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Investigation of thermal performance of newly multilayer wall/roof constructions for low-carbon buildings

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ABSTRACT

Increasing concerns about energy consumption for heating and cooling of buildings have made it necessary to improve the thermal performance of building materials. However, in addition to using materials with high insulation characteristics, an accurate calculation of the capacities of the heating and cooling systems is also an important factor in ensuring high energy efficiency for low-carbon buildings. The devices will not be selected at capacities larger than the capacities that should be on this point and energy wastage will be prevented. To achieve this goal, in this study, investigations are carried out to produce new concrete types with high thermal insulating characteristics. Besides, many new concrete wall and roof samples were produced with different types of aggregates at different volume ratios and their thermophysical characteristics are tested in accordance with ASTM and EN standards. To estimate the thermal performance of produced samples, a periodic solution method, the Complex Finite Fourier Transform technique, is developed by using thermophysical characteristics data of those structures. The results showed that the daily heat gain values were calculated as 65.909 W/m^2 for the EPC50 wall and 11.324 W/m^2 for the PC40-EPC60 wall with 20 cm thicknesses.

1. Introduction

Increasing energy consumption in parallel with population growth and the rapid depletion of existing energy resources have become a threat to the world. However, the amount of energy required for heating and cooling of buildings has a significant proportion of total energy consumption, and this ratio corresponds to approximately 37% in Turkey (Ozbalta, 2010). The amount of energy consumption increases proportionally with population growth, industrialization, urbanization, etc. However, due to its limited local energy resources, Turkey imports around 75% of the energy it needs from foreign countries. This situation necessitates energy saving and efficient use of energy in our country (Erdal *et al.*, 2008). By the way, it has been determined that 85% energy saving is achieved depending on the places where thermal insulation is applied (TMMOB, 2005). Therefore, it is extremely important for low-carbon buildings that the constructions have high thermal insulation properties. In our country, it is of great importance to developing domestic, low-density, and inflammable materials with high insulation properties. This will ensure efficient use of energy.

Although concrete is the most used, universal, and economical building material in building structures (Think harder concrete, 2013), the places where heat loss is the highest are concrete beams and walls. Buildings' energy consumption should be reduced as much as possible by enhancing their thermal properties. Since aggregates constitute the highest amount of concrete by volume, the components most affect its thermal, sound, and mechanical properties. Lightweight concrete can be produced by using lightweight and porous aggregates in concrete production. Concrete blocks produced from lightweight aggregates; low density, high insulation, fire resistance, heat shock resistance, etc. are the most important advantages of these structures. In many studies, it has been found that lightweight concrete has better insulation than conventional concrete (ACI Committee 122, 2002; Vaou and Panias, 2010; Real et al., 2021; Uysal et al., 2004; Demirboğa et al., 2004) which is due to the porosity of lightweight aggregates (Chandra et al., 2002; Argunhan et al., 2017; Oktay et al., 2015), but also provides the necessary mechanical properties (Bouguerra et al., 1998). Because they are exposed to climatic factors including convection and solar heat flux, the exterior surfaces of the buildings account for a significant portion of the overall cooling load. In addition to the use of building materials with high insulating properties, an accurate calculation of the

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capacities of heating and cooling systems is an essential task for low-carbon buildings. In this way, this waste of energy is prevented by not selecting devices with capacities larger than the required ones. However, due to the thermal storage effects of the building mass and the constantly changing external conditions, an accurate assessment of the cooling load is quite difficult and time-consuming (Bansal et al., 2008).

The thermal inertia of a building can be calculated using a variety of techniques (ASHRAE, 1993; De Rosa et al., 2016; Naji et al., 2019). Different analytical techniques, including the separation of variables, the orthogonal extension approach, Green's function, the Laplace transform, and integral procedures have been defined by Özışık and Hahn (2012). In another study, Ulgen (2002) investigated the thermal responses of various wall configurations under the influence of solar radiation experimentally and analytically. Additionally, Yumrutaş et al. (2007) developed a theoretical approach based on the periodic solution of the one-dimensional transient heat transfer issue in buildings for three different wall types and flat roofs, which is commonly used to calculate TETD values.

In the present study, both experimental and theoretical studies are performed. In the experimental study, new wall/roof materials with high thermal insulation properties, which are formed with materials such as perlite and pumice, which our country has world-class reserves in terms of resource maintenance, were produced. In the theoretical study, an analytical solution was developed to calculate the heat gain through the walls and to estimate the thermal performance of produced new lightweight wall elements. To determine the temperature distribution for multilayer wall or flat roof constructions, the calculation approach for the heat gain is based on a solution to the transient heat transfer problem.

