm
- Thickness mortar joint: 15 mm

The fraction equals 0.104

2nd case:

- Height of masonry unit (thermal block): 200 mm
- Length of masonry unit (thermal block): 400 mm
- Thickness mortar joint: 20 mm

The fraction equals 0.135

3rd case:

- Height of masonry unit (thermal block): 200 mm
- Length of masonry unit (thermal block): 400 mm
- Thickness mortar joint: 25 mm

The fraction equals 0.164

Fig. 3. Thickness of horizontal mortar joints

Fig. 4. Thickness of vertical mortar joints

Fig. 5. Mortar joint thickness

Usually, the pre-calculation of the thermal transmittance neglects the mortar joints, this underestimate affects hugely the subsequent values of thermal transmittance and leads to wrong calculation of the cooling loads. The thermal performance of the external wall part made of thermal blocks is significantly reduced as illustrated in the following graph.

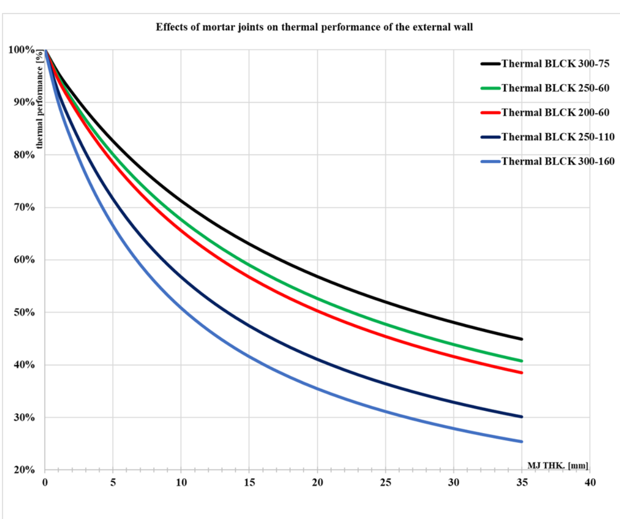

Fig. 6.

The thermal performance is fully considered (100%) without considering the mortar joints, however, it falls down intensely when mortar joints are taken into account. For example, for a wall made of thermal blocks 250 mm with 110 mm polystyrene and mortar joints of 15 mm, the thermal performance is less than 50%.

2) Thermal Bridges of Solid Blocks

The specifications of block masonry impose the use of solid blocks in the first raw of walls as well as around openings (windows and doors), therefore thermal bridges are created in the mentioned locations. As a result, the insulation layer does not continue and gaps occur in it, which creates important thermal bridges that allow a large flow of heat across them. The affected area is estimated at about 8% of the blockwork area of the external wall.

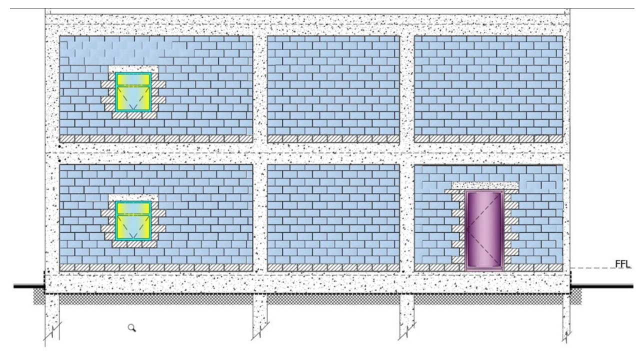

Fig. 7. Illustration of solid blocks

The solid blocks are usually disregarded also, however, they occupy in reality a considerable part of the external wall masonry. The following graph shows the actual performance of the masonry considering solid blocks as well as mortar joints in order to refer to the original base performance of external walls made of purely thermal blocks as it is wrongly considered usually.

The solid blocks accentuate the loss of the thermal performance of a wall made of thermal block 250mm with 110 of polystyrene by 10% more for the case of mortar joint thick 15mm.

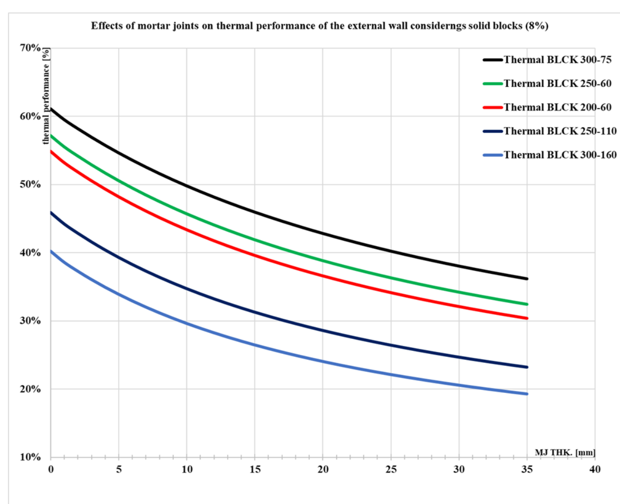

Fig. 8.

3) Thermal Bridges of the Concrete Elements within the Building Envelope

Thermal bridges are produced when the thermal insulation made by thermal block masonry is interrupted by concrete elements such as columns, beams, stiffeners, lintels, etc. The exposed concrete within the external walls area varies between 20 to 45 percent of the total area of external walls. This makes the most important thermal bridge crossing external walls.

Fig. 9.

