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Cost Effective Manufacturing of Thermal and Acoustic Insulating Bricks using Concrete Plates, Recycled Plastics and Fibers

Mehdi Meliani*, Jamal Echaabi, El Hassan Mallil , Aziz Maziri

ENSEM - Ecole Nationale Supérieure de l'Electricité et de Mécanique, Université Hassan II of Casablanca
Department of Mechanical Engineering, Route d'El Jadida, Km 7 – BP 8118, Oasis – Casablanca, Morocco

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mehdi.meliani@gmail.com
Phone: +212652027392;

Abstract

In this study, a new cost-effective method of manufacturing composite bricks is presented. These bricks are designed to achieve high thermal and acoustic insulation, with good mechanical resistance. The manufacturing process is based on relatively simple and fast steps. Firstly, filling a recycled thin plastic container with cellulose fibers. Secondly, bonding the filled and sealed plastic containers with precast concrete plates using adhesive glue. Finally, alternating three plates of cement concrete and two insulating plastic containers filled with cellulose fibers, to obtain the brick with a thickness of 23 cm, which can also be used as slab element. The physical features of the brick's materials are assessed, as well as the mass percentages of the its constituents. The cost of the brick per unit mass was therefore estimated, and it was found that this cost is approximately 50% higher than the one of ordinary bricks made of concrete. In the second part of this study, the analysis of the characteristics of the brick is carried out, based on the calculations of the predictive compressive, flexural and thermal resistances, as well as the predictive sound reduction index of a wall built by these bricks. These calculations are performed using either specific mechanical and thermal formulas or using acoustic software simulation applied for a wall built by these bricks. The obtained results show a good compressive strength R_c of 7.2 MPa, and especially excellent thermal resistance R_T reaching 3.6 m².K/W and very good sound reduction index R_w of 56 dB.

1. Introduction

Nowadays, the construction of walls and floors in residential buildings uses bricks and slabs made of conventional materials such as concrete and fired clay, with alveolar shapes, reduced thickness and lightweight, to make the construction cost-optimized and also to get lighter loads applied on the bearing elements. Nevertheless, the thermal and acoustic insulation features are not fully taken into consideration in the design of the walls and the floors, which implies lower energy efficiency and insufficient noise control that affects the life quality of inhabitants. For these reasons, building codes in many countries recommend compliance with the insulation norms in building envelopes, through setting minimum values for thermal resistance and sound reduction index for them [1, 2]. Even if the requirements of thermal and acoustic insulations are not the same, the most suitable insulation process for these two aspects is obtained by the use of double walls, and including an insulating layer between them such as mineral wool. This allows getting sufficient thickness of insulation layers that act as a heat transfer barrier [3] and also allows getting a system of two walls separated by a sound absorbent layer that acts together as a sound transmission barrier [4]. Other bricks or slabs with improved insulation features have been designed to enhance building insulation and taking into account the basic requirement of mechanical resistance including compressive, flexural and shear resistances. These construction elements include composite fillings, such as perlite or polystyrene foams included in the internal brick's cavities [5] and cellular concrete blocks containing a high fraction of air voids [6]. Bricks based on recycled industrial by-products and textiles can also be manufactured with fair insulating properties, and offering environmental benefits due to recycling materials and wastes [7-9]. Vacuum insulation represents currently the highest efficiency in thermal insulation but its high cost limits its use in buildings [10]. Other characteristics of construction elements such as fire classification, resistance to impacts, vapor permeability and environmental impact are also key parameters to take into consideration.

Insulation cannot be properly obtained if the thicknesses are small or reduced because it is not compliant with mass law used in acoustics and because the thermal resistance is directly related to the brick's thickness. At the same time, a single-layer wall thickness cannot exceed a certain limit to avoid wasting construction materials and the living space inside the building. Optimal wall thicknesses, including insulation should vary between 15 cm and 30 cm. In the case of double layer walls, the need for additional materials and layers implies that insulation requires an extra cost or at least two to three times of the cost of a single-layer conventional wall.

In this study, we propose a load-bearing composite brick that ensures both high thermal and acoustic insulation with competitive cost and using a simplified manufacturing method and environment friendly materials. It is based on a simplified design of alternating three cement concrete plates, with two insulating layers made of recycled PET containers filled with cellulose fibers, with a total thickness of 23 cm. Its geometry allows reducing the inner joints thickness to optimize its insulating characteristics.

