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COMBINED USE OF PHASE CHANGE MATERIAL AND THERMAL INSULATION IN THE BUILDING ENVELOPE TO ENHANCE THE THERMAL COMFORT AND ENERGY-SAVING

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Abstract: The combined use of phase change material (PCM) and thermal insulation (TI) is a crucial opportunity to enhance the thermal performance of buildings. This study aims to determine the optimum location and thickness of PCM and TI, as well as the melting temperature of PCM, in the exterior walls of an educational building located in five climate regions of Türkiye, and proposes a combination of PCM and TI techniques to reduce its cooling energy demand. Antalya, Istanbul, Ankara, Van, and Erzurum were selected to represent the various climatic regions of Türkiye. The simulation results revealed that the combined use of PCM and TI could effectively reduce the interior temperature (ITR) and provide better thermal comfort than incorporating PCM alone. The exterior wall type with PCM in the innermost layer and TI in the outermost layer was the most effective configuration for reducing the temperature fluctuations and cooling energy demand. The optimum melting temperature of the PCM was determined to be 27 ºC, ensuring a higher ITR and lower cooling energy consumption. The combined use of PCM (30 mm) and TI (10 mm), when properly selected according to local climatic conditions, can achieve considerable energy savings (9.12-19.95%).

Keywords: Phase change material, Thermal insulation, Indoor temperature, Thermal comfort, Energy-saving

Isıl Konforu ve Enerji Tasarrufunu Artırmak İçin Bina Kabuğunda Faz Değiştiren Malzeme ve Isı Yalıtımının Birleşik Kullanımı

Öz: Faz değiştiren malzeme (PCM) ve termal yalıtımın (TI) birlikte kullanımı, binaların termal performansını artırmak için önemli bir fırsattır. Bu çalışma, Türkiye'nin beş iklim bölgesinde yer alan bir eğitim binasının dış duvarlarında PCM ve TI'nin optimum yerleşim ve kalınlığını ve PCM'nin erime sıcaklığını belirlemeyi amaçlamış ve PCM ve TI'nin birlikte kullanım teknikleriyle soğutma enerji talebinin azaltılmasını hedeflemiştir. Antalya, İstanbul, Ankara, Van ve Erzurum, Türkiye'nin çeşitli iklim bölgelerini temsil etmek üzere seçilmiştir. Simülasyon sonuçları, PCM ve TI'nin birlikte kullanımının iç sıcaklık düşüşü (ITR) sağladığını ve yalnızca PCM kullanımına kıyasla daha iyi termal konfor sunduğunu göstermiştir. PCM'nin en içte ve TI'nin en dışta yer aldığı dış duvar tipi, sıcaklık dalgalanmalarını ve soğutma enerji talebini azaltmak için en etkili yapılandırma olmuştur. PCM'nin optimum erime sıcaklığı 27 ºC olarak belirlenmiş, bu da daha fazla ITR ve daha az soğutma enerjisi tüketimi sağlamıştır. PCM (30 mm) ve TI (10 mm) birlikte kullanımı, yerel iklim koşullarına göre uygun şekilde seçildiğinde %9,12-19,95 arasında önemli enerji tasarrufu oranları elde edebilir.

Anahtar Kelimeler: Faz değiştiren malzeme, Termal yalıtım, İç sıcaklık, Termal komfor, Enerji tasarrufu

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1. INTRODUCTION

The construction sector, which ranks second after industry in terms of worldwide energy demand accounts for 30-40% of global energy consumption (Ali, 2014) and is responsible for more than 30% of CO_2 emissions (Yang et al., 2014). Energy consumption in this sector is expected to increase by over 50% by 2050 because of population growth, higher living standards, and increased time spent indoors (International Energy Agency, 2015). In Türkiye, the construction sector accounts for 37% of final energy consumption and 30% of greenhouse gas emissions (T.C. Çevre, Şehircilik ve İklim Değişikliği Bakanlığı, 2023). Within the framework of the Energy Efficiency 2030 Strategy and the Second National Energy Efficiency Action Plan, achieving a 16% reduction in energy consumption is targeted for the 2024-2030 period, which is expected to reduce 100 million tons of CO_2 equivalent greenhouse gas emissions (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2023). To achieve these targets, improving the thermal properties of building envelopes, implementing energy efficiency technologies, and promoting green building certifications are essential (Ilıcalı, 2024).

The energy consumption can be significantly reduced by changing the thermal properties of the building envelope. The use of thermal energy storage systems in building envelopes is a method that is widely applied and accepted as an innovative technology (Akeiber et al., 2016). Phase change materials (PCM) are thermal energy storage systems applied in building envelopes (Beltran and Martinez-Gomez, 2019). When the ambient temperature increases during the day, the PCM absorbs heat energy and melts while storing it, thereby enabling an indoor temperature reduction (ITR) (Chan, 2011).

Thermal insulation materials (TI) increase the thermal resistance of a building envelope by reducing the heat transfer between the building envelope and the interior environment (Al-Homoud, 2005). The combined use of PCM and TI, which have positive thermal comfort properties, can increase the thermal performance of the building envelope. Alizadeh and Sadrameli (Alizadeh and Sadrameli, 2019) found that the combined use of PCM and TI in the building envelope reduced the overheating of the building by 13.83% in summer and the discomfort level by 2.61% in winter. Jin et al. (Jin et al., 2014), Kalbasi and Afrand (Kalbasi and Afrand, 2022), Arumugam and Ramalingam (Arumugam and Ramalingam, 2024), Zhang et al. (Zhang et al., 2024), and Lagou et al. (Lagou et al., 2019) determined that the ideal PCM location for summer is the innermost layer of the wall, which substantially reduces thermal fluctuations. On the other hand, Arumugam et al. (Arumugam et al., 2022) found that the cooling energy demand decreased by 57-64% with the use of PCM and TI on the outermost layer of the wall in five different climate regions of India. Al-Yasiri and Szabo determined that effective melting and solidification phases are guaranteed when TI is installed directly after PCM from the interior surface (Al-Yasiri and Szabo, 2023). Research results on the optimal location of PCM and TI within wall sections may contradict each other. In fact, the optimum location is defined as the location where the PCM can completely melt and solidify again during the day; that is, it can perform phase-change cycles (Arıcı et al., 2022).

Increasing the PCM thickness allows for interiors with higher comfort conditions. Qu et al. (Qu et al., 2021) reported that 10 and 70 mm PCMs reduced indoor temperature by 0.02-2.41 ºC and 1.76-5 ºC, respectively. Chen et al. (Chen et al., 2008) found that the energy-saving rate during the cooling season can reach 17% or higher by using 30 mm PCM. The lowest cooling energy was provided by a 30-mm PCM in five different cities that the Mediterranean climate prevails: Athens (Greece), Naples (Italy), Ankara (Türkiye), Seville (Spain), and Marseille (France) (Ascione et al., 2014).

The geographical location and climatic conditions should be considered when determining the optimum melting temperature of PCM. For example, the optimum PCM melting temperatures for the summer period in Diyarbakır, Konya, and Erzurum, which are located in different climatic conditions in Türkiye, were determined as 24-26 ºC, 24-25 ºC, and 27-32 ºC, respectively (Arıcı et al., 2020) and 23 ºC for Izmir (İlgar and Terhan, 2024). Another study determined that the PCM melting temperature should be 24-28 ºC in cooling-dominant climates and 18-22 ºC in heating-dominant climates (Saffari et al., 2017).