2. Material compositions and test methods

The new building's wall and roof components were made from a variety of materials which were locally available ordinary Portland cement (PC), silica fume (SF), fine aggregate, coarse aggregate, rubber aggregate (RA), pumice aggregate (PA), expanded perlite aggregate (EPA), and superplasticizer (SP). Concrete mixtures were designed with an effective water/cement ratio of 0.48 and a total cement amount of 350 kg/m^3. Natural aggregates were replaced by expanded perlite, waste tire, and pumice aggregates with fractions between 0% and 100% of the total aggregate volume to produce lightweight concrete samples. Due to insufficient mechanical strength for the concretes formed with the waste rubber and expanded perlite aggregates in volume ratios of 70% and higher, they were not included in this study.

Several tests were conducted on the produced concretes regarding the compressive strengths, bulk density, thermal conductivity, specific heat, and thermal diffusivity according to the ASTM and EN standards. The measurements of the thermal conductivity, specific heat capacity, and thermal diffusivity are performed by TPS (Transient Plane Source) technique (Figure 1.). In the TPS method, the heat is generated by a hot disc composed of a bifilar spiral, which also acts as a sensor for the rise in sample temperature. The benefit of transient methods over stationary or steady-state techniques is that some of them can provide a complete set of thermophysical characteristics in a single quick measurement.

Figure 1. The thermal properties analyzer device

Both mechanical and thermophysical property test results for the produced samples are presented in Table 1.

3. Solution of the transient heat transfer problem and computational procedure

To decide whether any one of the building wall/roof elements is the best performance by the heat transfer, it is necessary to compare heat gain or loss for these elements. Any wall types with lower heat gain values are recommended to applicants in low-carbon buildings. Since the smallest amount of energy is needed to heating and cooling any given space, it is crucial for pollution prevention, humanity, and environmental preservation.

Table 1. Mechanical and thermophysical property of samples

Sample	σ_c (Mpa)	λ(W/m.K)	ρ_k (kg/m^3)	c_p (J/kg.K)	α (m^2/s)
NC	61.52	2.075	2434.30	630.57	1.35×10^{-6}
EPC10	26.72	1.597	2065.56	776.59	9.95×10^{-7}
EPC20	19.68	1.140	1872.29	799.34	7.62×10^{-7}
EPC30	13.13	0.944	1751.14	817.87	6.59×10^{-7}
EPC40	11.54	0.820	1636.37	828.05	6.05×10^{-7}
EPC50	10.38	0.709	1449.40	918.69	5.32×10^{-7}
EPC60	6.43	0.520	1342.44	961.83	4.02×10^{-7}
PC20	26.75	1.390	2107.30	809.88	8.14×10^{-7}
PC40	18.14	1.060	1888.18	835.89	6.72×10^{-7}
PC50	17.37	0.911	1748.85	881.02	5.91×10^{-7}
PC60	13.32	0.639	1529.34	968.00	4.32×10^{-7}
PC80	11.83	0.421	1350.55	1049.94	2.97×10^{-7}
PC100	9.35	0.358	1112.25	1186.79	2.71×10^{-7}
RC10	35.03	1.720	2224.09	727.94	1.06×10^{-6}
RC20	19.90	1.417	2122.88	754.50	8.84×10^{-7}
RC30	10.39	1.070	1920.16	766.76	7.27×10^{-7}
RC40	6.24	0.829	1805.82	786.68	5.84×10^{-7}
RC50	4.47	0.722	1782.13	824.86	4.91×10^{-7}
RC60	2.94	0.548	1658.99	914.53	3.61×10^{-7}
EPC40-PC60	7.68	0.193	815.92	1189.46	1.99×10^{-7}
EPC50-PC50	5.89	0.158	726.14	1160.03	1.88×10^{-7}
EPC60-PC40	4.47	0.141	693.55	1122.26	1.81×10^{-7}

A mathematical formulation and boundary conditions are used to design a one-dimensional periodic heat transfer problem for a wall or roof component. The temperature of the inner surfaces of the building walls is determined using the problem's solution.