Nomenclature :

A: Area of Cross section (cm^2)	λ : Thermal conductivity (W/m.K)
Iz : Area Momentum of inertia – along z axis- (cm^4)	R_C: Compressive Strength (MPa)
H: Brick's height (cm)	R_F: Flexural Strength (MPa)
L: Brick's length (cm)	R_T: Thermal Resistance (m^2.W/K)
e: Brick's Thickness (cm)	R_{OCT}: Sound reduction Index by octave band (dB)
c : Cost per unit mass of a component in the brick	R_W: Weighted Standardized Sound Reduction Index (dB)
f: Surface fraction of a component within the brick (%)	C : Adapted Term for airborne noise (dB)
F_C: Compressive Failure force (kN)	Ctr : Adapted Term for traffic noise (dB)
F_F: Compressive Failure force (kN)	U: Coefficient of Thermal Conductivity

Subscripts: br : Brick ; **cr** : Concrete ; **il** : insulating layer ; **cell** : cellulose fibers ; **pet**: PET plastic.

2. Materials and methods

2.1. Concrete plates:

Precast concrete plates are placed at the external covers of the proposed brick as well as its central part. These plates can be produced like pavements. Three concrete plates will be used in the front and back faces and in the middle of the brick. They play the role of mechanical resistance as well as sound barriers. Each plate has rectangular shape, with 2.2 cm in thickness, 23.5 cm in height and 25.5 cm in length. The length and height dimensions are adjusted to the same dimensions of the insulating layers.

The dosing of cement concrete is carefully selected to ensure a compressive resistance of 25 MPa, a tensile strength of 2 MPa and a Young modulus of 30 GPa after 28 days of cure, with a density of 2000 kg/m^3 [11]. The dosing of concrete should include a fraction of Portland cement of at least 350 kg/m^3 and a ratio of water-to-cement between 0.35 and 0.55. Additionally, the diameters of aggregates should be smaller than 5 mm, because of the relatively narrow thickness of the precast plates. Therefore, the selected dosing for proportions of 1 m^3 of concrete are: Portland cement: 400 kg/m^3 ; water: 200 kg/m^3 ; fine sand: 500 kg/m^3 ; coarse sand: 900 kg/m^3 ; and liquid plasticizer adjuvant: 5 kg/m^3 that allows getting a smooth concrete plate surface. Concrete has a relatively high thermal conductivity because of its high density. Its common value is 1 W/m.K for a density in the same order of 2000 kg/m^3.

2.2. Cellulose fibers

Cellulose fibers are extracted from recycled paper. They have an open pore structure and low density that allow them to play the main insulation role, with low thermal conductivity λ_{cell} = 0.045 W/m.K. [12]. Also, such fibers have a good sound absorption coefficient α ranging from 30% to 80% depending on frequencies [13]. The optimal density used in filling the plastic containers is 45 kg/m^3. However, it is necessary to ensure the protection of these fibers from moisture, compaction and other contaminants. They should not be directly mixed with mortar to avoid hemicellulose deterioration due to alkali-reactions that occur in concrete [14] or adherence issues if blended with polymers [15]. The waterproof and sealing properties of the PET containers protect them durably, without extra treatments.

2.3. Recycled plastic container

The recycled thin plastic containers are made of PET: Polyethylene Terephthalate, which is a derivative of polyethylene; its molecule is $(C_{10}H_8O_4)_n$. The thin PET containers are obtained using the extrusion of a plastic preform. The container used in the brick is from the table water brand CIEL, with 2.5 Litres capacity, 26 cm in length, 11.7 cm in height and 8.2 cm in width and 0.3 millimeter in its thickness. Its top part was flattened through a compressing device to get a quasi-parallelepipedal shape that is suitable for bricks manufacturing. Each insulating layer within the brick gathers two containers. Like most of polymers, the mechanical properties of PET are interesting: the tensile strength reaches 25 MPa, the tensile deformation is up to 100%, the elastic modulus is at least 1000 MPa and the common thermal conductivity is 0.3 W/m.K [16]. The PET container membranes play many important roles in the brick's design. Firstly, they protect the fibers from the contamination factors. Secondly, they allow adherence improvement with concrete through application of glue. Thirdly, they reduce the thickness of the internal junctions of the brick, that act as heat bridge sand sound paths [17], to a fraction of a millimeter. Thus, thermal and acoustic features of the proposed brick will be enhanced.

2.4. Adhesive glue

The adhesive glue is the component that ensures adherence between the plastic containers with the concrete plates. The glue brand used is BISON, which offers high performance adhesive features, even at extreme temperatures between -40°C and 70°C and high air moisture. A thin applied thickness of the order of one millimeter applied on each surface is sufficient for bonding. The curing time of the glue is between 10 and 15 minutes. The adhesive glue is suitable for bonding PET membranes.

