Different Materials with High Thermal Mass and its Influence on a Buildings Heat Loss – An Analysis based on the Theory of Dynamic Thermal Networks

Eva-Lotta W Kurkinen [1], Jonathan Karlsson [2]

[1]*Section of Building Physics and Indoor Environment, SP Technical Research Institute of Sweden*
[2] *Division of Building Materials. Lund University, Box 118, 221 00 Lund, Sweden*

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ABSTRACT

The time-dependent heat loss through a building exposed to variable outdoor and indoor temperatures depends on the properties of the buildings envelope and its material. It may be beneficial to use high thermal mass in a buildings frame construction with respect to energy consumption and thermal comfort. The thermal memory effect of light and heavy constructions are well known, but is this effect significant for a buildings energy consumption and indoor temperature? In this paper we study the effect of different high thermal mass materials on the annual heat loss and indoor temperature for a building located in Gothenburg, Sweden. The high thermal mass materials are concretes with different aggregates such as magnetite, expanded graphite, steel fiber and copper fiber.

The analysis was performed with the Dynamic Thermal Networks theory, which is based on step-response and weighting functions. The significance of the shape of the response and weighting functions on a buildings annual heat loss is studied in order to find the material or material combination that results in the shape of the most optimal response function.

The analysis shows that there is a different thermal behaviour between the different high thermal mass materials, but the differences are too small to have an effect on the studied buildings annual heat loss and indoor temperature.

1. Introduction

The time-dependent heat loss through a building exposed to variable outdoor and indoor temperatures depends on the properties of the walls, materials and their layers. The thermal memory effect of light and heavy walls, effects of temperature variation on different time scales, etc, represent a basic problem in building physics. Several studies have been made to investigate the significance of the order of wall layers on the buildings thermal behaviour and heat loss: Kossecka, Kosny (1998), Ghrab-Marcos (1991) and Boji´c, Loveday (1997).

In this paper the theory of Dynamic Thermal Network is used to calculate the heat consumption rate needed-, to keep the indoor temperature around 20 ^{o}C, for a building with different thermal mass in the construction. The building's response and weighting functions are needed for the calculations (Claesson 2003). These functions give information about the buildings thermal behaviour. By changing the aggregate in the concrete used in an external wall-, the weighting function will change while the buildings U-value is still the same. In a numerical solution, we must use a discrete approximation. The buildings weighting functions are divided into weighting factors. A weighting factor is the average value of the weighting function during a time step *h*.

In this paper the shape of the weighting functions and the values of the weighting factors are compared with the buildings annual heat loss and indoor temperature variation. The significance of the shape of the response and weighting functions on the buildings annual heat loss is studied in order to find the material or material combination that results in the most optimal shape of the response function. Which material and material properties gives the most suitable indoor temperature and lowest energy consumption?

2. Dynamic thermal network

The dynamic heat loss of a building is the sum of an absorptive and a transmittive heat flux. Figure 1 shows the dynamic thermal network for a building's heat loss. The indoor temperature $T_1(t)$ is connected to the outdoor temperature $T_2(t)$ by the buildings thermal conductance K_{12}, this is the transmittive part. There is also an absorptive part with a heat flux over the surface conductance K_1. Summation signs are added to the conductance symbols. The signs signify that it is a dynamic case and that we have to take an average of the node temperatures according to (2).

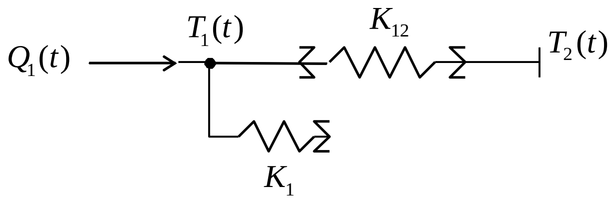

Fig. 1. Dynamic thermal network for the buildings heat loss.