In local studies on PCM and TI, it was revealed that the highest energy savings for the cooling season were achieved in Diyarbakır (Türkiye) with a wall configuration where a PCM with a 21 ºC melting temperature and 60 mm thickness was placed on the interior, and a 30 mm TI was placed on the exterior. In Erzurum, the highest energy savings were achieved with a wall configuration where a 21 ºC melting temperature and 60 mm PCM were placed on the interior, and a 60 mm TI was placed on the exterior (Depe, 2017). In Elazığ, the highest energy savings were achieved with a wall configuration where a 21 ºC melting temperature and 50 mm PCM were placed on the exterior, and a 50 mm TI was also placed on the exterior (Özdemir, 2023). In Istanbul and Van, the most effective wall configuration was found to be where a 29 ºC melting temperature and 70 mm PCM were placed on the interior, and a 40 mm TI was placed on the exterior (Anayurt, 2021). In another study, the most effective wall configuration for the cooling season in Diyarbakır and Erzurum was found to involve a 25 ºC melting temperature and 100 mm PCM placed on the interior and a 100 mm TI placed on the exterior. (Coşkuner, 2018).

It has been determined that studies investigating the ideal position, thickness, and melting temperature of PCM and TI as important parameters in terms of thermal comfort and energy performance of buildings, contain relatively limited and contradictory results. Particularly for Türkiye, which is a country where various climatic conditions coexist, a clear understanding of the behavior of wall sections containing PCM and TI in all climatic regions is required. This study aims to determine the optimum location and thickness of PCM and TI, and the melting temperature of PCM, in the exterior walls of an educational building located in five different climate regions of Türkiye. It also proposes the combined use of techniques of PCM and TI to reduce the cooling energy demand of buildings.

2. METHODOLOGY

2.1. Description of the Simulated Building

A basic single-story education building model (500 cm length x 400 cm width x 300 cm height) was designed for the simulation (Fig. 1). Because the building model consisted of a single zone, there were no inner walls, and all of the exterior walls were modelled identically. The building has a terrace roof. The west wall was equipped with a wooden door measuring 90 cm wide and 220 cm high. In the current study, the south wall of the building was equipped with a window 400 cm in length and 150 cm in height. The distance between the window bottom and floor was 80 cm. The glass was an air-filled double glass with an overall heat transfer coefficient (U) of 2.8 W/m^{2}K, solar heat gain coefficient of 0.7, and visible transmittance of 0.8.

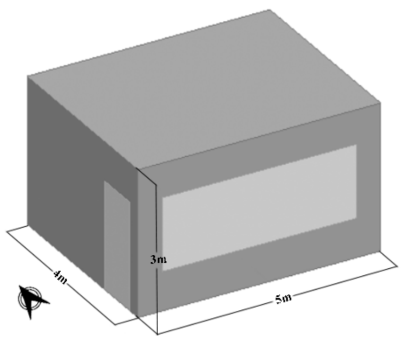

Figure 1:
Geometrical model of the education building analysed

The wall layer thicknesses were designed to comply with the overall heat transfer coefficient value specified in the TS 825-Thermal Insulation Requirements for Buildings (TS 825, 2013). While the thicknesses of the plaster and aerated autoclaved concrete wall materials were constant, the thickness of the thermal insulation (glasswool) was determined by considering the total heat transfer value, as provided by TS 825, for each climatic region. The details of the building envelopes are presented in Table 1. With the exception of the PCM, the thermophysical characteristics of the selected materials, which have an important impact on the energy consumption of buildings, were taken from TS 825 and are listed in Table 2.

Table 1. Details of the building envelope layers

Building Envelope	Layers (from inside to outside)
Roof	20 mm cement-based plaster, 120 mm reinforced concrete slab, 30 mm cement screed, 50 mm thermal insulation, waterproofing, and gravel roofing
Floor (Slabe on grade)	Flooring, thermal insulation, 100 mm blinding concrete, waterproofing, 50 mm sand, 150 mm blocage, and tamped soil
Reference Wall (without PCM)	20 mm plaster, 240 mm aerated autoclaved concrete, 10/20/30 mm thermal insulation, and 20 mm plaster

Table 2. Thermophysical properties of the selected materials

Material	Density (kg/m³)	Thermal conductivity (W/mK)	Water vapor diffusion resistance (μ)
Cement-based plaster	2000	1.6	15/35
Aerated autoclaved concrete	500	0.15	5/10
Thermal insulation (Glasswool)	32	0.04	1

The PCM (BioPCM® M27/Q21), which is widely used commercially, was selected directly from DesignBuilder. The thermophysical properties of the PCM are summarized in Table 3. Many preliminary simulation studies were conducted to decide on the usage ranges of PCM thickness and melting temperature. As a result of preliminary trials, it was decided to include 10, 20, and 30 mm thicknesses in the simulation program because they gave more positive results in terms of heat storage capacity, thermal comfort of the interior environment, and economy criteria. The higher thickness of PCM would increase the heat storage capacity as well as thermal comfort; however, it would lead to an increase in the cost of the building envelope. Because different climatic conditions coexist in the five climatic regions of our country, it was taken into consideration that the same PCM melting temperature might not give ideal results in all climatic regions. Thus, as a result of preliminary simulation studies, it was decided to use 21°C and 27°C PCM melting temperatures.

Table 3. Thermophysical properties of the PCM

Thermophysical properties		Values
Density (kg/m³)	Solid form	880
	Liquid form	760
Thermal conductivity (W/mK)	Solid form	0.2
	Liquid form	0.15
Specific heat (J/kgK)		2000

Four scenarios with different material layer combinations were investigated in this study. The wall without any PCM or TI layers (Fig. 2a) is hereafter referred to as the reference wall, and its details are listed in Table 1. To determine the optimum location and thickness of the PCM and TI, the melting temperature of the PCM in the exterior walls of the building is as follows:

- The PCM was placed in the innermost layer of the walls (Fig. 2b),

- The PCM was placed in the outermost layer of the walls (Fig. 2c),
- PCM was placed in the innermost layer, and TI was placed in the outermost layer (Fig. 2d),
- The PCM and TI were placed in the outermost layers, and TI was located in front of the PCM (Fig. 2e).

The placement of TI is also an important factor. In this study, TI has always been positioned as the outermost layer of the wall. This not only reduces heat loss but also serves as a critical element in eliminating the risk of condensation. Insulation materials placed in the inner layers can lead to condensation and moisture accumulation over time, which may threaten the structural integrity of the walls and indoor air quality. Therefore, positioning TI in the outermost layer not only contributes to energy savings but also helps maintain a healthy indoor environment. Increasing the thickness of the insulation material further reduces heat loss effectively, contributing to a more stable indoor temperature. Thicknesses ranging from 10 mm to 30 mm have been optimized according to the heat transfer coefficients and energy consumption requirements of each climatic region.

