Proposal Number: 285463 SUS-CON CP-IP

Sustainable, Innovative and Energy-Efficient Concrete, based on the Integration of All-Waste Materials

Deliverable D5.5
Modelling SUS-CON products for products design (Part B)

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Abstract:	Three types of SUS-CON components were considered: products (blocks and panels), elements (façade walls and floor screed underlay) and buildings (one and multi-story). The mechanical, thermal and acoustic behaviour of these components, exposed to realistic conditions and composed by various non-traditional SUS-CON mixtures, was numerically simulated.
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[1] Just mention the partner(s) responsible for the Deliverable

[2] PU: Public, RE: restricted to a group specified by the consortium CO: Confidential, only for members of the consortium; Commission services always included.

[3] Draft, Revised, Final

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1. Introduction

Under the aim of SUS-CON project, different concrete mixtures were formulated targeting different products: blocks and panels for façades and floor screed underlay. In the present deliverable, the performance of these products, made of non-traditional (SUS-CON) concrete exposed to realistic environmental conditions, is numerically simulated.

Firstly, the stress distribution in concrete products, such as blocks and panels for façades, are analysed, considering they are part of a non-loadbearing wall and experience thermal stresses.

Secondly, the mechanical, thermal and acoustic behaviour of elements, such as façade walls made of the formerly analysed blocks and panels, is studied.

Finally, an energy efficiency analysis is performed for houses/buildings composed by these elements and products. The responses of different concrete products are discussed with reference to the best performing concrete mixture in the environments considered. The building model was validated by comparing data measured for a mock-up with data obtained from the simulation study.

2. Concrete mixtures – Thermal and mechanical properties

The mechanical and thermal properties of eight non-traditional concrete mixtures with different target applications (blocks, panels and floor screed underlay), together with the properties of a normal concrete (NC) mixture, are shown in Table 1.

Table 1: Summary of performance of pre-selected SUS-CON concretes (adapted from D4.7[4])

		Mechanical performance				Thermal performance		
Mix	Target application	Density	Compressive resistance	Young's modulus	Poisson's ratio	Thermal conductivity	Heat Capacity	Coefficient of thermal expansion
		$kg·m^{-3}$	MPa	GPa	-	$W·m^{-1}·K^{-1}$	$J·kg^{-1}·K^{-1}$	$ºC^{-1}$
PU 4	Blocks	942	5.6	1.1	0.09	0.157	1323	$-2.17x10^{-5}$
PU 11	Blocks	1255	8.3	1.9	0.03	0.311	924	$-1.94x10^{-5}$
PU 19	Floor screed underlay	-	-	0.9	0.14	0.180	1805	$-1.29x10^{-6}$
PU 21	Panels	1089	6.6	1.2	0.06	0.167	1468	$-1.05x10^{-5}$
PU 30	Blocks	1184	15.1	3.1	0.02	0.205	1911	$-1.05x10^{-5}$
RX 4	Panels	1440	6.8	1.0	0.05	0.344	1275	$-3.36x10^{-5}$
RX 11	Blocks	1475	18.2	3.4	0.05	0.266	1737	$1.26x10^{-5}$
TR 4	Blocks	1501	4.2	0.9	0.05	0.323	1302	$-5.50x10^{-5}$
NC	-	2150	25	30	0.18	1.26	750	$1.45\ x10^{-5}$

For mixtures PU 19 density is missing. Consequently, only thermal insulation can be predicted for this mixture.

3. Concrete products: behaviour of blocks and panels

3.1. Geometry and boundary conditions

A block was considered to be part of a non-structural wall (2.7 m high) and composed by the mixtures shown in Table 1 (corresponding to blocks as target application). The dimensions and boundary conditions considered, for analysing the thermal and mechanical behaviour of the block, are as shown in Figure 1.

[4] Deliverable D4.7 - Test report Performance of 100% waste concrete

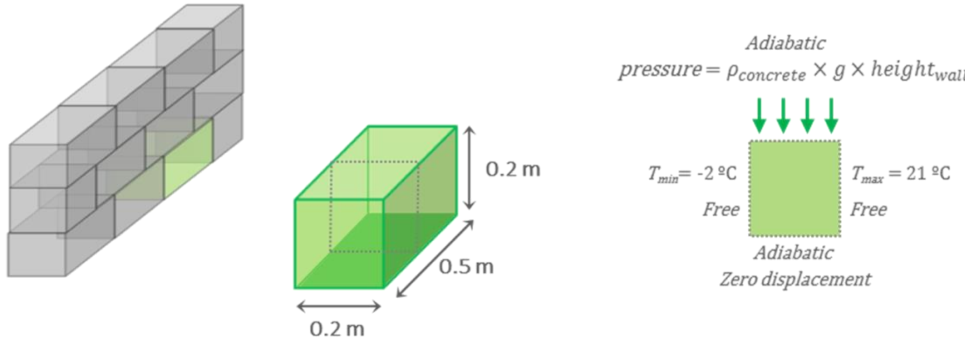


Figure 1: Dimensions and boundary conditions considered for analyzing the thermal and mechanical behavior of a concrete block

The pressure applied at the top of the block depends on the weight of the wall above it. Thus, because different mixtures have different densities (as shown in Table 1), different loads are obtained for the same height of the wall above the block (2.5 m), according to equation 1 and Table 2.

$$pressure_{(at\ top)} = \rho_{mixture} \times g \times h_{wall} \quad (1)$$

Table 2: Pressure applied at top of each block, corresponding to the weight of a 2.5 m high wall

Concrete mixture	PU 4	PU 11	PU 30	RX 11	TR 4	NC
Pressure at top (MPa)	0.0231	0.0308	0.0290	0.0362	0.0368	0.0527

In the present studies, also the mechanical and thermal behaviour of panels were analysed. The panel was considered to support its own weight and the weight of a panel above it, performing a wall with 3 m height, and composed by the mixtures corresponding to panels as target applications, as shown in Table 1. The dimensions and boundary conditions considered are according to Figure 2.

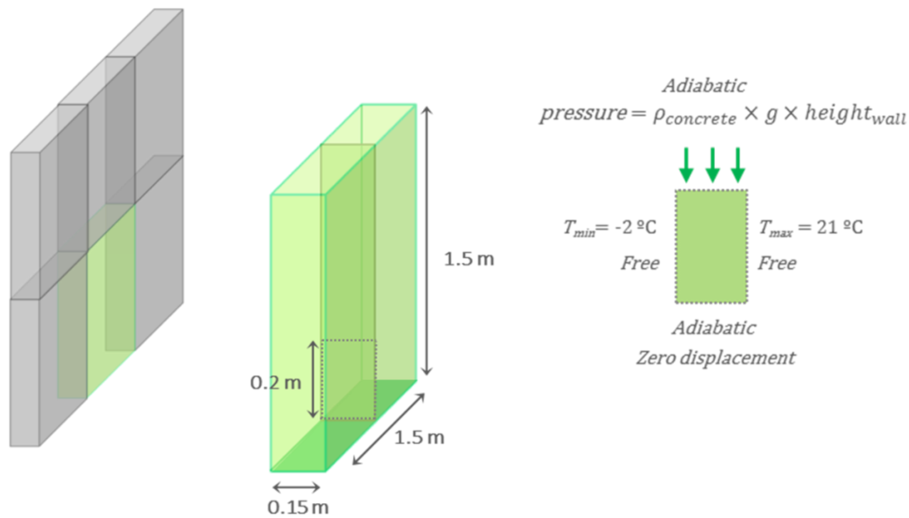


Figure 2: Dimensions and boundary conditions considered for analyzing the thermal and mechanical behavior of a concrete panel

Following the procedure used for simulating walls made of blocks, also in the case of a wall composed by panels, only a part of the wall was simulated. A part of the panel with 0.20 m high (as considered for blocks) was simulated and the effect of the remaining part of the wall was introduced in the model by imposing its corresponding load at the top of the panel part. The pressure applied at the top of the panel part depends on the weight of the wall above it and, as mentioned for blocks, different mixtures have different densities (as shown in Table 1), resulting in different loads for the same height of the wall above the panel part (in this case, 2.8 m). The loads imposed at the top of the panel part, for each mixture composing panels, are calculated according to equation 1 and shown in Table 3.

Table 3: Pressure applied at top of each panel part, corresponding to the weight of a 2.8 m high wall

Concrete mixture	PU 21	RX 4	NC
Pressure at top (MPa)	0.0299	0.0396	0.0590

The mechanical and thermal behaviour of concrete products were analysed in a 2D approach, based on a plain-strain assumption. The thermal expansion phenomenon is implemented as an additional strain, according to equation 2.

$$\varepsilon_{thermal} = \alpha \times (T - T_{ref}) \quad 2$$

where α is the coefficient of linear thermal expansion, T is the temperature of the block/panel and T_{ref} is the reference temperature, at which the block is at its normal size, without thermal expansion/shrinkage. The considered reference temperature is 20 ºC [1].