Fig. 10. External wall beams and columns

Regulations of green buildings impose the necessity of insulating the exposed concrete elements within the building envelope, however, most of the solutions and the practices implemented to ensure the insulation of exposed concrete faced a lot of problems. Several defects have been stated in this application, namely, lack of flatness highlighted by an oblique angle of sunlight striking the surface, cracks in the rendering along the insulation board joints, sweltering or delamination of the finishing coating or all rendering layers, lack of adhesiveness of the system causing its partial or total collapse. Although some of these defects are due to bad workmanship, other pertinent defects are characteristic of the system itself including the nature of the used material and its physical and chemical properties.

a. Low compressive strength resulting in weak resistance to normal impact forces. This is a problem, especially in accessible areas and it not only has an aesthetic impact but also may compromise the system performance.
b. The thermal insulation layer supports the coating and finishing layer, however, it is subject to defacement due to biological growth. Biological growth is due to high values of surface moisture content, which results mainly from the wetting due to surface condensation, which occurs mainly during the nights with clear sky and wetting due to wind-driven rain.

Fig. 11. Concrete stiffener beam for wall reinforcement

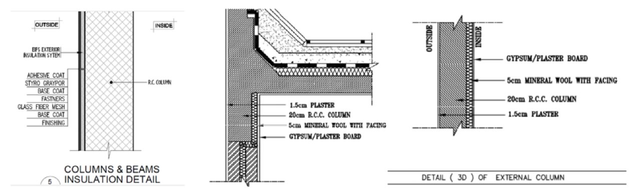

Fig. 12. Details of thermal bridges insulation

Fig. 13. Concrete frame within the external wall

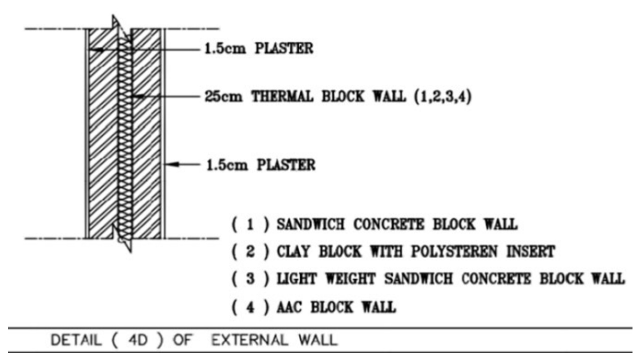

Fig. 14. Detail of external wall made of thermal masonry units not showing mortar joints

The following figure shows the drop in the thermal performance of the external walls according to the concrete percentage out of the wall area. The baseline reference remains the same as for mortar joints and solid blocks and the thickness of the mortar joints is considered 15 mm in the first case and 20 mm in the second case. Due to its higher thermal conductivity and its important area fraction, the concrete creates thermal bridges thermal bridges of higher importance.

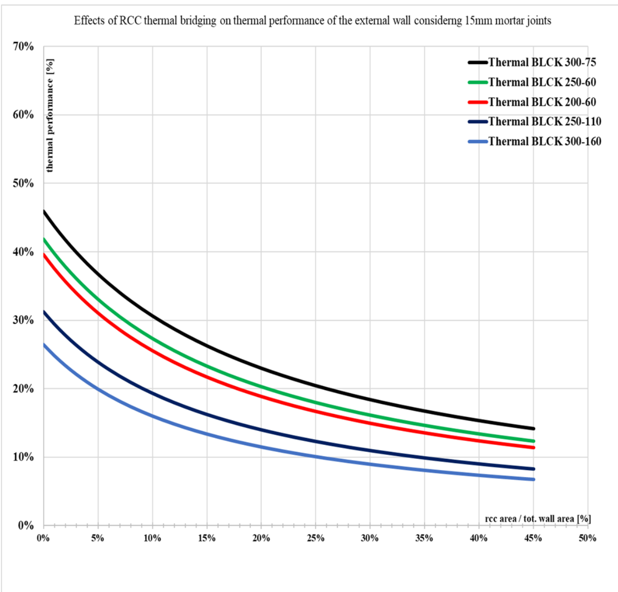

Fig. 15.

For a thermal block 250 mm wall with 110 mm polystyrene, mortar joint thick 15 mm and concrete percentage of 35% of the wall, the thermal performance attains only 10% of the pre-assumed value. The magnitude of error is huge. 90% of the heat traversing the wall is not considered.

For mortar joints thick 20 mm and with the same fraction of concrete area, the effects of bridging are almost stable. The thermal performance is at 9% of it presupposed value.

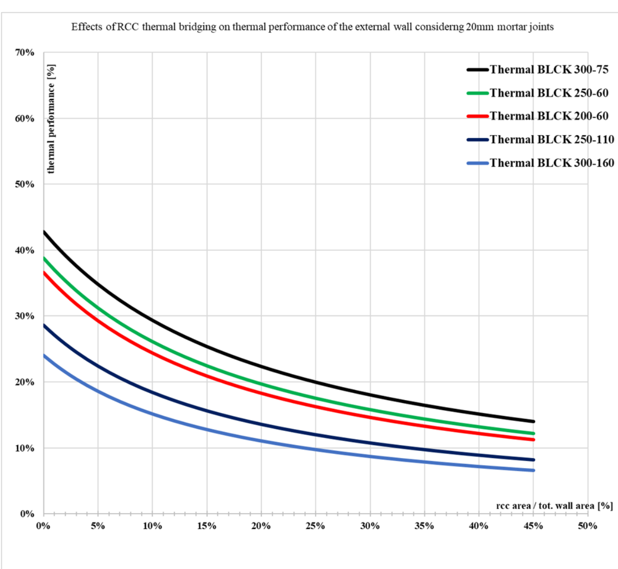

Fig. 16.