$$\frac{\partial^2 T_n}{\partial x^2{}_n} = \frac{1}{\alpha_n}\frac{\partial T_n}{\partial t} \qquad 1\leq n \leq N \qquad (1)$$

$$h_i(T_r - T_1) = -\lambda_1 \frac{\partial T_1}{\partial x_1} \qquad \text{at } x_1 = 0 \qquad (2)$$

$$-\lambda_{n-1}\frac{\partial T_{n-1}}{\partial x_{n-1}}(x_{n-1} = L_{n-1}) = -\lambda_n \frac{\partial T_n}{\partial x_n}(x_n = 0) \quad 2\leq n \leq N \qquad (3)$$

$$T(x_{n-1} = L_{n-1}) = T(x_n = 0) \qquad \text{for } 2\leq n \leq N \qquad (4)$$

$$-\lambda_N \frac{\partial T_N}{\partial x_N} = h_o[T_N - T_e(t)] \qquad \text{at } x_N = L_N \qquad (5)$$

$$T_e(t) = T_a(t) + \frac{\alpha_s I_t(t)}{h_o} - \frac{\varepsilon \Delta R}{h_o} \qquad \text{at } x_N = L_N \qquad (6)$$

$$I_T(t) = I_b(t)R_b + I_d(t)\left(\frac{1+\cos\beta}{2}\right) + I(t)\rho_g\left(\frac{1-\cos\beta}{2}\right) \qquad (7)$$

$$R_b = \frac{\cos\delta\sin\varphi\cos\gamma\cos\omega + \cos\delta\sin\gamma\sin\omega - \sin\delta\cos\varphi\cos\gamma}{\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta} \qquad (8)$$

$$T_n(z_n, \tau) = \sum_{j=-M}^{M} T_{nj}(z_n)\, e^{i\omega_j \tau} \qquad \omega_j = 2\pi j \qquad (9)$$

The periodic solution equation for the temperature distribution in a wall, given by Eq. (9), $T_n(z_n, \tau)$ is obtained as a function of the solar energy flux, $I_T(t)$, and ambient air temperature, $T_a(t)$. It is necessary to calculate solar radiation incidents on the structures to obtain temperature variation in the walls and flat roofs. $I_T(t)$ is the hourly solar heat flux on a tilted surface, which is equal to the intensity of solar radiation falling on unit area flux. It can also be expressed as the total of the beam, diffuse, and reflected radiation, given by Duffie and Backman (Duffie and Beckman, 1980).

A function of the interior surface temperatures of the building wall, the interior design air temperature, and the convective heat transfer coefficient is used to calculate the amount of heat gain through any wall. In other words, it may be determined by multiplying the temperature difference by the convection coefficient. As a result, the heat gain can be written as:

$$q_c = h_i[T_1(0,t) - T_r] \qquad (10)$$

The temperature difference shows the temperature difference between the inside surface of the wall $T_1(0, t)$ and interior air temperature, T_r which is commonly taken as 25 °C for the whole cooling season.

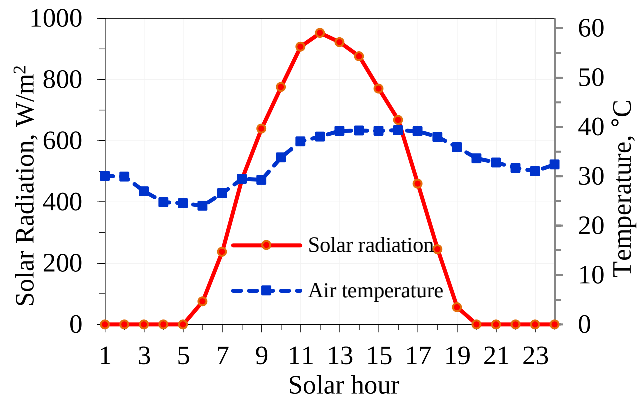

Figure 2. The hourly solar radiation incident and ambient temperature values

The detailed solution to the problem is presented in Ref. (Oktay et al., 2020) in detail. Hence, a computer program in MATLAB was prepared by using climatic data and thermophysical properties of the produced samples. The climatic data are hourly ambient air temperature and solar radiation on a horizontal surface which are measured with the meteorology system established at Batman University on July 26, 2016 given in Figure 2. The inner combined heat transfer coefficients and outer surfaces are taken as 9 and 22 W/m² °C, respectively. Solar absorptivity αs, which depends on the exterior surface color of a building envelope. The algorithm of the program is shown in Figure 3.