3.2. Stress distribution in blocks and panels

The von Mises stress distribution obtained for blocks, when considering and neglecting thermal expansion phenomena, are shown in Figure 3.

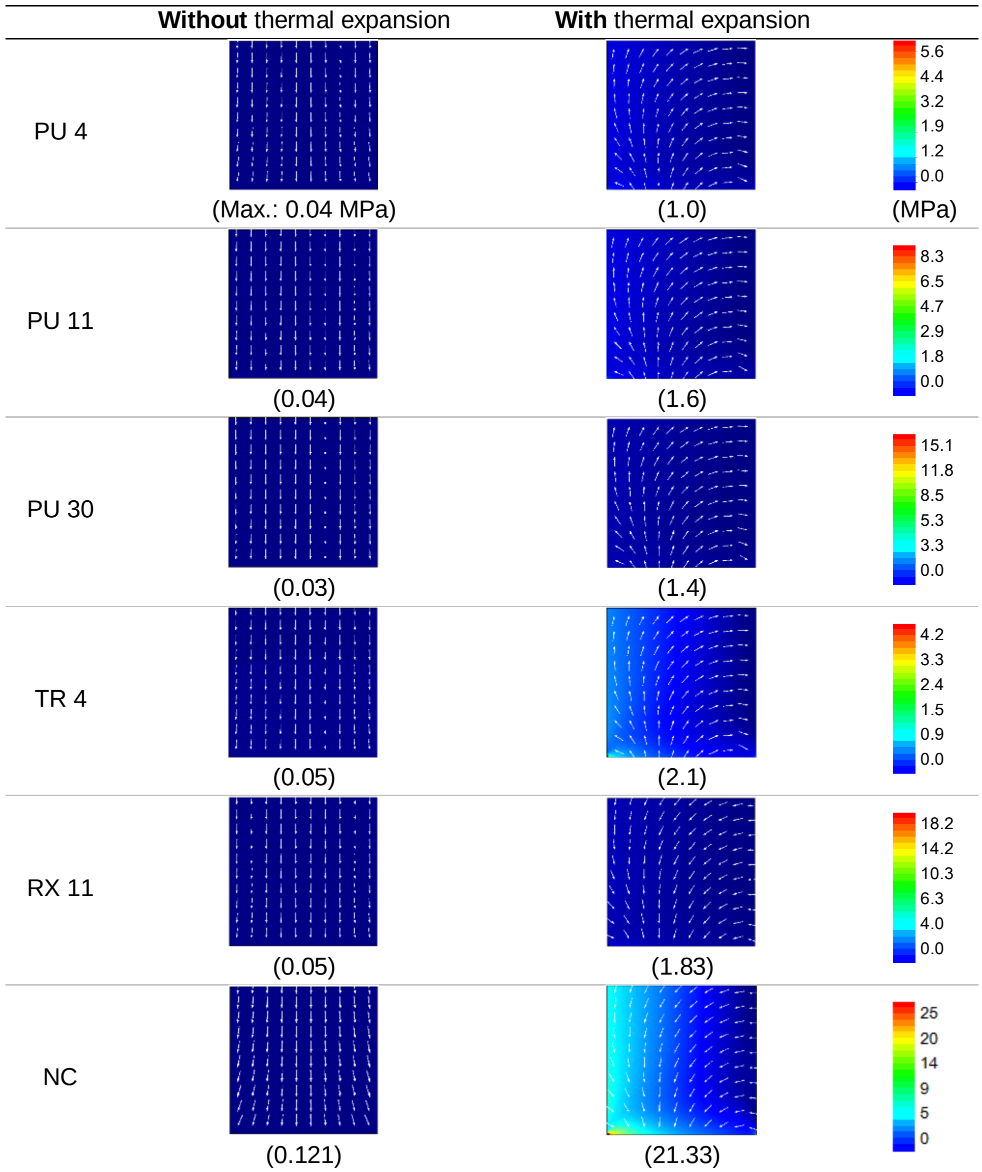


Figure 3: von Mises stress distribution (MPa), with and without thermal expansion phenomena, and arrows showing the direction of the deformation, for blocks; maximum stress obtained is reported

The von Mises stress distribution obtained for panels, when considering and neglecting thermal expansion phenomena, are shown in Figure 4.

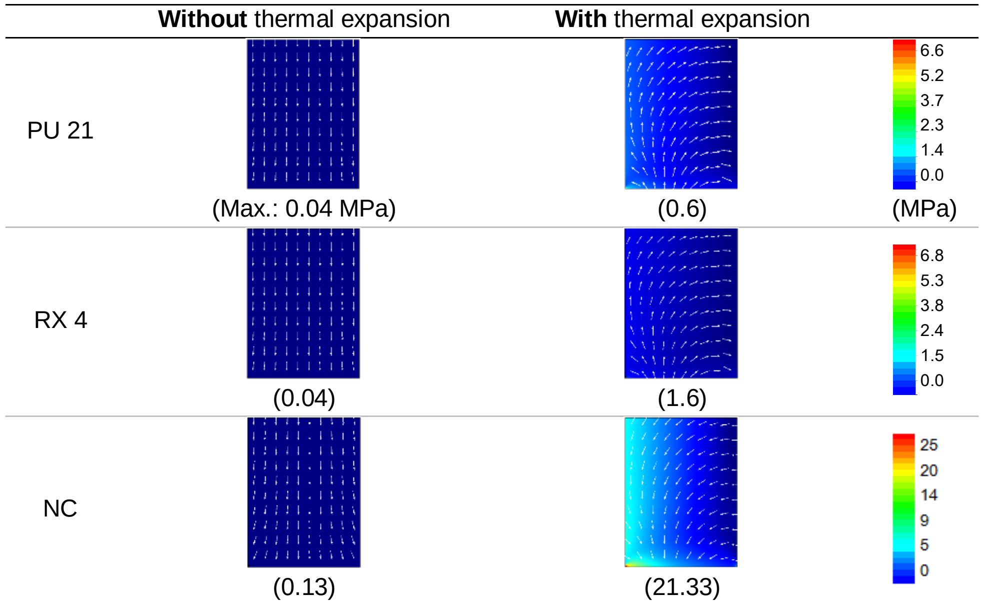


Figure 4: von Mises stress distribution (MPa), with and without thermal expansion phenomena, and arrows showing the direction of the deformation when thermal expansion is considered, for panels; maximum stress obtained is reported

A stress concentration in the bottom corners of the components occurs, mainly in the left corner when thermal expansion phenomena are considered. This inflated stresses are a numerical consequence of the discontinuity between boundary conditions (bottom fixed constraint vs lateral free displacement). In reality, the bottom boundary of the component is allowed to deform, depending on the material below it. Thus, although deviated from reality, this fixed constraint in the bottom boundary allows a feasible comparison between components by avoiding the possibly intrusive influence of the material below it. This analysis can be, instead of quantitative, a feasibly indicative analyses allowing comparison of the performance of concrete components. The non-traditional concrete mixtures that experience higher maximum stress are TR 4 and RX4, for blocks and panels, respectively. It could be concluded, for all mixtures composing blocks and panels, that the maximum stress is lower than compressive resistance. Also, the maximum stresses obtained in products made of non-traditional concrete mixtures are lower than the obtained in normal concrete products.

3.3. Maximum height of the wall (made of blocks or panels)

Taking into account the compressive resistance of each material, as shown in Table 1, the maximum height of the wall (composed by blocks or panels) was calculated, in order to achieve a load that would promote failure (maximum stress obtained = compressive resistance of the material). Thus, the maximum height of the wall was obtained for each mixture composing the blocks and panels (Figure 5 and Figure 6, respectively).

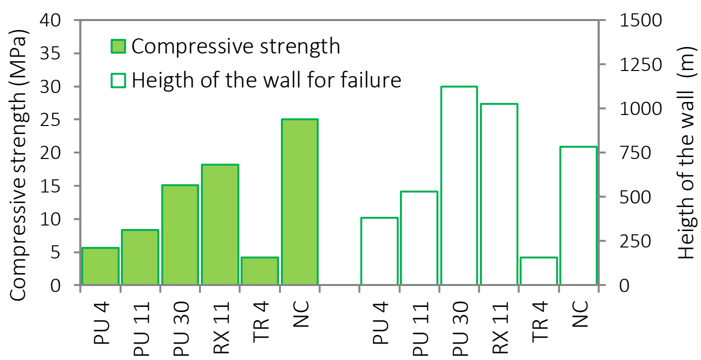


Figure 5: Compressive strength and height of the wall made of blocks to promote failure, for each concrete mixture, considering thermal expansion phenomena

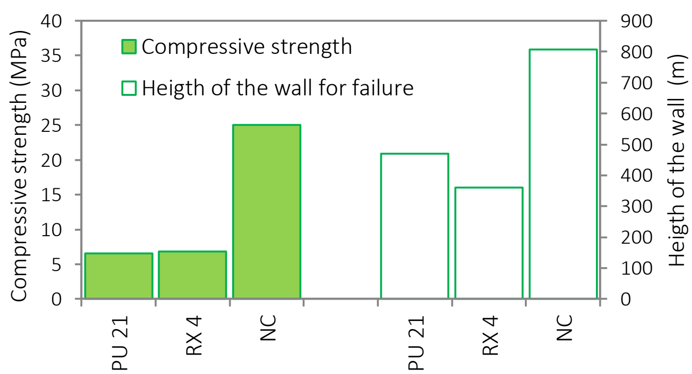


Figure 6: Compressive strength and height of the wall made of panels to promote failure, for each concrete mixture, considering thermal expansion phenomena

It could be concluded that higher compressive resistance does not necessarily mean that the wall above the block/panel can be higher. Firstly, because the load promoted by the wall in the block/panel depends, besides its height, on the density of the material by which it is composed. Also, in order to obtain the maximum height of the wall, the maximum stress (obtained in high stress zones) is considered. As mentioned (section 3.2), in left bottom corner of the components, stresses are inflated due to the numerical discontinuity in boundary conditions. In order to minimize the influence of this numerical abstraction in the analyses of the height of the wall, the maximum stress was calculated in the domain area except in the portion (equivalent to 0.01% of the total area) of domain around the mentioned point (Figure 7, Figure 3 and Figure 4).

