Modelling mechanical and thermal performance of concrete products: A multi-level approach

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The performance of concrete products depends not only on the concrete compositions but also on the dimensions and the environment they are placed in. Numerical simulations are excellent tools to predict the performance of concrete products before actually making them and thus serve as a tool for product design. The present numerical studies were focused, firstly, on the prediction of the mechanical and thermal behaviour of concrete products when applied in façade walls and, secondly, on the prediction of the energy efficiency of buildings composed by such products.

Different concrete mixtures were considered, depending to their target application (blocks or panels, e.g.). Façade walls were considered to be exposed to realistic weather conditions and focus was put on the stresses resulting from thermal expansion. For the "house/building" level, an energy efficiency analysis was performed for different types of buildings, which were assumed to be exposed to typical cold winter and hot summer weather conditions. This resulted in detailed information on the energy balance of the resulting structures such as energy consumption with HVAC (heating, ventilating, and air conditioning) systems.

An integrated multi-level approach, from concrete components to building structures, was developed, enabling to compare the performance of different concrete compositions.

Key words: Design, waste binder, waste aggregate, fresh concrete, finite element modelling, FEM, energy efficiency, performance prediction, numerical simulation

1 Introduction

Concrete is the most used building material in the world. Its constituents are widely available and relatively cheap, and the concrete itself is durable and reliable [P.-C. Aïtcin, 2000; R. J. Flatt, N. Roussel, and C. R. Cheeseman, 2012]. The reliability stems from its constant quality of performance that is assured by building codes such as EUROCODES. With respect to the mechanical properties of concrete, the quality has been quantified by means of the compressive strength class. All other mechanical properties have been linked to this compressive strength by means of relationships developed on the basis of experimental results (e.g. the relationship between tensile and compressive strength) [J.H.M. Visser and A. V. Bigaj, 2014; M. N. Hassoun and A. Al-Manaseer, 2012; EN 1992-1-1:2004, 2004].

When non-traditional concrete compositions are considered, the well-known material relationships in the building codes may not be applicable and thus may not be used a priori. In order to obtain proof of suitability and develop guidelines for non-traditional concretes and concrete products, their behaviour has to be tested and the relationships in the codes either proved or adjusted (Visser and Bigaj, 2014). Prior to starting such a time-consuming and often costly approval route, however, the suitability of the new materials can be analysed already under the (environmental) loads they are required to serve. If they prove to be unsuitable for an environment, then these can be excluded a priori, reducing cost and time.

To accelerate the experimental stage and reduce the number of experiments further, numerical simulations also can be used to study the suitability of different compositions for the intended applications. In addition, product design (shape and dimension) can be optimized according to the specifications. This produces, at early development stage, information on the potential performance and limitations in real applications.

Under the aim of SUS-CON project[1], different concrete mixtures were formulated targeting four different products: blocks, panels for façades, floor and floor screed underlay [J. Visser et al., 2015]. In the present paper, the performance of some products made of traditional and non-traditional concrete exposed to realistic environmental conditions, is investigated. The performance of the envisaged concrete products depends not only on their composition but also on the dimensions and on the environment they are placed in. Thus,

[1] SUS-CON: 'SUStainable, innovative and energy-efficient CONcrete based on the integration of all waste materials', 7th Framework Programme Grant 285463, http://www.sus-con.eu

three levels of numerical studies are performed. At the first level, the thermal and mechanical behaviour of concrete products, such as blocks and panels for façades, are analysed. Different concrete compositions are considered (by varying the material and volume fraction of aggregate) while the heterogeneity of the material is taken into account and stress distribution in mortar and aggregate particles is studied. At the second level, the mechanical and thermal performance of elements (façade walls) is assessed. At this level, the material is considered homogeneous and attention is focused on the response of the walls to time-varying external/ambient conditions. Finally, at the third level, an energy efficiency study 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.

2 Products: blocks and panels for façades

2.1 Average concrete properties based on its composition

The average properties of concrete mixtures used in the present analysis were obtained based on the spatial arrangement and properties of their constituents (following the method reported in Visser et al. [2015]). By taking into account the particle packing structure of concrete, instead of considering it a homogeneous medium with average properties, one obtains important information on weak points/zones that may be prone to failure when products (blocks and panels, e.g.) are loaded, as well as detailed information on the influence of particle packing structure on the overall performance of the final concrete.

Two types of concrete were considered, i.e. a lightweight concrete composed by PUR (rigid polyurethane) and a normal concrete composed by gravel. Both were composed by a Portland cement mortar (CEM I 42.5 N). The properties of the mortar and aggregates used in the concrete mixtures are shown in Table 1. Both combinations were simulated for 25 % and 50 % coarse aggregate fractions. The particles diameters ranged from 4 to 8 mm and finer aggregate particles were considered to be part of the fluid mortar, as explained in Visser et al. (2015). Also, the interfacial transition zone (ITZ) between aggregate and matrix was not modelled in the present approach.