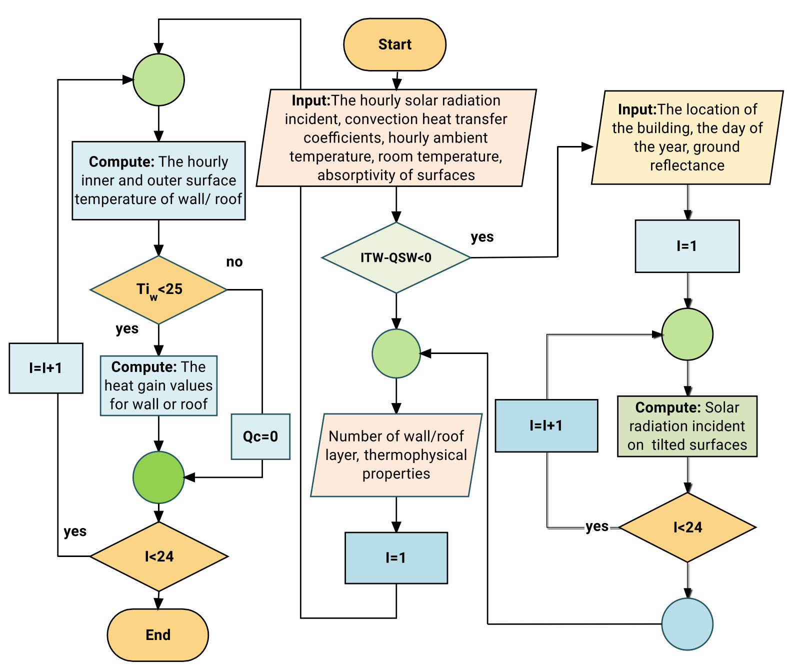

Figure 3. Algorithm of the program in MATLAB

In the program, the hourly air temperature and solar incident values were given as input data. When the program was executed, the type of wall/roof, the number of layers, and their thickness were given as input parameters. Firstly, the hourly sol-air temperature was calculated by using the procedure given in Eq. (6). Then, the inner surface temperature of the wall and the heat gain values were computed as given in Eqs. (9) and (10), respectively.

4. Results and discussions

In this section, an analytical method, the complex finite Fourier transform (CFFT) is obtained by using the thermal performance analysis of lightweight concrete samples. As stated before, the heat gain values passing for the walls/roofs were taken as a reference to compare the thermal performances of the buildings. The schematic representation and dimensions of the walls and flat roofs used in the study are given in Figure 4.

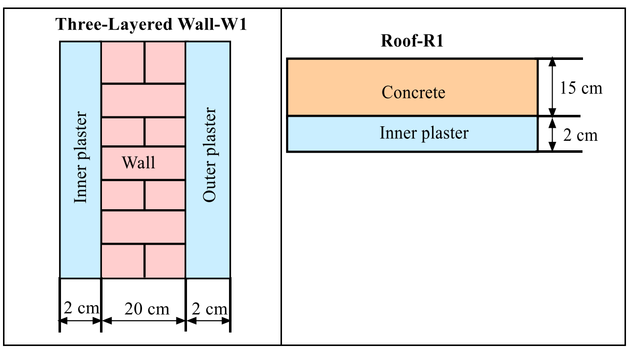

Figure 4. Schematic presentation of a multilayer wall/roof construction.

The heat gain values depending on the East, West, North, and South directions of the EPC50 wall are shown in Figure 5. This is essential for determining the wall constructions' highest heat gain. The heat gain values range from 9 to 10 hours for the lowest values to 20 to 21 hours for the greatest values in all directions. The north wall experienced the lowest daily average heat gain, calculated as 1.624 W/m², while the west wall experienced the highest daily average heat gain, calculated as 17.846 W/m².Since the cooling load of a building element depends on the heat gain and the West side has the most heat gain, it is recommended to designers that the area of the wall due to the West should be minimized for the building located in this region.