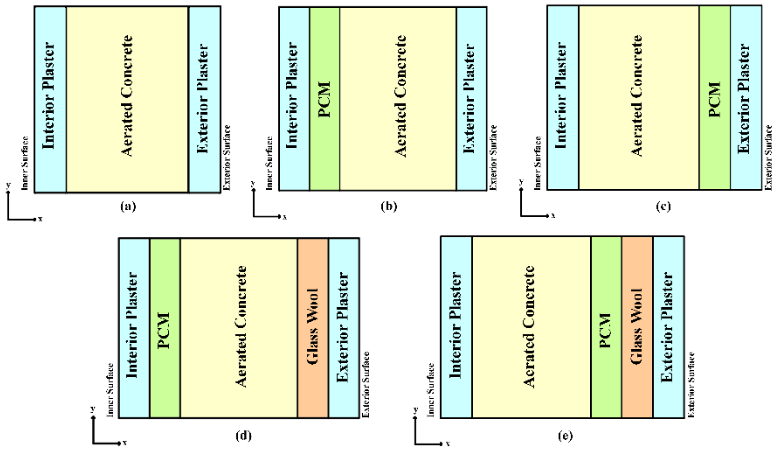

Figure 2:
Simplified drawing of wall sections simulated in the study

The wall sections were coded in [PCM(e)-X/TI-Y] or [PCM(i)-X/TI-Y] format. PCM and TI represent phase change material and thermal insulation, respectively. (e) and (i) indicate the positions of the PCM in the wall section (e = exterior, i = interior), X indicates the thickness of the PCM, and Y indicates the thickness of the TI.

2.2. Simulation Details

The analyzed building was intended for educational purposes, with working hours from 09:00 to 16:00. The building's occupancy rate was fixed at 0.55 occupants/m^2. Metabolic rates depend on the activities of the occupants in the education building. Furthermore, the use of equipment was input into the simulation based on weekly usage rates. An illumination level of 3.4 W/m^2–100 lx of was taken into consideration, during working hours.

As an exterior temperature of 18 °C can maintain the inside at a comfortable temperature of 24 °C; hence, the heating or cooling requirements for any place are usually calculated according to this exterior baseline temperature (Menyhart and Krarti, 2017). Fig. 3 illustrates that the outdoor air temperatures throughout the day in summer for all cities are higher than the baseline temperatures, indicating the need for cooling to provide adequate thermal comfort. As peak summer represents the maximum cooling energy requirement, all research was focused on the summer period with the goal of reducing the cooling energy demand (Arumugam et al., 2022).

It is expected that the stored energy in the building envelope from solar gains will be released into the interior space. Consequently, the interior temperatures will increase during the daytime. The comfortable range of indoor temperature is between 18 °C and 26 °C for Türkiye (Coşkun et al., 2010). Therefore, 26 °C was selected as the setting temperature during the cooling period of the educational building. If the interior temperature exceeded 26 °C during the periods of 09:00-16:00, when the building occupants attended, in accordance with the guidelines proposed by Saffari et al. (Saffari et al., 2016), the cooling system was automatically activated. The cooling requirements were met using an electrical split air-conditioning system. In the simulations, natural ventilation was assumed to be "closed," and cooling was preferred to be provided only by mechanical systems. The reason for this was to determine the maximum total cooling energy consumption caused by mechanical systems during summer periods, without reducing the solar gain-based temperature increases of the interior environment with natural ventilation and to determine the maximum energy saving ratio provided by PCM/TI integration.

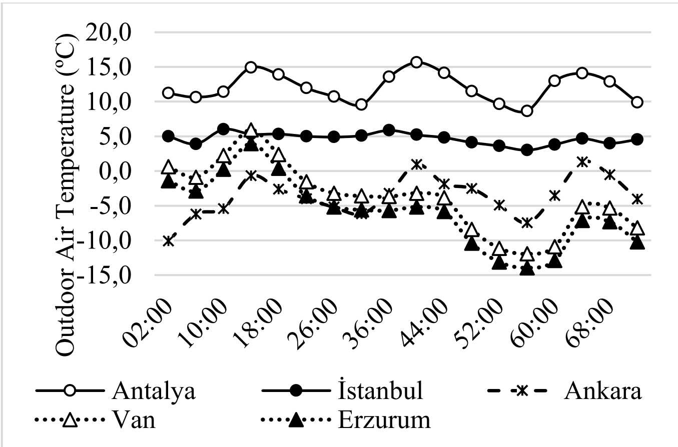

Figure 3:
Outdoor air temperatures in the selected cities

The DesignBuilder software was used to simulate the building. The DesignBuilder® is a graphical user interface simulation program developed for the EnergyPlus™ (EP) dynamic thermal simulation program. The main assumptions include that the building has a uniform temperature, uniform surface temperatures, uniform long- and short-wave radiation, and one-dimensional heat conduction (Crawley et al., 2001).

Successive stages were performed using DesignBuilder® software. In the first stage, the building location and meteorological files were selected. Hourly ambient conditions such as temperature, solar radiation, atmospheric humidity, and wind velocity were present in the weather files of the DesignBuilder® software. In the second stage, a building model designed using SketchUp software was used as the input. In the next stage, various inputs, such as construction details, window openings, material properties, occupancy and lighting loads, and HVAC system details, were selected. To precisely simulate the phase change procedure, a calculation technique known as the "Finite Differences Calculation Method" was selected (U.S. Department of Energy, 2021).

The effects of PCM and TI integration on the thermal performance of the building envelope were assessed by considering indoor temperature reduction (ITR) values. The term "ITR" describes the decrease in the maximum interior temperature of the simulated building (with PCM and PCM+TI) compared with the reference building (without PCM and TI). The mechanical systems were turned off during the ITR calculation to mitigate the risk of them changing the thermal performance of the building envelope. ITR was calculated as the temperature difference between the maximum indoor temperature of the PCM and TI-integrated building, and that of the reference building during the three-day peak summer. In Türkiye, cooling demands for buildings generally occur from May to September, with a peak cooling load in July. Therefore, 20-22 July was selected as “peak summer days”, which represents the worst weather conditions that were taken into consideration during the design period.

The effects of the PCM and TI on the energy performance of buildings were determined by considering the annual energy savings. The annual energy saving is the amount of energy saved when PCM and TI are incorporated into a building envelope. The annual energy saving, as a ratio (ESR), was calculated to represent the percentage of energy saved by incorporating the PCM and TI, according to Equation (1):

$$ESR = \frac{\text{EC (without PCM / TI)} - \text{EC (with PCM / TI)}}{\text{EC (without PCM / TI)}} \text{ x } 100\ (\%) \quad (1)$$

Where EC is energy consumption (kWh). The ESR and EC values were determined when the mechanical system was active between 07:00 and 24:00 with 100% efficiency and was inactive between 00:00 and 07:00.

2.3. Climate Conditions

To ensure the production and widespread use of a building material for external walls of buildings exposed to outdoor climate conditions, it must perform well against more than one climate characteristic. The material in question should be able to maintain the expected performance criteria over a long service life under different climatic conditions such as ambient temperature, humidity, wind speed, and type and amount of precipitation. Therefore, it is necessary to evaluate the effectiveness of the designed wall sections under different climatic conditions. Furthermore, in our country, where the characteristics of four seasons can be encountered simultaneously throughout the country, using the same wall section with the same layering, material types, and thicknesses in all climate regions can have adverse effects on both the properties of the building envelope and the health of occupants. Türkiye has five climate regions as determined by TS 825 (TS 825, 2013). Antalya (1st region) and Istanbul (2nd region) were selected to represent the characteristics of subtropical climates with very hot summers in Antalya and hot summers in Istanbul, along with cool winters. Ankara (3rd region) was selected to identify the characteristics of temperate continental climate, which has hot summers and cool winters. Van (4th region) and Erzurum (5th region) were also selected to represent the characteristics of temperate continental climates with warm summers and cold and very cold winters, respectively, according to Köppen-Geiger climate classification (Kottek et al., 2006).

