Quantitative evaluation of the mitigation effect of low-impact development pavement materials on urban heat island and tropical night phenomena

Na Mun-soo, Bae Woo-bin, Kang Hee-man, Kim Yong-gil and
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ABSTRACT

Rapid urbanization has led to altered thermal circulations in major cities that are responsible for the increasing occurrence of urban heat islands (UHIs) and events such as tropical nights and heat waves. To effectively mitigate such events, low-impact development (LID) and green infrastructure strategies have been developed. In Korea, LID techniques focus mainly on road pavement materials; however, issues regarding the reliability of measurements due to differences in the measurement equipment and studied specimens persist. This study presents the design of a green infrastructure surface temperature measurement (GSTM) instrument and a reliable methodology developed to evaluate the performance of pavement materials under controlled climate conditions. The developed GSTM instrument and methodology were tested by monitoring the surface temperature of materials based on LID practices and dense-graded asphalt and evaluating their ability to mitigate UHI and tropical night phenomena. The experiments were conducted under controlled climate conditions, using summer climate conditions of Seoul's typical meteorological year data. The UHI and tropical night phenomena mitigation performance of the pavement materials was evaluated by analyzing the correlation between the pavement materials' albedo and surface temperature using porous block specimens of different colors and LID-based pavement materials. The greening block recorded the most significant reduction in surface temperature, showing a difference of 22.6 °C, 185 min to the dense-graded asphalt. The white and yellow porous blocks showed surface temperature differences of 10.2 °C and 8.2 °C respectively compared to the dense-graded asphalt. The results revealed that pavement materials with higher albedo, more evaporation, and lower heat capacity have superior performance in mitigating UHI and tropical night events.

Key words | climate chamber, low-impact development (LID), pavement material, tropical night, urban heat island (UHI)

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HIGHLIGHTS

- Evaluate pavement material performance under controlled climate conditions.
- Thermal imaging camera is not recommended for evaluating surface temperature of pavement material.
- An experiment is needed to mitigate UHI and tropical night events considering albedo, evaporation, and heat capacity.

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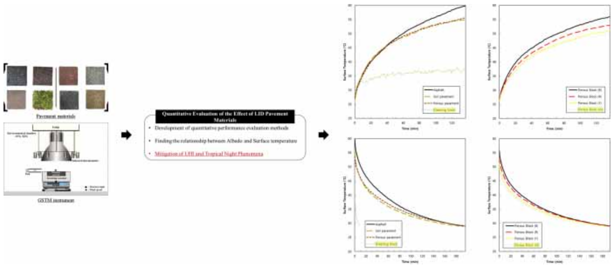
GRAPHICAL ABSTRACT



NOMENCLATURE

GSTM	Green infrastructure surface temperature measurement
LID	Low-impact development
UHI	Urban heat island
TMY	Typical meteorological year

INTRODUCTION

Rapid urbanization has led to an increased area of impervious surfaces in major cities. As rainwater cannot seep into ground covered with asphalt pavement, the amount of rainwater evaporated has significantly decreased, altering both water and thermal circulation (Kim 2016). In particular, distortions of thermal circulations result in an increasing number of urban heat islands (UHIs) and events such as tropical nights and heat waves. Heat stress imposed by UHIs and tropical night and heat wave events affect human health, and may even result in death (Wolf *et al.* 2009; Gartland 2010; Gabriel & Endlicher 2011). Therefore, exposure to extreme heat conditions has become a very serious issue around the world. In Korea, since 2011, the number of patients with heat-related illnesses due to heat waves during summer time has reached a peak of 4,526 patients and 48 deaths (Moon *et al.* 2006; Korea Meteorological Administration 2019). In the United States, due to the worst drought in 25 years from June to August 2012, 29 states were designated as disaster areas. Heat wave events in July 2012 alone claimed 39 lives in the Eastern US (Kim 2012). In 2018, Korea recognized heatwaves and cold waves as natural disasters in the Framework Act on the Management of Disasters and Safety (National Law Information Center Framework Act on the Management of Disasters and Safety 2018). In 2018, the average number of heatwave events was 31.4 days. In the same year, the average number of tropical night events was 17.7 days. In Korea, the annual number of tropical nights has sharply increased since the 1990s. Moreover, recently, Seoul recorded the highest tropical night temperature in 111 years since January 1, 1907, of 39.6 °C. Low-impact development (LID) and green infrastructure have been proposed as solutions for altered thermal circulations. LID is a land development strategy whose underlying principle is to maintain the post-development water circulation of a site close to the natural condition present before development occurred (USEPA 2000; Coffman 2002). Restoring water circulation of a densely populated city includes mitigating impervious surfaces by using natural infiltration, storage, and evaporation systems (Shin *et al.* 2016; Lee & An 2018). Roads and sidewalks account for approximately 50% of the impervious surfaces in Korea and, due to highly concentrated development, there is a lack of available land to restore thermal circulation in the country. Hence, most of the research applying LID techniques to restore thermal circulation has focused on road pavement materials such as permeable paving, porous blocks, and greening blocks (Koo *et al.* 2013; Ko *et al.* 2017). LID systems materials such as green roofs and permeable pavement have been considered as the most efficient strategies for urban flooding risk mitigation, water quality enhancement, and urban heat islands reduction, so various modeling studies have been conducted to confirm the suitability of these LID solutions (Ahiablame *et al.* 2012; Palermo *et al.* 2020; Peng *et al.* 2020).

