versa, depending on the ambient temperature. While the use of a storage device solves the problem of PCM leakage during phase transitions, it leads to an increase in not only the thermal resistance but also the cost of the system. A solution to these problems is the use of shape-stabilized PCMs (SSPCMs), which are composed of PCMs and supporting material. The supporting material must be chosen appropriately for the type of PCM used. For example, if a paraffin-based PCM is used, the supporting material should have a similar skeleton, such as high-density polyethylene (HDPE), polypropylene (PP), or styrene–butadiene–styrene (SBS). If the ambient air temperature is below the melting point of the supporting material, the SSPCM can maintain its shape even when the paraffin changes phase. (Seong and Lim 2013) In this paper, two types of paraffin-based materials, hexadecane and octadecane, and various ratios of SSPCMs to concrete were selected.

PHYSICAL PROPERTIES OF PCMS AND SSPCM CONCRETES

Two types of paraffin-based materials, hexadecane and octadecane, were selected to serve as the PCM that is contained in the supporting material. The octadecane exfoliated graphite nanoplate (xGnP) shape-stabilized PCM (SSPCM) was prepared by impregnating octadecane as the PCM into xGnP in a vucumn. Fourier transfer infrared spectroscopy determined that the heat storage characteristics of octadecane could integrate into the structure of xGnP due to its physical bonding, without a change in its chemical properties (Kim et al. 2014).

The melting temperature and heat capacity of each PCM and SSPCM were measured using a DSC (Differential Scanning Calorimeter) instrument (DSC Q 1000, TA instrument, USA). DSC measurements were performed with a 5℃/min heating rate in the temperature range of 0-80℃. The melting temperature was measured by drawing a line at the point of the maximum slope on the leading edge of the peak and extrapolating to the base line. The total latent heat of the PCM was determined by numerical integration of the area under the peaks that represent the solid-solid and solid-liquid phase transition.

The thermal conductivity was measured using a TCi thermal conductivity analyzer. The TCi, developed by C-Therm Technologies Ltd., is a device used for conveniently measuring the thermal conductivity of a small sample using the Modified Transient Plane Source (MTPS) method. In contrast to other devices, the TCi can measure the thermal conductivity of materials in solid, liquid, powder, and mixed states. The TCi consists of a sensor, a power control device, and computer software. A spiral-type heating source is located at the center of the sensor, and heat is generated at the center. The generated heat enters the material through the sensor, at which point a rapid voltage decrease occurs at the heating source; the thermal conductivity is calculated using the data obtained during the voltage decrease.

Table 1 shows the overall properties of hexadecane and octadecane PCMs and SSPCM-to-concrete ratios of 10, 20, and 30%, which were measured as described above (Kim et al. 2014).

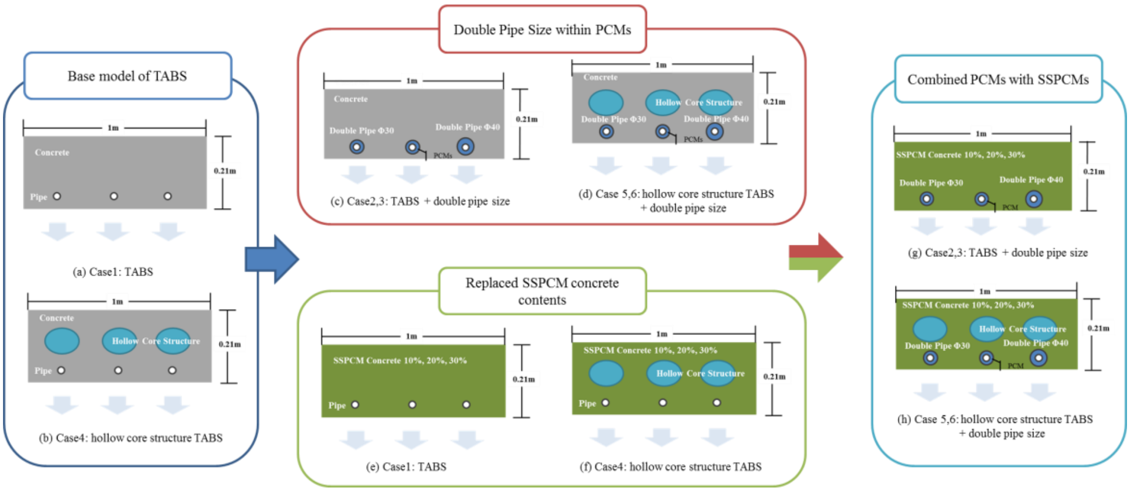
Table 1. *Physical properties of PCMs and various SSPCM to concrete ratios*