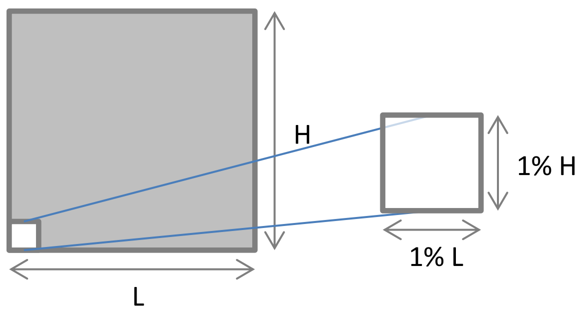


Figure 7. Area of the domain considered for calculating the maximum stress (grey) and portion of the domain excluded (white) equivalent to 0.01% of all domain

The maximum stress depends on the elastic properties of the material and on the thermal expansion coefficient. For blocks (Figure 5), the mixture RX 11 has the higher compressive resistance but the wall composed by PU 30 can be higher than one made of RX 11 without failure. For panels (Figure 6), the mixture RX 4 has the higher compressive resistance but the wall composed by PU 21 can be higher than one made of RX 4. Normal concrete panels present the higher compressive strength and was found to be the mixture that can support the higher wall without failure.

4. Concrete elements: behaviour of façade walls and floors

4.1. Thermal insulation of walls

The thermal insulation provided by a wall made of blocks or panels was analysed, for each mixture of Table 1 together with a mixture corresponding to normal concrete (considered to have a thermal conductivity of 1.26 $W \cdot m^{-1} \cdot K^{-1}$). Also, the thickness of the walls composed by different mixtures is calculated, in order to obtain the same thermal insulation of a 0.20 m thick wall composed by normal concrete. The results are shown in Figure 8 and Figure 9 for blocks and panels, respectively.

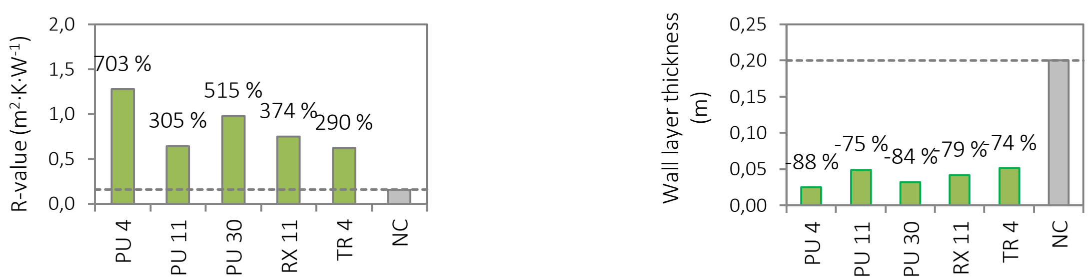


Figure 8: Thermal insulation (R-value) of a wall made of blocks (0.20 m thick) composed by different concrete mixtures, including normal concrete, and thickness of a wall made of different concrete mixtures, that results in the same thermal insulation of a wall made of normal concrete with 0.20 m thickness

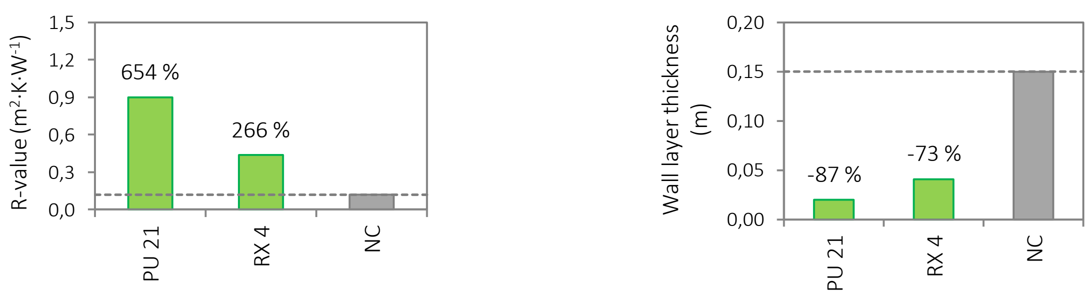


Figure 9: Thermal insulation (R-value) of a wall made of panels (0.15 m thick) composed by different concrete mixtures, including normal concrete, and thickness of a wall made of different concrete mixtures, that results in the same thermal insulation of a wall made of normal concrete with 0.15 m thickness

For mixtures composing blocks, it can be concluded that PU 4 has a 7 fold higher thermal insulation than normal concrete, resulting in a wall 88% thinner with same thermal insulation. In the case of mixtures composing panels, it can be concluded that PU 21 has a 6.5 fold higher thermal insulation than normal concrete, resulting in a wall 87% thinner with same thermal insulation. All the analysed mixtures perform better than the considered normal concrete in what concerns thermal insulation.

4.2. Thermal insulation of floor

The thermal insulation (R-value) of floors made of one layer of PU 19, of one layer of NC and of a multilayer of NC and EPS (expanded polystyrene) were analysed. The thermal insulation obtained for each configuration is shown in Figure 10.

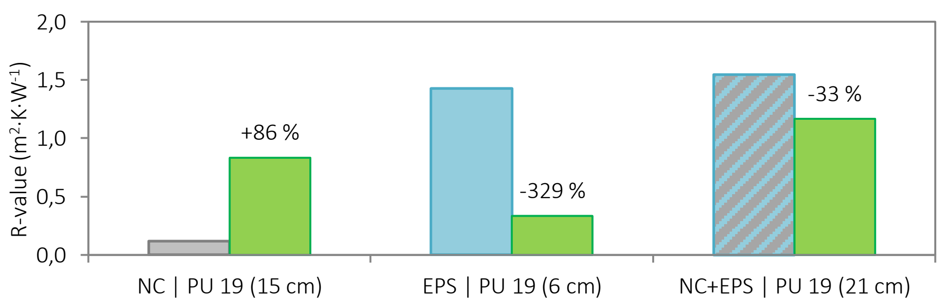


Figure 10. Thermal insulation provided by: one layer of NC (15 cm thick) and of PU 19 (15 cm thick); one layer of EPS (6 cm thick) and of PU 19 (6 cm thick); a multilayer composed by NC (15 cm thick) and EPS (6 cm thick) and one layer of PU 19 (21 cm thick)

The thermal conductivity of normal concrete (λ=1.26 W·m^{-1}·K^{-1}) is 7 fold the thermal conductivity of PU 19 (λ=0.180 W·m^{-1}·K^{-1}). Thus, when comparing the thermal insulation of NC and PU 19, for the same layer thickness, the latter has a thermal insulation that is 86% higher than that of the former. When a comparison is made between the thermal insulation provided by a layer of thermal insulator EPS (expanded polystyrene, λ=0.042 W·m^{-1}·K^{-1}) and of PU 19, the latter has a thermal insulation that is more than 3 fold lower than the former. Normally, floors are composed by more than one layer [2] and include a concrete layer and a thermal insulation layer. When comparing the thermal insulation provided by this set of layers (15 cm of NC + 6 cm of EPS, e.g.) with one layer of the same thickness (21 cm) but composed only by PU 19, the latter will provide a thermal insulation that is 33% lower than the former, because the thermal insulation provided by PU 19 is higher than that of NC but much lower than that of EPS.

Besides analyzing the thermal insulation of the layers composing the floor, an analysis was performed focusing on the thickness that the layers should have, in order to obtain an overall given thermal insulation value. The results are shown in Figure 11.