Using the properties of Table 1 and information on the particle packing structure , the two different types of aggregates at two volume fractions (25% and 50%), resulted in four concrete mixtures with different average mechanical and thermal properties (Table 2)

(following Hooke's law and the method described in Visser *et al*. [2015] [J. H. M. Visser *et al*., 2015] and He [2010] [H. He, 2010]).
The Young's modulus and thermal conductivity values of the gravel are higher than those of the mortar (Table 1). Thus, adding gravel in the mix results in a higher Young's modulus and a higher thermal conductivity (lower thermal insulation) of the concrete mixture. The

Table 1: Properties of the aggregates and mortar composing the concrete mixtures

	Units	Mortar: CEM I 42.5 N	Lightweight concrete Aggregate: PUR	Normal concrete Aggregate: Gravel
Density (fresh)	kg/m^3	2257	-	-
Density (hardened)	kg/m^3	2321	330	2620
Viscosity	Pa s	120	-	-
Yield stress	Pa	16	-	-
Coefficient of friction	-	-	1.5	0.6
Coefficient of restitution	-	-	1	1
Young's modulus	GPa	38.8	0.8	70.5
Poisson's ratio	-	0.19	0.3	0.22
Thermal conductivity	W/(m K)	0.65	0.026	4.8
Specific heat capacity	J/(kg K)	735	1450	790
Coef. Thermal expansion	1/K	$1.30\ 10^{-5}$	$5\ 10^{-6}$	$1.17\ 10^{-5}$

Table 2: Calculated mechanical and thermal concrete properties of concrete mixtures under study

Properties	Units	Mix 1	Mix 2	Mix 3	Mix 4
Aggregate		PUR	PUR	Gravel	Gravel
Volume fraction of aggregate		0.25	0.50	0.25	0.50
Density	kg/m^3	1825	1325	2405	2485
Specific heat capacity	J/(kg K)	767	824	750	764
Coef. thermal expansion	1/K	$1.29\ 10^{-5}$	$1.28\ 10^{-5}$	$1.25\ 10^{-5}$	$1.22\ 10^{-5}$
Young's modulus	GPa	18.1	3.4	44.4	57.0
Poisson's ratio		0.25	0.23	0.20	0.15
Thermal conductivity	W/(m K)	0.40	0.12	0.962	2.05

more gravel is added, the higher this difference. Note that, for the two considered volume fractions of aggregate (0.25 and 0.50), the mortar remains a continuous phase in the material. The opposite change in properties can be observed when the aggregate is PUR (whose Young's modulus and thermal conductivity are lower than those of mortar, Table 1).

Although the average properties of the concrete mixtures are of main concern when evaluating its average behaviour, the local stress distribution is also of high importance in spotting high stress zones in the concrete products that may be prone to failure. Since the Young's modulus of gravel is higher than that of the mortar, it is expected that the aggregate particles carry more stress than the mortar. In contrast, when concrete is composed by PUR particles, it is expected that the stress is mainly carried by the stiffer mortar matrix. The local stress distribution in blocks and panels made of the four concrete mixtures and the consequences for failure are discussed next.

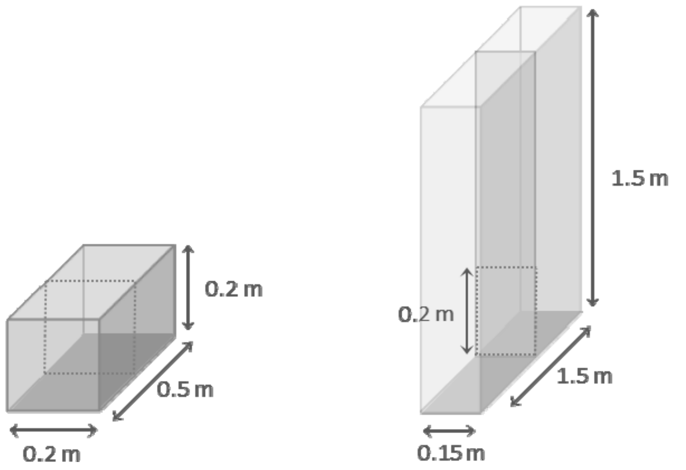
2.2 ***Load bearing capacity of blocks and panels***

Under the aim of SUS-CON project, different concrete mixtures, composed by non-traditional aggregates and mortars, were formulated targeting different non-structural products. On this basis, the simulated application for the blocks made of the mentioned concrete mixtures (Table 2) is part of a non-structural wall (2.7 m high), positioned in the bottom and carrying the weight of the wall (Figure 1). The panel (1.5 m high) was considered to bear its own weight and the weight of another panel; in total this yields a 3 m high wall. The simulation domain included only the bottom part of the panel (Figure 1b), which is where higher stresses are expected, being the effect of the remaining part of the wall considered as a load (Figure 1d), following the procedure used for the block made wall. This allowed to minimize the computational cost without jeopardizing the representativeness of the results.