Table 4. Solar radiation intensities and sunshine durations in selected cities <(Türkiye Güneşlenme Potansiyeli Atlası, 2010)>

Cities	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	kWh/m^2-year	Sunshine duration (h/day)	Altitude
Antalya	75	91	138	160	197	208	215	196	163	123	82	66	1715	8.4	39
İstanbul	41	56	95	129	166	180	184	161	127	83	50	36	1389	5.9	40
Ankara	50	67	108	128	164	178	189	172	137	96	58	41	1306	6.9	938
Van	82	102	142	163	197	215	218	201	163	120	82	69	1493	7.9	1726
Erzurum	70	91	132	138	162	181	193	174	142	103	68	56	1511	6.7	1890

Hourly ambient conditions such as temperature, solar radiation, atmospheric humidity, and wind velocity were present in the weather files of the DesignBuilder® software. These data were confirmed by comparing them with data provided by the Meteorological Service of Türkiye (İl ve İlçeler İstatistikleri, 2024). In addition, the solar radiation intensities and sunshine duration data for the selected cities were obtained from the Türkiye Solar Atlas (Türkiye Güneşlenme Potansiyeli Atlası, 2010), which was prepared by the Meteorological Service of Türkiye (Table 4).

Antalya has a subtropical climate characterized by very hot summers and mild winters. The average maximum temperature in July, the hottest month, reaches 40°C, while the average minimum temperature in January, the coldest month, is 5°C. The annual average temperature is 18.8°C. Relative humidity ranges from 40% in the summer to 70% in the winter, with an annual average of 53.6%. The annual average number of rainy days is 73.5 (İl ve İlçeler İstatistikleri, 2024) , with most of the rainfall occurring between November and March. Dry and strong winds, such as "Sou'wester" and "Northeaster," are frequently experienced. The annual total solar radiation intensity is 1715 kWh/m², and the average daily sunshine duration is 8.4 hours (Table 4) (Türkiye Güneşlenme Potansiyeli Atlası, 2010).

Istanbul is influenced by Mediterranean, Marmara, and Black Sea climates. The highest temperatures occur in July and August, averaging around 30°C. The lowest temperatures are recorded in January and February, with an average of 3°C. The annual average temperature is 16.4°C. The average number of rainy days is 116.5 (İl ve İlçeler İstatistikleri, 2024) with the majority of rainfall occurring between October and March. The relative humidity ranges from 60% to 80%, reaching higher levels in the fall and winter months. The annual total solar radiation intensity is 1389 kWh/m², and the average daily sunshine duration is 5.9 hours (Table 4). Istanbul is also particularly affected by strong northwest winds, especially in the winter months (Türkiye Güneşlenme Potansiyeli Atlası, 2010).

Ankara has a temperate continental climate, characterized by hot summers and cold winters. During the summer months, the highest temperature can reach up to 32.5°C, while in the winter months, the lowest temperature can drop to -10°C. The annual average temperature is 12.0°C. The annual number of rainy days is 103.3 (İl ve İlçeler İstatistikleri, 2024), with the most rainfall occurring in the spring and autumn months. The relative humidity is around 60% in the winter months, while it can drop to 35% during the summer months. The annual total solar radiation intensity is 1306 kWh/m², and the average daily sunshine duration is 6.9 hours (Table 4). Ankara is also known for its strong continental winds, which affect heat retention and energy efficiency (Türkiye Güneşlenme Potansiyeli Atlası, 2010).

Van is located in a hot-dry climate zone and experiences extreme temperature fluctuations due to its location far from the sea and high altitude. The summer months are hot and dry, while the winter months are cold and snowy. The lowest recorded temperature in winter is -7°C, and the highest temperature in summer is 30°C. The annual average temperature is 9.5°C. The average number of rainy days is 93.4 (İl ve İlçeler İstatistikleri, 2024), with the majority of rainfall occurring in the spring and early winter. The annual total solar radiation intensity is 1493 kWh/m², and the average daily sunshine duration is 7.9 hours (Table 4). Van is also under the influence of strong seasonal winds, which significantly affect thermal comfort (Türkiye Güneşlenme Potansiyeli Atlası, 2010).

Erzurum is the region with the coldest climatic conditions in Türkiye. Summers are mild and dry, while winters are very cold and snowy. The lowest temperature can drop to -20°C, making Erzurum one of the harshest climates in the country. The annual average temperature is 5.8°C. Snowfall typically begins in October and continues until the end of April, significantly affecting building insulation requirements. The annual number of rainy days is 122.1, with most of the precipitation occurring between October and April (İl ve İlçeler İstatistikleri, 2024). The annual total solar radiation intensity is 1511 kWh/m², and the average daily sunshine duration is 6.7 hours (Table 4). Erzurum is also characterized by strong and persistent winds, which increase heat loss in buildings (Türkiye Güneşlenme Potansiyeli Atlası, 2010).

2.4. Validation

The simulation tool of the current study was validated by using a similar office building, which was previously modelled in the literature (Qu et al., 2021) for summer conditions. The average internal temperatures of the current building with PCM and without PCM were compared with the reference building. The results show a good agreement since the internal temperature deviation ranges were between 0.22% and 4.10% for the cases with PCM and between 0.27% and 6.32% without PCM. Therefore, the used simulation tool is reliable and has validity to be used to analyse the thermal performance of PCM-integrated buildings.

3. RESULTS and DISCUSSIONS

3.1. Effects of PCM Position, Thickness, and Melting Temperature on the Thermal Comfort of PCM-Integrated Buildings

The maximum amount of ITR depending on the climate region and PCM position, thickness, and melting temperature is shown in Fig. 4. The location of the PCM has a significant impact on the ITR. PCM(21) with thicknesses of 10, 20, and 30 mm (PCM(e)-10, PCM(e)-20, and PCM(e)-30) integrated into the outermost layer of the wall achieved 0.45, 0.42, and 0.25 ºC ITR in Antalya, respectively (Fig. 4(a)). When PCM(21) of the same thickness was integrated into the innermost layer (PCM(i)) of the wall, 0.62, 0.75, and 0.85 ºC ITRs were determined, respectively. In Istanbul, which has a moderate-humid climate, 10, 20, and 30 mm PCM(21) integrated into the outermost layer could only provide 0.19, 0.15, and 0.10 ºC ITR. PCM(21) placed in the innermost layer was more successful in reducing the interior temperature (0.51, 0.69, and 0.77 ºC). Similarly, PCM(21) located in the outermost layer provided ITRs of 0.43, 0.39, and 0.30 ºC in Ankara, 0.61, 0.55, and 0.48 ºC in Van, and 1.18, 1.15, and 1.09 ºC in Erzurum, respectively. PCM(21) integrated into the innermost layer provided more effective ITRs in Ankara (0.64, 0.94, and 1.15 ºC, respectively), Van (1.15, 1.40, and 1.61 ºC, respectively), and Erzurum (1.37, 1.66, and 1.86 ºC, respectively).