While most of these studies identified the effect of pavement materials on mitigating the surface temperature based on evaporation measurements to determine the surface temperature, few studies have quantitatively evaluated the performance of the materials based on heat capacity, dissipation, and albedo measurements. Furthermore, since previous studies used thermal imaging cameras to measure, compare, and evaluate the surface temperature of the pavement materials in uncontrolled climate conditions, reliable and consistent results have been difficult to obtain (Park *et al.* 2017; Lee *et al.* 2019).

Figure 1 shows different experimental setups used in Korea and abroad to evaluate the surface temperature of pavement materials. The experiments were conducted with different lamp specifications, specimen dimensions, and geometries. Moreover, the measurement methods were all different, including the maximum surface temperature conditions and the time of increasing the surface temperature (Seoul Metropolitan Government Quality Inspection Office 2017). This caused different results depending on the measurement equipment and the geometry of the test materials used, which are thus unreliable.

The objective of this study was to develop a reliable method and apparatus to evaluate the performance of pavement materials under controlled climate conditions, focusing on the quantitative evaluation of the mitigation effect of pavement materials on UHI and tropical night phenomena by monitoring the surface temperature of LID-based materials and dense-graded asphalt. The instrumentation and methodology presented in this study are based on previously reported methods used in Korea and abroad.

MATERIALS AND METHODS

Pavement materials used for performance evaluation

To overcome the reliability issues of the experimental data discussed above, the dimensions of the specimens used in this study were those commonly used for road and sidewalk blocks in Korea. Dense-graded asphalt was selected as the control group according to Japan's surface temperature mitigation testing methods for the certification of cool and water retention pavement blocks (Japan Interlocking Block Pavement Engineering Association 2015).

The LID-based pavement materials selected for evaluating their performance in mitigating UHI and tropical night events are shown in Figure 2. These were porous pavement, soil and greening blocks, and colored porous blocks (white, yellow, red, and black). The colored porous blocks were used to analyze the correlation between the proportion of solar radiation reflected by a material surface (albedo) and surface temperature because several studies reported that the effect of pavement on surface temperature mitigation was largely affected by albedo.

Equipment for measuring the surface temperature of pavement materials

To overcome the issues regarding the reliability of the measured results due to differences in measurement equipment and specimens, in addition to selecting the dimensions of the specimens as described above, we considered controlled climate conditions for the design of the instrumentation used in this study. To simulate controlled

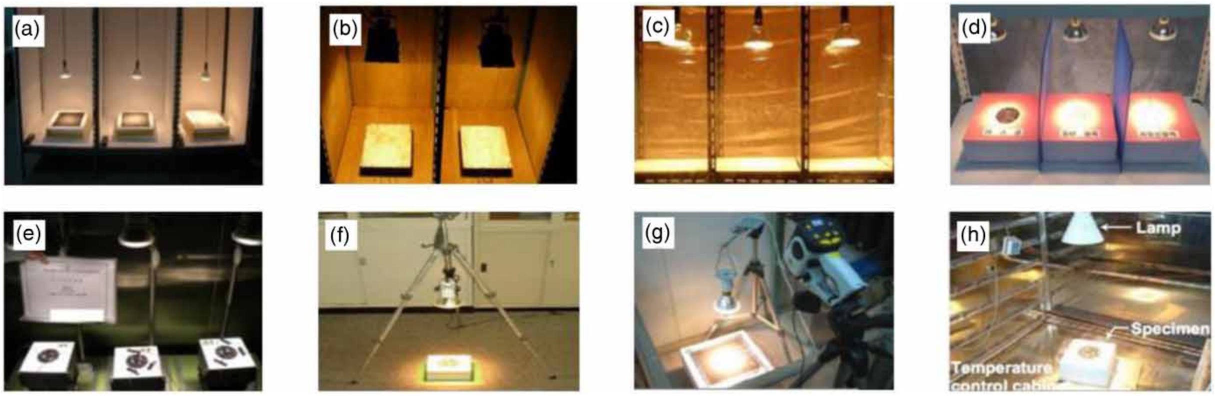


Figure 1 | Different indoor methods used for the evaluation of the surface temperature of pavement materials: (a) Park *et al.* (2009); (b) So *et al.* (2010); (c) Hong (2013); (d) Han (2016); (e) Road and Street Administration Division, the Bureau of Construction, the Tokyo Metropolitan Government; (f) Road Division, the Department of Civil Engineering, Shinjuku; (g) Nihon Kogyo Co., Ltd; (h) Tokyo Metropolitan Government.