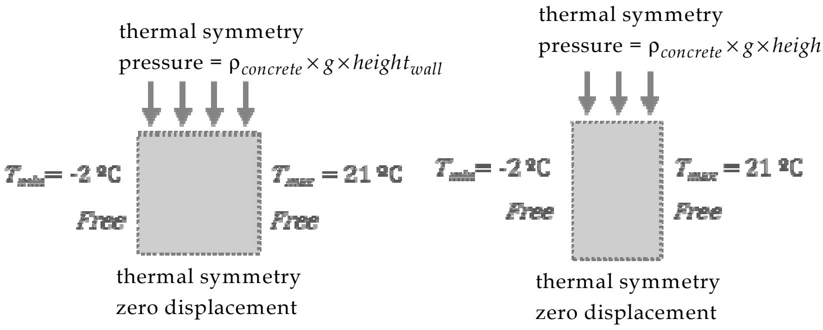
The geometry of blocks and panels depends not only on their size (Figure 1) but also on the simulated particle packing (Figure 2). Thus, meshes with 530 and 817 thousand triangular elements were used.

No external loads (such as wind loads) were considered except temperature load. The temperature was, on the inside of the wall, 21 ºC, being a comfortable temperature for living. On the other side, a temperature of -2 ºC was considered as average minimum monthly winter temperature, used in the climate simulation in section 3.

A summary of the simulated boundary conditions and geometries of panels and blocks is shown in Figure 1.



a) Block geometry *b) Panel geometry*



b) Block boundary conditions *c) Panel boundary conditions*

Figure 1: 2D Geometries of simulation domains and corresponding mechanical and thermal boundary conditions (BC) (heightwall is 2.7 m for blocks made wall and 3 m for panels made wall)

The thermal expansions were taken proportional to the temperature change in relation to a reference temperature (20 ºC), taken as the reference temperature for which the products are considered to be in normal shape, i.e. stress-free with respect to the temperature [H. Czichos, T. Saito, and L. R. Smith, 2006].

Two-dimensional simulations were performed on the cross-sections of blocks and panels as shown in Figure 1, based on a plane strain assumption.

The failure criteria based on the maximum principal stress theory is suited to brittle materials, such as concrete [E. Zahavi and D. M. Barlam, 2000]. Thus, the principal stresses were analysed and the stress distribution for each considered cross-section of concrete products is shown in Figure 2 (first principal stress, corresponding to tensile stress) and Figure 4 (third principal stress, corresponding to compressive stress). In Figure 3a and b, a zoom-in is made on the stress values shown in Figure 2 and the colour range is focused on an interval of tensile stress starting from -0.1 and -10 MPa, respectively, instead of 0 MPa.

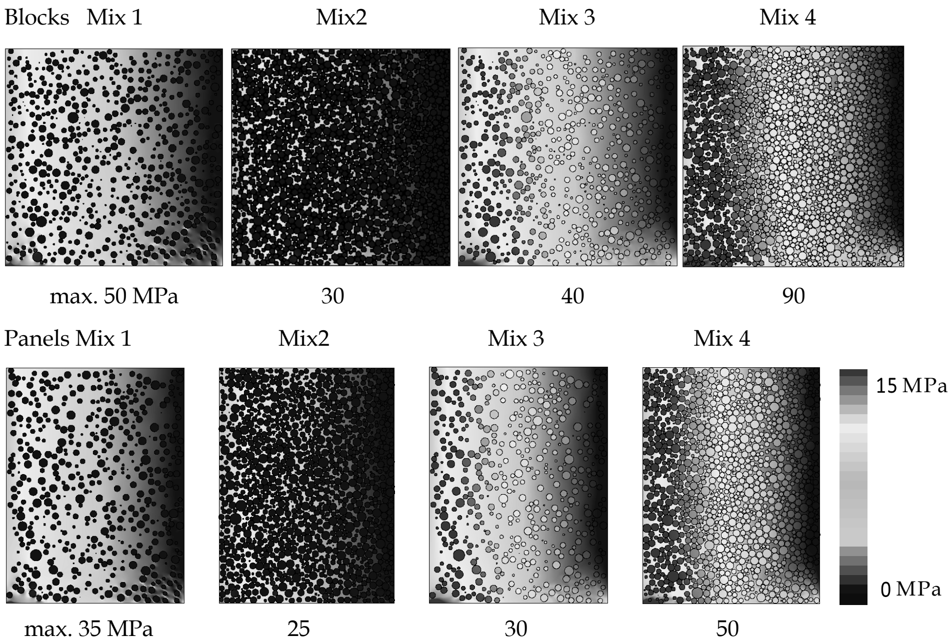
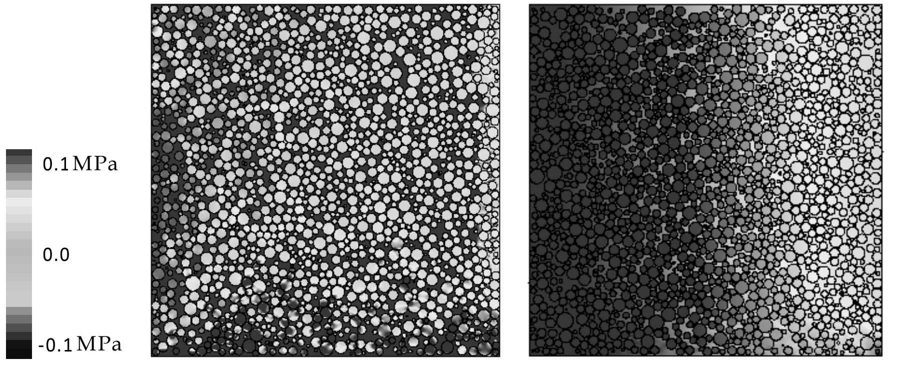