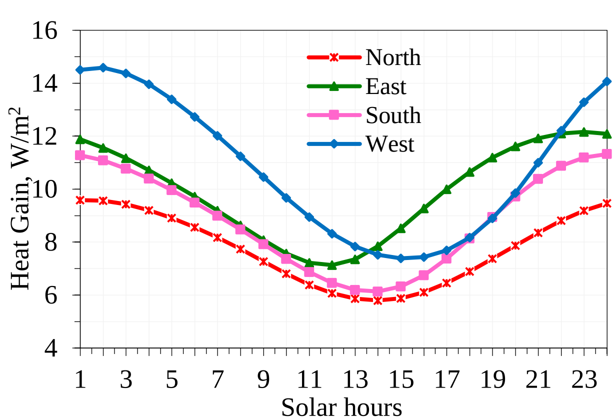

Figure 5. Heat gain values depend on the East, West, North, and South directions of the EPC50 wall

Figure 6 shows the hourly heat gain values of walls with different colors facing the South direction. Black, green, brown, and white colored surfaces have the highest and lowest heat gain values, respectively. The solar absorptance of the wall has a great influence on the heat gain values that the dark surfaces absorb more solar radiation. As a result, constructing buildings in white or near-white colors in regions with high outdoor temperatures and solar radiation intensity will reduce cooling expenditures.

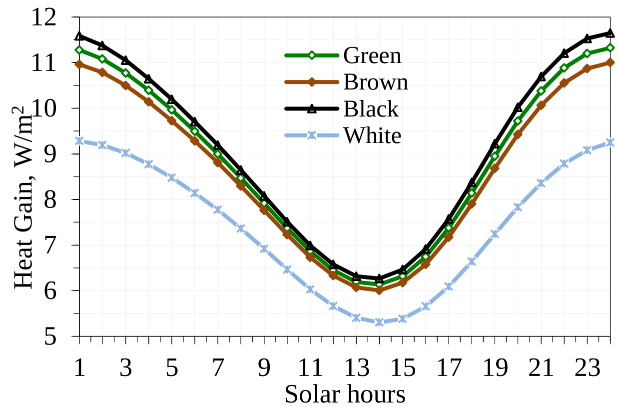

Figure 6. Hourly heat gain values of south-facing walls with different colors.

Hourly heat gain variations of green-colored NC and EPC walls/roofs with different expanded perlite ratios due to the South direction are shown in Figures 7 and 8, respectively. It was observed that the highest heat gain occurs for the wall and roofs constructed with NC and followed by EPC10, EPC20, EPC30, EPC40, EPC50, and EPC60, respectively. When the maximum heat gain values for the walls in 24 hours are compared; the highest heat gain value was calculated as 65.909 W/m² for NC and the lowest heat gain value was calculated as 32.724 W/m² for EPC60. While these values for roofs are 151.454 W/m² for NC, it is 78.668 W/m² for EPC60. An R1-type roof is widely used in Turkey, especially in old buildings. Since this roof type consists of only 2 cm plaster and 12 cm concrete, it is understood that it is highly affected by the outdoor temperature and solar radiation, and the hourly heat gain amplitude is very high for both light and dark colors. The value of 151.454 W/m² obtained for NC indicates that since the capacity of the cooling unit to be used for an R1-type roof dwelling must be very high, it will bring worse living conditions, a higher investment, and operating cost. As a result, an R1-type roof should not be preferred in residences.