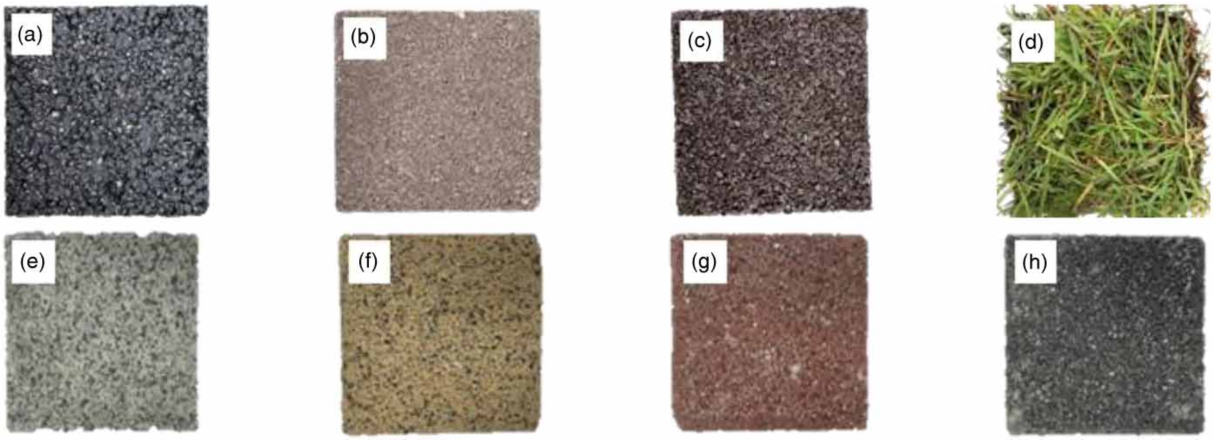


Figure 2 | Experiment specimen pavement materials: (a) dense-graded asphalt; (b) soil pavement; (c) porous pavement; (d) greening block; and (e, f, g, h) porous blocks (white, yellow, red, black).

climate conditions, the experiments were conducted in a climate chamber of the Center for Climate Environment Real-scale Testing, Korea Conformity Laboratories. The testing methods were based on Japans' indoor testing standards for cool pavement (Japan Road Surface Temperature Rise Control Pavement Research Institute 2011; Japan Society for Testing Materials 2015). Temperature and humidity sensors were installed at the height of the top of the pavement material and located near the pavement material where it was not affected by the solar radiation emitted by the lamp. In order to start up the designed instrument, and to quantitatively evaluate the effect of using different pavement materials to mitigate the surface temperature, we conducted experiments under constant temperature and relative humidity conditions (Figures 3 and 4). Table 1 lists the experimental conditions used in the climate chamber. The laboratory conditions were selected based on the summer climate conditions of Seoul's typical meteorological year (TMY) data (Korea Meteorological Administration 2017).

The green infrastructure surface temperature measurement (GSTM) instrumentation designed in this study consisted of a solar radiation lamp, a non-contact infrared thermometer, a fan, and a scale to measure the surface temperature of the tested pavement materials. The GSTM instrument was designed to control the solar radiation by adjusting the voltage and the height of the metal-halide lamp. The fan was installed to simulate the wind conditions on the surface of the pavement material. A non-contact infrared thermometer was preferred as temperature sensor because a thermocouple could detach due to heat when attached to the surface of the pavement material. Because JSA (2016) measures the surface temperature only at the center of the pavement material, it is difficult to be certain that the measured temperature is representative of the temperature on other parts of the pavement material. Thus, the GSTM instrument measured the surface temperature at five points, including the center and the four edges of the pavement material. The surface temperature of each pavement material was reported as the average temperature of these five points (Figure 5(c)). To quantitatively evaluate the effect of the pavement materials on mitigating the surface temperature under consistent conditions, we installed a climate chamber that simulated the climate conditions (Figure 5(a) and 5(b)). Table 2 provides the specifications of the GSTM instrument. Detailed information regarding

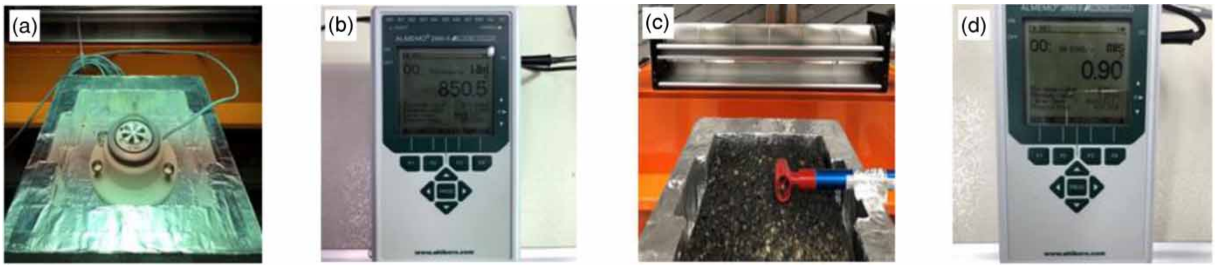


Figure 3 | Solar radiation and wind speed measurement instruments: (a, b) solar radiation measurement instruments; (c, d) wind speed measurement instruments.