	Hexadecane (PCM)	Octadecane (PCM)	Concrete with 10 wt% of SSPCM	Concrete with 20 wt% of SSPCM	Concrete with 30 wt% of SSPCM
Melting Point (℃)	20	29	-	-	-
Conductivity (W/m K)	0.39	0.26	1.97	1.69	1.60
Density (kg/m3)	777	777	2210	2050	2000

SIMULATION METHODS

To determine the thermal capacity of a TABS, data concerning the thermal output and storage effect of the TABS according to the supply water temperature and supply water flow rate are needed. In the simulated cases, the supply water flow rate is constant, and the thermal output of the TABS is controlled by the supply water temperature.

We consider a prototype of a TABS and a hollow-core TABS applied using PCMs. TABSs and hollow core TABSs are commonly applied after the analysis of structure and construction. Various parameters concerning PCMs and SSPCM-to-concrete ratios of the TABS prototype are described below. A double pipe within the PCMs, which are composed of octadecane and hexadecane, is a macro encapsulation type. Varying the SSPCM-to-concrete ratio is used to overcome the PCM problems. Combining a double pipe within the PCMs with various SSPCM-to-concrete ratios is a more effective design method for solving thermal storage issues (Figure 1).



(a) Case1: TABS
(b) Case4: hollow core structure TABS
(c) Case2,3: TABS + double pipe size
(d) Case 5,6: hollow core structure TABS + double pipe size
(e) Case1: TABS
(f) Case4: hollow core structure TABS
(g) Case2,3: TABS + double pipe size
(h) Case 5,6: hollow core structure TABS + double pipe size

Figure 1. *Various parameters of TABSs applied using PCMs and SSPCMs*

For this purpose, the simulation program BISTRA ver. 3.1, which is a thermal analysis program for transient heat transfer in two-dimensional free-form objects, was used to evaluate the thermal output and thermal storage of various TABS designs using different PCMs and varying SSPCM-to-concrete ratios (Table 2).

The models consist of 1 x 0.21 m (height) concrete slabs and hollow-core slabs, which are a double pipe form using various PCMs and various SSPCM-to-concrete ratios. The top and bottom of the slab are assumed to be indoor environments; the indoor temperatures are assumed to be 20℃ in winter and 26℃ in summer. The value on the top and bottom surface of the slab is 11.63 W/m^2K for heating and cooling, which is based on the domestic standard (Building Energy Saving Criteria). With these assumptions, heat transfer coefficient values for constant water flow through pipes were simulated for 8 hours. After 8 hours of the water flow schedule, the thermal storage effect durations were analyzed. The simulation material input data were based on the domestic standard and on the ASHRAE Handbook Fundamentals 2009. The operating simulation schedule and thermal storage durations are provided in Figure 2.

Table 2. *TABS components and materials in BISTRA simulation*

	Conductivity (W/mK)		Density (kg/m^3)		Specific heat (J/kgK)	
Concrete	1.7		2300.0		930.0	
PE-X Pipe	0.41		1200.0		1470.0	
Hollow core structure	0.043		15.0		1300.0	
	Temperature (℃)		Heat transfer coefficients in pipe (W/m^2K)		Operating Schedule	
	Cooling	Heating	Cooling	Heating	Total simulation durations	Cooling and Heating durations
Water flow	20	30	801.8	894.3	24 hours	8 hours

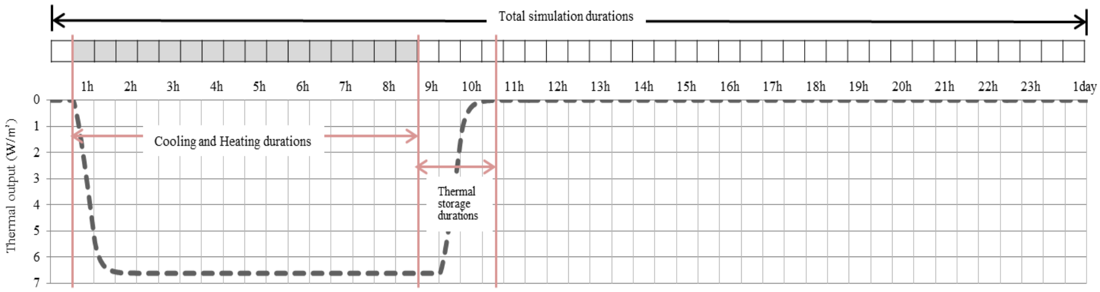


Figure 2. *Descriptions of simulation operating schedule and thermal storage durations*

SIMULATION RESULTS

Various parameters of TABSs and hollow core structural TABSs were simulated. We discuss each parameter of the simulation results below.

