Method for evaluating the heat-island mitigation effect of porous/water-retentive blocks using a climatic chamber

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ABSTRACT

This paper presents a method and mock-up design for evaluating the heat-island mitigation effect of porous/water-retentive blocks in a climatic environmental chamber using ambient temperature measurements. To create the proposed method, the heat circulation mechanism of blocks was considered. From this, we specified the climatic chamber design requirements, determined the required components and equipment for the mock-up, and developed the proposed method for evaluating heat-island mitigation performance based on ambient temperature. Using the proposed mock-up design and method, we confirmed that both surface and air temperatures were lower when porous/water-retentive blocks were installed compared to conventional blocks. This method can be used to analyze the difference between surface and ambient temperatures under various conditions to quantify the heat-island mitigation performance of different materials according to ambient temperature.

Key words | climatic chamber, heat-island mitigation, porous/water-retentive blocks

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INTRODUCTION

With the growing number of road and sidewalk networks, the impermeability of urban regions is increasing. Research has suggested that the impervious area of rapidly urbanizing areas in the world is expected to increase from 19.2% in 2010 to 38.2% in 2070 (Habete & Ferreira 2016). One consequence of increased urban impermeability is the urban heat-island effect (Mathew *et al.* 2016). According to the 'Korean Peninsula Climate Change Outlook Report' (KMA 2017), Seoul is expected to experience 39.8 heatwave days and 32.3 very hot and humid nights per year by the late 21st century based on Representative Concentration Pathway 6.0; this represents a 3.58-times increase in heatwave days and 3.93-times increase in very hot and humid nights compared with 2017.

Qin (2015) adapted a cool pavement strategy to battle the urban heat-island effect. As one strategy, reflective pavements could be considered for the areas experiencing a high intensity of solar radiation. In regions with abundant rainfall during the summer, evaporative pavements are suitable because they discharge the built-up heat as latent heat. Therefore, the uses of porous/water-retentive blocks, which exhibit water retentivity and permeability, can reduce the urban heat-island effect as well as drought and flooding. Greening is the most natural way to reduce heat-island phenomena, droughts, and floods; however, it is necessary to use porous/water-retentive blocks to achieve the above effects where these blocks need to function as a road. As such, the use of porous/water-retentive blocks for roads and sidewalks should be increased.

Several studies have evaluated the heat-island mitigation effect of blocks based on surface temperature measurements using thermo-graphic cameras or heat flows (Takebayashi & Moriyama 2007; Kimijima *et al.* 2009; Takebayashi & Masakazu 2009; Chui *et al.* 2018). However, it is difficult to achieve reliable results using such methods, because the urban heat-island effect should be determined by the air temperature. Therefore, the near-surface temperature rather than the surface temperature of blocks has been measured in recent studies (Qin 2015; Chui *et al.* 2018). For testing the heat-island mitigation effect of various blocks quantitatively, the weather conditions should be controlled,

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and large-scale testing should be conducted to measure the ambient/near-surface temperature (Japan Society for Testing Materials 2015; Ko et al. 2018; Wang et al. 2019). Previous studies have also been conducted with adjusted environmental conditions to quantify the cooling effect of the blocks. However, these studies also aimed to measure the surface temperature, and the unit undertaken for performance evaluations was small (such as one block).

In this study, we propose a method for evaluating the heat-island mitigation effect of porous/water-retentive blocks by taking ambient temperature measurements in a climatic environmental chamber. We tested this method through a heat-island mitigation evaluation of porous/water-retentive blocks compared to conventional blocks.

MATERIAL AND METHODS

The proposed method and mock-up design were developed based on the conceptual heat circulation mechanism (Figure 1). Heat flow around blocks is dictated by the retentivity and permeability of the blocks. Conventional blocks are impermeable; therefore runoff is greater than over porous/water-retentive blocks. As such, most net radiation should be transformed into sensible heat and conduction heat to the blocks, preventing heat from converting into latent heat. By contrast, porous/water-retentive blocks have high retentivity and permeability, reducing runoff compared to conventional blocks. As such, most net radiation can be converted into latent heat, which confers improved heat-island mitigation performance over conventional blocks.