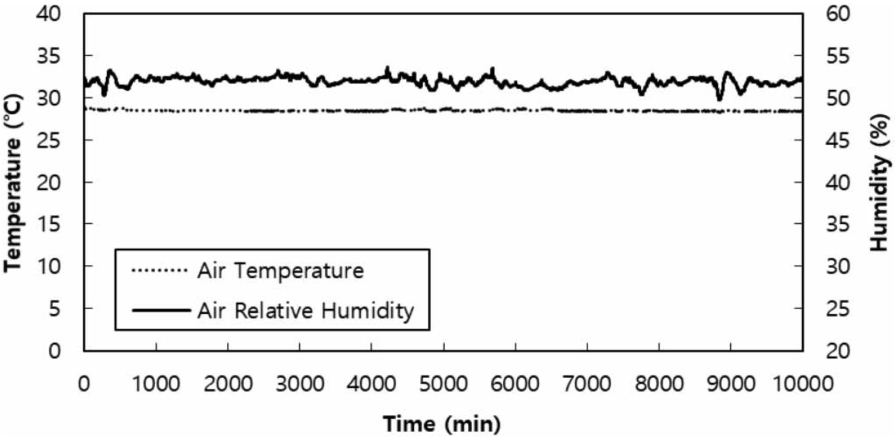


Figure 4 | Simulation of air temperature and relative humidity conditions in the climate chamber.

the measurements of the surface temperature of the pavement materials and the UHI and tropical night mitigation effects of the LID-based pavement materials are given in the following sections.

Table 1 | Experimental conditions in the climate chamber

Air temperature	**Relative humidity**	**Solar radiation**	**Wind speed**
$(29 \pm 1)\ ^{\circ}\mathrm{C}$	(52 ± 10) %	$(850 \pm 20)\ \mathrm{W/m^2}$	(0.9 ± 0.5) m/s

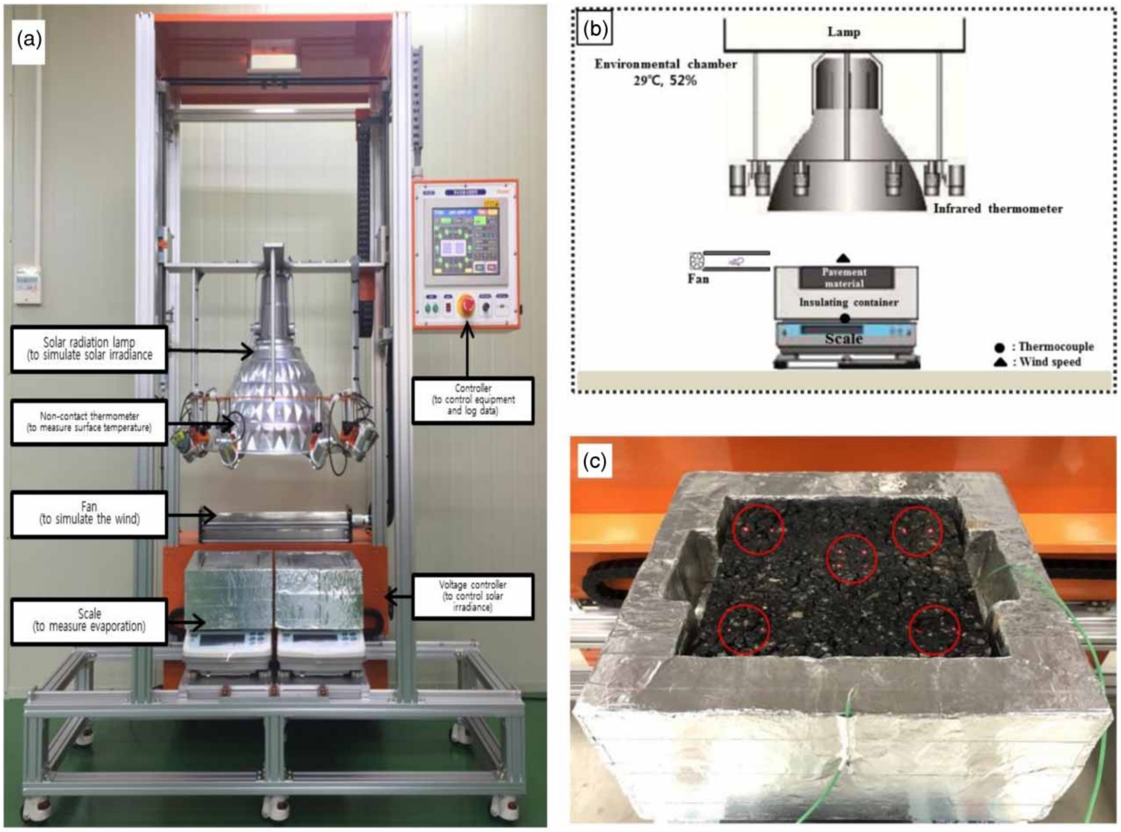


Figure 5 | Green infrastructure surface temperature measurement (GSTM) instrumentation. (a) Complete view; (b) scale-lamp detailed view; (c) temperature measurement points.