2.5. Brick's manufacturing method

The multi-layers brick's manufacturing method is based on the main operation of glue assembly of concrete plates with plastic membranes of the filled containers, according to the chosen density of cellulose fibers. Special attention must be given to check parallelism between the assembled layers and to adjust the contact surfaces to avoid any flaw. Also, the gluing process must cover all the surfaces of the plates and the container to enhance the adherence effect and also the durability of the brick or the slab.

The steps of manufacturing are summed up in the following Figure 1 to 6. As shown in those figures, the only tools required to, consist of a brush that enables applying the glue on the surfaces and an adjusting support to verify the parallelism and the adjustment of the plates with the containers. Thus, the time of assembly of one brick is relatively short, and takes less than 15 minutes to be completed. The energy required for assembling is relatively low too. It is necessary to mention that this design of alternating parallel layers made the geometry uncomplicated. This important fact will make easier the calculations and simulations carried out in the characterization of its mechanical and insulating properties.

Figure 1: Gathering the brick's constituents – filled containers, precast concrete plates and the glue

Figure 2: Bonding two containers with the first concrete plate to form the first insulating layer

Figure 3: Bonding the second concrete plate with the insulating layer, which has to be all adjusted

Figure 4: Adjusting and bonding the second insulating layer with the second concrete plate

Figure 5: Bonding the third concrete plate with the second insulating layer to obtain the whole brick

Figure 6: The brick can be used as a slab element when disposed of horizontally, along (z) axis showed as red dashed line

Once the brick is manufactured, the mass and volumetric percentages of the brick's constituents were measured, which allowed estimating the mass fractions of each component to the total mass of the brick. Using the densities of each material used, the volumetric densities were also estimated. Table 1 gathers the mass and volumetric fractions of the proposed brick's constituents.

Table 1: Physical properties of the brick with volumetric and mass fractions of its constituents

Physical properties of the composite brick		
Dimensions	Length L: 25,5 cm ; Height h: 23,5 cm - Thickness e: 23 cm	
Volume of brick	14.6 liters	
Mass of brick	10.3 kg	
Density & Surface Mass	700 kg/m^3 ; 160 kg/m²	
Percentage of cellulose fibers	Volumetric: 72 %	Mass: 4.5 %
Percentage of cement concrete	Volumetric: 26 %	Mass: 93 %
Percentage of PET	Volumetric: 1.8 %	Mass: 2.2 %
Percentage of the adhesive glue	Volumetric: 0.2 %	Mass: 0.3 %

From Table 1, we deduce that the component with the highest mass fraction is concrete, because of its high density compared to the other components and because of the use of three plates in the brick. Even if cellulose fibers have high volumetric fraction, their low density decreases their mass fraction. The thin thickness of the plastic containers allowed reducing their mass and volumetric fractions, which are in the order of 2 to 3%. Furthermore, the fraction of the adhesive glue is less than 1% as it is used at the required amount for bonding the layers together. We will show in the next part that this fraction distribution of the brick's components will keep the global cost reasonable compared to regular concrete bricks.

2.6. Cost evaluation

Although the costs of materials are not easy to determine, as they vary depending on the nature of the material, its location and its amount, it was suggested in this study to express all cost estimations on the based on the cost of cement concrete per unit kilogram, which is relatively well defined because concrete is made up of natural products such as gravels, sand, water and cement. We can assume that each kilogram of concrete has a cost per unit mass denoted c. For example, the cost of prepared or precast concrete in Morocco is between 0.5 and 1 Dirham, which is equivalent to 0.05 to 0.1 Euro. We can then relate the costs of recycled plastics, recycled fibers and the adhesive glue to the cost of concrete as shown in the Table 2. The global cost of the entire brick can be estimated as the sum of the costs per unit mass of the four constituent and it is expressed in terms of the cost c of a unit mass of concrete.

The cost per unit kilogram for each constituent matches its actual market price. All these costs are provided in the Table 2. This will allow calculating the cost of the brick, in terms of the unit cost c.

Table 2: Cost estimation table the brick's constituents

Constituents	Mass Fraction	Cost per unit kilogram	Resulting cost
Precast concrete	93 % => 9.58 kg	1 c /kg	9.6 c
Cellulose Fibers	4.5 % => 0.48 kg	5 c /kg	2.4 c
PET containers	2.2 % => 0.23 kg	10 c /kg	2.3 c
Adhesive glue	0.3 % => 0.03 kg	50 c/kg	1.5 c
Composite Brick	100% => 10.3 kg	Total cost	15.8 c

We notice that the total cost of the whole brick is 15.8 c for 10.3 kg, which results in a cost per kilogram of the brick of 15.8 c /10.3 kg = **1.53 c / kg**. This means that the cost of the brick per kilogram is 53% higher than the one of precast concrete, which is a reasonable difference. The approximate 50% difference in cost per kilogram is due to the relatively small mass fractions of other constituents of the brick which have higher cost. It is rather more accurate to express the cost of a wall built by the proposed bricks per meter square, which takes into account the surface mass of the wall. This cost per m² which is denoted c' can be deduced by multiplying the obtained cost per kilogram with the surface mass of the brick. This means that: c' = c x surface mass = 1.53 c / kg x 160 kg / m² = **245 c / m²**.