The evaporation rate of blocks differs depending on the degree of retentivity and permeability, where higher evaporation rates absorb more heat from the atmosphere, resulting in a lower air temperature. Thus, the degree of evaporation from the block is highly correlated with the heat-island mitigation effect, necessitating the measurement of evaporation rate from blocks. The evaporation rate can be estimated by first releasing a defined amount of rain onto the mock-up blocks, and then subtracting the amounts of runoff, water retained in the block and soil, and water in the lower gutter from the total amount of rain released.

To perform this experiment, it was necessary to set up a climatic environmental chamber capable of producing artificial rain. In addition, a mock-up of a pavement, which was used to measure the amounts of runoff, water in the blocks and soil, and water in the lower gutter, needed to be constructed. Additional measurement equipment was required to measure the surface temperature of blocks and ambient temperature around the blocks. The detailed information of the climatic environmental chamber, the mock-up, and the evaluation method are described in the following sections.

Climatic environmental chamber

The climatic environmental chamber is located in the Center for Climatic Environment Real-scale Testing (CERT) in Jincheon, Korea (MoLIT 2018). This testing facility was constructed for the climatic testing of real, full-scale buildings, vehicles, clothing, mechanical devices, and their components to evaluate their efficiency. CERT has one large, two medium, and two small climatic chambers. The climatic chambers artificially generate and control temperature, humidity, rainfall, snowfall, and solar radiation for the evaluation of target samples. Therefore, the heat-island mitigation

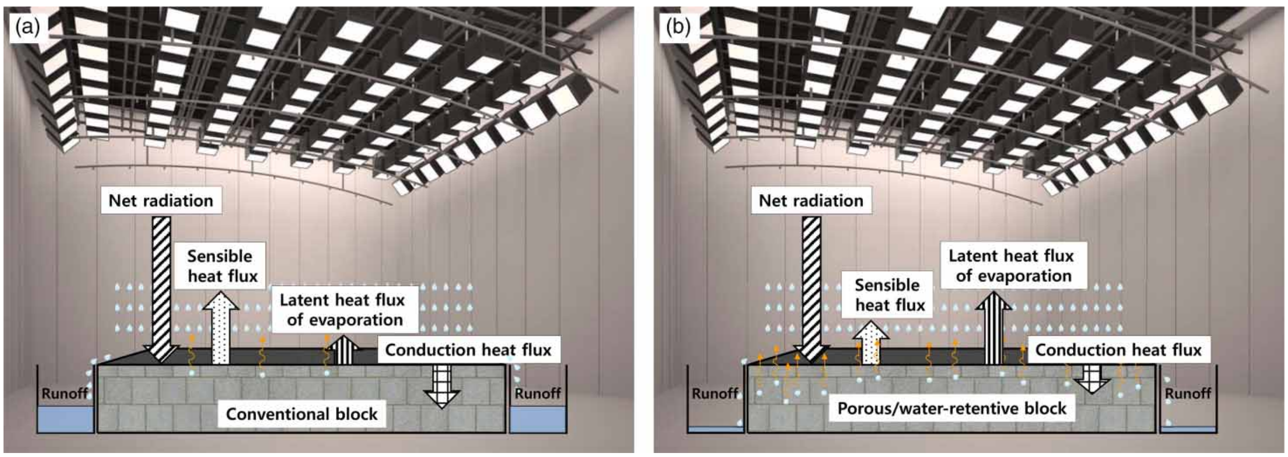


Figure 1 | Heat circulation mechanism of the (a) conventional and (b) porous/water-retentive blocks.

performances of the blocks were evaluated in a small climatic environmental chamber. Details of the small climatic environmental chambers are shown in Table 1.

Mock-up for evaluating the heat-island mitigation of blocks

For this study, because the width of a sidewalk on which the block can be installed is less than 2 m, the mock-up was constructed with the wider dimensions of 2.5 m × 2.5 m × 1.5 m. It comprised an upper gutter, upper drain, lower gutter, lower drain, load cell, and transparent window. In addition, the mock-up was constructed to allow for measurements of the amounts of runoff, water in the blocks and soil, and water in the lower gutter (Table 2). This equipment was installed in the climatic environmental chamber.