Table 2 | GSTM equipment specifications

Specimen dimensions (W × L × H)		200 mm × 200 mm × 60 mm 200 mm × 200 mm × 80 mm
Solar radiation lamp		Metal-halide lamp
Surface temperature measurement		Non-contact infrared thermometer
Curing time	Cool pavement permeability	Curing the oven-dried specimen at (29 ± 1) °C for 24 h
	Water retention	Underwater curing at (25 ± 5) °C for 1 h and then curing the air-dried specimen at (29 ± 1) °C, (52 ± 10) % R.H. for 24 h

Method to evaluate the mitigation of UHI and tropical night phenomena

Due to the lack of a standardized testing method and equipment specifications to measure the surface temperature mitigation effect of pavement materials in Korea, the methodology developed in this study is based on the experimental methods reported by the Japan Road Surface Temperature Rise Control Pavement Research Institute (2011) and Japan Interlocking Block Pavement Engineering Association (2015). The methodology presented in this study is further suitable to evaluate the performance of different pavement materials on UHI and tropical night event mitigation as described below.

The detailed experimental procedure for measuring the mitigation of UHI and tropical night events is shown schematically in Figure 6 and was as follows. For all experiments, the specimens in the control (dense-graded asphalt) and comparison groups (porous block, porous pavement, soil pavement, and greening block) were kept at (29 ± 1) °C for 24 h (curing time). Then, the temperature, humidity, solar radiation, and wind speed of the climate chamber were set to the summer climate conditions of Seoul's TMY data (Korea Meteorological Administration 2017).

For the evaluation of the UHI mitigation effect of the pavement materials, the time required (t_1) for the surface temperature of the control group (T_{asp}) to reach 60 °C was recorded under the influence of the solar radiation energy from the lamp. Then, the specimens of the comparison group were placed into the instrument, and the surface temperature (T_{sur}) change recorded. The temperature difference between the control and comparison groups was then calculated for the same time (t_1). The UHI mitigation effect of the pavement materials was measured as the surface temperature difference between the two groups (ΔT_{sur}) measured under the same time (t_1) and simulated climate conditions as depicted in Figure 7.

The evaluation of the tropical night mitigation effect of the pavement materials was carried out following the end of the UHI performance evaluation. When the UHI performance experiment ended, the solar radiation lamp was automatically turned off, and the T_{sur} of the comparison group was recorded. Then, the instrument measured the time (t_2) it took the comparison group to reach the same temperature as that of outdoor air (29 °C). The tropical night mitigation performance was then evaluated as the time difference (Δt) to reach thermal equilibrium between the control (t_3) and comparison groups (t_2) as depicted in Figure 7.

To accurately measure temperature and time, the instrument was equipped with a temperature and time control system that minimized measurement errors. The implemented temperature and time control system stopped the instrument when the average temperature of the specimen reached the set-point temperature and after the operating time reached its set-point, regardless of the average temperature.

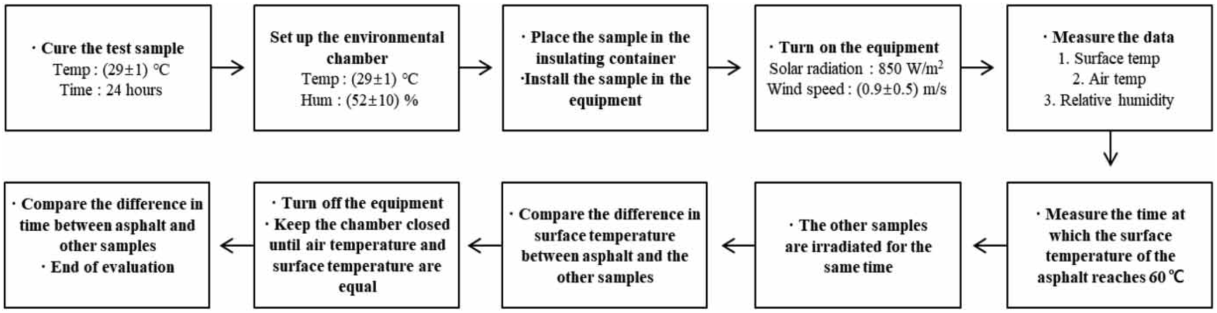


Figure 6 | Experimental procedure for the performance evaluation of UHI and tropical night mitigation.

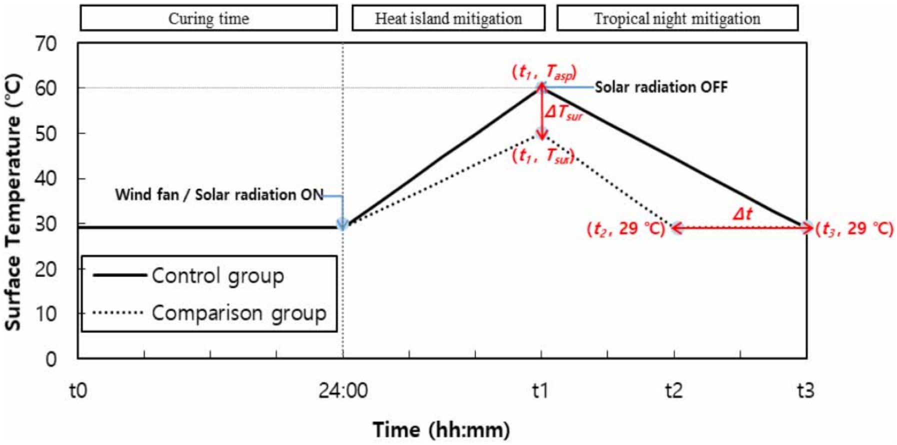


Figure 7 | Methodology diagram for UHI and tropical night mitigation performance evaluation. (—) Control group; (···) Comparison group.