2.1 Basic formula

The dynamic heat loss of a building according to Figure 1 is:

$$Q_1(t) = K_1 \cdot \left[T_1(t) - \bar{T}_{1a}(t) \right] + K_{12} \cdot \left[\bar{T}_{1t}(t) - \bar{T}_{2t}(t) \right] \quad (1)$$

The (steady-state) *thermal conductance* for the whole building is K_{12} (W/K). The factor K_1 is the *surface heat* *transfer coefficient* at the buildings inside. It is equal to the surface area A_1 times the surface heat transfer coefficient α_1: $K_1 = A_1 \cdot \alpha_1$. The temperatures that are used are the indoor temperature $T_1(t)$ and average temperatures backward in time. The temperature averages are given by:

$$\bar{T}_{1a}(t) = \int_0^\infty \kappa_{1a}(\tau) \cdot T_1(t-\tau) d\tau$$
$$\bar{T}_{1t}(t) = \int_0^\infty \kappa_{12}(\tau) \cdot T_1(t-\tau) d\tau \qquad (2)$$
$$\bar{T}_{2t}(t) = \int_0^\infty \kappa_{12}(\tau) \cdot T_2(t-\tau) d\tau$$

Here, τ assume values from zero to infinity or sufficiently far back in time to give stable solutions. The absorptive weighting function $\kappa_{1a}(\tau)$ and the transmittive weighting function $\kappa_{12}(\tau)$ are discussed below.

2.2 Step-response and weighting functions

The weighting functions for preceding boundary temperatures in (2) are obtained from a step-response solution (Claesson 2003). The temperature at the inside is changed from zero to one, while the outdoor surface is kept at zero. Let $Q_{12}(\tau)$ be the outward heat flux at the outside and $Q_{11}(\tau)$ the inward heat flux at the building's inside. We use the time τ in order to distinguish it from the current time t in (2). The transmittive part, $Q_{12}(\tau)$, is zero at the very beginning, and it increases to the steady-state value K_{12} after long time. The heat flux at the inside, $Q_{11}(\tau)$, starts with the high value K_1 and decreases to the same steady-state value K_{12}. In the calculations we will use the transmittive response flux and the following absorptive response flux:

$$Q_{1a}(\tau) = Q_{11}(\tau) - Q_{12}(\tau) \qquad (3)$$

This response flux starts with a high value (K_1) and decreases to zero.

The weighting functions are the derivative of the response heat fluxes divided with their respective thermal conductance.

$$\kappa_{1a}(\tau) = \frac{-1}{K_1} \cdot \frac{dQ_{1a}(\tau)}{d\tau}, \quad \kappa_{12}(\tau) = \frac{1}{K_{12}} \cdot \frac{dQ_{12}}{d\tau} \qquad (4)$$

The weighting functions are positive and their integrals become equal to one.

2.3 Discrete approximation

In a numerical solution, we must use a discrete approximation. Let h>0 be the time step. The time interval under consideration, $nh - h \le t \le nh$, has index n. The preceding intervals, $nh - \nu h - h \le t \le nh - \nu h$, are enumerated backwards in time (ν = 1, 2, …). We consider a linear temperature variation during each time step with the temperature $T_{1,n-\nu} = T_1(nh - \nu h)$ at the right hand end point of interval n-ν. The heat flux at the considered time is $Q_{1,n} = Q_1(nh)$. In discrete form we have:

$$Q_{1,n} = \bar{K}_1 \cdot \left[T_{1,n} - \bar{T}_{1a,n} \right] + K_{12} \cdot \left[\bar{T}_{1t,n} - \bar{T}_{2t,n} \right] \qquad (5)$$

In the discrete form of (2), we get the following average values of the boundary temperatures:

$$\bar{T}_{1a,n} = \sum_{\nu=1}^{\nu_s} \kappa_{1a,\nu} \cdot T_{1,n-\nu}$$
$$\bar{T}_{1t,n} = \sum_{\nu=0}^{\nu_s} \kappa_{12,\nu} \cdot T_{1,n-\nu} \qquad (6)$$
$$\bar{T}_{2t,n} = \sum_{\nu=0}^{\nu_s} \kappa_{12,\nu} \cdot T_{2,n-\nu}$$