Heat-island mitigation evaluation method

We developed the method for evaluating the heat-island mitigation performance based on temperature, humidity, and enthalpy of the ambient air around the blocks, which change according to the solar radiation and wind speed after rainfall. First, conventional blocks were installed, and the time required for the ambient air temperature to reach 60 °C via solar radiation was measured. In fact, 60 °C is criterion for surface temperature in the Japan Society for Testing Materials (2015). Although the air temperature is not the same as the surface temperature, a standard/reference is lacking to determine the criterion of ambient air temperature. Therefore, the test was designed based on the ambient air temperature of 60 °C and observations regarding the surface temperature were made. Then, porous/water-retentive blocks were installed and the increase in temperature was measured for the same length of time (120 min). The heat-island mitigation performance was defined as the difference between the ambient air temperatures of the two cases (Figure 2). The values of temperature, humidity, and solar radiation were derived from the Seoul standard weather data set (KMA 2017). The amount of rain (50 mm/h) was determined by considering the average value of maximum precipitation per hour from 2011 to 2015 in Seoul (47.8 mm/h) (KMA homepage 2019). Table 3 presents an example describing the evaluation of the heat-island mitigation effect of blocks.

The mock-up, including blocks, was installed in a small chamber at the CERT (Figure 3). The bottom of the mock-up was covered with non-woven fabric to prevent loss off standard soil. Expanded polystyrene insulation was installed instead of rubble as at real sites, and 150 mm of dry standard soil was spread across the surface of the non-woven fabric. Three soil moisture sensors were installed at a depth of 10 cm below the soil surface. After installation of the blocks over the soil, three thermocouples were installed on the surface of the blocks to measure the surface temperature. In addition, load cells were installed on the four side walls of the mock-up to evaluate the evaporation amount

Table 1 | Specifications of the small climatic environmental chamber in CERT

Size (W × L × H)*	5 m × 5 m × 3.5 m
Temperature	−40 °C–80 °C
Relative humidity	10–90% R.H.
Rainfall	Max. 0–150 mm/h
Snowfall	Max. 0–50 mm/h
Solar radiation	800–1,200 W/m^2
Environmental control system	– Heating, ventilation, air conditioning (HVAC): heater (130 kW), chiller (94.3 kW), fan (350 m^3/min) – Humidification: 40 kg/h – Dehumidification: 1,000 m^3/h

*W, width; L, length; H, height.

Table 2 | Specifications of the mock-up

Size (W × L × H; m)*		2.5 × 2.5 × 1.5	
Section		**Function**	**Purpose**
Component	Upper gutter	Gathers runoff from blocks	Runoff measurement
	Upper drain	Drains runoff	
	Lower gutter	Carries infiltrated water to the lower gutter	Permeability measurement
	Lower drain	Drains infiltrating water	
	Load cell	Measures amount of evaporation	Evaporation measurement
	Transparent window	Allows observation of sections of the block and soil	Visual observation

*W, width; L, length; H, height.

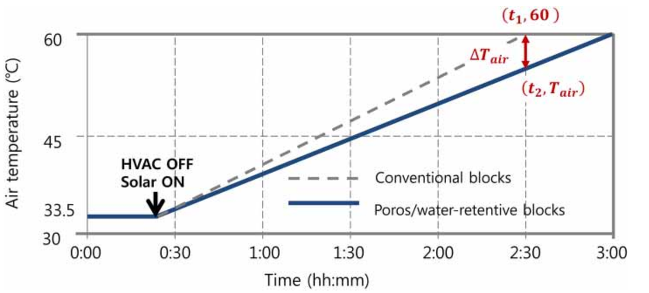


Figure 2 | Conceptual graph of the heat-island mitigation performance evaluation of two types of blocks.

by measuring the mass change of the mock-up during changes in solar radiation. The wind velocity satisfied the existing standard: 1 m/s at 20 cm above the surface of the block (Japan Society for Testing Materials 2015). Details of the sensors used are shown in Table 5.