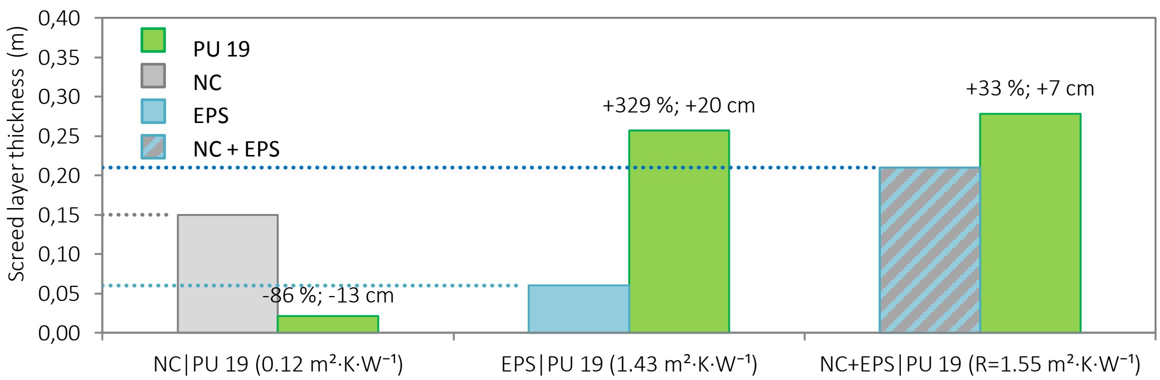


Figure 11. Thickness of PU 19 layer that provides the same thermal insulation of: one layer of NC (15 cm thick), one layer of EPS (15 cm thick) and a multilayer composed by 15 cm of NC and 6 cm of EPS

A layer of PU 19 can be 86% thinner than a layer of NC and provide the same thermal insulation. Thus, the same thermal insulation provided by a layer of 15 cm of NC (R-value = 0.12 $m^2 \cdot K \cdot W^{-1}$), can be obtained by a layer of PU 19 with only 2 cm (-13 cm than NC). When compared with a 6 cm layer of thermal insulator layer (EPS, R-value = 1.43 $m^2 \cdot K \cdot W^{-1}$), the PU 19 layer would have to be 329% thicker than the former in order to provide the same thermal insulation. Instead of 6 cm of EPS, one would have 26 cm of PU 19 (+20 cm than EPS). If a multilayer of 15 cm of NC and 6 cm of EPS is considered, the resulting thermal insulation would be 1.55 $m^2 \cdot K \cdot W^{-1}$. In order to obtain the same thermal insulation of this multilayer, with a wall made of PU 19 only (removing the need of the thermal insulator layer), a thickness of 28 cm would be necessary (+7 cm than the multilayer wall). This is a consequence of the 13 cm saving relative to NC and of the extra 20 cm necessary to compensate EPS.

4.3. Thermal diffusivity and thermal stress in the wall

The thermal diffusivity relates the amount of heat that is transferred (thermal conductivity) with the amount of heat that can be stored (heat capacity). A good thermal insulator that is highly capable of storing heat is thermally advantageous because it is capable of keeping the temperature close to a constant value over time, by dampening and delaying heat transfer.

In order to analyse the thermal and mechanical response, over time, of a wall made of the studied blocks and panels, realistic weather conditions were assumed (Figure 12), typical of hot summer (18th July in Évora, Portugal) and cold winter (18th January in Bragança, Portugal). A detailed description of the conditions considered is given in Annex 1.

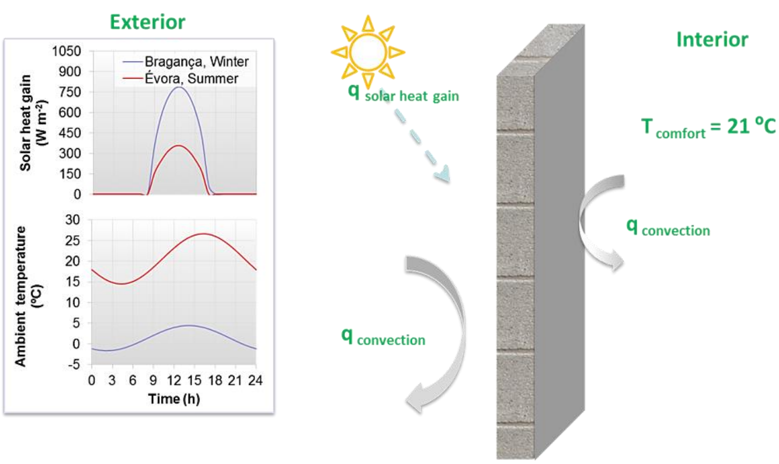


Figure 12: Façade wall and climatic conditions considered

The temperature on the interior of the wall (made of blocks or panels), and the stresses in its centre, were analysed, for the conditions formerly mentioned. The results for blocks and panels are shown in Figure 13 and Figure 14, respectively.

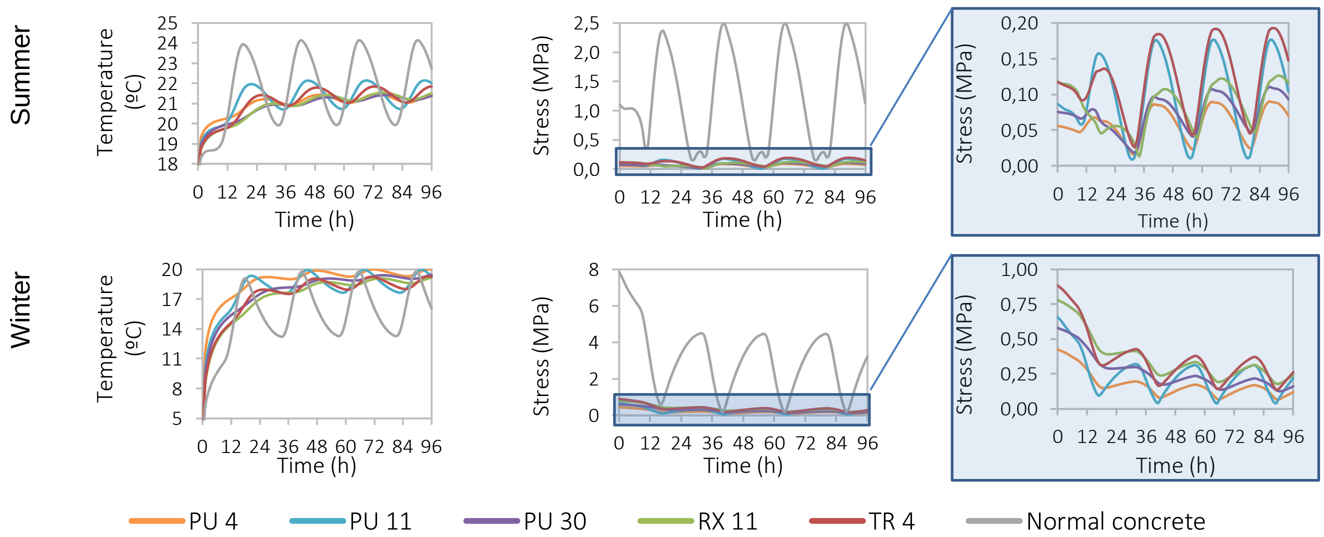


Figure 13: Temperature on the interior of the wall and von Mises stresses in its center, for summer and winter conditions, for walls made of blocks (20 cm thick) composed by different concrete mixtures, including normal concrete

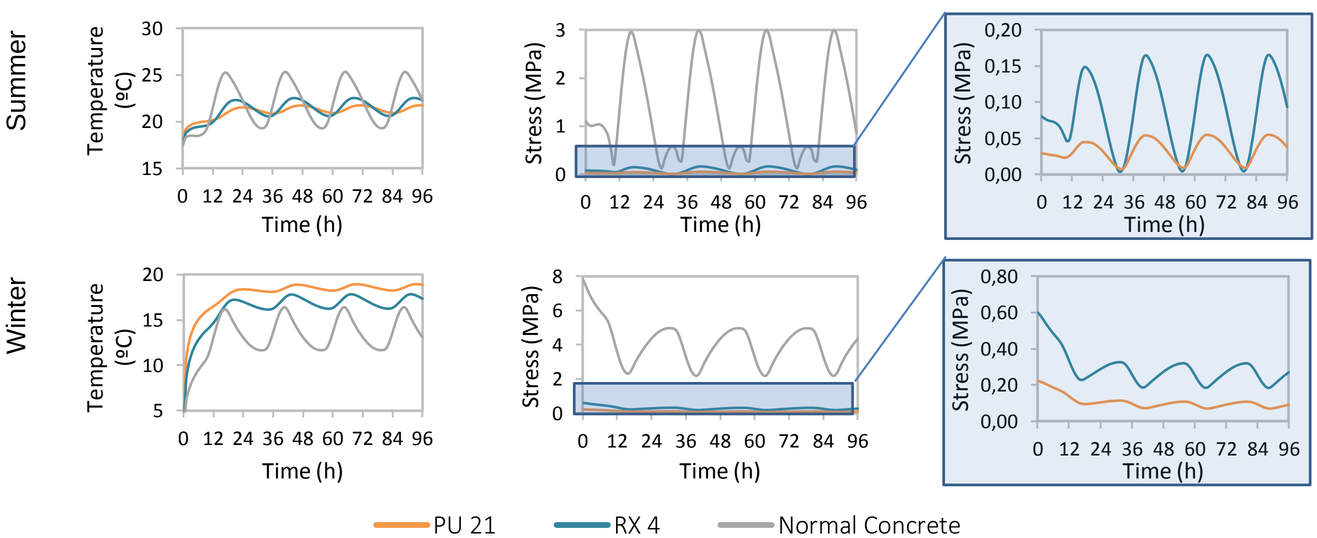


Figure 14: Temperature on the interior of the wall and von Mises stresses in its center, for summer and winter conditions, for walls made of panels (15 cm thick) composed by different concrete mixtures, including normal concrete