RESULTS AND DISCUSSION

UHI mitigation effect

The evaluation of the performance of the pavement materials on UHI mitigation was carried according to the methods described above. Before the experiments, the pavement materials in the control and comparison groups were kept at (29 ± 1) °C for 24 h (curing time). Figure 8 shows the heating kinetics of each material. The dense-graded asphalt in the control group showed an initial surface temperature of 27.3 °C. The initial surface temperature of the LID-based pavement materials in the comparison group ranged from 25.6 to 27.9 °C. Under the influence of the solar radiation energy from the lamp, the surface temperature in the control group reached 60 °C in 137 min.

For similar time intervals, the surface temperature of the LID-based pavement materials in the comparison group ranged from 37.4 °C (greening block) to 56.1 °C (black porous block). Figure 9 shows the surface temperature reduction for each pavement material for the same conditions and time. The surface temperature of the control group was higher than that of the comparison group. The greening block recorded the most significant reduction in surface temperature, showing a difference of 22.6 °C compared to the control group, due to evaporation of the moisture on its surface. Compared to the control group, the white porous block and the yellow porous block mitigated the surface temperature

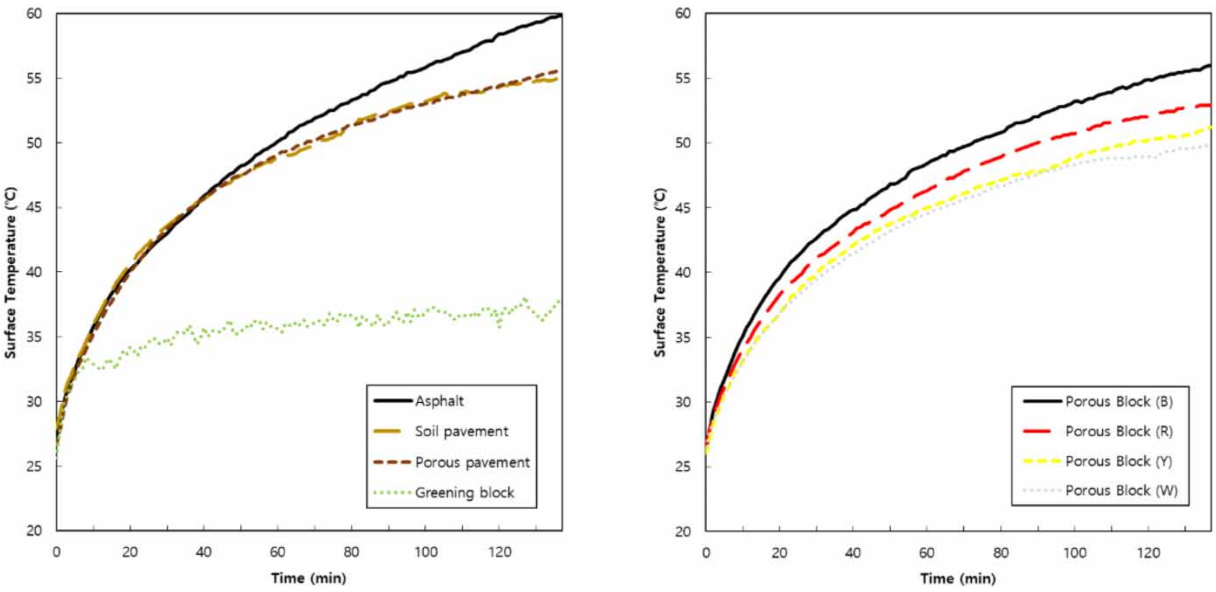


Figure 8 | Heating kinetics of pavement materials.