4) Interpretation

The performed calculations show clearly that the effects of thermal bridging on the thermal performance of external walls are extraordinary. It creates a big difference between the presumed insulation and the actual performed on sites. The most used insulation of external walls includes insulating masonry units, solid blocks, mortar joints, and reinforced concrete of structural elements within the envelope of the building.

i. Insulation masonry units:
   a. Thermal Block Normal Weight Thin Cavities (Sandwich), 400x300x200, 75 mm insert.
   b. Thermal Block Hollow Normal Weight (Sandwich) 400x250x200, 60 mm insert.
   c. Thermal Block Hollow Normal Weight (Sandwich) 400x200x200, 60 mm insert.
   d. Thermal Block Hollow Normal Weight (Sandwich) 400x250x200, 110 mm insert.
   e. Thermal Block Normal Weight Thin Cavities (Sandwich), 400x300x200, 160 mm insert.

ii. Mortar joint thickness is the variable to determine its effects on the thermal performance of the external wall.

iii. Solid Concrete Block.

iv. Reinforced Concrete with variable fraction to determine its effects on the thermal performance of the external wall. The mortar joint is considered 15mm and 20mm.

The effects of mortar joints are proportional to their thickness; however, their impact is more important for walls made of masonry units with more thermal insulation. The same effect is remarkable for concrete fraction areas. External walls are made of different layers other than the insulation layer. These layers, unlike the core layer of the wall previously described, are generally homogeneous. The calculation of the thermal transmittance of the whole wall is performed using the combined method.

The average case of the wall considers 15mm as mortar joint thickness and 35% as reinforced area fraction; the results of this case show a terrible chute of the thermal performance of the insulating layer of the wall. In fact, for a thermal block of 300 mm with a 160 mm polystyrene insert, the thermal performance is about 8% only of the presumed values. The magnitude of mistaking the actual physiognomies of the wall is very big and cannot be negligible. It is transformed into a huge requirement of energy to neutralize the big quantities of heat leaked through the neglected thermal bridges.

4. Description of Study Cases

The study considered three cases of actual buildings. The design of the three buildings consists of a concrete frame and external walls made of thermal blocks. The thermal insulation of the external walls is made of thermal blocks constructed with cement mortar. The technical specification is the use of solid blocks in the first line of walls and around openings. The elements of the concrete frame within the external wall make a part of it.

A. Case 1

The building is made of a reinforced concrete frame and thermal blocks covered internally and externally by a layer of plaster. The total area of the considered external wall is 724 SQM. The masonry units used in the external wall are thermal blocks of 250mm thickness with 60 insert of polystyrene.

Fig. 17.

Fig. 18. Photos of external wall during construction

Fig. 19. Thickness of mortar joints

Table 2
Fraction areas of external wall as per material

Material	Area [SQM]
Cement mortar	54
Reinforced concrete	276
Thermal Block	308
Solid block	86

1) Upper Limit of the Total Thermal Resistance

The morphology of the external wall is composed of a homogeneous layer made of plaster applied to an inhomogeneous layer on the internal side. The upper limit of the thermal resistance consists of 4 thermal paths. The detailed calculation is developed as follows as per BS EN ISO 6946 and BR 443 as follows.

1st path: outside surface resistance – cement mortar – plaster – inside surface resistance.

2nd path: outside surface resistance – reinforced concrete – plaster – inside surface resistance.

3rd path: outside surface resistance – thermal block – plaster – inside surface resistance.

4th path: outside surface resistance – solid block – plaster – inside surface resistance.

Table 3
Fractions of paths

Path	Fraction
1^{st} path	0.075
2^{nd} path	0.425
3^{rd} path	0.381
4^{th} path	0.119

The upper limit of the total thermal resistance is 0.59 [m^2K/W].

2) Lower Limit of the Total Thermal Resistance

The external wall has a homogenous layer of plaster and inhomogeneous layer consisting of the wall core made of thermal blocks, solid blocks, mortar joints and reinforced concrete.

Thermal resistance calculation of the inhomogeneous layer

The thermal resistance of the inhomogeneous layer is 0.255 [m^2K/W].

The lower limit of the thermal insulation of the external wall equals 0.475 [m^2K/W] and the upper limit, previously calculated, equals 0.587 [m^2K/W].

3) Interpretation

The total thermal resistance of the external wall equals, as the arithmetic mean of the upper and lower limits of thermal resistance, 0.526 [m^2K/W]. The assumed thermal resistance of the wall is of the thermal block without considering thermal bridging equals 2.252 [m^2K/W]. The actual thermal resistance is enormously affected by the thermal bridging; the thermal performance of the wall realizes 23% of its preplanned values. This is converted into a huge heat flow through the external wall and it requires a lot of energy to counterbalance it.