Figure 2: First principal stress (tensile stress) distribution in the cross-sections of blocks and panels, for each concrete mixture, at the steady-state heat transfer (left = -2 °C and right = +21 °C) and considering the wall self-weight (colour figures are available at www.heronjournal.nl)



a) Mix 2 blocks *b) Mix 4 blocks*

Figure 3: Detail of Figure 2 with different scale ranges focusing positive and negative first principal stress, showing, respectively, tension and compression zones

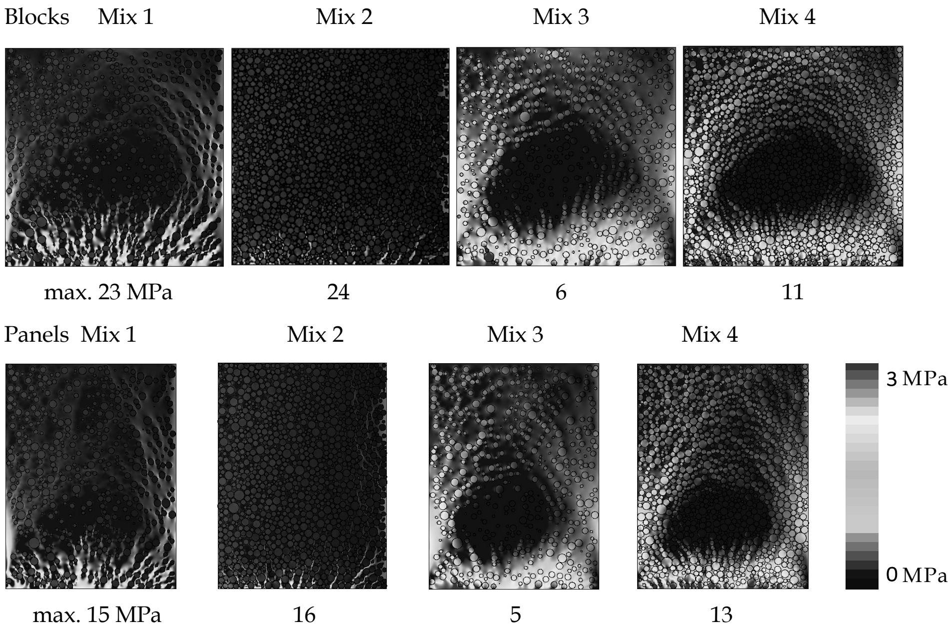


Figure 4: Third principal stress (compressive stress) distribution in the cross-sections of blocks and panels, for each concrete mixture, at the steady-state heat transfer (left = -2 °C and right = +21 °C) and considering the wall self-weight

The stress differences in the concrete products of Figure 2 are mostly due to the thermal expansion and thus mostly show a horizontal distribution. The expansion/shrinking is larger at the outside wall (at -2 ºC), as it has been taken linearly varying with the temperature change relative to 20 ºC, i.e. its stress-free reference temperature. Since near the colder boundary the temperature is lower than the reference value, considerable shrinking occurs, resulting in a stress distribution near this boundary (Figure 2).
The thermal expansion coefficient of PUR is slightly less than half of that of the mortar, meaning that their thermal shrinkage is affected by the higher thermal shrinkage of the mortar matrix. Moreover, the degree of shrinkage varies horizontally with the temperature prevailing across the wall thickness, which adds to the effects of the different deformations experienced by the materials in question and imposed loading conditions. Therefore, different conditions affect the particles throughout the structure. For the case of PUR-based mixtures (Mix 1 and 2), this results in some particles experiencing very slight compression

(e.g. towards the cold outside wall, Figure 3a) and others experiencing very slight tension (e.g. towards the centre-right and lower portions of the wall, Figure 3a). For the case of gravel-based mixtures (Mix 3 and 4), this results in particles experiencing mostly tension (Figure 2 and Figure 3b). Near the inside boundary (at 21 ºC), a very slight expansion occurs although at 1 ºC difference with the stress-free condition (20 ºC), the expansion-related stresses are negligible.

Overall, in Figure 2 and Figure 3, it can be seen that the PUR aggregates in Mix 1 and Mix 2 remain almost stress-free. The Young's modulus (0.8 MPa) and the bulk modulus (at this Poisson's ratio) of the PUR aggregates are very small. Thus, regarding stress-bearing capacity, PUR aggregates act quite like air, carrying hardly any stress. In such cases (Mix 1 and Mix 2), the stresses are mainly carried by the matrix (because the mortar is stiffer than the aggregates). Moreover, as expected, for Mix 3 and Mix 4, the aggregate particles carry more stress than the matrix, because gravel is stiffer than mortar.