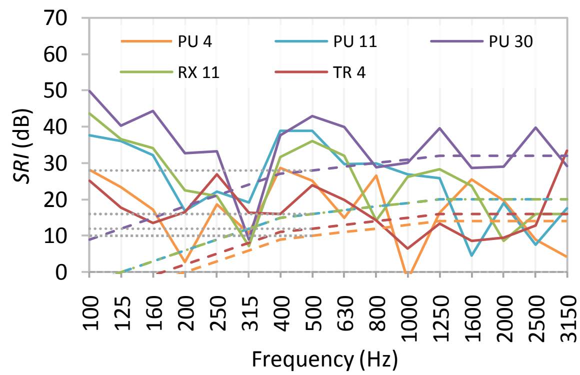
The mixture PU 4 has the lower thermal conductivity and experiences lower thermal stresses (which are proportional to the coefficient of thermal expansion and Young's modulus of the material) than the other mixtures. This is consistent with the studies previously performed for blocks (section 3.2). Yet, it is mixture PU 30 that has lower thermal diffusivity which results in a temperature always closer to 21 ºC on the interior wall, as can be observed in Figure 13.

For panels, PU 21 is the mixture presenting lower thermal diffusivity, which result is flatter temperature variations over time, that are closer to 21 ºC, in the interior surface of the wall. Also, it is mixture PU 21 that presents lower stresses and lower stress oscillations.

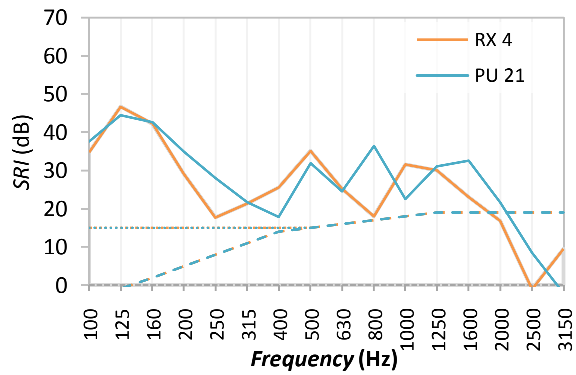
All the mixtures present a better thermal behaviour than the considered normal concrete.

4.4. Acoustic performance of walls

The acoustic performance of walls composed by blocks and panels was assessed by numerically simulating "virtual labs". The airborne sound insulation capacity was analysed, because it is the main way of sound transmission in walls. A sound source room and a sound receiving room, separated by the "sample" wall, were modelled, following ISO 10140-1. The sound insulation rating quantities, described in ISO 717-1 (sound reduction index (SRI) for 1/3 octave band, weighted sound reduction index (Rw) and spectrum adaptation terms for indoor (C) and traffic (Ctr) noise), were obtained, as shown in Figure 15 and Table 4.



a)



b)

Figure 15. Sound reduction index (solid lines) obtained for walls made of: a) blocks composed by corresponding mixtures and b) panels composed by corresponding mixtures; shifted reference curve (dashed-lines) and weighted sound reduction index (dotted-line) are shown for each mixture

Table 4. Weighted sound reduction index and spectrum adaptation terms for indoor and traffic noise, for walls made of blocks or panels

	Blocks					Panels	
	PU 4	PU 11	PU 30	RX 11	TR 4	RX 4	PU 21
Rw(C;Ctr):	10(-4;-5)	16(-5;-3)	28(-3;-6)	16(-1;0)	12(-1;-1)	15(-8;-4)	15(-8;-4)

The walls made of blocks presenting the higher sound insulation capacity are those made of PU 30. Panels present the same acoustic performance for both mixtures although the sound reduction index curves are slightly different.

5. House/Building composed by façade walls made of blocks or panels

The energy efficiency of building with façade walls composed by a multilayer structure (Figure 16, details in Annex 2) including one concrete layer corresponding to the previously studied concrete mixtures (Table 1) was assessed.

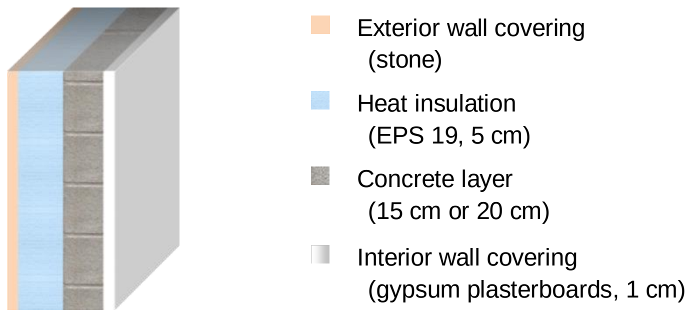


Figure 16. Schematics of a simple multilayer façade wall configuration

Two different locations were considered for two types of buildings: one-story building and multi-story building placed in one location typical of hot summer (Évora, Portugal) and other typical of cold winter (Bragança, Portugal). The energy consumption obtained for the four resulting scenarios (one-story in Bragança and Évora and multi-story in Bragança and Évora), and for the façade walls composed by blocks or panels, are shown in Figure 17 and Figure 18, respectively. Also, the costs of energy consumption are shown, when the energy source is electricity and the HVAC equipment is considered to be 100% efficient.

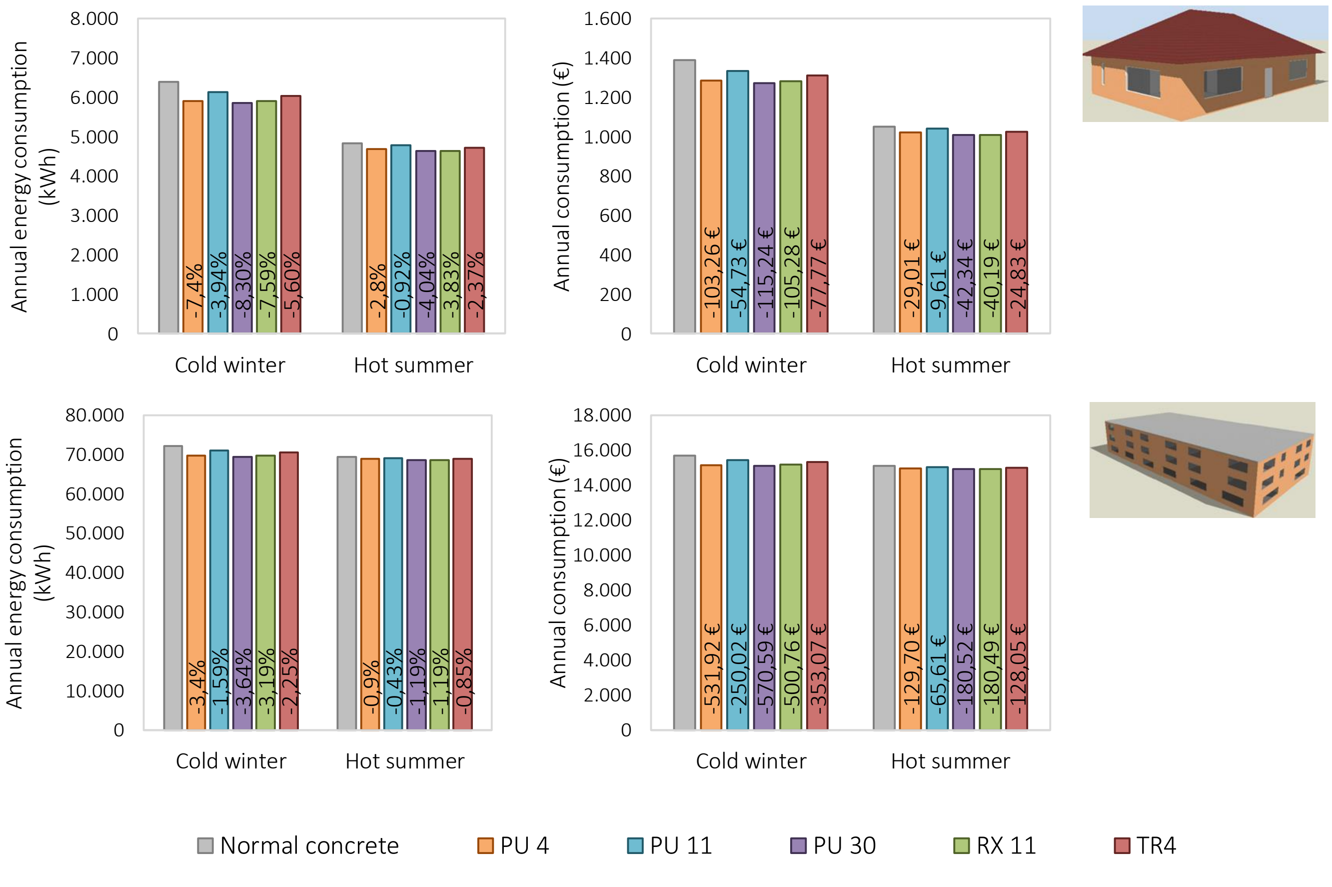


Figure 17: Energy consumption and corresponding costs for façade walls made of blocks, for summer and winter, and for one-story and multi-story buildings

