Thermal simulation of building performance with different loadbearing materials

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Abstract. In recent years, overheating of buildings during the summer has become a serious problem. This is the result of a significant increase in the number of cooling degree days over the last thirty years in Europe. As a consequence, increasing energy is consumed by buildings to keep the temperature at a relatively low level in the summer. This prompted us to examine the thermal simulation performance of a typical 50m² flat with different loadbearing materials used for the external walls. Calculations were made for lightweight cement composites aerated with air-entraining admixture or with the addition of aerogel particles. The results were compared with those obtained for walls based on conventional materials. Simulations were carried out using the Wufi Plus software. The components had a variable width of thermal insulation so that thermal transmittance of all the tested walls was constant. This assumption made it possible to evaluate parameters related to the thermal accumulation of the tested walls. These results demonstrate that the use of lightweight cement-based materials not only improves the thermal insulation of the whole building, but also significantly increases thermal mass of the walls. As a consequence, these type of wall component improve the microclimate, i.e. by lowering the internal temperature of buildings during the summer.

1. Introduction

Currently, specialists look for material and technology solutions that would contribute to radical reductions of energy consumption of buildings. An objective evaluation of the obtained results requires the application of more accurate methods of assessment of energy consumption and, consequently, more complex models of calculation.

To base solely on data concerning the thermal conductivity of the constituent materials, and, consequently, on the thermal transmittance $U$ of separate component is, therefore, rendered insufficient.

Currently, testing the material and construction solutions in non-stationary conditions of heat flux which correspond to the real climate data is considered more justified.

Such analyses, on the one hand, increase the accuracy of the results, but also allow to reflect the characteristics of new material-related solutions (for example, PCM) whose properties are not properly recognised by the stationary models. Moreover, these analyses allow for comprehensive use of the data on heat accumulation and its effect on short-term and long-term heat losses and gains in buildings.
In the papers [1] and [2] the authors review present thermal energy storage active and passive systems. The main aim of the papers is to review and identify thermal storage building integrated systems and to classify them depending on the location of the thermal storage system. The most commonly used systems has been described, such as: buildings core activation (walls and floors) systems, thermal mass ventilation systems, external solar façades, TES solar collectors, photovoltaics and water tanks systems. In relation to passive systems the authors reviewed different types of high thermal mass materials and latent heat storage materials.

Another review which describes thermal energy storage systems is presented in the paper [3]. The prime intention of this paper is to review the potential research studies pertaining to a variety of latent heat energy storage (LHES) and cool thermal energy storage (CTES) systems solely dedicated for building heating, cooling and air conditioning (A/C) applications. Technical revelations regarding the integration and performance evaluation of heat storage materials in building fabric elements have been gleaned from numerous research contributions and presented.

Different types of TES systems has also been shown in [4]. The goal of this paper is to give a comprehensive review of a wide variety of TES technologies, with a clear focus on the combination of storage technology and building type. The authors emphasize that it is important to remember that there are specific demands and conditions that have to be fulfilled for each type of a building, and this is something that has to be evaluated separately for every new construction or renovation project. It is therefore important to analyze storage aspect early in the process of design.

Another paper [5] reviews the aspect of thermal dynamics which in most cases is omitted. Many of the current numerical models for building energy systems assume empty rooms and do not account entirely for the internal thermal inertia of objects like furniture. This review article points out that such assumption is not valid for dynamic calculations. The furnishing elements and other internal content can have a significant impact on the indoor thermal dynamics and on the occupants’ comfort.

The next paper [6] focuses on the energy storage materials. The manuscript reviews recent advances in the development of thermal energy storage materials for building applications oriented towards zero energy buildings. Two main types of materials have been evaluated: latent energy storage and thermochemical energy storage materials. The authors suggest that applications of the first group of materials in free-cooling ventilation systems, solar energy storage solutions for short and long-term storage periods, and demand-side management strategies towards the road to zero energy buildings are highlighted as promising, leading to a reduction of energy consumption of more than 30%. On the other hand, for the second group there is currently no available material for thermochemical energy storage that satisfies all the requirements for building operations.