Superimposed to the above mentioned expansion/shrinking effects, there are the stresses due to the self-weight/weight of the wall. As this is a vertical, gravity-based load, the highest stresses can be found at the bottom, as shown by the compressive stress distribution, in Figure 4 . The results are stress concentrations in the lower left corners of the walls.

Mix 4 is equivalent to normal concrete, made of gravel and Portland cement. Thus, if a typical compressive strength of 50 MPa is considered for this mixture, no compressive failure is expected to occur for blocks and panels subjected to the present loading conditions (Figure 4). In Visser *et al.* (2015), the compressive strength of a non-traditional concrete mixture composed by 50% PU (such as the present Mix 2, although with a mortar matrix of PFA instead of CEM) is reported as 5.6 MPa. Assuming that the compressive strength of Mix 2 is similar to that of the mentioned mixture, then compressive failure is expected to occur for blocks and panels made of Mix 2, under the present loading conditions (Figure 4).

The tensile strength of normal concrete mixtures can be obtained, from compressive strength, by applying known rules, as explained in Visser *et al.* (2015). Thus, for Mix 4 and for a compressive strength of 50 MPa, a tensile strength of 4 MPa is obtained. For Mix 2 (non-traditional mixture), assuming again it is similar to the mixture (50% PU + PFA) reported in Visser *et al.* (2015), a tensile strength of 0.9 MPa is considered. These tensile strengths (0.9 MPa and 4 MPa for Mix 2 and Mix 4, respectively) are much lower than the maximum obtained tensile stresses (Figure 2). Thus, for the present simulated loading conditions and assumed tensile strengths, tensile failure is expected to occur in blocks and panels made of Mix 2 and Mix 4.

It is important to note that the studies performed are based on the assumption of linear elastic behaviour of the materials which is considered reasonable until a stress, equivalent to the strength of the material, is achieved. Beyond that, a non-linear study should be performed in order to obtain more realistic stress and deformation distribution in the structure.

3 Elements: Façade walls

In order to predict the behaviour of the previously studied products in real building elements, when exposed to time-varying realistic weather conditions, the thermal performance and stress distribution in simple layer structures (façade walls) were assessed (by FEM), based on the average properties obtained in previous section 2.1 for each mixture (Table 2).

3.1 Geometry and material properties

A simple façade wall, composed by a layer of Mix 2 (50% PUR) or Mix 4 (50% Gravel), was considered, with a thickness of 0.20 m and height of 2.7 m. A mesh of triangular elements was used to discretize the wall domain, with a total of 2 thousand elements. The materials were considered to be linear elastic and the average properties of the mixtures were used according to Table 2.

3.2 Boundary conditions

In order to simulate a wall exposed to realistic weather conditions, the clear-sky model [ASHRAE, 2009] was applied for obtaining the outdoor environment conditions, taking into account solar irradiance contribution and both radiative and convective heat transfer between wall and environment . This model was applied for two different locations, resulting in two outdoor scenarios: a hot summer (in Évora/Portugal: 14.5 – 26.6 ºC) and a cold winter (in Bragança/Portugal: -1.6 – 4.4 ºC). Thermal comfort conditions were assumed for indoor environment, i.e. a constant indoor air temperature of 21 ºC and convective and radiant heat transfer between walls and indoor environment (see details in Table A1).

3.3 *Thermal performance of façade walls*

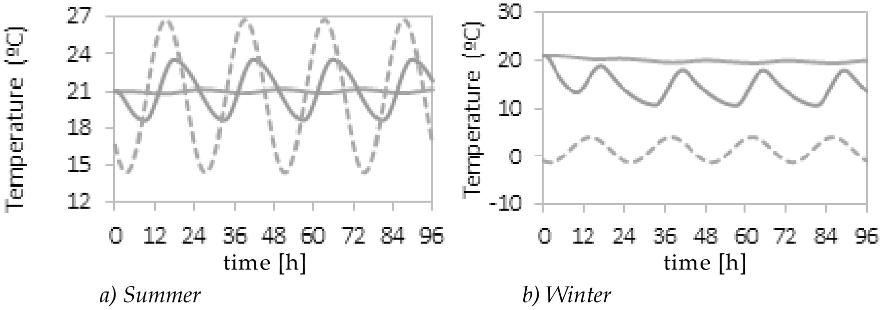
In the simulations of the façade walls, two thermal performance indicators have been calculated: the thermal resistance (equation 1) and the thermal inertia (equation 2), the latter giving an indication of the time-dependent behaviour of temperature, for the boundary conditions discussed in section 3.2.

$$\text{thermal resistance} = \frac{\text{thickness}}{\text{thermal conductivity}} \quad (1)$$

$$\text{thermal inertia} = \sqrt{\text{density} \times \text{thermal conductivity} \times \text{specific heat capacity}} \quad (2)$$

The thermal resistance of a wall of Mix 2 is 1.67 m^{2}K/W, which is approximately seventeen-fold higher than a similar wall made of Mix 4 (0.10 m^{2}K/W). Thus, a wall made of Mix 2 can offer the same thermal resistance of one made of Mix 4 (0.20 m thick) while being approximately 94% thinner (0.012 m instead of 0.20 m). A typical simple wall containing a layer of normal concrete (0.20 m thick) and a layer of thermal insulation (EPS, 0.06 m thick) has a thermal resistance of about 2 m^{2}K/W [C. A. P. dos Santos and L. Matias, 2006]. This thermal resistance can be achieved with only one 0.24 m thick layer of Mix 2, which is thinner than the typical considered wall (0.26 m) and eliminates the need of the extra insulation layer. If Mix 4 were to be used instead of Mix 2, a thickness of 4.10 m would be necessary to achieve the same thermal resistance of a simple wall. Thus, unlike Mix 4, Mix 2 allows for a highly improved thermal resistance compared to typical simple walls with insulation.