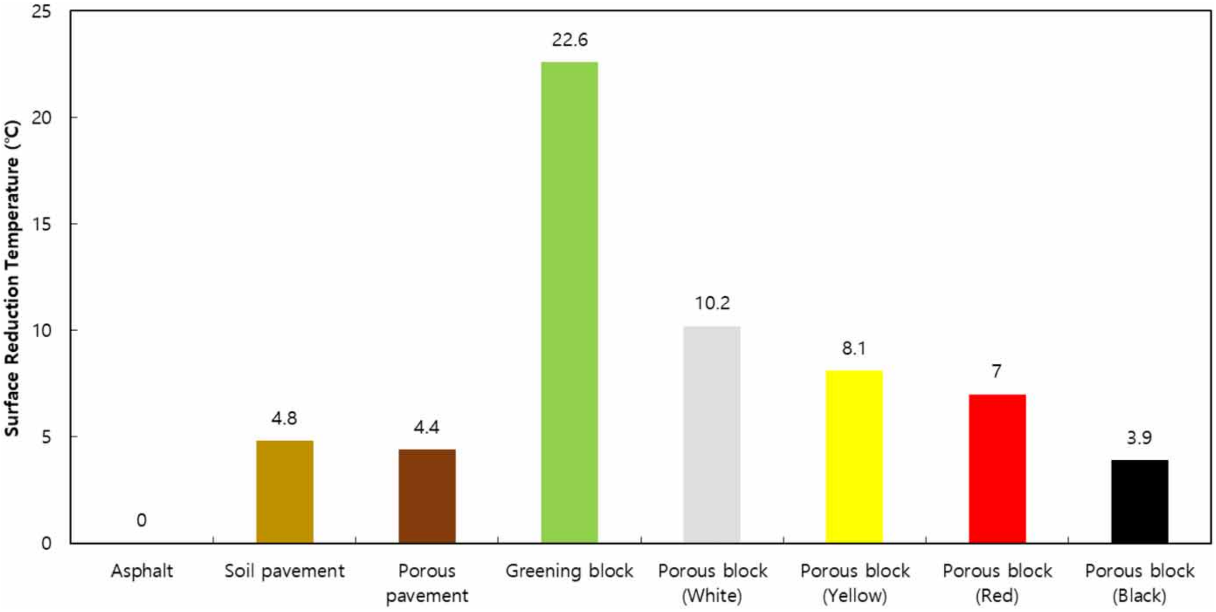


Figure 9 | Surface temperature reduction compared to the control group (surface temperature difference; °C).

by 10.2 °C and 8.1 °C, respectively. The other LID-based materials in the comparison group showed surface temperature mitigation in the range 3.9–10.2 °C (Figure 9).

Tropical night mitigation effect

The tropical night mitigation performance of the pavement materials was evaluated following the UHI mitigation effect measurements according to the method described above. After being exposed to the solar radiation energy from the lamp for 137 min, the surface temperatures of the materials in the comparison group in the range of 37.4–56.1 °C began to decrease with time. Figure 10 shows the heat dissipation of the tested pavement materials over time. The surface temperature of the control group took longer to reach thermal equilibrium with the outdoor air

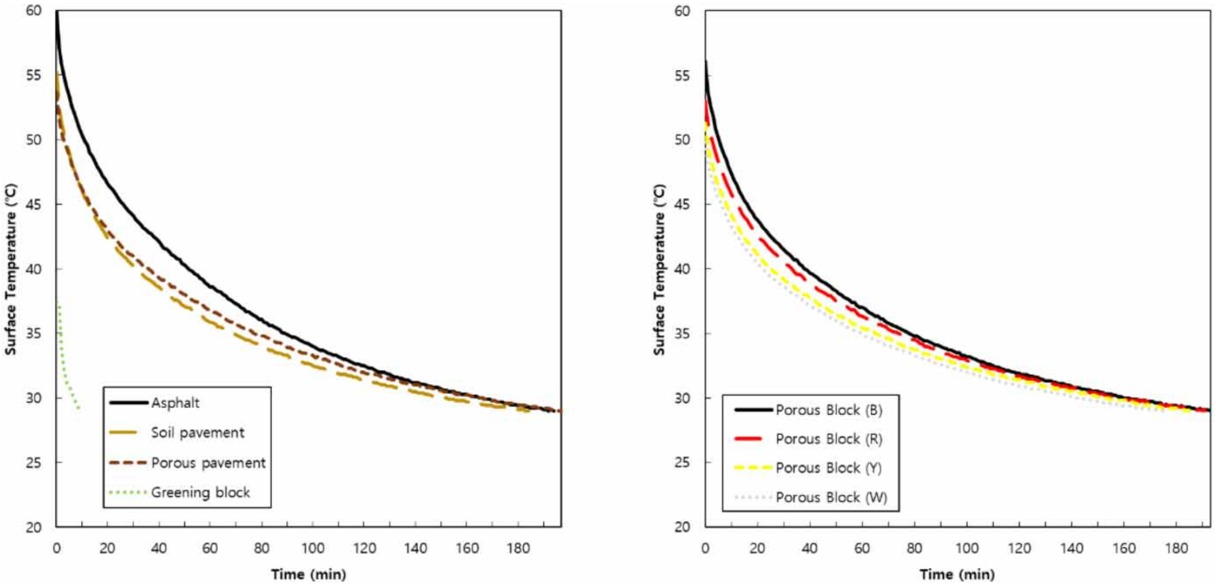


Figure 10 | Heat dissipation of pavement materials in time (tropical night).

than the comparison group. Compared to the dense-graded asphalt (control), the LID-based pavement materials took from 1 to 185 min less to reach thermal equilibrium with the surrounding air, except for the porous pavement (Figure 11). The greening block reached thermal equilibrium in 185 min less than the control group, showing the highest time reduction, while it took porous pavement 3 min longer than the control asphalt to reach thermal equilibrium with the surrounding air. The white and yellow porous blocks reached thermal equilibrium in 19 and 9 min less than the control, respectively (Figure 11).