Relations (5) and (6) are the discrete form of (1) and (2) for the dynamic thermal network in Figure 1. The surface conductances are replaced by modified surface conductances and the weighting functions by weighting factors for each time step. The integration to infinity in the temperature averages (2) must be limited to a finite value τ_s at which time the weighting functions are zero with a sufficient accuracy. Then steady-state conditions are attained within the considered accuracy. The summations are performed up to a large $\nu = \nu_s$ with $\nu_s = \tau_s/h$ We use time-step averages $\bar{Q}_{1a}(\tau)$ and $\bar{Q}_{12}(\tau)$ of the response functions $Q_{1a}(\tau)$ and $Q_{12}(\tau)$:

$$\bar{Q}_{1a}(\tau) = \frac{1}{h} \cdot \int_\tau^{\tau+h} Q_{1a}(\tau') d\tau', \quad \bar{Q}_{12}(\tau) = \frac{1}{h} \cdot \int_\tau^{\tau+h} Q_{12}(\tau') d\tau' \qquad (7)$$

The *modified* surface conductance $\bar{K}_1$ is:

$$\bar{K}_1 = \bar{Q}_{1a}(0) \qquad (8)$$

From (2) with piece-wise linear boundary temperatures, we get the weighting factors (Claesson 2003):

$$\kappa_{1a,\nu} = \frac{\bar{Q}_{1a}(\nu h - h) - \bar{Q}_{1a}(\nu h)}{\bar{K}_1}$$
$$\kappa_{12,\nu} = \frac{\bar{Q}_{12}(\nu h) - \bar{Q}_{12}(\nu h - h)}{K_{12}} \qquad (9)$$

3. Studied building

The studied building is a student building with two floors and four single rum apartments on each floor, see Figure 2a and 2b. The building is located in Gothenburg the south west part of Sweden. Only the second floor is considered in this study. Table 1 shows the data of the building. The building's total U-value for the studied part is 0.26 W/m^{2}K.

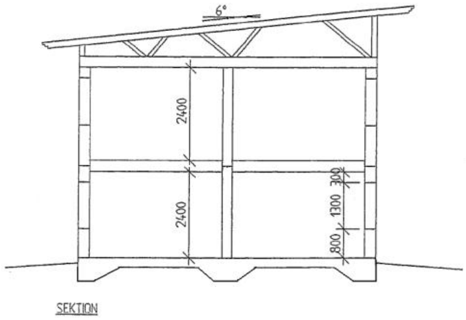

Fig. 2a. Sectional drawing of the studied building.

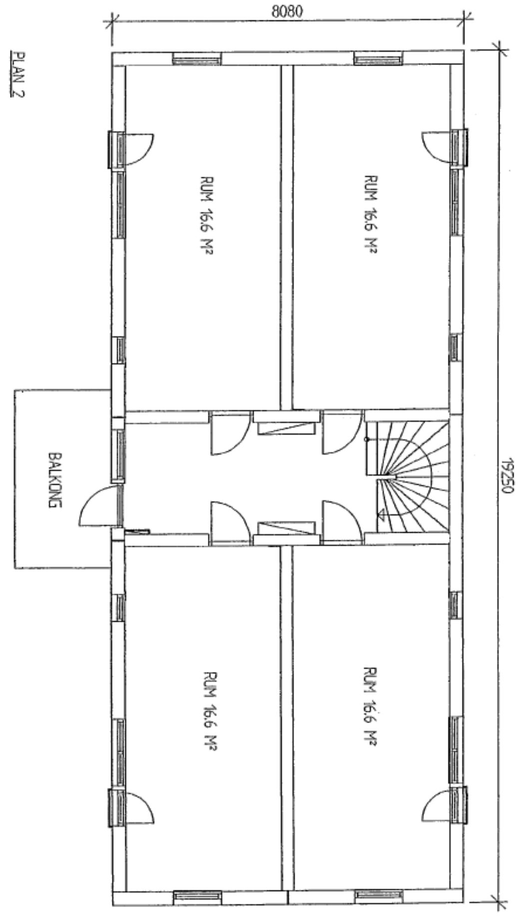

Fig. 2b. Plan drawing of the studied building.