3. Composite brick characterisation

3.1. Compressive and flexural strengths

In order to predict the compressive resistance of the proposed brick, denoted $R_{c,br}$, we assume that precast concrete is the only part of the brick that bears the compressive force. The filled container has a much lower elastic modulus and consequently it cannot bear any fraction of the compressive force. This leads to consider that the compressive strength of the brick is directly related to the area fraction of concrete plates over the total area of the composite brick. We consider that compressive resistance of concrete is $R_{c,cr}$ is 25 MPa, after 28 days of curing. Therefore, this leads to the following Equation (1).

$$R_{c,br} = R_{c,cr} \cdot \frac{A\_cr}{A\_br} \qquad (1)$$

where $\frac{A\_cr}{A\_br}$ is the ratio of the areas as indicated above:

$$\frac{A_{cr}}{A_{br}} = \frac{3\ .\ 2{,}2\ cm\ .25{,}5\ cm}{23\ cm\ .25{,}5\ cm} = 28.7\ \%$$

Then, $R_{c,br} = R_{c,cr} \cdot A_{cr} / A_{br}$ = 25 MPa x 0.287 = 7.18 N/mm² = **7.18 MPa.**

The obtained resistance allows classifying the brick as a load-bearing element, with the resistance class between 7 MPa and 8 MPa.

In order to predict the flexural strength of the composite brick, we make the same assumption that concrete plates are the ones that bear the flexural force and momentum. In this case, the flexural resistance of the brick is the product of the flexural resistance of concrete $R_{f,cr}$ and the ratio of momentums of inertia of the concrete plates over the one of the whole brick, along the transverse axis (z) shown in Figure 6. Therefore, the flexural strength of the brick $R_{f,br}$ can be expressed in Equation (2).

$$R_{f,br} = R_{f,cr} \cdot \frac{I\_cr}{I\_br} \qquad (2)$$

where $\frac{I\_cr}{I\_br}$ is the ratio of the area momentums of inertia:

$$\frac{I_{z_{cr}}}{I_{z_{br}}} = \frac{3 . \left(\frac{23,5 .2,2^3}{12}\right) + 2. \left[(10,4)^2 . (23,5. 2,2)\right] cm^4}{\frac{23,5 .23^3}{12} cm^4} = 47 \%$$

Then: $R_{f,br} = R_{f,cr} . I_{cr} / I_{br} = 2$ MPa x 0,47 = **0.94 MPa**.

This relatively low flexural stress does not reflect the relatively high flexural momentum or force due to the high area momentum of inertia of the brick, due to its dimensions L, h and e. Using the basic flexural formula of Equation (3), we find both the failure momentum as well as the flexural failure force:

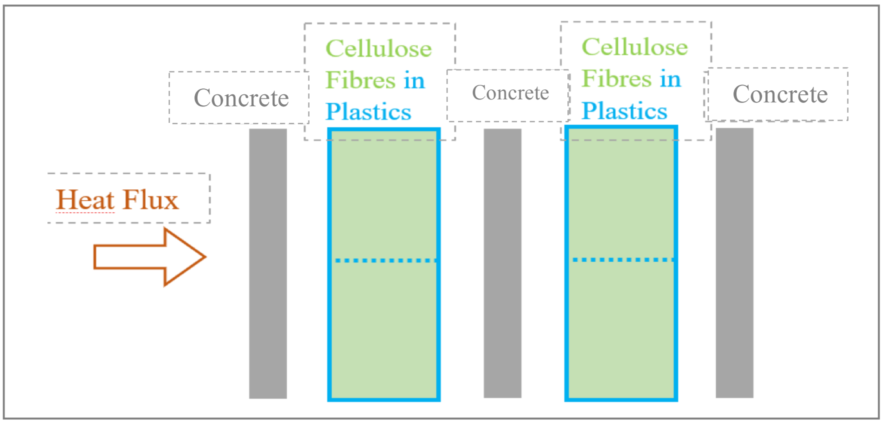
$M_f = R_{f,br} . I_{z_{br}} / (e_{br} /2)$ = **1947 N.m** (3)

Hence, the corresponding 3 points flexural failure force is: $F_f = M_f / (L/4)$ = **30.54 kN.**

3.2. Thermal resistance calculation

The thermal resistance of the brick is calculated through the thermal resistance model for homogenous and heterogenous layers from the norm NM ISO 6946 [18]. In this calculation, the thermal resistance of the brick is expressed as the sum of the resistances in series of its five layers as shown in Figure 7. Since each precast concrete layer is considered homogenous, its thermal resistance is expressed as the ratio of the thickness and the conductivity λ of each concrete plate. However, each insulating layer made of recycled PET plastics filled with cellulose fibers is considered heterogeneous, and its thermal resistance will be expressed as the arithmetic average of the superior limit and the inferior limit of the thermal resistances, which are denoted R'_T and R''_T respectively, as mentioned in Equations (6) and (7).