Most of the regulations impose maximum values of thermal transmittance like NGBR, ALGAFA, DM, DBC, etc. The reference values vary between 0.29 to 0.57. The recommended values by NGBR (National Green Building Regulation) concerning thermal transmittance are considered as references;

Table 4

Thermal block	**Total area**	**308.00**	**42.5%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
plaster (cement, sand)	0.020	0.72	1860	0.028
Thermoblock Hollow Normal Weight (Sandwich) 250, 60mm insert	0.250	0.12	1390	2.033
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.290**			**2.252**
Heat transmission coefficient - U value [W/m²K]	**0.444**			

Mortar joint	**Total area**	**54.00**	**7.5%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
plaster (cement, sand)	0.020	0.72	1860	0.028
Cement, mortar	0.250	0.94	1900	0.266
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.290**			**0.486**
Heat transmission coefficient - U value [W/m²K]	**2.060**			

Reinforced concrete	**Total area**	**276.00**	**38.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
plaster (cement, sand)	0.020	0.72	1860	0.028
Reinforced Concrete	0.250	1.85	2400	0.162
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.340**			**0.355**
Heat transmission coefficient - U value [W/m²K]	**2.819**			

Solid block	**Total area**	**86.00**	**11.9%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
plaster (cement, sand)	0.020	0.72	1860	0.028
Solid Block	0.250	1.27	2240	0.196
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.290**			**0.416**
Heat transmission coefficient - U value [W/m²K]	**2.404**			

Uo Value	**1.70**	**[W/m²K]**
Total thermal resistance	**0.59**	**[m²K/W]**

the average thermal transmittance of the external wall including all components should not exceed 0.48 [W/m²K]. The compliance with NGBR requirement is only 25%.

4) Elimination of Thermal Bridging as a Reference Case

To evaluate the effect of the different thermal bridges previously mentioned, the thermal bridging is eliminated by applying THERMOCOAT system to the external wall. This system consists simply of wrapping externally the whole building with a layer of insulation material (extruded polystyrene thick 75mm) and a concrete protection layer thick 60mm. The same calculations have been performed considering the new system, the results are as follows:

Upper Limit of the Total Thermal Resistance:

The calculation of the upper limit of the thermal resistance considers four different paths of heat transfer through the external wall.

The upper limit of the total thermal resistance is 3.382 [m2K/W].

Lower Limit of the Total Thermal Resistance

Thermal resistance calculation of the inhomogeneous layer.

The lower limit of the thermal insulation of the external wall equals 2.927 [m²K/W] and the upper limit, previously calculated, equals 3.382 [m²K/W].

5) Interpretation and Conclusion

The total thermal resistance of the external wall equals, as the arithmetic mean of the upper and lower limits of thermal resistance, 3.154 [m²K/W]. The assumed thermal resistance of the wall is of the thermal block without considering thermal bridging equals 2.252 [m²K/W]. The application of a continuous thermal insulation layer without thermal bridges reaches a very high level of the thermal insulation performance of the external wall; it fulfills the requirement of the national green building regulations by 151%. It also improves the thermal performance of the external wall by 500%.

The simple use of thermal blocks as thermal insulation solution for external walls is not efficient. The comparative analyses show undoubtedly that the main cause of not making this solution effective is thermal bridging.

Table 5
Thermal resistance calculation of the inhomogeneous layer

Thermal block	**Total area**	**308.00**	**42.5%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Thermo Block Normal Weight Thin Cavities, 250 60mm insert	0.250	0.12	1390	2.033
Total	**0.250**			**2.033**
Heat transmission coefficient - U value [W/m²K]	**0.492**			

Mortar joint	**Total area**	**54.00**	**7.5%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Cement, mortar	0.250	0.94	1900	0.266
Total	**0.250**			**0.266**
Heat transmission coefficient - U value [W/m²K]	**3.760**			

Reinforced concrete	**Total area**	**276.00**	**38.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Reinforced Concrete	0.250	1.85	2400	0.135
Total	**0.250**			**0.135**
Heat transmission coefficient - U value [W/m²K]	**7.400**			

Solid block	**Total area**	**86.00**	**11.9%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Solid Block	0.250	1.27	2240	0.196
Total	**0.250**			**0.196**
Heat transmission coefficient - U value [W/m²K]	**5.092**			

Uo Value	**3.916**	**[W/m²K]**
Total thermal resistance	**0.255**	**[m²K/W]**

Table 6
Lower limit of total thermal resistance

Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m2K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
plaster (cement, sand)	0.020	0.72	1860	0.028
Inhomogeneous layer	0.250	#N/A	#N/A	0.255
plaster (cement, sand)	0.020	0.72	1860	0.028
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.290**			**0.475**
Heat transmission coefficient - U value [W/m²K]	**2.106**			

Table 7

Thermal block	Total area	308.00	43%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m^2K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
plaster (cement, sand)	0.020	0.72	1860	0.028
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Thermo Block Hollow Normal Weight (Sandwich) 250, 60mm insert	0.250	0.14	2200	1.838
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.425**			**4.510**
Heat transmission coefficient - U value [W/m^2K]	**0.222**			

Mortar joint	Total area	54.00	7.5%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m^2K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
plaster (cement, sand)	0.020	0.72	1860	0.028
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Cement, mortar	0.250	0.94	1900	0.266
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.425**			**2.937**
Heat transmission coefficient - U value [W/m^2K]	**0.340**			

Reinforced concrete	Total area	276.00	38.1%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m^2K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
plaster (cement, sand)	0.020	0.72	1860	0.028
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Reinforced Concrete	0.300	1.85	2400	0.162
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.475**			**2.834**
Heat transmission coefficient - U value [W/m2K]	**0.353**			

Solid block	Total area	86.00	11.9%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m^2K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Plaster (cement, sand)	0.020	0.72	1860	0.028
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Solid Block	0.250	1.27	2240	0.196
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.425**			**2.868**
Heat transmission coefficient - U value [W/m^2K]	**0.349**			