Table 1. Data for the studied building

construction	Area (m^2)	U-value ($W/(m^2K)$)
Roof	155	0.089
External walls	117	0.17
Internal walls	143	-
Floor structure	155	-
Windows/doors	50	1.0

The internal walls and floor structures are of the same material as the external walls inside. The external walls consist of concrete sandwich element with 200 mm EPS insulation between the concrete slabs. The inner slab is 150 mm and the exterior is 70 mm. The floor structure consists, from the inside, of 30 mm plaster on top of a 30 mm thick sound insulation which is placed on a 60 mm concrete slab. The roof is a concrete slab with 400 mm insulation above the slab. The external surface heat transfer coefficient is 25 W/m^2K. For interior surfaces we use, 5.9 W/m^2K for downward heat flow, 10 W/m^2K for upward heat flow and 7.7 W/m^2K otherwise. The thermal envelope has the same U-value for all used materials.

The light weight construction consists of gypsum and EPS insulation.

4. Different frame materials

In order to investigate which influence the concrete properties has on the buildings indoor temperature and energy consumption, buildings with five different concretes with different values of thermal conductivity and heat capacity, were studied. As a reference, also a light frame building was studied.

Material data (Table 2) was taken from Herlin & Johansson (2011).

4.1 Measurement of material data

The measurement was made by a Hot Disk 1500 instrument (HotDisk, Gothenburg, Sweden). This is a technique for simultaneous determination of volumetric heat capacity, thermal conductivity and thermal diffusivity of materials. The method is of a transient heat-flow type where the heating element serves both as a heat source and temperature detector. The experiment is arranged in such a way that the temperature development in the sample is close to adiabatic condition that makes it possible to use smaller test specimens.

The HotDisk measurements started 35 days after casting. The samples were dried in a furnace at 105°C one week before the measurement.

One day before the measurements, the specimens were placed in room climate. The Hot Disk sensor is encapsulated in kapton and has a radius of 28.40 mm (HotDisk No. 5599). A large model of the sensor was used to achieve representative measurements, the concrete itself is not a homogeneous material as it has large aggregate particles (about 1/3 the size of the used sensor). To obtain a smooth and representative surface the specimens were cut into two parts. The sensor was then placed between the two parts when measured. Each sample was measured three times in each of three points, to reduce the influence of local variations. At each measurement the temperature was registered 200 times in 640 seconds with a heating power of 2 W. The input of heat resulted in a temperature increase of 1-2 K. Subsequent measurements were therefore not made until the specimens had cooled off to room temperature again.

4.2 Material data

Magnetite has a good heat-storing capacity and the strength is high. Even steel fibre and brass shavings gave good results in strength, and also good results of the heat-storing ability, but not as heavy as magnetite. Expanded graphite has a high electrical conductivity (even under dry conditions) which can be utilized in many other ways. These types of concrete mixtures are suitable for supporting structures, which also include an improved thermal property.

Table 2. Material data for the different mixed concrete (from Herlin & Johansson 2011)

Material	Thermal conductivity (W/(mK))	Volumetric heat capacity ($MJ/(m^3K)$)
Normal concrete	2.2	1.8
Magnetite concrete	2.6	2.3
Exp. graphite concrete	3.5	1.5
Steel fiber concrete	2.6	1.9
Copper fiber concrete	3.6	1.8

5. Weighting factors

The response and weighting functions are calculated analytically, Claesson (2002). Floor, walls and roof are calculated separately for one dimension and added together as a whole building. The weighting factors for the building are calculated from (9) with a time step of one hour (h=3600 s). Figure 3-4 shows the buildings transmittive and absorptive weighting factors. For all building the sum of weighting factors become one for 120 time steps (ν_s=120), this means five days.