Figure 7: Layout of the brick with its five sublayers, subjected to perpendicular heat flux



We start by expressing the thermal resitance of the whole brick:

$R_{T,br} = 3.R_{T,cr} + 2.R_{T,il}$ (4)

The thermal resistance of each precast concrete layer $R_{T,cr}$ is calculated below :

$R_{T,cr} = e_{cr} / \lambda_{cr} = 0,022$ m / 1 (W/m.K) = 0,022 m².K/W (5)

Before calculating the thermal resistance of each insulating layer $R_{T,il}$, we express both expressions of superior and inferior limits expressed below, and using the appropriate subscripts :

$$\frac{1}{R'_T} = \frac{f_{pet}}{R_{T\_pet}} + \frac{f_{cell}}{R_{T\_cell}} \quad (6) \quad ; \quad R''_T = \frac{e\_il}{(\lambda pet .fpet + \lambda cell .fcell)} \quad (7)$$

According to the norm ISO 6946, f_{pet} and f_{cell} represent the surface fractions of each component, PET plastic or cellulose fibers, within the heterogenous insulating layer. In order to calculate f_{pet} and f_{cell}, we divide the actual cross-section area of each component, by the total cross-section area of the heterogenous layer, as shown in equations (8)-(9). We also note that the sum of f_{pet} and f_{cell} equals 1.

$$f_{pet} = (4 \times 0.3 \text{ mm} \times 235 \text{ mm}) / (235 \text{ mm} \times 255 \text{ mm}) = 0{,}005 \quad (8)$$

$$f_{cell} = 1 - f_{pet} = 0{,}995 \quad (9)$$

The surface fraction f_{pet} is very low value because of the very thin thickness of 0.3 mm of the 4 plastic membranes of PET used in each insulating layer. This allows to have the value of f_{cell} close to 1. The thermal resistances of both components: PET plastic and cellulose fibers, are calculated below. Both components have the same thickness of each insulating layer, which is 8.2 cm.

$$R_{T,cell} = e_{Cell} / \lambda_{cell} = 0.082 \text{ m}/(0{,}045 \text{ W/m.K}) = 1.82 \text{ m}^2\text{.K/W} \quad (10)$$

$$R_{T,pet} = e_{pet} / \lambda_{pet} = 0.082 \text{ m}/(0{,}3 \text{ W/m.K}) = 0.27 \text{ m}^2\text{.K/W}$$

We find from Equation (6): $\frac{1}{R'_T} = \frac{0{,}005}{0{,}27} + \frac{0{,}995}{1{,}82} = 0.565$ m².K/W, then R'_T = <u>1.77 m².K/W</u>

Likewise, the equation (7) gives: $R''_T = 0{,}082\text{m} / (0{,}046 \text{ W/m.K})$ = <u>1.77 m².K/W</u>

The values of the limits R'_T and R''_T are the same, therefore, the average is: $R_{T,il}$ = <u>1.77 m².K/W</u>

Recalling Equation (4), we find the predictive thermal resistance of the whole multi-layers brick:

$R_{T,br} = 3 \times 0.022 + 2 \times 1.77 =$ **3.6 m².K/W**

This value enables obtaining the thermal transmission coefficient U_{br} and the thermal conductivity λ_{br}:

$U_{br} = 1/ R_{T,br} =$ **0.27 W/(m².K)** and $\lambda_{br} = e_{br} / R_{T,br} =$ **0.064 W/(m.K)** (11)

The values found of U-coefficient and the thermal conductivity of the brick are considered one of the lowest ever achieved for construction elements. This high performance is due to the extensive fraction of the cellulose fibers layers that exceeded 16 cm in thickness. It is also due to the minimum thickness of the PET junctions with less than 1.5 millimetre, that reduced the heat transfer within the insulating layers.