The variation of temperature over time on the interior of the wall is shown in Figure 5, for each concrete mixture and for summer and winter ambient conditions (as detailed in Table A1).



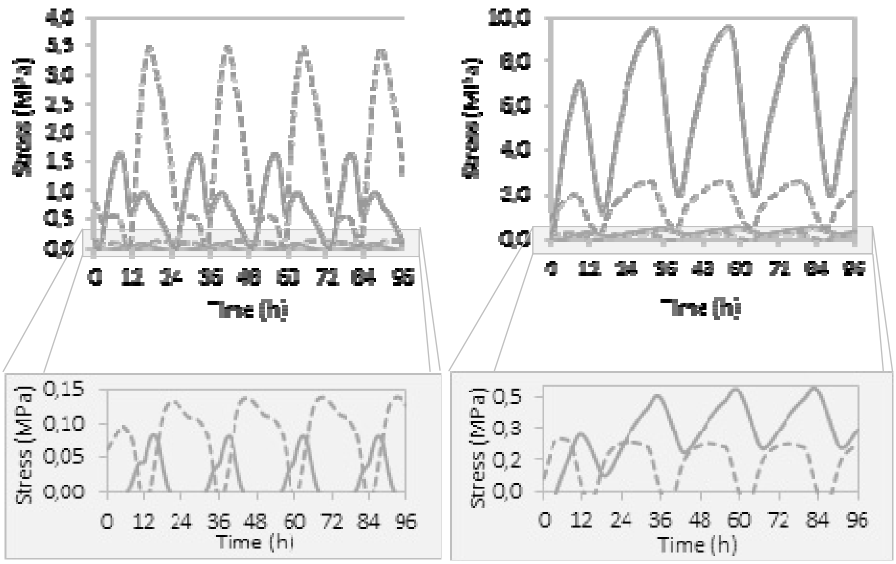
a) Summer *b) Winter*

Figure 5: Temperature in the interior surface of walls as a function of time for each concrete mixture —— *interior wall surface Mix 2,* —— *interior wall surface Mix 4,* - - - *outdoor ambient temperature*

For summer and winter, Mix 4 results in higher temperature variations than Mix 2, in the interior surface of the wall (4.6 - 10.2 ºC *vs* 0.3 - 1.7 ºC, Figure 5). Mix 2 can be considered to have the best thermal performance, because its (seventeen-fold) higher insulation and thermal inertia dampens and delays the heat transfer through its structure.

Load bearing capacity of façade walls

The stress distribution in the wall, including the wall self-weight in addition to the thermal expansion has been calculated as well. The thermal expansion effect was introduced in the mechanical analysis by including thermal strains proportional to temperature change relative to a reference temperature (20 ºC), in the same way as in Section 3.2. The resulting variation of stresses were analysed in the bottom centre of the concrete layer, the results of which are shown in Figure 6. Temperature oscillations (relative to the reference temperature of 20ºC) cause different degrees of expansion which affect the stress distribution. Thus, thermal expansion phenomenon has more impact in the stress distribution in winter than in summer because of the higher temperature variation relative to the reference temperature of 20 ºC, thus resulting in higher expansion (Figure 6). If the formerly mentioned (section 2.2) compressive strengths are assumed (5.6 MPa and 50 MPa



a) Summer *b) Winter*

Figure 6: Stress (solid lines) and horizontal displacement (dashed lines) as a function of time, evaluated in the bottom center of the concrete layer

— tensile Mix 2, — tensile Mix 4, ----- compressive Mix 2, ----- compressive Mix 4

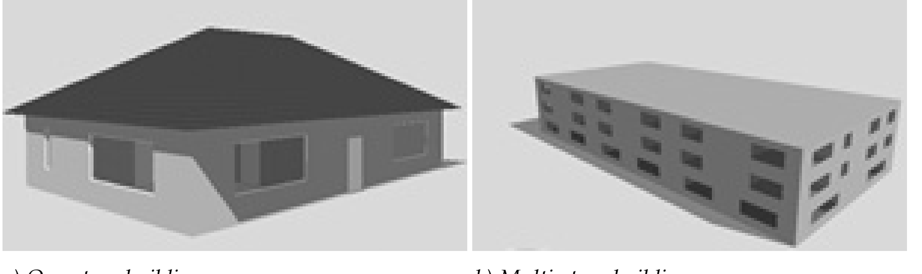
for Mix 2 and Mix 4, respectively), no compressive failure is expected to occur in summer or winter.