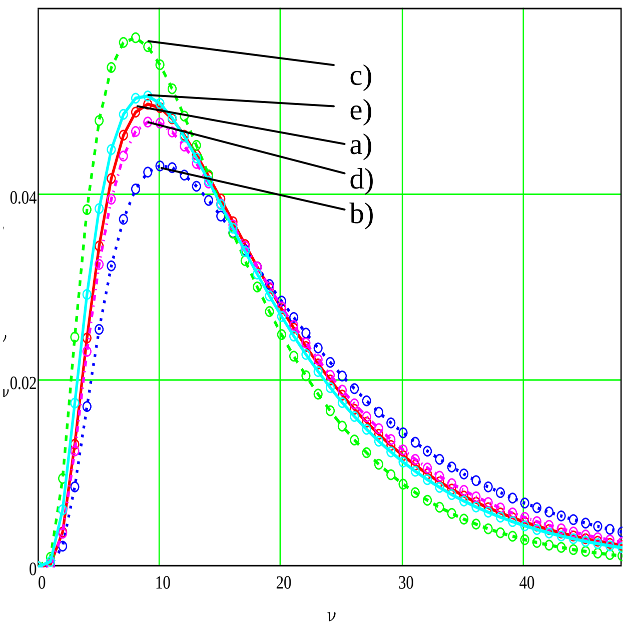

Fig. 3. Transmittive weighting factors for the building with a frame construction of; a) normal concrete, b) magnetite concrete, c) exp.graphite concrete, d) steel fibre concrete, e) copper fibre concrete

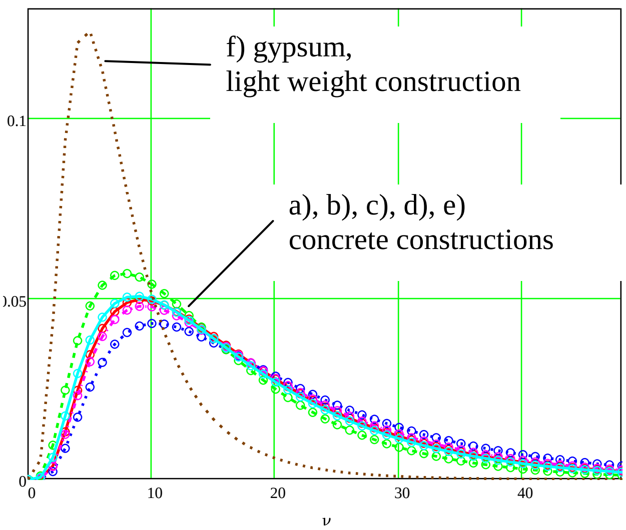

Fig. 4. Transmittive weighting factors for the building with different concretes compared to the weighting factors for the lightweight construction.

The transmittive weighting factors show how long time it takes for the heat flow to leave the building and at which time the heat flow has the fastest increase. From Fig. 3 we can see that for all materials it will take almost one hour for the heat flux to reach the outside of the buildings envelope. The expanded graphite concrete has the fastest response, high peak and short tail, and the magnetite concrete the slowest, low peak and long tail.

In Figure 4 we can see that all concrete constructions has a relative slow response compared to the light weight construction, which has its highest peak 3-4 hours earlier then the concrete constructions.

The absorptive weighting factors show how quickly the heat flows reaches the inner surface of the building. An earlier study (Wentzel & Gollvik 2005) shows that a low value in the beginning of the absorptive weighting factors is beneficial according to heat loss and indoor temperature in a Nordic climate. From Fig. 5 we can see that normal concrete (a) has the lowest value in the beginning followed by expanded-graphite concrete (c), steel fibre concrete (d), gypsum (f), copper fibre concrete (e) and magnetite concrete (b) has the highest value.