3.3. Sound reduction index (SRI) simulation

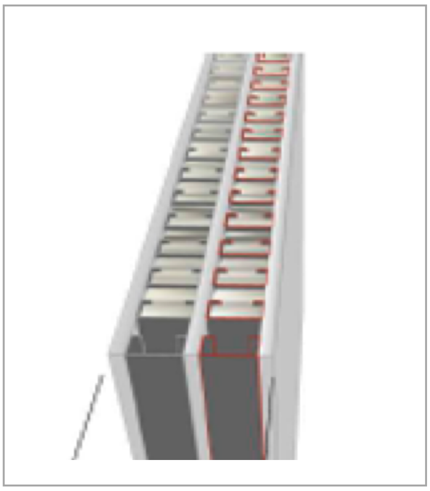
In order to obtain a predictive value of SRI for the proposed composite brick at all audible frequencies and in diffuse field, a simulation using INSUL 9.0 software has been carried out. A wall that has the same structure as an assembly of proposed bricks has been modeled in this software. The selected wall surface is 11 m², and it consists on a three-leaf wall made of two layers of mortar of 22 mm in thickness for each layer, and each two layers are separated by an internal cavity of 82 mm in depth. This cavity contains a frame of internal steel studs having 0.55 mm in thickness, and spaced with the available distance of 100 mm. Cellulose fibers fill all the cavity depth. The choice of steel studs is the most appropriate option in INSUL 9 software to model the PET inner junctions for each insulating layer with similar thickness, equalling 0.6 mm, which results from the sum of two PET membranes with 0.3 mm in thickness. Table 3 sums up the specifications of the wall used in this simulation.

INSUL 9.0 software provides high accuracy of the predictive SRI value, with a margin error generally within R_w +/- 3 dB.

Table 3: Specifications of the wall used in INSUL 9 Simulation

Panel 1: Concrete: thickness 22 mm
Density: 2000 kg/m^3 – Young Modulus: 30 GPa
Frame 1: Steel Studs: thickness 0.55 mm
Stud Depth 81 mm, Stud Spacing 100 mm, Stud Width 50 mm
Absorbent: Cellulose Fibers: Thickness 82 mm (50 kg/m^3)
Panel 2: Concrete: thickness 22 mm
Density: 2000 kg/m^3 – Young Modulus: 30 GPa
Frame 2: Steel Studs: thickness 0.55 mm
Stud Depth 82 mm, Stud Spacing 100 mm, Stud Width 50 mm
Absorbent: Cellulose Fibers: Thickness 82 mm (50 kg/m^3)
Panel 3: Concrete: thickness 22 mm
Density: 2000 kg/m^3 – Young Modulus: 30 GPa

Figure 8: Layout of the wall



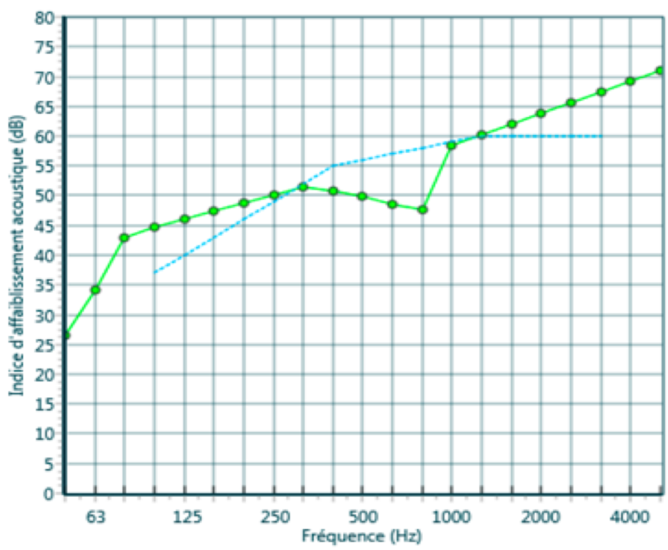
The INSUL 9 simulation provides the predicted SRI values of R_{oct} by octave band showed in Table 4, and the predicted weighted value of R_w. The curve of reference values of airborne sound is plotted in blue color in the same Figure 9**,** which enables finding the adapted terms of airborne and traffic noise C and C_{tr}. Therefore, the predicted value for SRI of this wall is provided in Equation (12) below.

$$R_W = \mathbf{56\ dB\ [\ C = -2\ dB,\ C_{tr} = -4\ dB]} \quad (12)$$

Table 4: SRI values: R_w and R_{oct}

Frequency (Hz)	R_{OCT} (dB)
63	30
125	46
250	50
500	50
1000	52
2000	64
4000	69
R_w(dB)	**56 [-2 ; -4]**
C= -2 dB	**C_{tr} = -4 dB**

Figure 9: SRI curve: R_{oct} versus frequencies



The obtained curve shows the values of SRI by octave band R_{OCT}, at specific frequencies showed in Table 4. The values of SRI are particularly good at low frequencies below 1000 Hz, where it exceeds 45 dB. A slight drop in SRI around 900 Hz is mainly due to a coincidence frequency of the three-leaf wall made by these bricks; starting from 1000 Hz, the values of SRI increase continuously to reach interesting values between 59 dB and 69 dB. The average weighted R_w for all frequencies is set at 56 dB (-2, -4), which is considered a very good value. For example, this SRI value of 56 dB enables reducing a noisy level of sound at 76 dB in a given room to a quiet sound level of 20 dB in a room separated from it by the wall built by the proposed bricks. This quiet sound level results from the difference of the sound level of the noisy room and the considered SRI of the wall.