Rainfall intensity and homogeneity were adjusted via nozzle adjustment, installation angle, and mass flow rate to meet the MIL-STD-810G 506.6 Procedure I (US Department of Defense 2014) and were evaluated with a laser disdrometer (Parsivel; OTT HydroMet) and five collection beakers. Solar radiation intensity and homogeneity were adjusted via lamp output and were evaluated with a pyranometer at five points to ensure that the output was 615 ± 20 W/m^2 (Figure 4).

RESULTS AND DISCUSSION

The heat-island mitigation performance of the porous/water-retentive blocks was tested according to the proposed method. When the conventional blocks were installed, the increase in ambient air temperature to 60.1 °C by solar radiation required 120 min. When porous/water-retentive blocks were installed, during the same period, the ambient air temperature increased to only 55.5 °C in 120 min; thus, the porous/water-retentive blocks showed an air temperature reduction performance of 4.6 °C 50 cm above the blocks (Figure 5). Furthermore, the ambient air temperature was lower and relative humidity higher when the porous/water-retentive blocks were installed, due to greater evaporation.

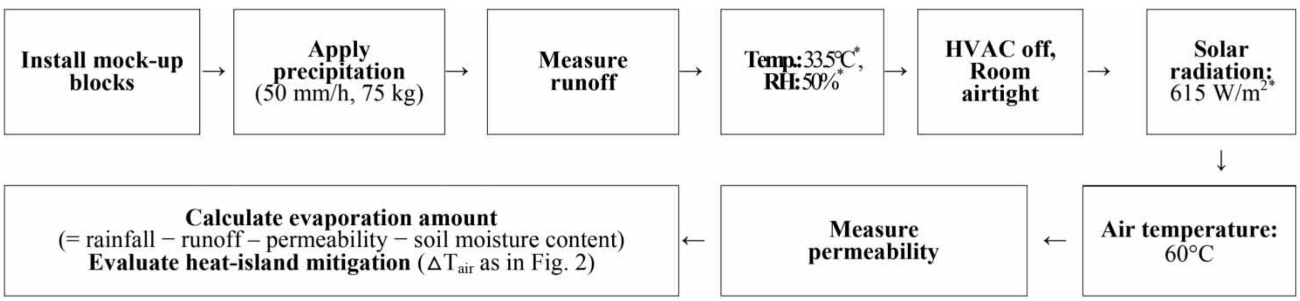
The surface temperature of the conventional blocks was 2.6 °C higher than that of the porous/water-retentive blocks. Moisture remained on the surface of the porous/water-retentive blocks after reaching 60 °C, allowing for additional evaporation. In addition, the greater degree of water retention could improve the heat capacity of the porous/water-retentive blocks. Therefore, the temperature change was lower under the same amount of solar radiation (Figure 6).

Ambient air temperature differed more between the two block types than surface temperature. Therefore, using surface temperature to evaluate the heat-island mitigation performance would result in an undervalued performance of the porous/water-retentive blocks compared to their actual impact.

The permeability of the porous/water-retentive blocks was about three times greater than of the conventional blocks and runoff was one-tenth that of the conventional blocks. Because these blocks retained more moisture, more evaporation could occur (Figure 7).

The soil moisture content of the porous/water-retentive and conventional blocks after the rainfall experiment were

Table 3 | Method for evaluating the heat-island mitigation performance of blocks



*Temperature, humidity (RH), and solar data applied based on Seoul standard weather data during heatwave warnings (>33 °C) (see Table 4).

Table 4 | Seoul standard weather data during heatwave warnings (days >33 °C) (KMA 2017)

Jul. 1 to Aug. 31 (12:00–16:00)	Air temperature (°C)	Relative humidity (%)	Solar radiation (W/m^2)
Average	33.53	49.29	615.08
Maximum	34.70	58.00	741.67
Minimum	33.00	41.00	288.89

32.0% and 28.5%, respectively, at 10 cm below the block; therefore, the porous/water-retentive blocks showed better permeability performance (Figure 8).