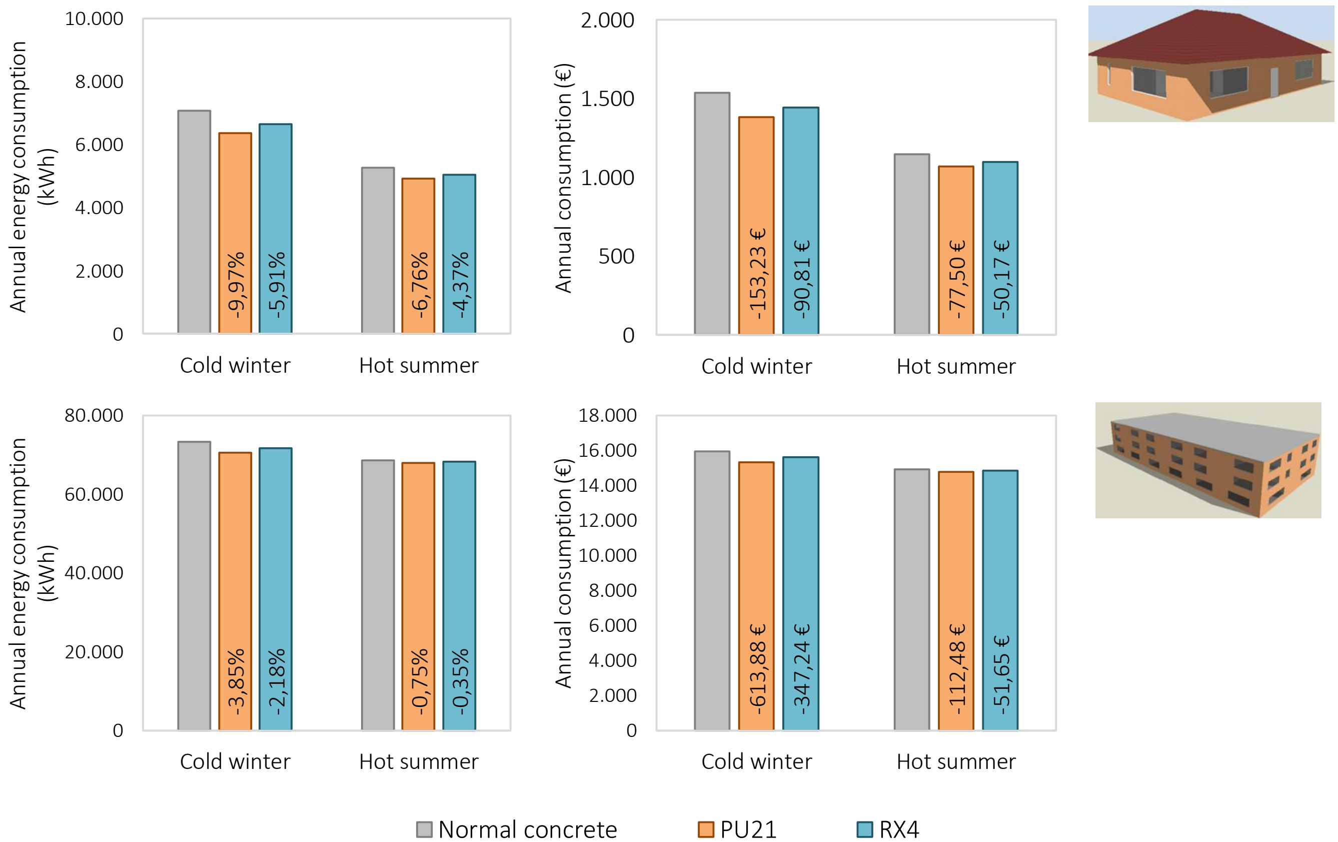


Figure 18: Energy consumption and corresponding costs for façade walls made of panels, for summer and winter, and for one-story and multi-story buildings

The energy consumption is higher for multi-story building than for one-story building, as expected, and higher for winter than for summer.

In winter, when the façade walls are composed by PU 30, higher savings in energy consumption are achieved, both for one-story and multi-story building, (8.3% and 3.6%, respectively). Considering that all the necessary energy is provided by HVAC equipment that is 100% efficient, savings of 115 €/year and 570 €/year are achieved for one-story and multi-story buildings, respectively. Obviously, the HVAC equipment is not 100% efficient so higher savings can be obtained, depending on the efficiency of the equipment.

When the mixtures composing panels are considered, higher savings in energy consumption are obtained for PU 21. In winter, savings of 10% and 3.8% are obtained for one-story and multi-story buildings, respectively. Again, assuming that the HVAC equipment is 100% efficient and electricity is the energy source, 153 €/year and 613 €/year can be spared if PU 21 is used instead of normal concrete.

For all studies performed and under the conditions considered, the SUS-CON concrete mixtures perform better thermally and mechanically than normal concrete.

6. Mock-ups built with SUS-CON products

In order to validate the results obtained from numerical studies, these were compared with experimental data obtained for a mock-up, made of RX4 panels, located in Madrid (see D6.4).

6.1. Geometry and materials composing the mock-up

The mock-up composed by RX4 panels was simulated. The walls had a surface of 2.5 m x 2.5 m and were 2.5 m high. A door and a window existed in the north and east walls, respectively, as shown in Figure 19. The door size is 90 cm x 210 cm and the window size is 55 cm x 55 cm. This window was considered to have a double glass (4/6/4) with U-value of 2.5 $W{\cdot}m^{2}{\cdot}K^{-1}$ but it was assumed to be highly reflective in order to simulate the aluminium covering that existed in the real mock-up.

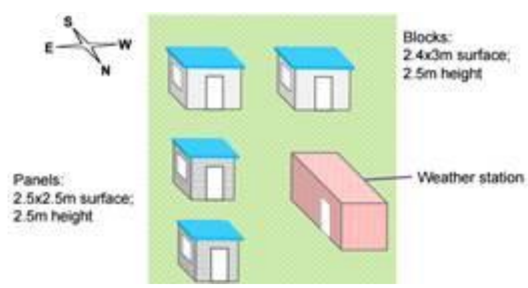


Figure 19. Schematics of the mock-up geometry and orientation

The stratigraphy of the panels composing the wall is shown in Figure 20 and the thermal properties of each layer composing the panel are shown in Table 5.

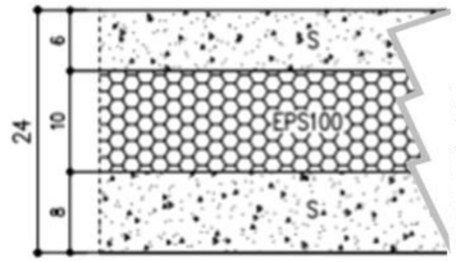


Figure 20. Stratigraphy of the RX4 panel

Table 5. Thermal properties of each layer composing the panel

	Thickness (cm)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)
RX4	6 and 8	0.344	1275	1440
EPS100	10	0.040	1400	15

The roof consisted of a flat multilayer structure composed by two aluminium layers with 5 cm each and an intermediate 5 cm layer of polyurethane. The thermal properties of the materials composing the roof are shown in Table 6.

Table 6. Thermal properties of each layer composing the roof

	Thickness (cm)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)
Aluminum layer	5	230	880	2700
Polyurethane core	5	0.028	1470	30

The floor was assumed to consist of a 15 cm layer of concrete, with thermal properties as shown in Table 7.

Table 7. Thermal properties of the material composing the floor

	Thickness (cm)	Thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	Specific heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)	Density ($kg \cdot m^{-3}$)
Concrete	15	0.380	1000	1200

6.2. Equipment, lighting, occupation patterns, etc.

In order to obtain realistic temperature results (comparable to those measured), the mock-up was considered to have no activity, occupation, lighting or equipment in its interior. No air entrances and no HVAC system were considered.