After two hours the magnetite concrete (b) has the lowest value followed by copper fibre concrete (e), steel fibre concrete (d), normal concrete (a), expanded-graphite concrete (c) and the gypsum construction (f) has the highest value.

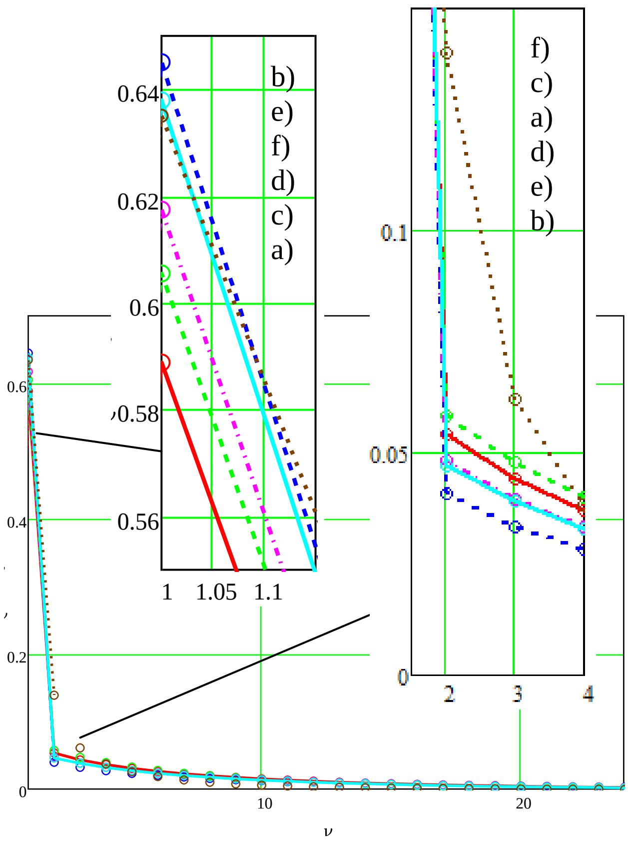

Fig. 5. Absorptive weighting factors for the building with a frame construction of; a) normal concrete, b) magnetite concrete, c) exp.grafit concrete, d) steel fibre concrete, e) copper fibre concrete, f) gypsum.

6. Calculation of the heat loss and indoor temperature

The indoor temperature depends on a variable outdoor temperature, solar radiation through the windows, ventilation rate and the heating system. Figure 5 shows the thermal network for the heat balance. The outdoor temperature and solar radiation are values from Gothenburg Sweden. The solar radiation that reaches the inside Q_{sun} is reduced due to window transmittance, shadings etc. (ASHRAE 1997). Less than fifty percent of the solar radiation reaches the building's inside. The heating system Q_{heat} turns on when the indoor temperature drops below 20 °C. The ventilation rate is normally 0.5 h^{-1} and it is 2 h^{-1} when the indoor temperature is above 25 °C. The indoor temperature $T_{1,n}$ at time step n is obtained from a heat balance at the node $T_1(t)$ in Figure 5. We get:

$$T_{1,n} = \frac{Q_{heat}(T_{1,n-1}) + Q_{sun,n} + \bar{K}_1 \cdot \bar{T}_{1a,n} - K_{12} \cdot \left[\bar{T}^*_{1t,n} - \bar{T}_{2t,n}\right] + K_{12}^{window} \cdot T_{2,n} + K_v(T_{1,n-1}) \cdot T_{2,n}}{\bar{K}_1 + K_{12} \cdot \kappa_{12,0} + K_{12}^{window} + K_v(T_{1,n-1})}$$

(10)

The average temperature $\bar{T}^*_{1t,n}$ is the sum (6) with $\nu = 0$ excluded:

$$\bar{T}^*_{1t,n} = \sum_{\nu=1}^{\nu_s} \kappa_{12,\nu} \cdot T_{1,n-\nu} \qquad (11)$$

The conductances K_{12}^{window} and K_v are for the building's windows (including doors) and ventilation, respectively. The need of heat to keep the indoor temperature around 20 °C is calculated by:

$$Q_{heat}(T_{1,n}) = \left[K_{12} + K_{12}^{window} + K_v(T_{1,n})\right] \cdot \left(20 - T_{2,n}\right) \quad if \quad T_{2,n} < T_{1,n} < 20 \qquad (12)$$

The calculations with the presented method are quite rapid. The annual cycle requires a few seconds of computer time.