1. Size of double pipe: All Φ40 mm double pipes had slightly longer thermal storage durations compared to the Φ30 mm double pipes. The Φ30 mm double pipes in the PCM models were more effective than the Φ40 mm double pipes. (The difference is shown in Figure 3 (a) and Figure 3 (b).)
2. Double pipe in PCMs: All double pipes in the octadecane PCM had longer thermal

storage durations compared to all double pipes in the hexadecane PCM because the concrete slab temperature around the double pipe met the temperature-specific heat curve of octadecane. (The difference is shown in Figure 3 (c) and Figure 3 (d),)

3. Various SSPCM-to-concrete ratios: Models including concrete replaced with 30 wt% SSPCMs had longer thermal storage durations compared to those using 10 and 20 wt% SSPCMs.

4. Combined PCMs with SSPCMs: Models including a combination of hexadecane PCM with 30 wt% SSPCM concrete exhibited higher thermal output compared to those combining octadecane PCM with various SSPCM-to-concrete ratios. (The difference is shown in Figure 3 (e) and Figure 3 (f).)

Table 3. *Simulation results of various TABS models*

	Without PCM	PCM		SSPCM Concrete contents			Code Name	Cooling 20℃/8hours			Heating 30℃/8hours		
		Octa -decane	Hexa -decane	10%	20%	30%		Thermal Storage Duration (min)	Thermal output (W/㎡)	Minimum Tempera-ture(℃)	Thermal Storage Duration (min)	Thermal output (W/㎡)	Minimum Tempera-ture(℃)
Case1: TABS	√						c1_w	71	6.7	21.29	77	11.2	27.85
				√			c1_sp10	61	6.8	21.22	63	11.4	27.97
					√		c1_sp20	63	6.7	21.29	66	11.2	27.85
						√	c1_sp30	65	6.7	21.32	68	11.1	27.8
Case2: TABS+double pipe Φ30		√					c2_octa	69	6.0	21.84	75	9.9	26.94
			√				c2_hexa	68	6.2	21.67	74	10.4	27.22
		√		√			c2_octa_sp10	64	6.0	21.79	66	10.0	27.01
		√			√		c2_octa_sp20	67	6.0	21.84	69	9.9	26.94
		√				√	c2_octa_sp30	69	5.9	21.86	71	9.9	26.91
			√	√			c2_hexa_sp10	63	6.3	21.62	66	10.5	27.3
			√		√		c2_hexa_sp20	66	6.2	21.67	68	10.3	27.21
			√			√	c2_hexa_sp30	68	6.2	21.69	71	10.3	27.18
Case3: TABS+double pipe Φ40		√					c3_octa	71	5.5	22.19	77	9.1	26.36
			√				c3_hexa	70	5.9	21.91	77	9.8	26.81
		√		√			c3_octa_sp10	65	5.5	22.15	67	9.2	26.41
		√			√		c3_octa_sp20	68	5.5	22.19	70	9.1	26.35
		√				√	c3_octa_sp30	71	5.5	22.2	72	9.1	26.33
			√	√			c3_hexa_sp10	65	5.9	21.87	69	9.9	26.88
			√		√		c3_hexa_sp20	68	5.9	21.91	71	9.8	26.81
			√			√	c3_hexa_sp30	70	5.9	21.93	73	9.8	26.79
Case4: Hollow core structure TABS	√						c4_w	64	6.3	21.65	70	10.5	27.25
				√			c4_sp10	61	6.4	21.56	63	10.7	27.4
					√		c4_sp20	62	6.3	21.65	65	10.5	27.25
						√	c4_sp30	64	6.3	21.68	67	10.4	27.19
Case5: Hollow core structure TABS+double pipe Φ30		√					c5_octa	66	5.8	22.03	71	9.6	26.62
			√				c5_hexa	65	6.0	21.88	71	10.0	26.87
		√		√			c5_octa_sp10	62	5.9	21.97	64	9.8	26.72
		√			√		c5_octa_sp20	64	5.8	22.03	65	9.6	26.62
		√				√	c5_octa_sp30	66	5.8	22.05	67	9.6	26.59
			√	√			c5_hexa_sp10	62	6.1	21.82	64	10.1	26.97
			√		√		c5_hexa_sp20	64	6.0	21.88	66	10.0	26.87
			√			√	c5_hexa_sp30	65	6.0	21.9	67	10.0	26.83
Case6: Hollow core structure TABS+double pipe Φ40		√					c6_octa	68	5.4	22.27	72	9.1	26.21
			√				c6_hexa	69	5.8	22.02	73	9.7	26.63
		√		√			c6_octa_sp10	63	5.5	22.23	65	9.1	26.28
		√			√		c6_octa_sp20	65	5.4	22.27	66	9.1	26.21
		√				√	c6_octa_sp30	67	5.4	22.29	68	9.0	26.19
			√	√			c6_hexa_sp10	63	5.9	21.98	66	9.8	26.7
			√		√		c6_hexa_sp20	65	5.8	22.02	68	9.7	26.63
			√			√	c6_hexa_sp30	67	5.8	22.04	69	9.6	26.6