3.4. Complementary characteristics: Fire resistance, Impact resistance, moisture resistance

The Complementary characteristics of the brick such as fire resistance, impact resistance and moisture resistance are also important to mention. Fire resistance is due to the fire classification of concrete plates that cover the brick, which is the highest classification A1 among all materials; it can hold the flames spread up to one hour [19]. Impact resistance is due to the high tensile elongation of plastics, that are bonded to concrete plates with adhesive glue. Therefore, the fragile failure mode of concrete is mainly reduced. Moisture resistance due to the waterproof feature of PET plastics, and the adhesive glue, that prevent moisture contamination and damage to the fibers.

Overall, the characteristics of the brick provide real advantages in major aspects, especially for the insulating ones, but it remains necessary to compare the obtained characteristics with the ones of other conventional walls, including the cost factor.

4. Discussion

4.1. Brick's performance overview

The design of the brick which alternate concrete and insulation layers with reducing its internal junctions allowed enhancing both thermal and acoustic resistances, while keeping good mechanical resistances: the good compressive resistance of 7.2 MPa allows classifying the brick as a load-bearing element, and the failure flexural force and moments are also good due to the high momentum of inertia of the brick.

It is interesting to note that the resulted thermal conductivity of the brick equals λ_{brick} = 0.064 W/m.K, which is considered one of the lowest thermal conductivities ever found for construction elements, much lower than fired clay bricks with conductivities ranging between 0.2 W/m.K and 0.3 W/m.K [20].

The predicted SRI value found 56 dB is very good and is compliant to many acoustic building codes [1]. The SRI of single wall made of ordinary concrete blocks will reach a value between 38 to 48 dB, depending on its surface mass, but in the case of double-leaf walls separated with an absorbent (or insulating layer) the actual SRI is higher than single walls, and it depends on the nature and thickness of the walls and the wools used. In general, the SRI values of double walls range between 48 to 58 dB [21], with particular cases of double walls including one lightweight wall have SRI exceeding 60 dB [21]. This shows that a wall built by these bricks has very good SRI compared to conventional wall systems.

The cost per kilogram of the brick is 50% higher than that of concrete and the resulted cost of the brick remains reasonable for constructing building walls and slabs. However, the cost per m² indicates more precisely the actual cost of a wall, as it takes into account the optimized mass density obtained.

As stated in the previous part, it is necessary to make comparisons of the costs and performances between a wall built by the proposed composite brick and other walls built by conventional bricks. In particular, the wall built by the proposed composite bricks will be compared with two different walls as shown in Table 5, including the mechanical, thermal, acoustic and cost parameters. The first wall considered is a single wall made by hollow concrete blocks with cavities with a thickness of 20 cm and a mass surface of 240 kg/m². The second wall consists of a double wall with insulating layer of mineral glass wool with 5 cm in thickness in its middle. The walls are made of hollow fired clay bricks with two different thicknesses of 15 cm and 9 cm, and both of them are rendered with a mortar layer with 2 cm thick.

In order to estimate the mechanical, thermal and acoustic performances of both walls, the common features of concrete, hollow clay bricks and mineral wool are extracted from various references [20] and [21]. We assume that the cost of fired clay per kilogram is set at the same value c.

Table 5: Predicted mechanical, thermal, acoustic and cost characteristics of comparative three walls

Predictive characteristic	Single wall built by hollow concrete blocs	Double wall of fired clay bricks with wool	Wall built by proposed composite bricks
Class of resistance R_C	8 – 10 MPa	6 – 8 MPa	7 – 8 MPa
Thermal resistance R_T	0.3 m².K/W	3 m².K/W	3.6 m².K/W
SRI value R_w ($C;C_{tr}$)	46 dB	56 [-4;-10] dB	56 [-2;-4] dB
Surface Mass	250 kg/m²	420 kg/m²	160 kg/m²
Estimated Cost per m²	250 c/ m²	450 c/ m²	245 c/ m²