6.3. Climatic data

The measured weather data (temperature, humidity, wind direction and velocity, solar radiation incidence, etc.) regard only specific time intervals. In order to approach the simulation results to realistic weather conditions, data regarding an entire year (2002, Madrid) was simulated but, for the measured time intervals, the data regarding year 2002 was replaced by the measured data. Also, the measured solar radiation incidence cannot be directly assumed by the simulation software. Thus, due to the lack of time to find a proper conversion of the measured data to values that could be used by the software, solar radiation incidence regarding year 2002 was used instead. This simplification can originate discrepancies between the experimental and simulation results. The experimental and simulation results regarding the temperature in the west wall are shown in Figure 21, for the available/measured time intervals.

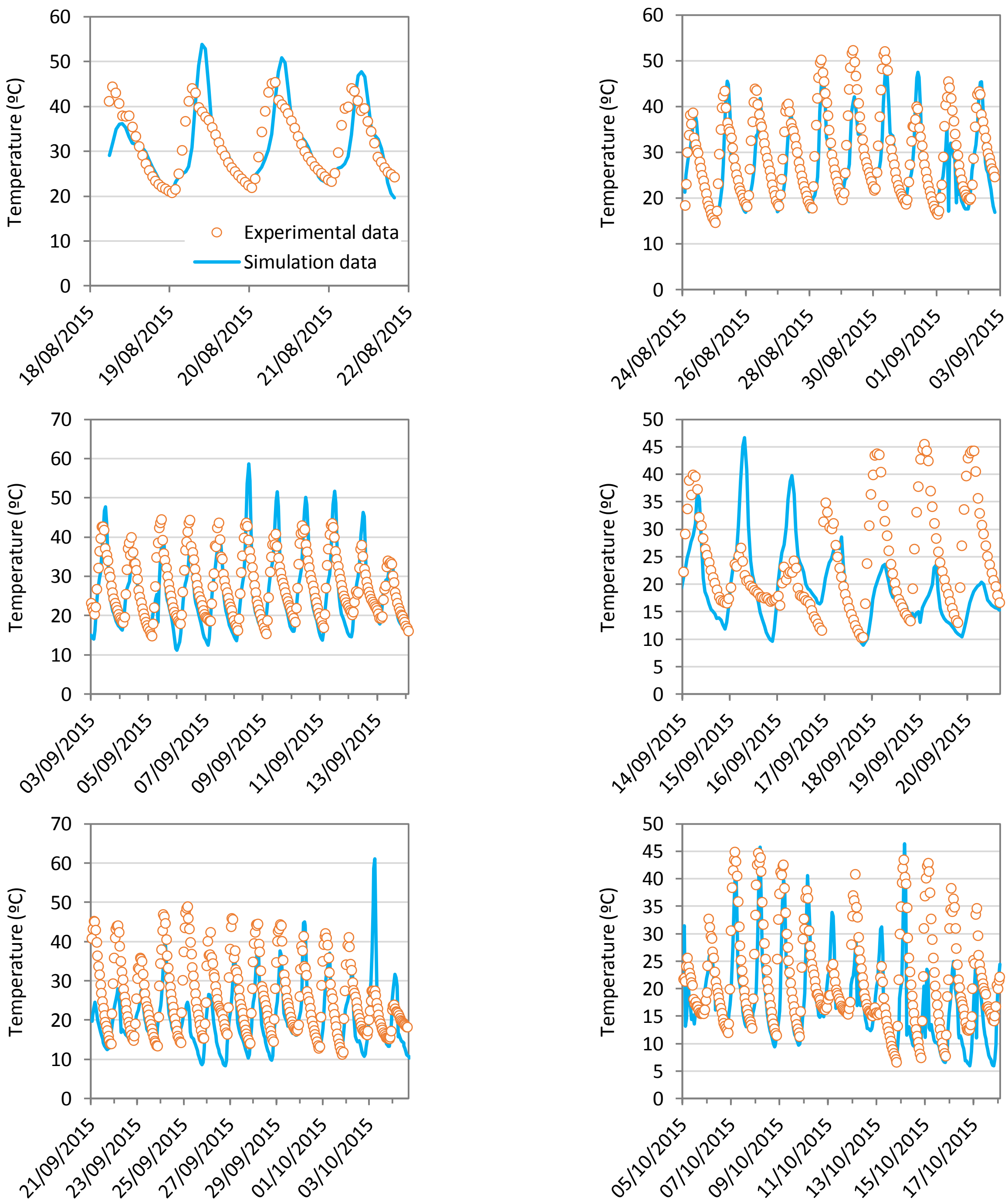


Figure 21. Temperature in the west wall of the mock-up made of RX4 panels: experimental and simulated data

For the period between 18th and 27th of September there are high temperature discrepancies in the temperature peaks. This can be a consequence of the difference between the assumed (year 2002) and the measured (year 2015) solar radiation. These results indicate that, in the period between 18th and 27th of September of 2015, there was more solar incidence than in the same period of 2002.

6.4. Energy efficiency of the mock-up

In order to assess the energy efficiency of the mock-up, the previous analysis was repeated but an HVAC system was assumed in the interior of the mock-up, in order to maintain an interior temperature between 18ºC (onset of heating) and 25ºC (onset of cooling). In this study, panels with the same structure but composed by PU21 instead of RX4 were also analysed in order to make an energy efficiency comparison between these two SUS-CON mixtures. The results are shown in Figure 22.

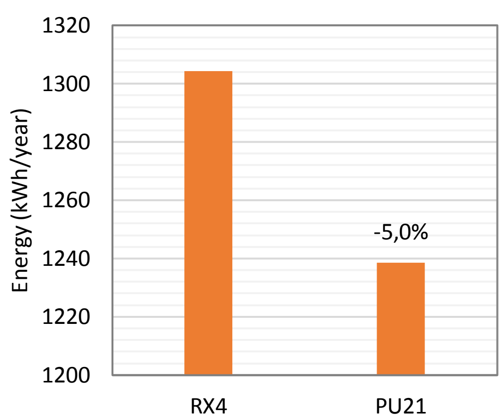


Figure 22. Energy necessary to keep temperature between 18ºC and 25 ºC in the mock-up interior, when walls are composed by RX4 and PU21 panels

As was previously referred (chapter 4 and 5), panels made PU21 result in lower energy consumption than those made of RX4. In the case of the simulated mock-up, 5% of energy could be spared if the panels were made of PU21 instead of RX4.

7. Conclusions

A multi-scale analysis of the thermal, mechanical and acoustic behaviour of non-traditional concrete mixtures (SUS-CON concretes) was performed.

Concrete components, such as blocks and panels, were considered to be composed by non-traditional concrete mixtures. The stress distribution in blocks and panels was analysed, when they are part of a non-structural wall and accounting with thermal expansion phenomena. It was concluded that the mixtures that experiences higher compressive stress are RX 11 and RX 4, for blocks and panels, respectively. It could be concluded, for all mixtures composing blocks and panels, that the maximum compressive stress is lower than compressive resistance. Also, besides compression, attention should be payed to tension zones.

The maximum height that a wall made of the studied blocks and panels can have, before failure occurs, was also calculated. It was found that higher compressive resistance does not necessarily mean that the wall above the block/panel can be higher. The allowed height of the wall depends on the load promoted by the wall in the block/panel (which, in turn, depends also on the density of the material composing it) and on the maximum stress, occurring in high stress zones, which, in turn, depends on the elastic properties of the material and on its thermal expansion coefficient. Thus, it was concluded that the wall composed by PU 30 (for blocks) and PU 21 (for panels), can be higher than the others, although RX 11 (for blocks) and RX 4 (for panels) have higher compressive resistance.

The thermal insulation of a wall composed by one layer of the formerly analysed blocks or panels was studied. The wall composed by blocks of PU 4 has 8 fold higher thermal insulation than NC, resulting in a 88% thinner wall with same thermal insulation. Also, PU 4 wall shows lower thermal stresses ($\propto CTE \times Young's\ modulus$). Walls composed by panels of PU 21 show 6.5 fold higher thermal insulation than NC, resulting in a 87% thinner wall with same thermal insulation.

Regarding the acoustic performance of walls, those made of blocks of PU 30 show higher sound insulation capacity, while for panels both mixtures RX 4 and PU 21 show the same acoustic performance.

The thermal behaviour of the wall over time was also assessed. Walls made of blocks composed by PU 30 (mixture with lower thermal diffusivity) show the best thermal behaviour, keeping temperature always closer to 21 ºC. When this mixture is applied in building's façade walls, it results in higher savings in energy consumption by HVAC systems than the other mixtures used for blocks: until 8.3% lower consumption, compared to normal concrete. By using panels of PU 21b for façade walls, the temperature on the interior of the facade wall is kept closer to 21ºC than the other mixtures (because it has lower thermal diffusivity). Thus, PU 21 results in higher savings in energy consumption by HVAC systems (10% lower consumption compared to NC).