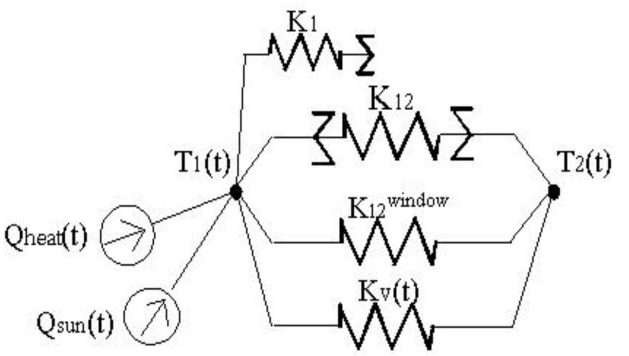

Fig. 6. Dynamic thermal network for the buildings indoor temperature, $T_1(t)$.

6.1 Results

Figure 6 and 7 shows the calculated heat during a year for the building with normal concrete frame (a) (Fig. 7) and for the building with magnetite concrete frame (b) (Fig. 8). We see that they are almost the same.

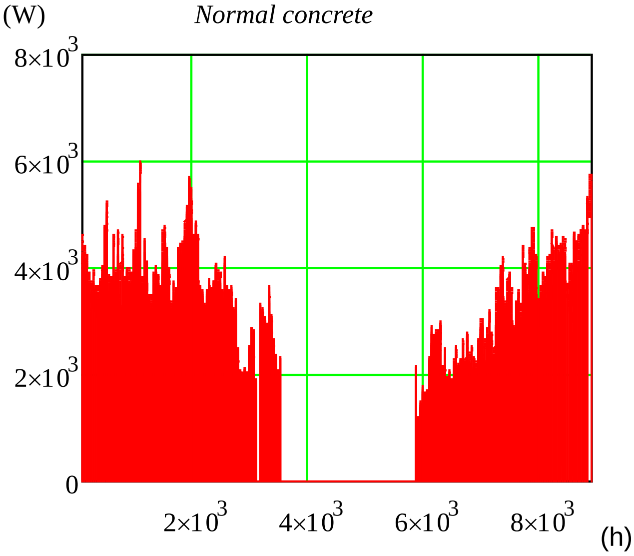

Fig. 7. The consumption of heat to keep the indoor temperature around 20 °C. The building with normal concrete frame (a).

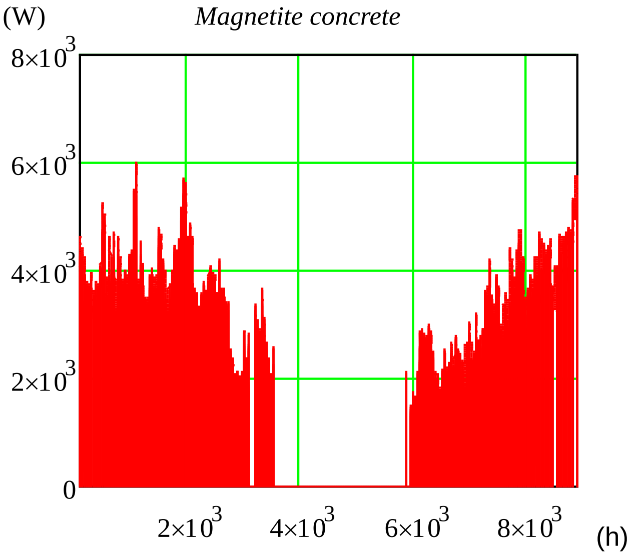

Fig. 8. The consumption of heat to keep the indoor temperature around 20 °C. The building with magnetite concrete frame (b).