Another issue related to use of thermal mass is its impact on thermal comfort [7]. In the paper four methods of mass activation are discussed: surface activation, forced-air activation, hydronic activation and electrical activation. The performance and control for such systems with peak shaving and shifting as an objective is discussed and barriers to its application and development is also addressed.

In the review paper [8] the authors describe different approaches to quantify thermal inertia using specific properties and parameters of materials and whole components. This paper also presents a literature review focussing on the reported impacts of building thermal inertia on thermal comfort and energy use for space heating and cooling.

The most commonly used material in buildings for thermal mass is concrete. The authors of [9] reviewed factors affecting the heat storage capacity of concrete. In addition, common measurement methods of cement-based materials’ thermal conductivity, thermal diffusivity and specific heat capacity are presented in paper. Various studies presented in the paper reveal that temperature, humidity, aggregate type, cementitious material type as well as phase change material (PCM) used influence the thermal properties of concrete [10] to be used as thermal mass.

Numerous studies are also conducted that aim at determining the behaviour of buildings in non-stationary conditions.

In the paper [11], the object of assessment was an office building for which the analysed parameter was the time constant dependent of the specific heat of the thermal mass of the building, specific heat
of internal air and air-exchange rate of night ventilation. It was shown that with the increasing time constant, the energy demand for cooling purposes decreases significantly.

The paper [12] presents a comparative analysis of buildings with external walls made of normal concrete with the insulation variably located on the outside or the inside. All the wall components were characterised by a fixed value of total thermal resistance. In the transitional months (spring/autumn), the values of the dynamic thermal resistance of walls were clearly different from the values of resistance determined using stationary calculations. The obtained results proved that high thermal mass can reduce heat flux in the months in which the outdoor temperature is very variable and fluctuates around the internal temperature.

Experiments with various kinds of external walls were also conducted for locations with warm climate, such as Australia [13]. The study tested solutions for components with variable thermal mass, such as: light wooden cavity wall with facade brick exterior finish, ceramic brick wall with fibre cement facade, hollow brick wall and a lightweight wooden cavity wall. In the warm climate of Australia characterised by large daily temperature fluctuations, the lowest energy consumption was observed for variants with massive inner bearing layer of ceramic brick. Moreover, the window area had a very large impact on the results. The greater the window area, the greater the differences in the behaviour of light and heavy walls.

The paper [14] assessed the influence of location of thermal insulation in the concrete wall on the total energy consumption of the studied building. Variants of outer concrete layer walls were characterised by a significantly higher thermal admittance. Thanks to this fact, these variants could more effectively reduce the fluctuations of room temperature.

The reports [15], [16] analysed a one-story building consisting of five rooms/zones. Different variants of exterior walls with variable heat capacity were tested. The assessment concerned the impact of the building heat capacity on the number of hours with exceeded levels of adaptive comfort (80% and 90%). The differences between the massive and the low heat capacity objects was significant, and the results are definitely in favour of the massive walls.

The study [17] compares the dynamic properties of three types of external walls and their influence on the internal temperature of the building. A comparison was made of variants of walls made of ultra-lightweight 70 cm thick concrete and two walls of ordinary concrete with a thickness of 20 cm and a 19 cm thick insulation layer on the inner and the outer side. While the homogeneous ultra-lightweight concrete wall demonstrated very good damping properties (high damping ratio and heat transmittance), it had a mediocre internal heat capacity.

Variants of PCM material exterior walls are also the subject of research, for instance in [18], [19]. According to the authors, an additional PCM layer in the appropriate climatic conditions allows for a reduction of heat loss in winter and a decrease of heat gains during the summer season.

The work [20] analysed the influence of additives to reduce gypsum plaster heat conductivity. An improvement of thermal properties of inside plasterwork may potentially influence the indoor microclimate as well as the energy efficiency of the entire building.

Studies are also being conducted over the influence of various additives and admixtures which greatly affect the thermal properties of the whole composite. Papers [21], [22] examine the effect of addition of recycled glass cullet aggregate. The resulting composite is characterised by a significantly higher degree of thermal insulation compared to concrete materials based on natural quartz aggregate. Solutions are also checked for using slag from sewage sludge as a replacement for natural aggregates [23].