Uo Value	**0.296**	**[W/m^2K]**
Total thermal resistance	**3.382**	**[m^2K/W]**

Table 8

Thermal block	**Total area**	**308.00**	**42.5%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Thermoblock Hollow Normal Weight (Sandwich) 250mm, 60mm insert	0.250	0.12	1390	2.033
Total	**0.250**			**3.033**
Heat transmission coefficient - U value [W/m2K]	**0.492**			

Mortar joint	**Total area**	**54.00**	**7.5%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Cement, mortar	0.250	0.94	1900	0.266
Total	**0.250**			**0.266**
Heat transmission coefficient - U value [W/m²K]	**3.760**			

Reinforced concrete	**Total area**	**276.00**	**38.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Reinforced Concrete	0.250	1.85	2400	0.135
Total	**0.250**			**0.135**
Heat transmission coefficient - U value [W/m²K]	**7.400**			

Solid block	**Total area**	**86.00**	**11.9%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Solid Block	0.250	1.27	2240	0.196
Total	**0.250**			**0.196**
Heat transmission coefficient - U value [W/m2K]	**5.092**			

Uo Value	**3.916**	**[W/m²K]**
Total thermal resistance	**0.255**	**[m²K/W]**

Table 9

Lower limit of total thermal resistance

Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Plaster (cement, sand)	0.020	0.72	1860	0.028
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Inhomogeneous layer	0.250	#N/A	#N/A	0.255
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.425**			**2.927**

B. *Case 2*

Fig. 20. External wall under construction showing external surfaces and morphology

Fig. 21. Thickness of mortar joints

Fig. 22. External walls under construction

The building considered in the second case is constituted of a reinforced concrete frame and thermal blocks covered internally by a layer of plaster. The total area of the considered external wall is 1183 SQM. The masonry units used in the external wall are thermal blocks of 250mm thickness with 60 insert of polystyrene.

1) *Upper Limit of the Total Thermal Resistance*

The morphology of the external wall is identical to the previous case, except the outer surface in this case is finished with plaster. The upper limit of the thermal resistance consists of 4 thermal paths. The detailed calculation is developed as follows as per BS EN ISO 6946 and BR 443 as follows.

1st path: outside surface resistance – cement mortar – plaster – inside surface resistance

2nd path: outside surface resistance – reinforced concrete – plaster – inside surface resistance

3rd path: outside surface resistance – plaster – thermal block – plaster – inside surface resistance

4th path: outside surface resistance – solid block – plaster – inside surface resistance.

Table 10
Fractions of paths

Path	Fraction
1st path	0.057
2nd path	0.421
3rd path	0.422
4th path	0.100

The upper limit of the total thermal resistance is 0.538 [m^2K/W].

2) *Lower Limit of the Total Thermal Resistance*

The external wall has a homogenous layer of plaster and inhomogeneous layer made of thermal blocks, solid blocks, mortar joints and reinforced concrete.

Thermal resistance calculation of the inhomogeneous layer

The lower limit of the thermal insulation of the external wall equals 0.439 [m^2K/W] and the upper limit, previously calculated, equals 0.538 [m^2K/W].

3) *Interpretation*

The total thermal resistance of the external wall equals, as arithmetic mean of the upper and lower limits of thermal resistance, 0.488 [m^2K/W]. The assumed thermal resistance of the wall is of the thermal block without considering thermal bridging equals to 2.224 [m^2K/W]. The actual thermal resistance is reaches only 22% of its preplanned values.

4) *Elimination of Thermal Bridging as Reference Case*

In order to evaluate the effect of the different thermal bridges previously mentioned, the thermal bridging is eliminated by applying THERMOCOAT system to the external wall. This system consists simply in wrapping externally the whole building by a layer of insulation material (extruded polystyrene thick 75mm) and concrete protection layer thick 60mm. The same calculations have been performed considering the new system, the results are as follows:

Upper Limit of the Total Thermal Resistance:

The calculation of the upper limit of the thermal resistance considers four different paths of heat transfer through the external wall.

The upper limit of the total thermal resistance is 3.344 [m^{2}K/W].

Lower Limit of the Total Thermal Resistance:

The lower limit of the thermal insulation of the external wall equals 2.889 [m^{2}K/W] and the upper limit, previously calculated, equals 3.344 [m^{2}K/W].

5) Interpretation and Conclusion

The total thermal resistance of the external wall equals, as arithmetic mean of the upper and lower limits of thermal resistance, 3.117 [m^{2}K/W]. It fulfills the requirement of the national green building regulations by 150%. It also improves the thermal performance of the external wall by 538%.

The second case confirms the figures of the first case, in fact the use of a full thermal insulation of the external walls improves amazingly the thermal performance of external walls; it growths up to more than 5 times. This is directly transformed into a huge energy saving and reflected and electrical bills.