Assuming the same tensile strengths as previously (0.9 MPa and 4 MPa for Mix 2 and Mix 4, respectively), no tensile failure is expected in summer. In winter, the maximum obtained tensile stress for Mix 2 is lower than its tensile strength. Thus, no tensile failure is expected for this mixture. On the contrary, for Mix 4, the maximum obtained tensile stress in winter is more than double of its tensile strength. So, Mix 4 is expected to fail due to tension, under the present loading conditions.

The failure criteria used for walls in transient analysis are the same as used for blocks and panels in the steady-state analysis (section 2.2). Yet, different results are obtained: compressive and tensile failure is expected for blocks made of Mix 2 (section 2.2), while no failure is expected, in winter, for a wall composed by the same blocks (this section). This is a consequence of using average mixture properties for simulating walls, neglecting the stresses due to interaction between aggregate particles and mortar matrix with different properties. This indicates the importance of considering these interactions in the stress distribution analyses in order to avoid misleading results.

4 House / Building

Energy efficiency analyses were performed, using a finite difference method (FDM) tool, for two types of buildings: a one-story building and a multi-story building, as shown in Figure 7 (see structural features in Annex, Table A2 and Table A3).



a) One-story building *b) Multi-story building*

Figure 7: Building structures considered in the energy efficiency study

The sizes of the domain discretization nodes in FDM were determined using equation 3.

$$\Delta x = \sqrt{C \alpha \Delta t} \quad (3)$$

where a default value of 3 was used for the space discretization constant *C* and 15 minutes was used for the time-step Δt. The size of the node was calculated considering the thermal diffusivity of each material α.

Representative scenarios were simulated, based on the Portuguese building regulation for residential buildings [ITeCons, 2013]. One heat source of 4 W/m² per room was assumed for the one-story building and for the second and third floors of the multi-story building (in this case the first floor was considered to be composed by warehouses, thus having no heat-generating equipment). The temperatures for the onset of air-conditioning systems were 18 ºC for heating and 25 ºC for cooling, in order to ensure thermal comfort; the air renewal values were 0.6/h for April-September season and 0.4/h for October-March. The HVAC system was specified to guarantee that the above conditions were met for each building, depending on its location and weather conditions. Two weather scenarios were considered, typical of hot summer (in Évora/Portugal) and cold winter (in Bragança/ Portugal). The annual energy consumption for heating or cooling the two types of building is presented in Figure 8, for each considered location and concrete mixture used in the façade walls.

For both locations, and as expected, more energy is needed for maintaining the indoor temperatures within the thermal comfort range (i.e. 18 ºC – 25 ºC) in the multi-story building than in the one-story building. The ratio between the envelope area (i.e. the area of the heat transfer between building and the environment) and volume is lower for the

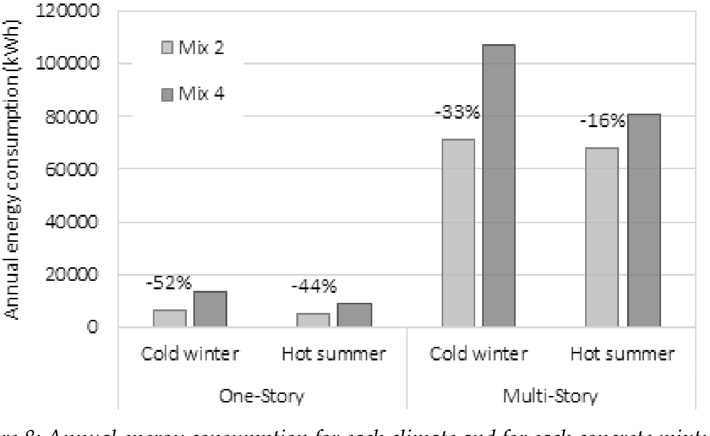


Figure 8: Annual energy consumption for each climate and for each concrete mixture, for one-story and multi-story building

multi-story building than for the one-story building. Thus, on a volume basis comparison, the heat exchange between multi-story building and environment is lower while more heat is generated because of the higher number rooms. As shown in Figure 8, lower energy consumption is obtained when the façade walls are composed by a layer of Mix 2. When Mix 2 is used in one-story building, an energy saving of 44% and 52% is obtained for summer and winter, respectively. For the same mixture in the multi-story building, savings in summer and winter are of 16% and 33%, respectively. This corroborates what was found in previous analyses performed for products (blocks and panels) and elements (façade walls), showing that Mix 2, composed by PUR aggregate particles, performs better mechanically and thermally.

5 Conclusions

This paper presents a multi-level modelling strategy that allowed comparing the response of different concrete products, composed by non-traditional concrete mixtures, when exposed to different ambient conditions, providing information about the best performing concrete mixtures from the aggregate level to the full house analysis.