Over the 120-min increase in air temperature (i.e., the time required to reach 60 °C over the conventional blocks), the moisture on the upper surface of the blocks evaporated, while the soil moisture content increased by about 3.1% and 0.5% for the porous/water-retentive and conventional blocks, respectively. Overall, evaporation at the upper surface of the block and water permeation into the soil below the block were considered to have a low correlation.

CONCLUSIONS

This paper describes a method for evaluating the heat-island mitigation performance of blocks, using a climatic environmental chamber to experimentally control climatic elements, to evaluate the urban heat-island mitigation performance of blocks (e.g., porous/water-retentive blocks) by taking ambient temperature measurements. Using the proposed method, the heat-island mitigation effect of porous/water-retentive blocks was analyzed and compared with conventional blocks. Both the surface and ambient temperatures of porous/water-retentive blocks were lower than those of conventional blocks, highlighting the improved heat-island mitigation performance of the porous/water-retentive blocks. Because the porous/water-retentive blocks had a higher permeability/retentivity coefficient, there was minimal runoff; therefore, most solar radiation was converted into latent heat when using the porous/water-retentive blocks, and little was converted into sensible heat, which could be conducted to the block. The degree of temperature difference

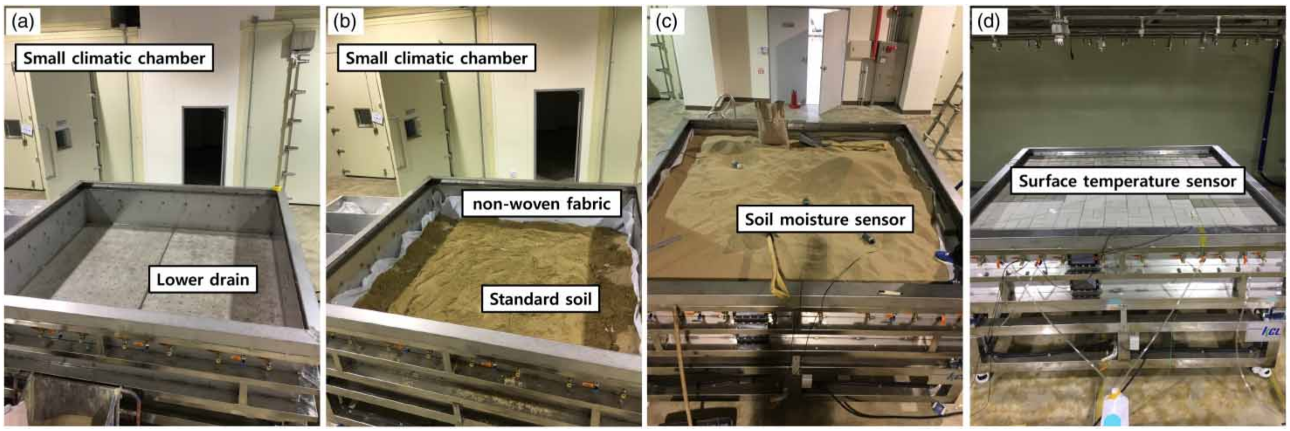


Figure 3 | Mock-up installation: (a) small climate chamber; (b) addition of non-woven fabric lining and standard soil; (c) placement of soil moisture sensors; (d) placement of test blocks and surface temperature sensors.

Table 5 | Details of the sensors used

Measuring point	Sensor type	Range	Accuracy
Surface temperature	K-type thermocouple	−200–205 °C	±0.1 °C
Air temperature	Thermo-hygrometer	−100–200 °C	±0.1 °C
Relative humidity	Thermo-hygrometer	0–100% R.H.	±1.3% R.H.
Solar radiation	Global solar radiation meter	0–1,500 W/m^2	±0.1 W/m^2
Mass	Load cell	0–2,500 kg	±500 g
Wind	Rotary wind gauge	0–40 m/s	±0.01 m/s