5. Proper TABS and hollow core structural TABS guidelines: When the thermal output of TABSs for heating is determined, comfort issues should dictate the acceptable surface temperature of a ceiling. REHVA recommends that the maximum acceptable surface temperature during heating is 27℃. Additionally, when the thermal output of a TABS for cooling is determined, the risk of condensation is important to consider. The dew point temperature for indoor ceilings is lower than 19.5℃. The proper design guidelines, except for cooling condensation and uncomfortable heating

ceiling surface temperature conditions, are shown with a grey hatch in Table 3.

CONCLUSION AND IMPLICATIONS

This research developed design guidelines for and provided simulations using BISTRA (a thermal analysis program for transient heat transfer in two-dimensional free-form objects) of various TABSs using PCMs. Design guidelines for various TABSs using PCMs are shown for thermal output, thermal storage durations and ceiling surface temperatures in Table 3. The main conclusions are as follows:

It is necessary to consider physical design parameters, including the size of the double pipe and the thermal design parameters, which were analyzed using proper PCMs, various SSPCM-to-concrete ratios and PCMs combined with various SSPCM-to-concrete ratios. Using TABSs with PCMs and various SSPCM-to-concrete ratios, we consider the physical design parameters for the macro encapsulated type, thermal design parameters of proper temperature-specific heat curves, and the heat capacity of PCMs and SSPCM concrete.

Additionally, it is important to consider comfort issues, including indoor ceiling condensation with cooling and uncomfortable ceiling surface temperature with heating.

Subsequently, we analyzed the parameters of a water flow operating schedule and various water temperatures for cooling and heating. Then, we suggested design guidelines for TABSs with various PCMs and SSPCM-to-concrete ratios.

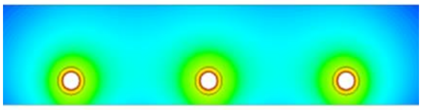
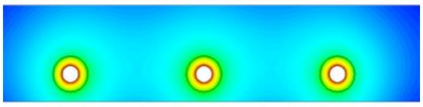
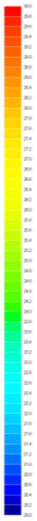
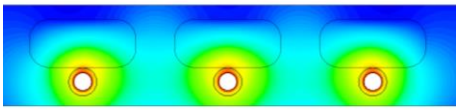
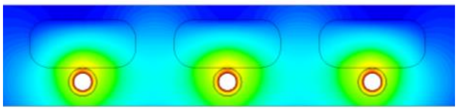
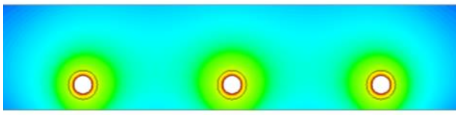
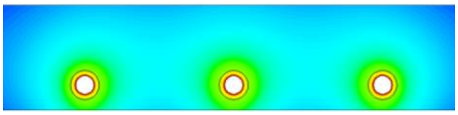
Size of double pipe (min 20℃, max 30℃)	 (a) after 9 hours in heating: c2_hexa	 (b) after 9 hours in heating: c3_hexa	
Double pipe in PCMs (min 20℃, max 30℃)	 (c) after 9 hours in heating: c5_hexa	 (d) after 9 hours in heating: c5_octa	
Combined PCMs with SSPCMs (min 20℃, max 30℃)	 (e) after 9 hours in heating: c2_hexa_sp30	 (f) after 9 hours in heating: c2_octa_sp30	

Figure 3. *Results of various parameters according to temperature difference*

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