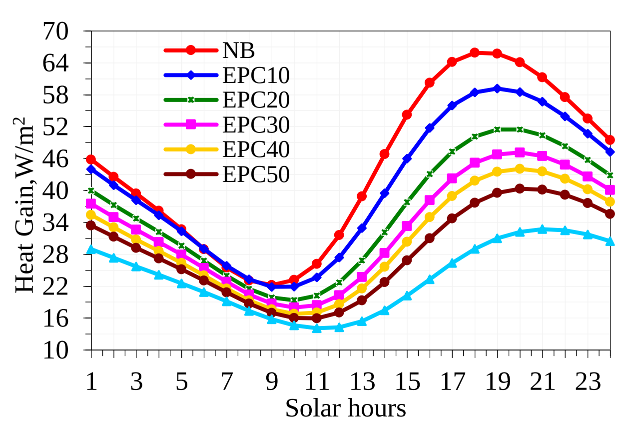

Figure 7. Daily variation of heat gain values of NC and EPC walls facing south

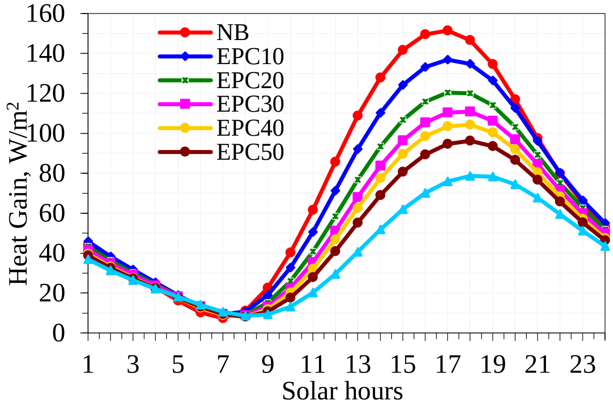

Figure 8. Daily **v**ariation of heat gain values of NC and EPC flat roofs

Hourly variations of heat gain values of NC and PC walls and flat roofs with different pumice aggregate ratios due to the South direction are shown in Figures 9 and 10, respectively. It was observed that the wall and roof constructed with NC material had the highest heat gain values, followed by PC20, PC40, PC50, PC60, PC80, and P100, respectively. When the maximum heat gain values for the walls in 24 hours are compared; the highest heat gain value was calculated as 65.909 W/m² for NC and the lowest heat gain value was calculated as 24.09 W/m² for PC100. While these values for the roof were 151.454 W/m² for NC, and 58.319 W/m² for PC100.

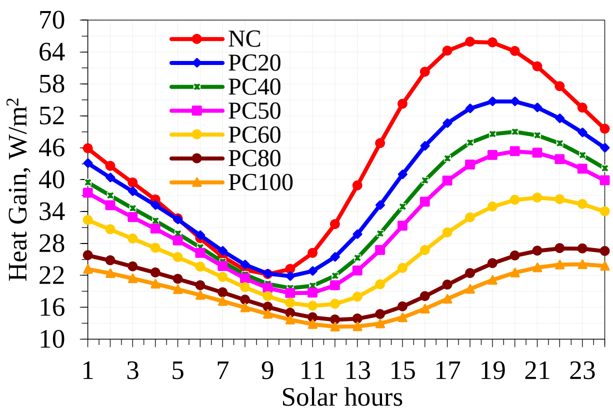

Figure 9. Daily **v**ariation of heat gain values of NC and PC walls facing south

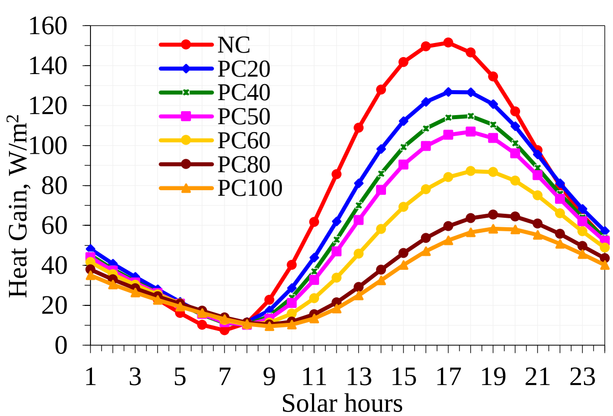

Figure 10. Daily **v**ariation of heat gain values of NC and PC flat roofs

Hourly heat gain variations of NC and RC walls and flat roofs with different waste rubber aggregate ratios due to the South direction are shown in Figures 11 and 12, respectively. It was observed that the wall and roof constructed with NC material had the highest heat gain values, followed by RC10, RC20, RC30, RC40, RC50, and RC60, respectively. When the maximum heat gain values for the walls in 24 hours are compared; the highest heat gain value was calculated as 65.909 W/m² for NC and the lowest heat gain value was calculated as 32.558 W/m² for RC60. While these values for the roof were 151.454 W/m² for NC, it was 77.85 W/m² for RC60.

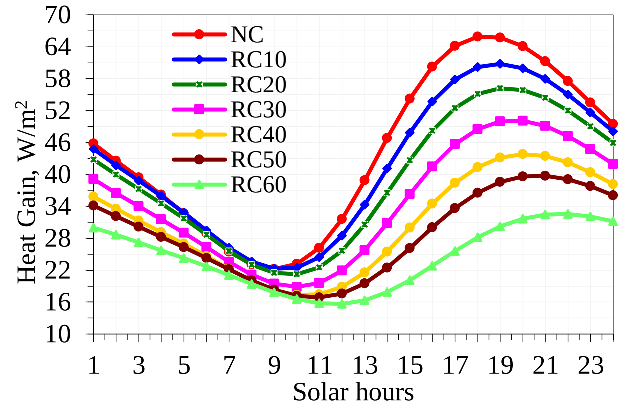

Figure 11. Daily **v**ariation of heat gain values of NC and RC walls facing south