When PCM(27) was used instead of PCM(21), the effects of the PCM position on the ITR exhibited a similar changing trend (Fig. 4(b)). PCM(27) with a thickness of 10, 20, and 30 mm integrated into the outermost layer of the wall, achieved 0.52, 0.46, and 0.39 ºC ITR in Antalya. When PCM(27) of the same thickness was integrated into the innermost layer (PCM(i)) of the wall, 1.22, 1.35, and 1.45 ºC ITRs were determined, respectively. In Istanbul, the use of PCM(27) in the outermost layer brought about 0.49, 0.40, and 0.24 ºC ITR, and its use in the innermost layer brought about 1.01, 1.19, and 1.27 ºC ITR, respectively. Similarly, PCM(27) located in the outermost layer provided ITR values of 0.68, 0.60, and 0.55 ºC in Ankara, 1.23, 1.18, and 1.10 ºC in Van, and 1.29, 1.20, and 1.15 ºC in Erzurum, respectively. PCM(27) integrated into the innermost layer provided more effective ITR values in Ankara (1.44, 1.74, and 1.95 ºC, respectively), Van (1.81, 2.08, and 2.27 ºC, respectively), and Erzurum (2.07, 2.36, and 2.56 ºC, respectively). From these findings, it can be concluded that PCM integrated in the outermost layer was less effective in providing effective ITR than PCM integrated in the innermost layer. Because, in summer, the outer surface temperature of the building envelope is higher than the inner surface temperature, the PCM integrated into the outermost layer cannot fully realize the phase transition consisting of melting and re-solidification. Thus, it cannot function sufficiently as an energy store (Qu et al., 2021). The PCM integrated into the innermost layer could provide more ITR at melting temperatures of 21 ºC and 27 ºC during the hours when daytime temperatures reached their maximum in all climate regions. In other words, when the surface temperature of the vertical elements in the building envelope increases owing to the increase in solar radiation intensity during the daytime (Salihi, 2022), the PCM absorbs and stores this heat energy, thus preventing further heating of the interior environment. When the outside air temperature decreases at night, the PCM solidifies by returning the energy stored. Cold ambient air was stored in PCM at night.

The stored cool energy was discharged to the building during the day, providing free cooling for a period of time without the need for a mechanical system (Chan, 2011). Jin et al. (Jin et al., 2014), Kalbasi and Afrand (Kalbasi and Afrand, 2022), Arumugam and Ramalingam (Arumugam and Ramalingam, 2024), Zhang et al. (Zhang et al., 2024), and Lagou et al. (Lagou et al., 2019) determined that the optimum PCM location for summer was the innermost layer of the wall, which provided the most convenient comfort conditions. The findings of this research are important for their compatibility with the literature.

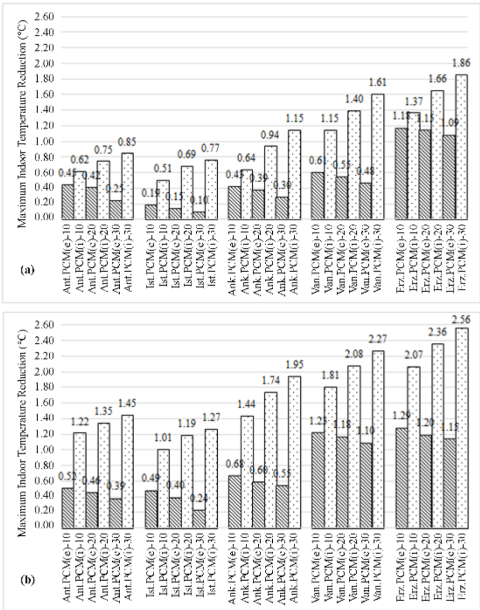

Figure 4:
Maximum ITR depending on the climate region and the position, thickness, and melting temperature of PCM: (a) PCM-21 ºC; (b) PCM-27 ºC

The thickness of the PCM is another parameter that affects ITR. Increasing the PCM thickness from 10 mm to 20 and 30 mm in the outermost layer reduced the effectiveness of ITR. When PCM was integrated into the innermost layer, ITR gradually increased in all climatic regions by increasing the PCM thickness from 10 mm to 20 and 30 mm, respectively, regardless of the PCM melting temperature. The optimum PCM thickness was 30 mm, which increased the thermal comfort of the interior by providing the maximum ITR and thus reducing the need for mechanical cooling. There are reports in the literature in which the optimum PCM thicknesses were determined as 30 mm (Chan, 2011) and 40 mm (Meng et al., 2013). Depending on the climatic conditions, the function of the building, the properties of the building envelope, the type, thickness, and melting temperature of PCM, the lowest ITR of less than 1 ºC (Soares et al., 2017; Heim and Clarke, 2004) and the highest of 5 ºC (Qu et al., 2021) were determined during the summer period. In another study, 0.02-2.41 ºC ITR was determined using 10 mm PCM, and 1.76-5 ºC ITR was determined using 70 mm PCM (Qu et al., 2021). In this study, 30 mm PCM(i), which showed the highest efficiency, provided an ITR of 1.27-2.56 ºC, which was compatible with the literature data. A higher ITR rate can be achieved with the use of thicker PCMs. However, the cost increases resulting from increasing the PCM thickness should be taken into consideration, and thickness-thermal performance-cost optimization should be performed.

When Figs. 4(a) and 4(b) were compared, it was concluded that PCM(27), which integrated both inner and outer layers, had a higher rate of ITR than PCM(21) in all climatic regions. Because the air temperature was relatively high at night during the summer, the solidification temperature of PCM must also be high. As night temperatures dropped below 27 ºC in all climatic regions, PCM(27) completed the phase transformation. On the other hand, in cities such as Antalya and Istanbul, where the night temperature did not drop to 21 ºC, PCM(21) could not complete the phase transformation and remained in the liquid phase. However, the low ITR detected as a result of PCM(21) integration in Antalya and Istanbul was due to the lower thermal conductivity coefficient of the PCM in the liquid phase (0.15 W/mK) compared to the solid phase (0.20 W/mK), resulting in higher thermal resistance (Lei and Yang, 2016). Because night temperatures decreased to 19.8, 14.3, and 13.1 ºC in Ankara, Van, and Erzurum, respectively, PCM(21) and PCM(27) completed the phase transformation. Similar to this finding, Lei et al. (Lei and Yang, 2016) determined that melting temperatures below 23 ºC were not effective in completing the PCM phase transformation for the tropical Singapore climate. In another study, it was determined that a melting temperature of 24-28 ºC during the summer period was more efficient for providing effective ITR (Saffari et al., 2017). However, the influence of climate characteristics and geographical location should always be taken into account. For example, the optimum melting temperature of PCM in summer in Seville (Spain) was 26 ºC (Saffari et al., 2017), whereas that in Adelaide (Australia) was 25 ºC (Alam et al., 2014). The optimum melting temperatures of PCM for the cooling period in Diyarbakır, Konya, and Erzurum in Türkiye were 24-26 ºC, 24-25 ºC, and 27-32 ºC, respectively (Arıcı et al., 2020), while for Izmir it was 23 ºC (İlgar and Terhan, 2024).

The effectiveness of PCM on ITR varies depending on the climatic region in which the building is located. PCM(21) and PCM(27), integrated into the innermost region, provided the highest ITR in Erzurum, the coldest city in the region. The lowest ITR was detected in Istanbul, which has a moderately humid climate. The reason for this may be the difference in temperature between day and night in cities with different climate characteristics. The city with the highest temperature difference (17.05 ºC) was Erzurum. This was followed by Van (14.68 ºC), Ankara (14.41 ºC), and Antalya (10.49 ºC) (Fig. 3). In Istanbul, where the temperature difference was the least (7.45 ºC), the effectiveness of PCM was less than that in other cities.