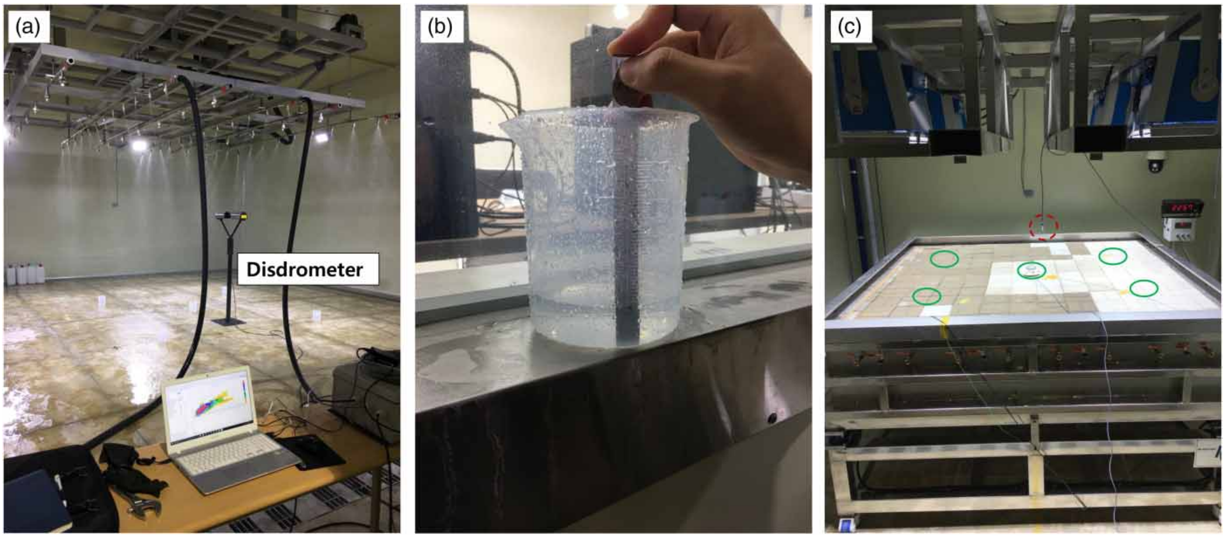


Figure 4 | Adjustment and measurement processes of (a, b) rainfall using spray nozzles, a laser disdrometer, and rain collection vessels, and (c) solar radiation using lamps, a pyranometer at five points (circles on the blocks) and air temperature (a circle with dotted line above the blocks).

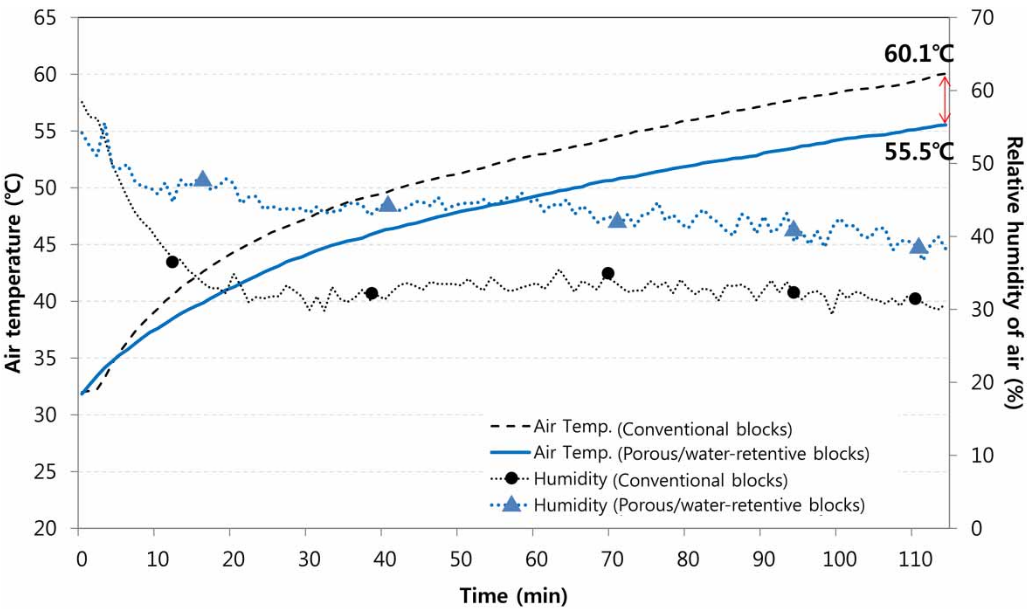


Figure 5 | Ambient air temperature and relative humidity 50 cm above the tested blocks.

between the two block types differed between ambient and surface temperatures; therefore, ambient temperature, as a better measure of heat-island mitigation effects, should be preferentially used in evaluations.