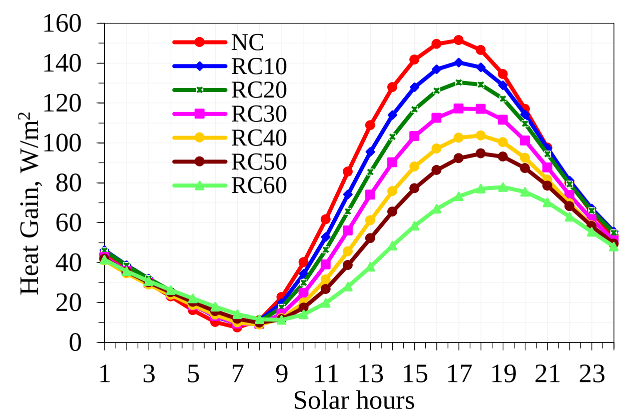

Figure 12. Daily **v**ariation of heat gain values of NC and RC flat roofs

The hourly heat gain values obtained by using some building materials on the roof and south-facing walls are indicated in Figure 13 and Figure 14, respectively. It can be shown that walls and roofs made of NC, which have the maximum thermal conductivity and thermal diffusivity, have the greatest heat gain. The thermal conductivity and diffusivity of the materials have been found to significantly affect the thermal performance of the constructions. A heat gain of 11,324 W/m² for the walls and 28,194 W/m² for the roof was obtained for the walls constructed with PC40-EPC60, which has the lowest thermal conductivity and thermal diffusivity values. As can be seen here, the heat gain of the PC40-EPC60 wall is approximately 1/6 of the NC wall. High heat gain is undesirable in terms of both comfort and high cooling load. Consequently, with a high cooling load, the capacity of a cooling system, the initial investment, and the operating cost will increase.

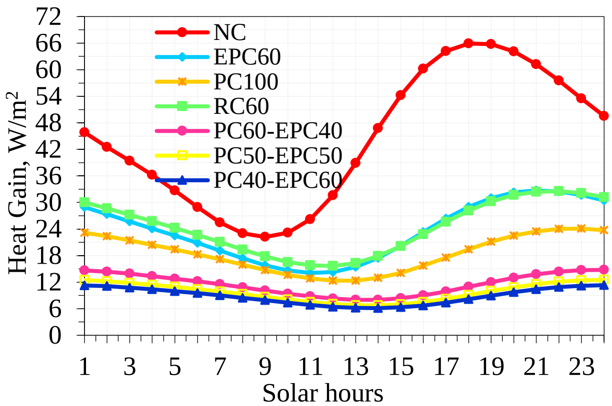

Figure 13. Daily **v**ariation of heat gain values of different wall constructions due to south

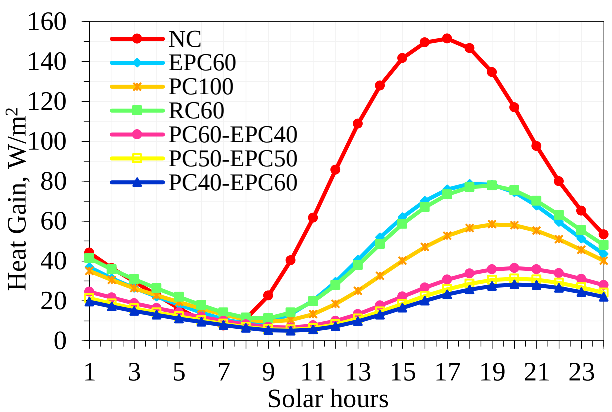

Figure 14. Daily **v**ariation of heat gain values of different roof constructions