Table 11

Thermal block	**Total area**	**499.00**	**42.2%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m2K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Thermo Block Normal Weight Thin Cavities 250mm, 60mm insert	0.250	0.12	1390	2.033
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.270**			**2.224**
Heat transmission coefficient - U value [W/m^{2}K]	**0.450**			

Mortar joint	**Total area**	**68.00**	**5.7%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m^{2}K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Cement, mortar	0.250	0.94	1900	0.266
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.270**			**0.458**
Heat transmission coefficient - U value [W/m^{2}K]	**2.185**			

Reinforced concrete	**Total area**	**498.00**	**42.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m^{2}K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.250	1.85	2400	0.135
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.270**			**0.327**
Heat transmission coefficient - U value [W/m^{2}K]	**3.059**			

Solid block	**Total area**	**118.00**	**10.0%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m^{2}K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Solid Block	0.250	1.27	2240	0.196
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.270**			**0.388**
Heat transmission coefficient - U value [W/m^{2}K]	**2.576**			

Uo Value	**1.860**	**[W/m^{2}K]**
Total thermal resistance	**0.538**	**[m^{2}K/W]**

Table 12
Thermal resistance calculation of the inhomogeneous layer

Thermal block	**Total area**	**499.00**	**42.2%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Thermo Block Normal Weight Thin Cavities, 250mm, 60mm insert	0.250	0.12	1390	2.033
Total	**0.250**			**2.033**
Heat transmission coefficient - U value [W/m²K]	**0.492**			

Mortar joint	**Total area**	**68.00**	**5.7%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Cement, mortar	0.250	0.94	1900	0.266
Total	**0.250**			**0.266**
Heat transmission coefficient - U value [W/m²K]	**3.760**			

Reinforced concrete	**Total area**	**498.00**	**42.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Reinforced Concrete	0.250	1.85	2400	0.135
Total	**0.250**			**0.135**
Heat transmission coefficient - U value [W/m²K]	**7.400**			

Solid block	**Total area**	**118.00**	**10.0%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Solid Block	0.250	1.27	2240	0.196
Total	**0.250**			**0.196**
Heat transmission coefficient - U value [W/m²K]	**5.092**			

Uo Value	**4.047**	**[W/m²K]**
Total thermal resistance	**0.247**	**[m²K/W]**

Table 13
Lower limit of total thermal resistance

Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m2K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Inhomogeneous layer	0.250	#N/A	#N/A	0.247
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.270**			**0.439**
Heat transmission coefficient - U value [W/m²K]	**2.278**			

Table 14

Thermal block	**Total area**	**499.00**	**42%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Thermoblock Hollow Normal Weight 250, 60mm insert	0.250	0.14	2200	1.838
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.405**			**4.482**
Heat transmission coefficient - U value [W/m²K]	**0.223**			

Mortar joint	**Total area**	**68.00**	**5.7%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Cement, mortar	0.250	0.94	1900	0.266
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.405**			**2.910**
Heat transmission coefficient - U value [W/m²K]	**0.344**			

Reinforced concrete	**Total area**	**498.00**	**42.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Reinforced Concrete	0.300	1.85	2400	0.162
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.455**			**2.806**
Heat transmission coefficient - U value [W/m²K]	**0.356**			

Solid block	**Total area**	**118.00**	**10.0%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Solid Block	0.250	1.27	2240	0.196
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.405**			**2.840**
Heat transmission coefficient - U value [W/m²K]	**0.352**			

Uo Value	**0.299**	**[W/m²K]**
Total thermal resistance	**3.344**	**[m²K/W]**

Table 15

Thermal block	**Total area**	**499.00**	**42.2%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Thermoblock Hollow Normal Weight, 250mm, 60mm insert	0.250	0.14	2200	1.838
Total	**0.250**			**1.838**
Heat transmission coefficient - U value [W/m²K]	**0.544**			

Mortar joint	**Total area**	**68.00**	**5.7%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Cement, mortar	0.250	0.94	1900	0.266
Total	**0.250**			**0.266**
Heat transmission coefficient - U value [W/m²K]	**3.760**			

Reinforced concrete	**Total area**	**498.00**	**42.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Reinforced Concrete	0.250	1.85	2400	0.135
Total	**0.250**			**0.135**
Heat transmission coefficient - U value [W/m²K]	**7.400**			

Solid block	**Total area**	**118.00**	**10.0%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Solid Block	0.250	1.27	2240	0.196
Total	**0.250**			**0.196**
Heat transmission coefficient - U value [W/m²K]	**5.092**			

Table 16
Lower limit of total thermal resistance

Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.075	0.03	35	2.419
Inhomogeneous layer	0.250	#N/A	#N/A	0.246
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.405**			**2.889**
Heat transmission coefficient - U value [W/m²K]	**0.346**			

C. Case 3

In this case, the full insulation system Thermocoat has been meritoriously used. The insulation is continuously applied to the external wall. The considered opaque area is of 230 SQM. Thermocoat consists, in fact, in applying two layers to the external surface of the wall. The first layer is an insulation layer of extruded polystyrene has 2 added parallel layers. The total area of considered external wall is 1183 SQM. The masonry units used in the external wall are thermal blocks of 200mm thickness with 60mm insert of polystyrene.