3.2. Effects of PCM Position, Thickness, and Melting Temperature on the Energy Saving of PCM-Integrated Buildings

Fig. 5 shows the monthly cooling energy consumption of the reference and PCM-integrated buildings. The cooling energy consumption of Antalya, with the highest average air temperature, was the highest among cities (Fig. 5(a)).

While the total cooling load of the reference building in Istanbul was 58.62 kWh, PCM(e) and PCM(i) integration reduced this load to 55.81 and 48.99 kWh, respectively (Fig. 5(b)). The months with the highest cooling loads were July, August, June, and September. In Ankara, which has a moderate-dry climate, the cooling period started in mid-May and ended at the end of September. The annual cooling energy consumptions of the reference, PCM(e) and PCM(i) integrated buildings were 39.10, 37.5, and 30.77 kWh, respectively. The annual cooling energy consumption of the reference, PCM(e), and PCM(i) integrated buildings in Van, which has a hot-dry climate, were 110.45, 107.11, and 92.63 kWh, respectively. In Erzurum, the representative city of the cold climate region, 111.63, 110.20, and 92.56 kWh cooling loads were determined for reference and PCM(e) and PCM(i) integrated buildings, respectively.

The average air temperature in Istanbul and Ankara was higher than those in Van and Erzurum, as shown in Fig. 3. However, the total cooling loads determined in Van and Erzurum were higher than those in Istanbul and Ankara, which revealed that average air temperature is not the sole parameter related to cooling energy consumption. Generally, global solar radiation increases with altitude above sea level (Saffari et al., 2017). The altitudes of Van and Erzurum are 1726 and 1890 m, respectively, and the altitudes of Ankara and Istanbul are 938 and 40 m, respectively (Table 4).

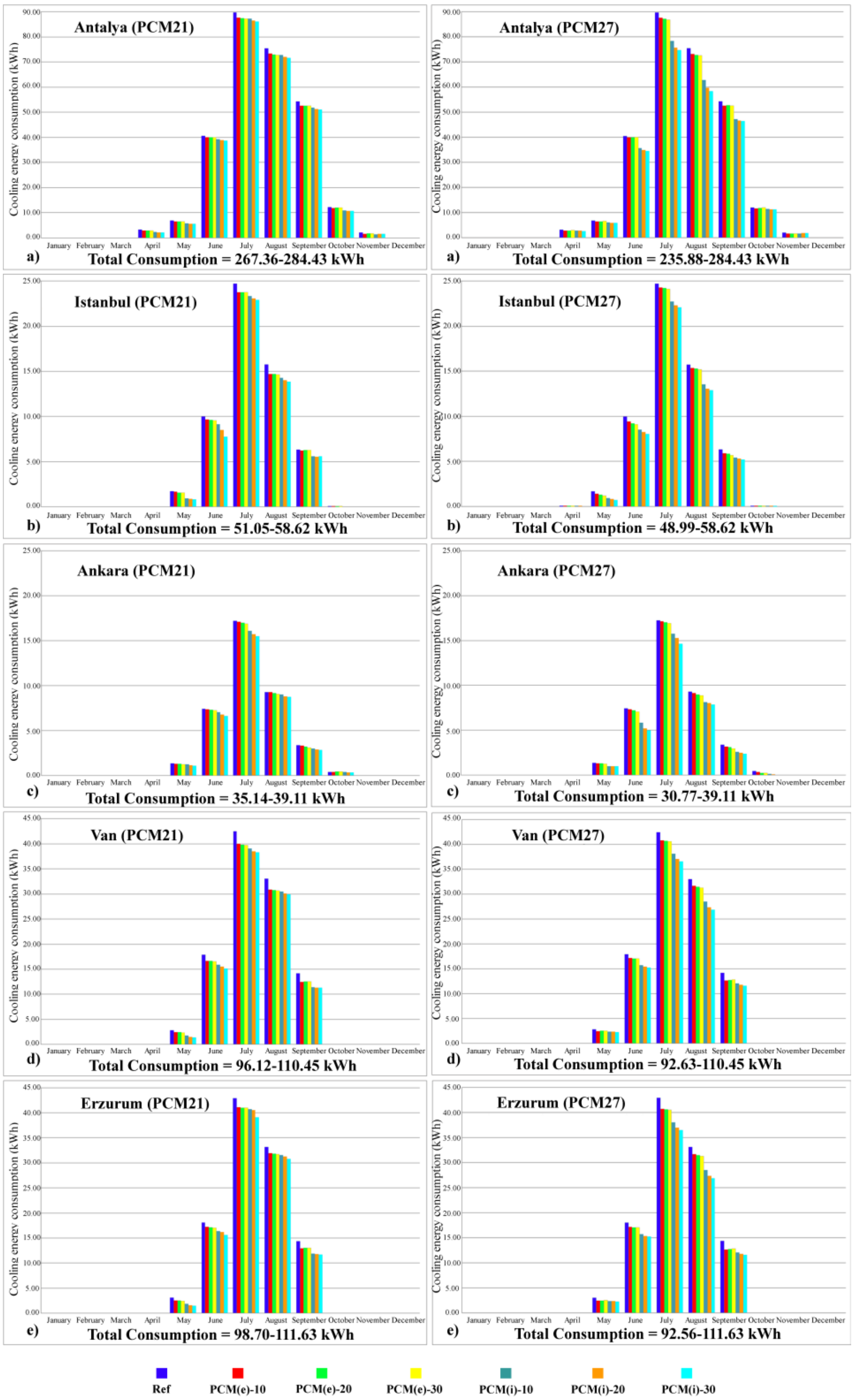

Figure 5:
Monthly cooling energy consumptions of the reference and PCM-integrated buildings: (a) Antalya; (b) Istanbul; (c) Ankara; (d) Van; (e) Erzurum

In Van and Erzurum, the higher solar radiation intensity resulting from high altitudes increased the heat gain of the building envelope at noon, resulting in more energy being consumed for cooling. This finding can be confirmed from Table 4, which lists the solar radiation intensities of the cities. Since the solar radiation intensities of Van and Erzurum (1493 and 1511 KWh/m^2, respectively) are higher than those of Istanbul (1389 KWh/m^2) and Ankara (1306 KWh/m^2), the total cooling energy consumption of the building may be higher.

The conclusion to be drawn here is that when designing passive buildings using PCM technology, not only should climate classification be adhered to, but also other geographical factors, such as altitude above sea level and solar radiation intensity, should be taken into account.

Fig. 6 shows the cooling energy saving ratios based on the climate region, position, thickness, and melting temperature of PCM.