Finally a comparison was made between temperatures measured in one mock-up placed in Madrid and the temperatures obtained by numerical simulating the mentioned mock-up. Some differences between the realistic mock-up weather data and the simulated one existed, which can justify some discrepancies obtained in the results, although they are very similar for some time intervals. The energy efficiency of the simulated mock-up, made of RX4, was assessed and compared to a mock-up made of PU21. Again, it was found that panels made PU21 result in lower energy consumption than those made of RX4. In the case of the simulated mock-up, 5% of energy could be spared if the panels were made of PU21 instead of RX4.

8. References

[1] H. Czichos, T. Saito, and L. R. Smith, *Springer Handbook of Materials Measurement Methods*. Springer, 2006.

[2] C. A. P. dos Santos and L. Matias, "Coeficientes de transmissão térmica de elementos da envolvente dos edíficios." ICT informação técnica; Edifícios - ITE 50, Lisboa, 2006.

[3] ASHRAE, *ASHRAE®HANDBOOK: Fundamentals*, vol. 30329, no. 404. 2009.

9. Annex 1 – Indoor and outdoor conditions considered for walls

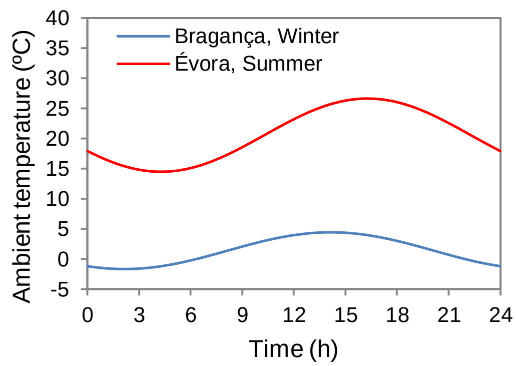
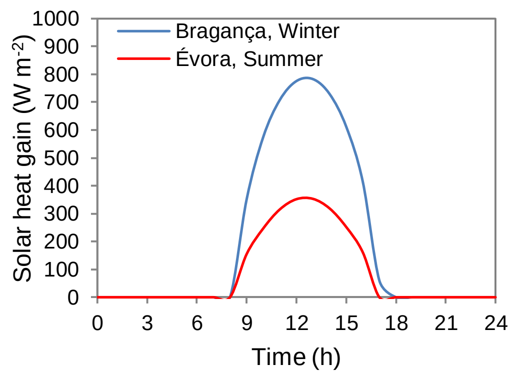
In order to assume realistic weather conditions, the clear-sky model [3] was applied in order to obtain two outdoor scenarios: one typical of summer (Évora, Portugal, 18th July) and other typical of winter (Bragança, Portugal, 18th January). Thermal comfort conditions were assumed for indoor environment – a constant indoor air temperature of 21 ºC and convection and radiation heat transfer between walls and indoor environment, following Newton's law (equation 1).

$$q = h_{c+r} \cdot (T_{wall} - T_{indoor}) \tag{1}$$

h_{c+r} = combined convective-radiative heat transfer coefficient for indoor conditions, in $W \cdot m^{-2} \cdot K^{-1}$
T_{wall} = Temperature in the interior surface of the wall, in ºC
T_{indoor} = Temperature in the indoor ambient, in ºC

The assumed conditions for each scenario are listed in Table 8.

Table 8. Indoor and outdoor conditions

Scenario:	summer	winter
Location:	Évora	Bragança
Time:	18th July	18th January
Orientation of the building:	South	South
Outdoor temperature (ºC):		
Solar heat gain (W·m^{-2}):		
Heat transfer coefficient for outdoor conditions (W·m^{-2}·K^{-1}):	14.8	10.4
Indoor temperature (ºC):	21	21
Heat transfer coefficient for indoor conditions (W·m^{-2}·K^{-1}):	3.08	3.08

10. Annex 2 – Details of the buildings structures and model

Table 9. Structural features of the buildings

Multi-story building	
Number of floors	3
Number of rooms per floor	6
Floor area (m^2)	881.9
Ceiling height (m)	2.7
Description of floor 1 (6 Warehouses)	Areas (m^2)
Central/North/South	
Floor	136.1
North/South glass pane	12.1
East/West areas	
Floor	136.1
North/South glass pane	12.1
East/West glass pane	7.93
Description of floor 2 and 3 (6 Apartments/floor)	Areas (m^2)
Central/North/South	
Floor	138.7
Kitchen	
Floor	17.81
Room 1	
Floor	28
Room 2	
Floor	24.95
North glass pane	4.66
Room 3	
Floor	38.95
North glass pane	5
Hall	19.93
Floor	
WC	9.04
Floor	
East/West apartments	
Floor	138.7
Kitchen	
Floor	17.81
East glass pane	2.52
Room1	
Floor	28
Room 2	
Floor	24.95
North glass pane	4.66
Room 3	
Floor	38.95
North glass pane	5
East glass pane	5.48
Hall	
Floor	19.93
WC	
Floor	9.04

One-story building	
Number of rooms	6
Description of floor	Areas (m^2)
Floor	138.7
Kitchen	
Floor	17.81
North glass pane	5.02
West glass pane	0.84
Room 1	
Floor	28
South glass pane	4.66
Room 2	
Floor	24.95
East glass pane	3.78
Room 3	
Floor	38.95
West glass pane	5.49
South glass pane	5.02
Hall	
Floor	19.93
WC	
Floor	9.04

Table 10. Building elements properties

	Thickness m	Density $kg \cdot m^{-3}$	Thermal conductivity $W \cdot m^{-1} \cdot K^{-1}$	Specific heat capacity $J \cdot kg^{-1} \cdot ºC^{-1}$
Façade walls				
Exterior wall covering (stone: granite)	0.05	2640	1.6	820
Heat insulation (EPS 19)	0.05	19	0.04	1470
Concrete layer	0.20 or 0.15	VARIABLE - DEPENDING ON STUDIED MIXTURE		
Interior wall covering (Gypsum)	0.01	1150	0.57	1090
Internal walls				
Gypsum layer	0.012	900	0.21	850
Thermal insulation	0.010	35	0.035	1400
Gupsum layer	0.012	900	0.21	850
Roof covering/exterior floor				
Floor covering	0.004	1500	0.23	1500
Cement layer	0.06	2000	1.4	850
Thermal insulation (XPS)	0.04	35	0.035	1400
Concrete screed	0.018	1600	0.85	750
Internal floor				
Ceramic floor covering	0.02	2300	1.3	1000
Cement layer	0.06	2000	1.4	850
Thermal insulation layer	0.04	35	0.035	1400
Concrete screed	0.18	1600	0.85	750
For one-story building:				
Roof garret				
Concrete layer	0.18	1600	0.85	750
Thermal insulation	0.04	35	0.035	1400
Cement layer	0.06	2000	1.4	850
Inclined roof				
Ceramic covering	0.13	2300	1.3	1000

For each floor of the multi-story building, a central corridor connecting all the divisions was considered, with a floor area of 64 m^2. Also, it was assumed that 30% of the area of the walls was composed by glass panes. The glass pane was composed by aluminium frames and 3 mm thick simple glass, with a solar factor of 0.8 and a heat transfer coefficient of 5 $W \cdot m^{-2} \cdot ºC^{-1}$. For the one-story building, also 30% of the exterior walls were considered to be glass panes. Yet, depending on the type of divisions of the house, different glass areas were considered, according to specified in table 9. The inclined roof was assumed to have an angle of 30º and an area of 138.7 m^2.

Occupation patterns, equipment, etc.

Building regulations may be different from country to country. Occupation patterns for residential buildings are not defined in Portuguese building regulations due to the random patterns of occupation and activities in this type of buildings. Thus, and in order to keep the model as generic as possible (among scenarios and among countries), the studies were performed considering that the building was not occupied.

The heat sources present in the building correspond to equipment (household appliances, televisions, etc.). The first floor of the multi-story building was considered to have no equipment generating heat, since it is composed by warehouses. The second and third floor of the multi-story building, as the first (and only) floor of the one-story building, are considered to have one heat source per room, corresponding to 4 $W \cdot m^{-2}$ of heat generation, as recommended by the Portuguese building regulation for residential buildings.

Regarding the thermal conditions in the interior of residential buildings, the recommended temperatures for the onset of air-conditioning systems are 18ºC for heating and 25ºC for cooling, in order to keep thermal comfort.

The air renewal values for residential buildings are also defined in the building regulation. The recommended values for April-September season is 0.6 h^{-1} and for October-March season is 0.4 h^{-1}.

The HVAC system is designed in order to guarantee that the above conditions are met for each building, depending on its location and weather conditions. Since the first floor of the multi-story building is not a residential floor, no HVAC system is considered in that floor.

Location and weather conditions

Following the procedure used for the “wall-thickness” studies, two weather scenarios corresponding to two locations were considered: one typical of hot summer (Évora) and one typical of cold winter (Bragança). Unlike in the “wall-thickness” studies, these studies are performed on yearly-averaged results, and not only for a typical summer day or typical winter day.