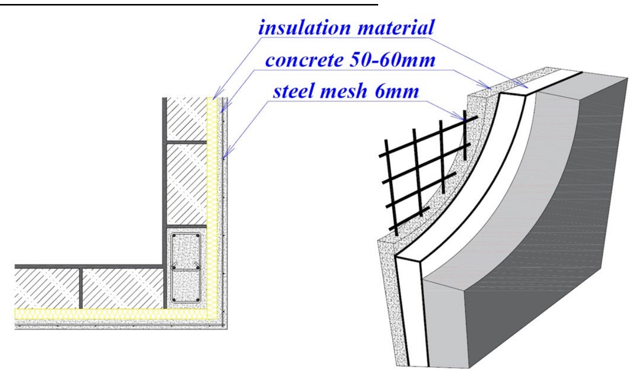

Fig. 23. Illustration of thermocoat system

Fig. 24. Installation of insulation layer

Fig. 25. Thermocoat fully applied on the external wall

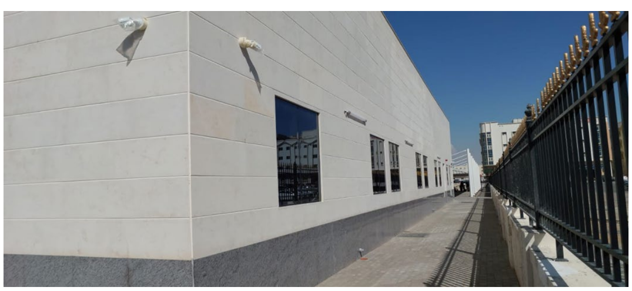

Fig. 26. Stone cladding after application of thermocoat system

1) Upper Limit of the Total Thermal Resistance

The upper limit of the thermal resistance of the external wall considers 4 different thermal paths according to the materials used to construct the external wall. In fact, it is made of 200mm thermal blocks, solid blocks, joint mortar and reinforced concrete. The detailed calculation is developed as follows as per BS EN ISO 6946 and BR 443 as follows.

1st path: outside surface resistance – thermal block – plaster – inside surface resistance.

2nd path: outside surface resistance – reinforced concrete – plaster – inside surface resistance.

3rd path: outside surface resistance – plaster – mortar joints – plaster – inside surface resistance.

4th path: outside surface resistance – solid block – plaster – inside surface resistance.

Table 17

Path	Fraction
1st path	0.545
2nd path	0.229
3rd path	0.091
4th path	0.134

The upper limit of the total thermal resistance is 0.620 [m^2K/W].

Lower Limit of the Total Thermal Resistance

The external wall has a homogenous layer of plaster and an inhomogeneous layer made of thermal blocks, solid blocks, mortar joints and reinforced concrete.

Thermal resistance calculation of the inhomogeneous layer

The lower limit of the thermal insulation of the external wall equals 0.465 [m^2K/W] and the upper limit, previously calculated, equals 0.620 [m^2K/W].

2) Interpretation

The total thermal resistance of the external wall equals, as the arithmetic mean of the upper and lower limits of thermal resistance, 0.542 [m^2K/W]. The assumed thermal resistance of the wall is of the thermal block without considering thermal bridging equals 1.845 [m^2K/W]. The actual thermal resistance reaches only 24% of its preplanned values.

3) Elimination of Thermal Bridging as Reference Case

In order to evaluate the effect of the different thermal bridges previously mentioned, the thermal bridging is eliminated by applying THERMOCOAT system to the external wall. This system consists simply in wrapping externally the whole building by a layer of insulation material (extruded polystyrene thick 60mm) and concrete protection layer thick 60mm. The same calculations have been performed considering the new system, the results are as follows:

Upper Limit of the Total Thermal Resistance:

The calculation of the upper limit of the thermal resistance considers four different paths of heat transfer through the external wall.

The upper limit of the total thermal resistance is 3.068 [m^2K/W].

Lower Limit of the Total Thermal Resistance

The lower limit of the thermal insulation of the external wall equals 2.433 [m^2K/W] and the upper limit, previously calculated, equals 3.068 [m^2K/W].

4) Interpretation and Conclusion

The total thermal resistance of the external wall equals, as the arithmetic mean of the upper and lower limits of thermal resistance, 2.750 [m^2K/W]. It fulfills the requirement of the national green building regulations by 132%. It also improves the thermal performance of the external wall by 407%.

The third case maintains almost the same figures as previous cases. This makes certain the inefficiency and the unsuccessfulness of the conventional thermal insulation of external walls based on the simple use of thermal masonry units. The use of full thermal insulation of the external walls becomes unavoidable to reach the required level of thermal insulation performance of external walls.

Table 18

Thermal block	**Total area**	**126.00**	**54.5%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Thermo Block Normal Weight Thin Cavities (200, 60mm insert	0.200	0.10	1350	2.083
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.220**			**2.275**
Heat transmission coefficient - U value [W/m²K]	**0.440**			

Mortar joint	**Total area**	**21.00**	**9.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Cement, mortar	0.200	0.94	1900	0.213
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.220**			**0.405**
Heat transmission coefficient - U value [W/m²K]	**2.472**			

Reinforced concrete	**Total area**	**53.00**	**22.9%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.200	1.85	2400	0.108
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.220**			**0.300**
Heat transmission coefficient - U value [W/m²K]	**3.335**			

Solid block	**Total area**	**31.00**	**13.4%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Solid Block	0.200	1.27	2240	0.157
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.220**			**0.349**
Heat transmission coefficient - U value [W/m²K]	**2.866**			

Uo Value	**1.614**	**[W/m²K]**
Total thermal resistance	**0.620**	**[m²K/W]**

Table 19
Thermal resistance calculation of the inhomogeneous layer

Thermal block	**Total area**	**126.00**	**54.5%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Thermo Block Normal Weight Thin Cavities, x200, 60mm insert	0.200	0.10	1350	2.083
Total	**0.200**			**2.083**
Heat transmission coefficient - U value [W/m²K]	**0.480**			

Mortar joint	**Total area**	**21.00**	**9.1%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Cement, mortar	0.200	0.94	1900	0.213
Total	**0.200**			**0.213**
Heat transmission coefficient - U value [W/m2K]	**4.700**			

Reinforced concrete	**Total area**	**53.00**	**22.9%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Reinforced Concrete	0.200	1.85	2400	0.108
Total	**0.200**			**0.108**
Heat transmission coefficient - U value [W/m2K]	**9.250**			