The additives and admixtures used in cement composites also largely affect other properties, i.e. water vapour transport, capillarity and frost resistance. The evaluation of these parameters is discussed in detail in i.a. [24] and [25]. How these processes occur is of great importance given the effect of composite moisture on their thermal conductivity, which issue was the subject of research presented in the publications [26], [27]. In this context, great importance is attached to the processes of sorption and desorption of moisture in building materials and determination of isotherms linking the extent of material humidity with the thermal and moisture conditions in the environment, for example [28], [29].
The authors decided to evaluate the effects of different wall construction materials on the energy demand for cooling purposes. A comparison was made of different solutions for traditionally finished external walls - using normal concrete, sand-lime bricks, autoclaved aerated concrete, extruded ceramic bricks and lightweight composite walls - based on artificial aggregates further modified by an air-entraining admixture [30] or aerogel particles [31].

2. Materials and methods

The analysis was conducted for a flat with an area of 50 m². Simulations were performed using the Wufi Plus thermal calculation module. The analysed object was modelled as repeatable part of a multifamily residential building located in Kolobrzeg. The simulation was performed for the full calendar year. The object model is presented in figure 1.

![Figure 1. The model of the analysed part of the building – flat.](image)

The internal load-bearing walls and floors above and below the apartment were assumed to be adiabatic boundaries due to the proximity of flats with similar internal temperature. All the inner walls of the flat were defined as partition walls of thickness of 12 cm with plaster gypsum finish. Exterior walls were modelled as double-layer components with polystyrene foam insulation. For all variants the external walls thermal transmittance $U$ was assumed equal to 0.15 (W/m²·K). To maintain the constant value of $U$, the thickness of the insulation with thermal conductivity $\lambda = 0.036$ W/(m·K) was modified accordingly. This made it possible to assess the dynamic properties of different solutions which, however, had the same value of the coefficient $U$.

The windows in the model with the total area of 16.28 m² were modelled as triple glazed windows with thermal transmittance $U = 0.80$ W/(m²·K). The model did not take into account any sunshade or solar control systems.

The simulations were performed in two variants: with the cooling system and without it. The assumed minimum internal temperature was equal to 20°C and the maximum temperature, in the variant with cooling, was 21°C.

The analysis included a mechanical ventilation providing air exchange at 1.5 1/h rate periodically increased for the summer period (from 16.05 to 15.09) to the level of 2.0 1/h. In addition, separate calculations with the use of night ventilation from 01.06 to 31.08 were made. Ventilation heat recovery with efficiency of 80% was included in the period from 16.10 to 15.05.

It was further assumed that the heating system would be disabled in the period from 16.05 to 15.09.

A total of eight types of load-bearing wall materials were tested. These included four traditional materials: autoclaved aerated concrete (AAC), silicate (S), normal concrete (NC) and extruded ceramic brick (CB). In addition, calculations were made for four types of lightweight composites based on expanded clay aggregate (EC) and sintered fly ash aggregate (FA), modified by air-entraining admixture (A) or aerogel particles (Aero). Data on the density and thermal properties of individual materials are given in table 1.
Thermal parameters of the first four lightweight concretes have been gathered during earlier experimental research [30], [31]. Data for the remaining materials have been adopted on the basis of general standards.

The thermal properties of the lightweight concretes have been determined during a wide range research project. The main aim of the project was to analyse thermal and dynamic properties of composites modified by different additions and admixtures. For the selected four of them, it was decided to perform an additional simulation analysis in comparison to traditional materials.