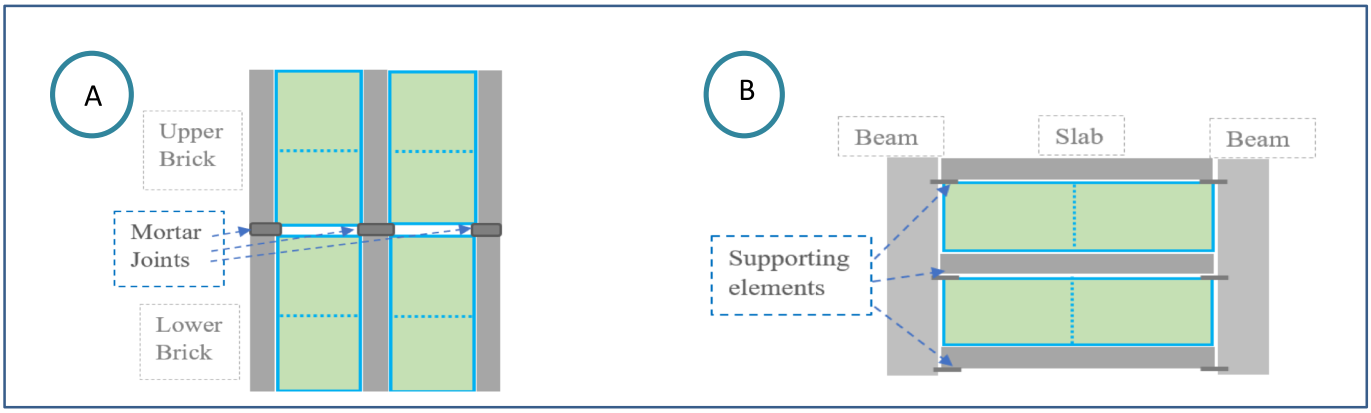
We notice from Table 5 that wall built by the proposed bricks offers high thermal resistance and high SRI, with lower cost and also lighter surface mass. In particular, the composite wall built by the proposed bricks provides 1200% more in thermal resistance than the single wall, and 20% more in thermal resistance than the double wall. It also has a predictive SRI higher than the single wall by 10 dB, and similar one compared to the double wall. The surface mass of the composite wall is 33% lower of that of the single wall and 62% lower than the double wall. Regarding the costs, the composite wall has almost the same cost than the single wall, and a 42% lower in cost than the double wall. This proves the cost efficiency of the wall built by the proposed composite brick.

4.2. Adapted assembly in walls construction

The assembly method is similar to assembling other bricks, but it should be noted that mortar joints have to be applied only upon the concrete plates, as shown in Figure 10, to avoid adding thicker internal junctions within the brick that will decrease the insulation features. Moreover, the mortar joints used between two bricks improve the relatively low shear resistance of the adhesive glue used between the layers of a brick. Therefore, the wall assembly can be compact and resistant. In addition to this, when the mortar joints are correctly applied between the smooth surfaces of precast concrete plates, there is no need of adding an extra render layer before painting the wall.

In order to run cables and pipes within the wall, we can consider special bricks with the same geometry, but with empty PET containers. Thus, they contain openings that allow passage of these cables. If this proposed brick has to be used as slab blocks in floors, it should be used with special supporting elements, placed either within the beam or within the slab, as shown in Figure 10.

Figure 10: Assembly method of bricks in walls (A) and slabs in floors (B)



4.3. Environmental benefits

The environmental benefits of the brick are numerous. Firstly, the brick's production requires less energy than the firing process of clay or the thermal treatment of fibers or wools. This will enable reducing CO_2 emissions in the atmosphere. Secondly, it ensures durable energy efficiency in buildings and noise reduction for indoors inhabitants. Thirdly, this production allows recycling plastic containers and packaging paper that are already produced at very large amounts.

Nevertheless, the organization of recycling chains of such products is essential to gather the required amounts to produce these composite bricks at large scale. Moreover, the large-scale production would require the use of industrial process that shall be based on the manufacturing method of this brick, that is presented in this article.

Conclusion

A Cost-Effective method of manufacturing high insulating bricks is presented, along with its main properties:

- The assembly of brick's components for its production is fast and simple.
- The mechanical, thermal resistances and acoustic reduction index found using specific calculations or simulations show that the brick can be used in load-bearing walls, with a high predictive SRI which is compliant with acoustic standards of many countries, and a low thermal conductivity which is considered among the lowest values ever found for construction elements.
- The cost of the composite brick per kilogram is 50% higher than that of concrete, due to the cost of the other components. However, the cost per m² of a wall built by the proposed composite brick is proven to be more competitive to the cost per m² of other conventional walls.
- Adapted brick and slab assembly methods are presented for constructing walls and floors.

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