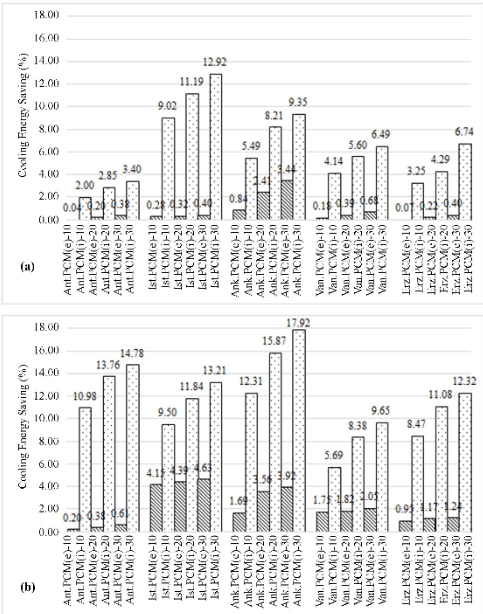

Figure 6:

Cooling energy-saving ratios depending on the climate region, position, thickness, and melting temperature of PCM: (a) PCM-21 ºC; (b) PCM-27 ºC

PCM(e) could not provide high cooling energy efficiency. Regardless of the melting temperature of PCM, PCM(i) exhibited higher energy-saving efficiency than PCM(e) in all climatic regions. As the PCM position shifted from the inner to outer layers, the indoor temperature of the buildings increased. Increasing the PCM thickness from 10 mm to 20 and 30 mm increased the cooling energy-saving ratios in all climatic regions. The highest energy-saving ratios were achieved with the use of 30 mm PCM(27), especially in the innermost layer, and the values were as follows: Antalya 14.78%; Istanbul 13.21%; Ankara 17.92%; Van 9.65%; and Erzurum 12.32%. The lowest energy-saving ratio reported in the literature was 1%, whereas the highest was 90% (Zhu et al., 2018). It was determined that the use of 30 mm PCM in Beijing (China) provided energy savings of up to 17% (Chen et al., 2008). The lowest cooling energy was provided by a 30 mm PCM in five different cities where the Mediterranean climate prevails: Ankara (Türkiye), Athens (Greece), Naples (Italy), Marseille (France), and Seville (Spain) (Ascione et al., 2014). In another study (Silva et al., 2012), it was found that a 25-mm PCM provided more effective ITR and a higher cooling energy-saving compared to a 19-mm PCM. The cooling energy-saving ratios obtained with the optimum 30 mm PCM in this study are compatible with the results of previous studies.

In all climatic regions, PCM(27) provided higher cooling energy-savings than PCM(21). This was because PCM(27) provided maximum ITR and thus less need for the HVAC system. The optimum PCM melting temperature, determined as 29 ºC in two European cities (Chambéry (France, temperate climate) and Catania (Italy, hot Mediterranean climate)), provided cooling energy-savings of 2.5-7.2% (Evola et al., 2013). The optimum PCM melting temperature for the tropical Singapore climate was determined to be 28 ºC, which provided cooling energy-savings of 11-32% (Lei and Yang, 2016). The cooling energy-saving ratios (5.69%-17.92%) obtained in this research by using the PCM(27) for the summer period under various climatic conditions in Türkiye, are compatible with the literature findings.

3.3. Effects of Position, Thickness, and Melting Temperature of PCM and TI on the Thermal Comfort of PCM- and TI-Integrated Buildings

Fig. 7 shows the maximum ITR depending on the position and thickness of the PCM and TI and the melting temperature of the PCM.

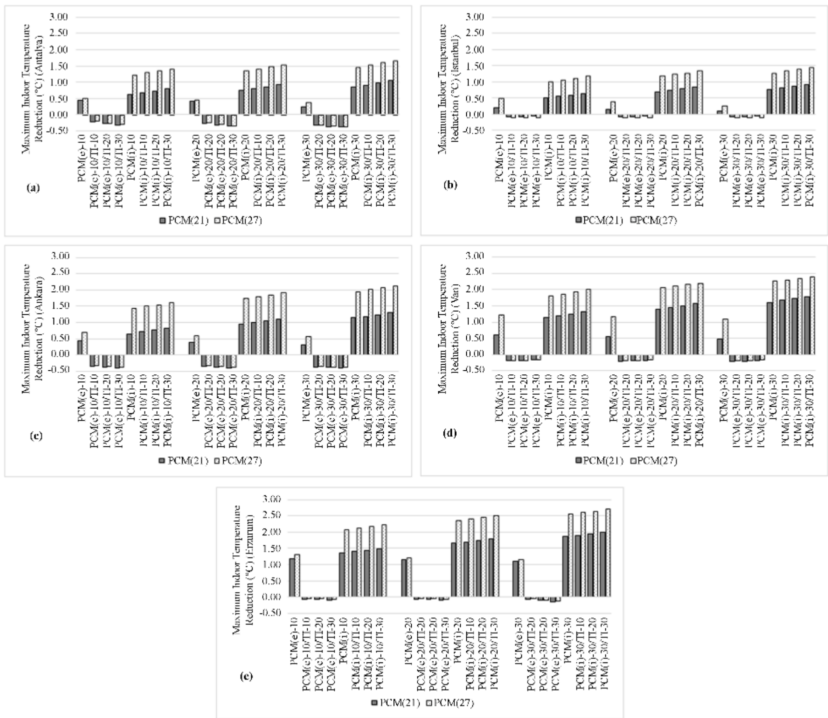

Figure 7:

Maximum ITR depending on the positions and thicknesses of PCM and TI and the melting temperature of PCM: (a) Antalya; (b) Istanbul; (c) Ankara; (d) Van; (e) Erzurum

As explained in Section 3.1, the effect of integrating the PCM in the outermost layer of the wall on ITR was negligible. When PCM and TI were placed in the outermost layers and TI was located in front of PCM (PCM(e)/TI, Fig. 2e), the indoor temperature of the building was determined to be higher than that of the reference building in all climatic regions. This means that the TI located in front of the PCM negatively affected the thermal performance of the building envelope. The reason for this finding might be that TI, which has a very low thermal conductivity coefficient (0.04 W/mK), prevented warmer outdoor air from passing through the building envelope and thus delayed the reaching of warmer air necessary for PCM phase transformation. A similar finding was reported by Al-Yasiri and Szabo (Al-Yasiri and Szabo, 2023). However, in this wall section, the effects of the PCM and TI thickness and PCM melting temperature on the ITR were negligible.

In all climatic regions, buildings with integrated PCM on the innermost layer and TI on the outermost layer (PCM(i)/TI, Fig. 2d) tended to reduce indoor temperatures more than both the reference and only PCM-integrated buildings. When the thickness of the TI was kept constant, increasing the thickness of the PCM provided a more effective ITR, similar to the performance achieved in buildings with PCM integration only. On the other hand, when the thickness of

PCM(21) was kept constant at 30 mm, integration of 10 mm TI (PCM(i)-30/TI-10) provided 1.90 ºC TIR compared to the reference building in Erzurum. When the thickness of TI was increased to 20 and 30 mm (PCM(i)-30/TI-20 and PCM(i)-30/TI-30), respectively, 1.94 and 2.00 ºC TIR spectra were detected. Using PCM(27) with thicknesses of 10, 20, and 30 mm instead of PCM(21) ensured a more effective TIR (2.60, 2.70, and 2.80 ºC, respectively) in Erzurum. This finding is also valid for other climatic regions. TIR showed the highest efficiency in Erzurum, followed by Van, Ankara, Antalya, and Istanbul. The further reduction in the indoor temperature by increasing the PCM and TI thicknesses is explained by Fourier's law. According to Fourier's law, increasing the thickness of any material in the building envelope can further reduce the indoor temperature because it reduces the rate of heat transmission from one environment to another and increases the thermal resistance of the building envelope (Garrido et al., 2001).

3.4. Effects of Position, Thickness, and Melting Temperature of PCM and TI on the Energy-Saving of PCM- and TI-Integrated Buildings

Fig. 8 shows the cooling energy-saving ratios depending on the climate region, position, and thickness of PCM, TI, and the melting temperature of PCM.