In this study, the varying wind speed was not considered because it was difficult to place a fan in a narrow space. Also, it is difficult to speculate that the air temperature would be higher than the surface temperature. The higher air temperature was the result of supplying heat using a lamp in a closed chamber with a narrow space above the mock-up. Therefore, a large-scale test for ensuring adequate space above the mock-up is required for a more accurate heat-island mitigation effect test.

In future work, the differences between surface and ambient temperatures under various conditions should be determined to more accurately quantify the heat-island mitigation performance of blocks considering

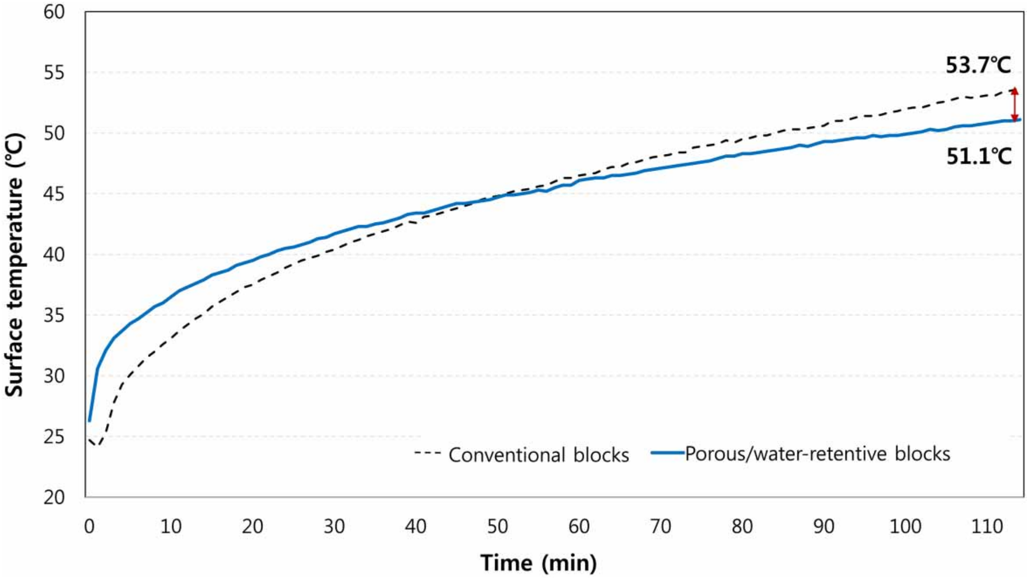


Figure 6 | Surface temperatures of conventional and porous/water-retentive blocks.