At the aggregate level, the local stress distribution in blocks and panels, composed by traditional and non-traditional concrete mixtures and exposed to loading conditions corresponding to the wall self-weight and thermal stresses, were analysed. Based on the studies performed, high stress zones were identified for blocks and panels so an assessment of failure prone zones was performed. Components made of Mix 2 were found to fail under compression and tension, while those made of Mix 4 were found to fail only under tension, for the considered loading conditions and assumed tensile and compressive strengths. The obtained results, based on the assumption of a linear elastic study, inform about failure-prone zones in the tested materials/structures. Moreover, for the cases where the obtained stresses exceed the material strength, it is important to consider a non-linear study in order to determine more realistic stress and deformation distribution.

A comparative study of stress distribution and thermal performance of façade walls was performed. It was found that, for façade walls, Mix 2 (non-traditional concrete made of PUR aggregate) showed the best thermal performance by promoting lower temperature fluctuations over time and a temperature closer to the comfort temperature of 21 ^{o}C. Concerning the mechanical performance, Mix 4 (traditional concrete made of gravel aggregate) showed to experience higher stresses and higher stress variation with temperature than Mix 2. For Mix 4, in winter, the tensile stresses were found to be higher than its estimated tensile strength. Thus, failure might occur for walls made of this mixture, for the simulated loading conditions. No failure was found to occur in walls made of Mix 2. These results diverge from those obtained for blocks/panel made of the same mixtures. Yet, for walls, the concrete mixture was assumed to be homogeneous and average properties were considered, while for blocks/panels, the interaction between aggregate and mortar in a heterogeneous mixture were taken into consideration. This indicates that the local stresses due to interaction between aggregate particles and mortar matrix should not be disregarded.

Finally, an energy efficiency study was performed for houses/buildings (one-story and multi-story) composed by the mentioned concrete mixtures for two locations characterized by hot summer and cold winter. Lower energy consumption was obtained for façade walls composed by a layer of Mix 2. This corroborates the findings obtained for walls and for concrete products (blocks and panels). When compared to normal concrete, Mix 2 results in energy saving between 16% and 52% (for multi-story building in summer and one-story building in winter, respectively).

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Annex

Table A1: Environment conditions applied for the walls performance evaluation [EnergyPlus Energy Simulation Software, 2014][ASHRAE, 2009]

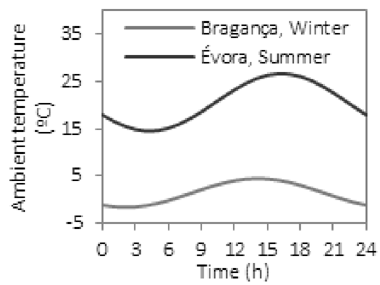
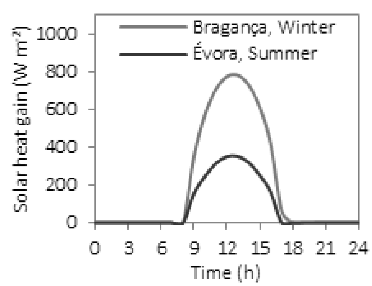
Scenario:	summer	winter
Location	Évora	Bragança
Time	18th July	18th January
Orientation of the wall	South	South
Outdoor temperature ºC		
Solar heat gain W/m²		
Heat transfer coefficient for outdoor conditions W/(m²K)	14.8	10.4
Indoor temperature ºC	21	21
Heat transfer coefficient for indoor conditions W/(m²K)	3.08	3.08
Emissivity of the wall surface	0.44	0.44

Table A2: Floor and glass pane areas (m²) distribution

	Floor area	North/South glass pane		East/West glass pane	
		OSB	MSB	OSB	MSB
Kitchen	17.81	5.02	-	0.84	2.52 (type B)
Room 1	28	4.66	-	-	-
Room 2	24.95	-	4.66 (type A & B)	3.78	-
Room 3	38.95	5.02	5 (type A & B)	5.49	5.48 (type B)
Hall	19.93				
WC	9.04				
Total apartment	138.7				
Warehouses	136.1				

OSB: one-story building; MSB: multi-story building;

MSB is composed by 6 warehouses in first floor and 6 apartments in each of the second and third floors. They are distributed in the building in a matrix of 2 x 3; type A apartments are those placed in column 2 of the building matrix and type B are those placed in the limits – column 1 and 3 of the building matrix (see figure in the left). A central corridor connecting all the divisions was considered, with a floor area of 64 m². It was assumed that 30% of the area of the walls was composed by glass (3 mm thick) panes with aluminium frames with a solar factor of 0.8 and a heat transfer coefficient of 5 W/(m² ºC).

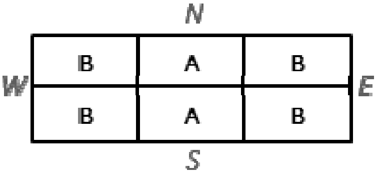


Table A3: Building elements properties

	Thickness	Density	Thermal conductivity	Specific heat capacity
	m	kg/m^3	W/(m K)	J/(kg °C)
For multy-story building:				
Façade walls				
Concrete layer	0.20		(*)	
Internal walls				
Gypsum layer	0.012	900	0.21	850
Thermal insulation	0.010	35	0.035	1400
Gypsum 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

(*) properties given in Table 1