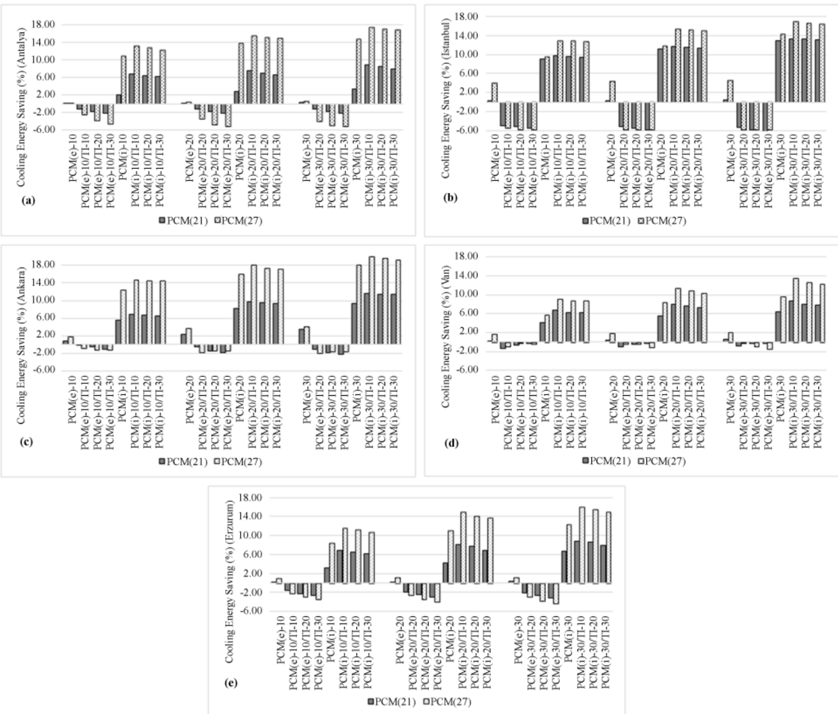

Figure 8:
Cooling energy-saving ratios depending on the climate region, position and thickness of the PCM and TI, and melting temperature of the PCM: (a) Antalya; (b) Istanbul; (c) Ankara; (d) Van; (e) Erzurum

It was determined that the integration of only PCM (PCM(e)-10, PCM(e)-20, and PCM(e)-30) in the outermost layer provided cooling energy-savings of 0.20-0.61% in Antalya, 0.28-4.63% in Istanbul, 0.84-3.92% in Ankara, 0.18-2.05% in Van, and 0.22-1.24% in Erzurum. When the PCM and TI were placed in the outermost layers (TI was located in front of PCM, Fig. 2e), the cooling energy-saving ratios shifted in the negative direction.

In all climatic regions, buildings with integrated PCM on the innermost layer and TI on the outermost layer (PCM(i)/TI, Fig. 2d), provided a higher annual energy-saving ratio than both the reference buildings and the only PCM-integrated buildings. However, while the thickness of PCM was constant, increasing the thickness of TI gradually reduced the energy-saving ratio. For example, in Ankara, when the PCM(21) thickness was kept constant at 30 mm, 10 mm TI (PCM(i)-30/TI-10) ensured 11.67% annual energy-savings. When the thickness of the TI was increased to 20 and 30 mm, the ratio decreased to 11.51 and 11.39%, respectively. In addition, when PCM(27) was used instead of PCM(21), PCM(i)-30/TI-10 achieved a 19.95% energy-saving ratio, which decreased to 19.60 and 19.23% as the thickness of the TI increased to 20 and 30 mm, respectively. The results obtained in this study are also valid for other climatic regions. In this case, the HVAC system worked harder to cool the indoor environment, and the energy-saving resulting from the use of PCM+TI decreased as the thickness of the TI increased. Integrating TI into the innermost layer of the wall can eliminate this disadvantage. Al-Yasiri and Szabo (Al-Yasiri and Szabo, 2023) determined that the use of a thick TI in the innermost layer resulted in higher energy savings during the summer. Considering that using TI in the innermost layer may cause more serious damage to the building materials, such as condensation, especially in the winter months, TI was used only in the outermost layer.

In line with the findings obtained above, buildings designed with 30 mm PCM(27) in the innermost layer and 10 mm TI in the outermost layer achieved an optimal wall layering that resulted in energy-savings of 17.47% in Antalya, 16.85% in Istanbul, 19.95% in Ankara, 13.54% in Van, and 15.98% in Erzurum. Since these values were higher than those for all wall sections containing only PCM, it was determined that the combined use of PCM in the innermost layer and TI in the outermost layer was advantageous in terms of annual cooling energy-saving. However, in geographies such as Türkiye, where different climatic characteristics coexist, the performance of the PCM and TI integrated wall sections should be evaluated in both summer and winter. Furthermore, because the layering of the building envelope cannot be changed during the climatic transition seasons, the performance of the optimum building envelope should be evaluated in both the summer and winter periods, as well as during the climatic transition periods.

4. CONCLUSION

The conclusions drawn from the findings of this study are as follows:

- The ITR and annual cooling energy demand of the building were significantly affected by the location and thickness of the PCM and TI, as well as the melting temperature of the PCM used in the exterior wall of the building envelope.
- The combined use of PCM and TI in the building envelope could effectively provide ITR, save energy, and increase the thermal comfort of the occupants. The exterior wall type with PCM in the innermost layer and TI in the outermost layer was the most effective configuration for reducing temperature fluctuations and cooling energy demand.
- Although a larger the thickness of the PCM (30 mm) improves the effect of temperature control and the energy-saving effect, increasing the thickness of the TI led to an increase in energy consumption. A thicker TI delayed the accumulated heat transfer from the indoor environment to the outdoor environment; consequently, the mechanical cooling requirement increased.
- The optimum melting temperature of the PCM was determined to be 27 °C, ensuring a higher ITR and less energy consumption during the summer period.
- The effectiveness of PCM on ITR varied depending on the climatic regions of Türkiye. The highest ITR was achieved in Erzurum, where the temperature difference between day and night was higher than that in other cities. The higher temperature difference during the day made it easier for the PCM to complete the melting and re-solidification phase cycles.
- Both climate classification and other geographical factors, such as altitude above sea level and solar radiation intensity, should be considered when designing buildings with the combined use of PCM and TI. Although the average air temperatures in Van and Erzurum

were lower than those in Istanbul and Ankara, the higher altitudes of Van and Erzurum led to increased solar radiation intensity. This increased the heat gain of the building envelope at noon and caused more energy to be consumed for cooling.

- Although different climatic regions in Türkiye have various energy-saving effects, the combined use of PCM with 30 mm and TI with 10 mm in the building envelope can achieve considerable energy-saving ratios between 9.12 and 19.95% as long as they are properly selected according to local climatic conditions and other geographical factors.
- Since the layering of the building envelope cannot be changed according to the seasons, the performance of the optimum building envelope should be evaluated during both the summer and winter periods as well as during climatic transition periods.
- The construction cost increases resulting from increasing the thickness of the PCM and TI layers should also be taken into consideration, with a detailed analysis of the thickness, thermal performance, and cost optimization undertaken in future work.

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CONFLICT OF INTEREST

The authors confirm that there are no known conflicts of interest or shared interests with any organization, institution, or individual.

AUTHOR CONTRIBUTIONS

"Doğukan Kadir Yemenici conceptual and/or design process identification, management of conceptual and/or design processes of the study, data collection, data analysis and interpretation, drafting of the article, critical review of intellectual content and final approval and full responsibility, Kübra Ekiz Barış conceptual and/or design process identification, management of conceptual and/or design processes of the study, data collection, data analysis and interpretation, drafting of the article, critical review of intellectual content and final approval and full responsibility"

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