Solid block	**Total area**	**31.00**	**13.4%**	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Solid Block	0.200	1.27	2240	0.157
Total	**0.200**			**0.157**
Heat transmission coefficient - U value [W/m2K]	**6.365**			

Uo Value	**3.666**	**[W/m²K]**
Total thermal resistance	**0.273**	**[m²K/W]**

Table 20
Lower limit of total thermal resistance

Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Inhomogeneous layer	0.200	#N/A	#N/A	0.273
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.220**			**0.465**
Heat transmission coefficient - U value [W/m²K]	**2.152**			

Table 21

Thermal block	Total area	126.00	55%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.060	0.03	35	1.935
Thermo Block Normal Weight Thin Cavities 200mm, 60mm insert	0.200	0.10	1350	2.083
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.340**			**4.243**
Heat transmission coefficient - U value [W/m²K]	**0.236**			

Mortar joint	Total area	21.00	9.1%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.060	0.03	35	1.935
Cement, mortar	0.200	0.94	1900	0.213
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.340**			**2.372**
Heat transmission coefficient - U value [W/m²K]	**0.422**			

Reinforced concrete	Total area	53.00	22.9%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.060	0.03	35	1.935
Reinforced Concrete	0.200	1.85	2400	0.108
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.340**			**2.268**
Heat transmission coefficient - U value [W/m²K]	**0.441**			

Solid block	Total area	31.00	13.4%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.060	0.03	35	1.935
Solid Block	0.200	1.27	2240	0.157
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.340**			**2.317**
Heat transmission coefficient - U value [W/m²K]	**0.432**			

Uo Value	**0.326**	**[W/m²K]**
Total thermal resistance	**3.068**	**[m²K/W]**

Table 22

Thermal block	Total area	126.00	54.5%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Thermo Block Normal Weight Thin Cavities, 200mm, 60mm insert	0.200	0.10	1350	2.083
Total	**0.200**			**2.083**
Heat transmission coefficient - U value [W/m²K]	**0.480**			

Mortar joint	Total area	21.00	9.1%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Cement, mortar	0.200	0.94	1900	0.213
Total	**0.200**			**0.213**
Heat transmission coefficient - U value [W/m²K]	**4.700**			

Reinforced concrete	Total area	53.00	22.9%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Reinforced Concrete	0.200	1.85	2400	0.108
Total	**0.200**			**0.108**
Heat transmission coefficient - U value [W/m²K]	**9.250**			

Solid block	Total area	31.00	13.4%	
Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Solid Block	0.200	1.27	2240	0.157
Total	**0.200**			**0.157**
Heat transmission coefficient - U value [W/m²K]	**6.365**			

Uo Value	**3.666**	**[W/m²K]**
Total thermal resistance	**0.273**	**[m²K/W]**

Table 23
Lower limit of total thermal resistance

Elements description	**Thk. [m]**	**l [W/mK]**	**r [Kg/mc]**	**R [m²K/W]**
Outside Surface Film Resistance for Walls	0.000	0.00	0	0.044
Reinforced Concrete	0.060	1.85	2400	0.032
Polystyrene - Extruded	0.060	0.03	35	1.935
Inhomogeneous layer	0.200	#N/A	#N/A	0.273
plaster (cement, sand)	0.020	0.72	1860	0.028
Inside Surface Film Resistance for Walls	0.000	0.00	0	0.120
Total	**0.340**			**2.433**
Heat transmission coefficient - U value [W/m²K]	**0.411**			

5. General Conclusion

This research demonstrates that it is impossible to attain the required insulation of the building envelope without eliminating thermal bridges; it shows how huge the negative impact of thermal bridging on the thermal performance of external walls is. Concrete within the building envelope, mortar joints, and solid blocks which are the main thermal bridges present in external walls, vain the efforts to insulate the walls by using thermal blocks and make their contribution to block the thermal flow through the wall almost null. Although the efforts realized to eliminate these thermal bridges and minimize their effects, the problem persists and still defects the thermal insulation of buildings.

The present research is vital to attain the objective of sustainability in the UAE concerning the building sector. It makes clear the real situation of the thermal insulation of external walls and how far it is from the levels targeted by different authorities and regulations. Although the results are unsatisfactory, they give an etat des lieux and a real diagnostic of the situation; this would lead to taking necessary action to reduce the drastic effects of thermal bridging phenomena on the thermal performance of external walls. However, the authorities governing the industry of building are aware of the issue and adopted policies and regulations to control the mentioned issue and reduce its effects, the market remains dominated by conventional building systems and methods which are not yet able to solve the thermal bridging problem. This keeps a huge heat flow traversing the building envelope through the different thermal bridges and leads to high energy consumption to neutralize transmitted heat.

Interest seems not enough attractive for real estate developers to adopt new solutions and techniques in the designs and the construction industry since energy saving for example is not interesting for them as long as they are not the users of residential units and as a consequence, they are not the payer of the electricity bills. However, individual owners of residential units like villas and government buildings could get direct profits, they are not yet enough aware of the thermal bridging phenomena and its drastic effects on the thermal insulation of external walls. In the absence of efficient solutions for thermal bridging, the problem persists.

Considering the importance of the thermal bridging issue, it is recommended that energy audits and assessments be implemented to identify the actual problems, including the thermal insulation of external walls and especially the effects of thermal bridging. Moreover, energy-saving and sustainability policies must include more incentives to adopt energy-efficient technologies and practices in their measures and regulations.

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