*Table 1. The properties of the tested materials.*

| Material                                           | Symbol        | \( \rho \) (kg/m\(^3\)) | \( \lambda \) (W/m·K) | \( c_\rho \) (J/kg·K) | \( c_v \) (10\(^6\)·J/(m\(^3\)·K)) |
|---------------------------------------------------|---------------|--------------------------|------------------------|------------------------|---------------------------------|
| Sintered fly ash based concrete with air-entraining admixture | FA/A          | 1164.1                   | 0.273                  | 1239.80                | 1.443                           |
| Sintered fly ash based concrete with aerogel particles     | FA/Aero       | 1358.5                   | 0.431                  | 1144.60                | 1.555                           |
| Expanded clay based concrete with air-entraining admixture | EC/A          | 880.8                    | 0.269                  | 1684.00                | 1.483                           |
| Expanded clay based concrete with aerogel particles       | EC/Aero       | 1032.5                   | 0.380                  | 1560.90                | 1.612                           |
| Autoclaved aerated concrete                           | AAC           | 500.0                    | 0.170                  | 850.00                 | 0.425                           |
| Silicate                                             | S             | 1973.0                   | 0.619                  | 800.00                 | 1.578                           |
| Normal concrete                                      | NC            | 2234.0                   | 1.650                  | 797.67                 | 1.782                           |
| Extruded ceramic brick                                | CB            | 600.0.0                  | 0.120                  | 850.00                 | 0.510                           |

3. Results and discussion
Figure 2 shows the results regarding energy demand for cooling purposes obtained with different variants of external walls of the studied apartment. The difference between the variants with and without night ventilation is clearly seen. The simulations assumed a five-hour period of intensive ventilation at the level of 4 air exchanges per hour. The use of night ventilation leads to a decrease in cooling demand from 25% in the variant with autoclaved aerated concrete by up to 31% in the case of normal concrete.

There are also clear differences in the demand for energy for cooling purposes between the individual variants. In the comparison, normal concrete wall and silicate wall demonstrated the best results. Similar results were also obtained in the case of the use of lightweight concrete composites.

Furthermore, the simulations examined the differences in terms of energy consumption for heating purposes. In this case, the differences between the variants are less than 1%, and the average value of heat consumption amounted to approx. 1500 kWh/year (30 kWh/(m\(^2\)·year)), when ventilation heat recovery was applied.

The results point to the justifiability of using massive components only in the case when the outdoor temperature fluctuates around the internal temperature. In the situation when the outdoor temperature is significantly higher or lower than the room temperature, additional heat capacity generally does not affect the energy efficiency of the building.
Figure 2. Cooling demands for each variant.

Figure 3 shows the required theoretical thicknesses of the thermal insulation necessary for the thermal transmittance $U$ to be 0.15 W/(m²·K) in each case. Also, the percentage difference of the energy demand for cooling purposes between the normal concrete variant and other solutions was presented.

Figure 3. The relative differences in cooling energy demand compared to the normal concrete variant and the required thicknesses of thermal insulation.

The greatest differences were exhibited in the case of autoclaved aerated concrete and extruded brick ceramic variants (23.4% and 22.6% respectively). The differences between normal concrete and lightweight concretes were significantly lower.

However, it should be noted that the normal concrete variant would require the use of the thickest theoretical layer of insulation (228 mm), and the autoclaved aerated concrete variant would need insulation thinner by 46 mm compared to normal concrete.
Figure 4 shows the maximum internal temperatures obtained in the simulations without the cooling system. Similarly to previous results, night ventilation led to the lowering of maximum temperature by about 1 degree. Also, significantly large differences between the individual variants can be observed. The lowest temperatures were obtained for the massive normal concrete walls.

![Graph of maximum internal temperatures for each variant.](image)

**Figure 4.** Maximum internal temperatures for each variant.

Figure 5 shows the overall amount of hours with temperatures exceeding 23°C and 24°C. The differences between the variants of lightweight materials with low thermal capacity (AAC, CB) and other systems are very high. In particular, in case of temperature exceeding 24°C, between the best (NC) and the worst variant (AAC) the difference is more than 230%.

![Graph of number of hours above 23°C and 24°C.](image)

**Figure 5.** The number of hours during the year with exceeded temperature over 23°C and 24°C.
4. Conclusions
The article presents the results of simulations concerning an object with different wall variants. The following main conclusions arise from the results:

- the use of such materials as normal concrete, silicates or lightweight concrete composites results in a reduction in energy demand for cooling purposes in the given climate,
- the type of load-bearing material has virtually no effect on the energy demand for heating purposes in the given climate,
- the materials used for constructing walls with large heat capacity cause a decrease in the maximum internal temperature during the summer period, helping to reduce the load on the air conditioning system,
- the high heat capacity materials reduce room overheating and minimise more efficiently the amount of hours with exceeded thermal comfort temperature.

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