Briquette, blockbims, curtain concrete, aerated concrete, and brick are generally used as wall materials in Turkey. Figure 14 shows the comparison of the highest heat gain values of the commonly used in our country according to their thickness in a design day due to the South direction. The highest heat gain in a day for a building construction occurs at different hours depending on the thermophysical properties and heat storage capabilities of the wall material. For each wall material, the heat gain decreases as the wall thickness and, accordingly, the thermal resistance increase. This figure explains which wall thickness for NC-constructed walls corresponds to brick, block, briquette, aerated concrete, PC40-EPC60 walls, or to each other. By the way, it is shown how much wall heat gain is necessary for a wall thickness and each of the structures. As can be seen from the figure, the highest heat gain for the NC wall with a thickness of 20 cm will be equal to the same heat gain with briquettes and bricks of 12.91 cm and 10.72 cm thickness, respectively. However, it is seen that the highest heat gain for the 10 cm thick PC40-EPC60 wall corresponds to 29.75 cm brick, 15.43 cm blockbims, and 11.8 cm aerated concrete. The heat gains of aerated concrete and PC40-EPC60 walls are generally close to each other. Although by using PC40-EPC60 as wall material, which is easily produced from domestic sources and cheaper than aerated concrete having disadvantages such as high production costs and lack of plaster adhesion, is important in reducing energy consumption due to heating and cooling, as well as operating and initial costs for low-carbon buildings. The results also reveal that, especially in massive buildings, the thicker element would absorb heat and delay the time when conditions would become uncomfortable. Although the obtained result is consistent well with Refs. (Jin et al., 2012; Barrios et al., 2011) the thickness of the wall material is not particularly deterministic in terms of heat gain due to limits of practical applications in residential buildings.

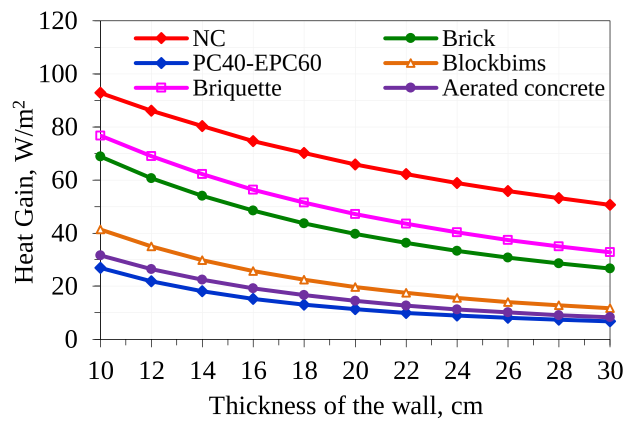

Figure 15. Comparison of the highest heat gain values of commonly used wall materials with different thicknesses

5. Conclusions

In this study, experimental and theoretical investigations were carried out to determine the best thermal performance wall or roof types for low-carbon buildings. The followings conclusions obtained from the study can be drawn:

1. The results indicated that the highest heat gain values in a design day for flat roofs and walls are obtained; respectively, as follows; 151.454 W/m² and 65.909 W/m² for NC, 78.668 W/m² and 32.724 W/m² for EPC60, 58.319 W/m² and 24.09 W/m² for PC100 and 77.85 W/m² and 32.558 W/m² for RC.
2. When the wall materials commonly used in Turkey are compared, it is seen that the highest heat gain in the 10 cm thick PC40-EPC60 wall corresponds to 29.75 cm brick, 15.43 cm blockbims, and 11.8 cm aerated concrete.
3. The improvement of heat gain values is greatly influenced by the thermal characteristics of the wall or roof materials. Thermal diffusivity and conductivity are two crucial properties in particular, and materials with low thermal conductivity have small heat gain amplitude values.
4. In all types of roofs and walls, the lowest heat gain value was obtained for the PC40-EPC60, but the highest ones were obtained for the NC.

Consequently, using construction types with high thermal insulation characteristics in the buildings provides energy efficiency and contributes directly to the economy of our country.

Nomenclature

c	specific heat (kJ/kg K)
h_i	heat transfer coefficient at inner surface (W/m^2 K)
h_o	heat transfer coefficient at outer surface (W/m^2 K)
i,j	complex arguments
I_T	radiation flux on tilted surface (W/m^2)
I_{bT}	beam radiation flux on tilted surface (W/m^2)
I_{dT}	diffuse radiation flux on tilted surface (W/m^2)
I_{rT}	reflected radiation flux on horizontal surface (W/m^2)
λ	thermal conductivity (W/m K)
L	thickness (m)
p	time period (h)
t	time (s)
T_a	ambient air temperature (°C)
T_e	sol-air temperature (°C)
T_r	room temperature (°C)

Greek symbols

α	thermal diffusivity (m^2/s)
α_s	absorptance of surface
ρ	density (kg/m^3)
ω_j	complex frequency
δ	declination
ε	emissivity of a surface
ΔR	difference between long-wave radiation incident on the surface from the sky (W/m^2)
τ, τ_n, τ_{np}	dimensionless time terms
ρ_g	ground reflectance
ω	hour angle
ϕ	latitude angle
γ	surface azimuth angle

Subscripts

i	inside
o	outside
N	number of layers

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