Table 3 shows the calculated consumption of heat to keep the indoor temperature around 20 °C for all different concrete materials. We can see that they are almost identic.

Table 3. Annual heat consumption to keep the indoor temperature around 20 °C.

Mixture name	Annual heat consumption (MWh/year)
Normal concrete	16.27
Magnetite concrete	16.28
Exp. graphite concrete	16.27
Steel fibre concrete	16.27
Copper fibre concrete	16.28
Gypsum (light weight construction)	16.56

An annual heat consumption of 16.3 MWh/year is the same as 105 kWh/m^2 and year.

Figure 9 shows a duration graph of the calculated indoor temperature in the studied buildings. We see that the temperature varies between 24.8 °C and 20.0 °C for the studied frame materials of concrete. The lines are almost perfectly superimposed and therefor impossible to separate. The thin black line shows the indoor temperature for the light weight construction. That temperature varies between 26.0 °C and 19.9 °C.

The temperature variation is more beneficial for the different concrete constructions then for the light weight construction.

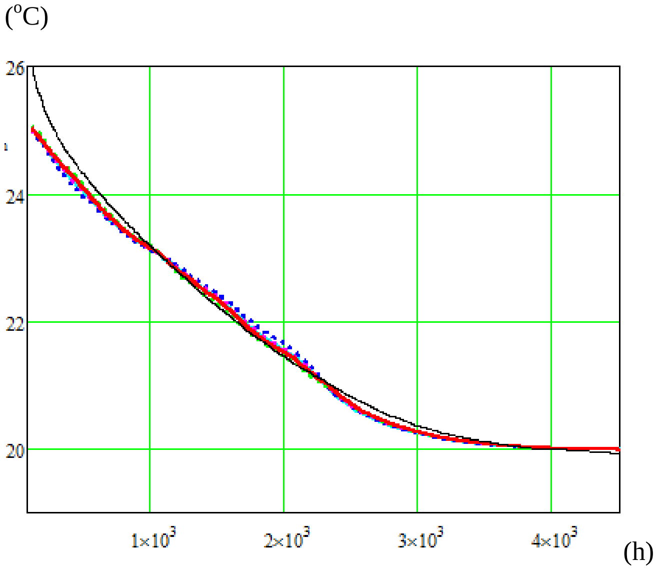

Fig. 9. The indoor temperature during a whole year for the studied building different concrete combinations in the frame.

7. The influence of thermal mass on the shape of the weighting factors and on the buildings heat loss

By studying the weighting factors for the different frame materials we can see that they have different thermal behaviour. For example, the transmittive heat flow through the expanded graphite concrete construction is more rapid than for the magnetit concrete construction. The absorptive weighting factors show that the magnetite concrete responds faster on a temperature change in the indoor temperature than what for example normal concrete does. The construction with magnetite concrete has the highest value for the first absorptive weighting factor. The construction with normal concrete has the lowest value for the first absorptive weighting factor, see Fig 5. Due Based on a previous investigation (Wentzel & Gollvik 2005) this should mean that the normal concrete is more beneficial than the magnetite concrete with respect to heat consumption and indoor temperature. Unfortunately the difference in this analysis is too small to have an influence on the buildings heat consumption. But we can still see a trend that a low first value on the absorptive weighting factor is beneficial on the heat consumption and indoor temperature.

8. Conclusions

The analysis shows that there is a different thermal behaviour between the different high thermal mass materials, but the differences are too small to have an effect on the studied buildings annual heat loss and indoor temperature.

The effect of thermal mass in the frame construction will probably have bigger influence on the heat loss and indoor temperature, if the buildings heating system is optimised for it.

The knowledge of older buildings and structures tend to reflect our knowledge of system thinking and the use of thermal inertia. Building traditions in various climate conditions gives us new knowledge about adjustments to our system solutions, system solutions in the sense that the materials function in relation to indoor environment work together in an intelligent way.

Acknowledgements

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