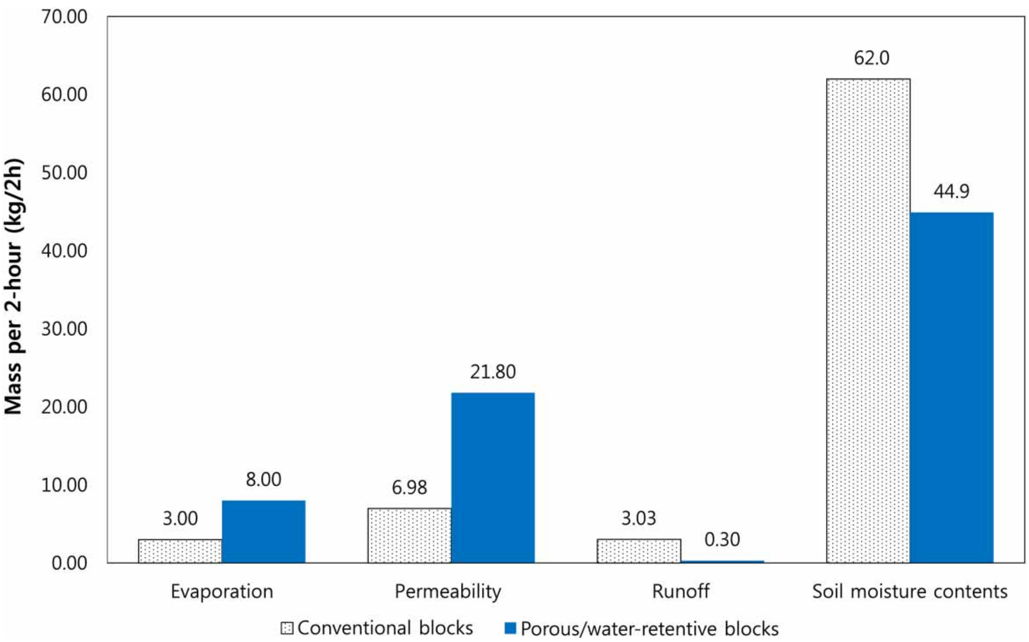


Figure 7 | Evaporation, permeability, runoff, and soil moisture content of conventional and porous/water-retentive blocks.

wind speed and the space above the test specimen. In addition, proper criteria for measuring air temperature should be determined. Nevertheless, the method and mock-up construction proposed in this study offer a foundation for improved evaluation of materials to ultimately realize improved urban design and reductions in heat-island phenomena.

The experimental data obtained through the proposed full-scale test procedure is different from that for the unit block. Data from full-scale experiment are considered to be more accurate; however, for conducting experiments, unit blocks are more convenient. Thus, to address errors that may appear in unit block experiments, data from full-scale experiments can be used. At present, we are

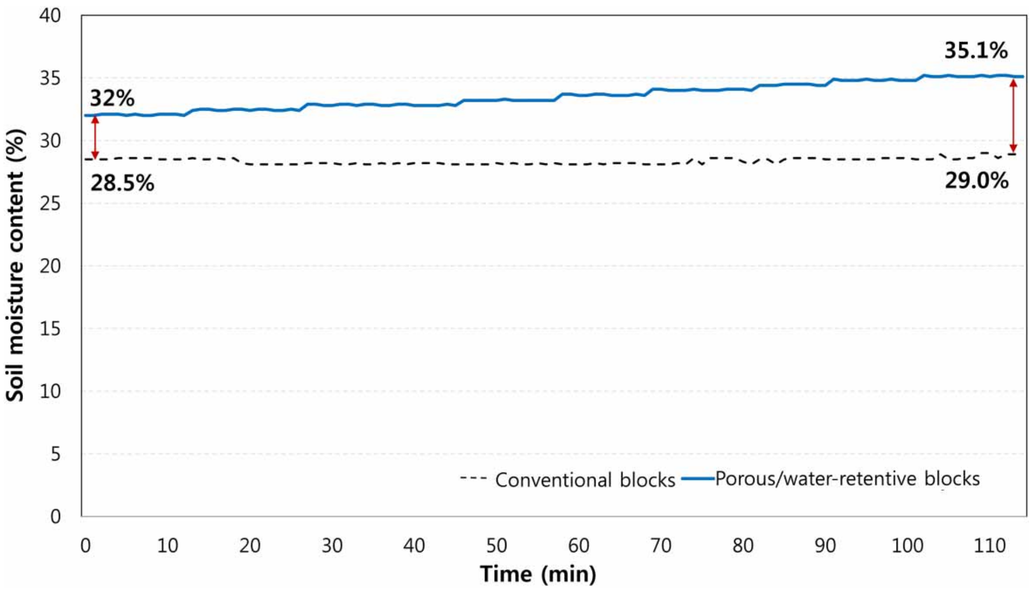


Figure 8 | Soil moisture content below the blocks.

developing a device for evaluating the performance of air and surface temperature reduction of unit blocks. This study will be supplemented and proposed as a collective standard for block manufacturing companies in Korea.

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