Albedo and surface temperature mitigation analysis

This experiment was conducted using the porous block specimens of different colors. The albedo was measured to quantitatively evaluate the mitigation effect of the pavement materials on the surface temperature. Figure 12 shows the

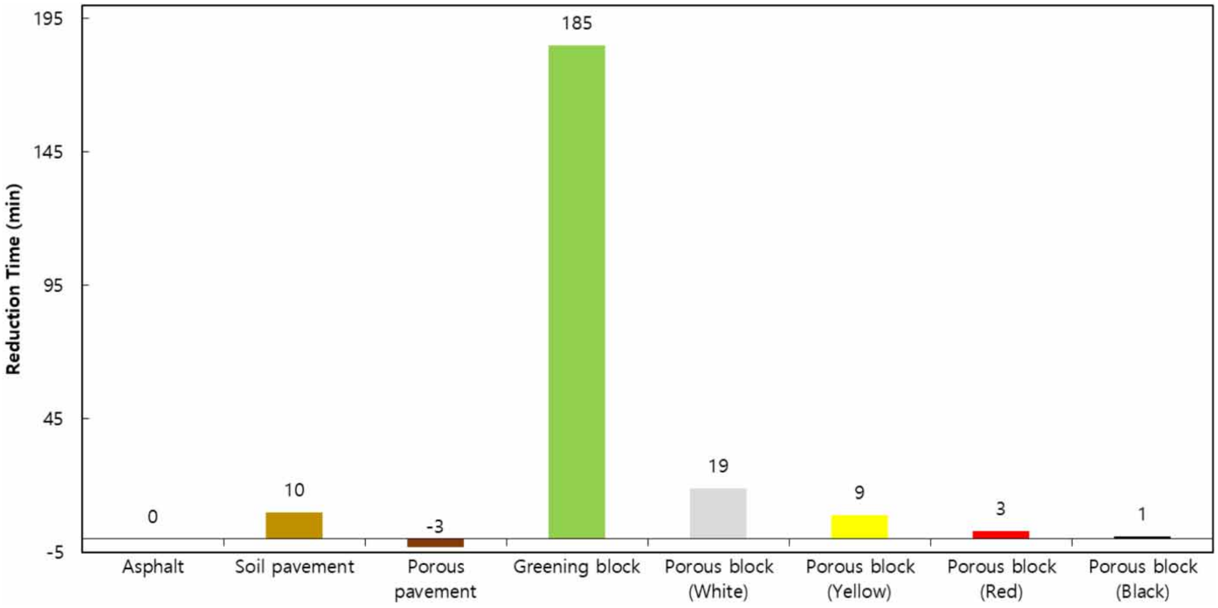


Figure 11 | Comparison of tropical night mitigation performance between the control group and the comparison group (time difference, Δt, minutes).

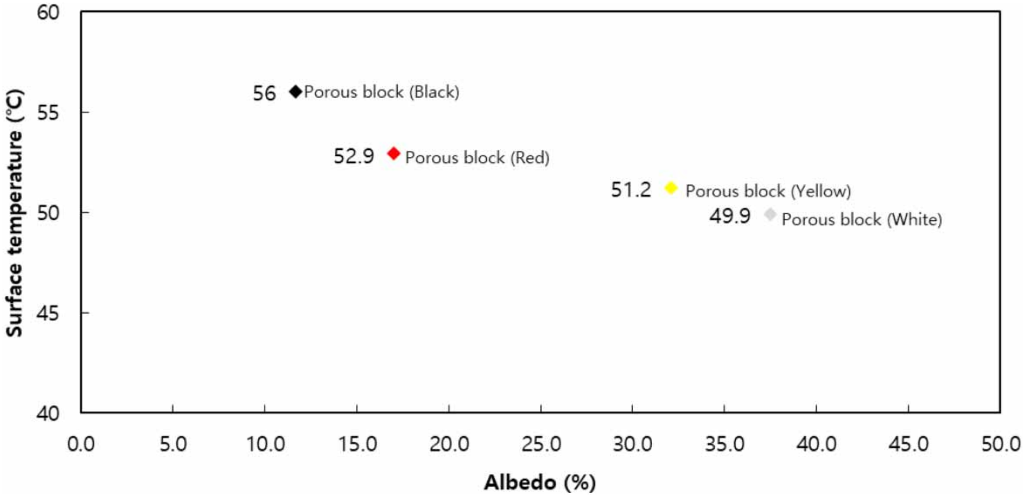


Figure 12 | Surface temperature of pavement materials versus albedo.

surface temperature of the colored porous blocks during the time it took the dense-graded asphalt of the control group to reach 60 °C. The black porous block, which showed the lowest albedo, reached a temperature of 56 °C, followed by the red porous block with 52.9 °C, the yellow porous block with 51.2 °C, and the white porous block with 49.9 °C. As shown in Figure 12, the mitigation effect of the pavement materials on the surface temperature was largely influenced by albedo, suggesting that pavement materials with high albedo values, under solar radiation incidence, will show lower surface temperatures.

CONCLUSIONS

This study presents the design of a GSTM instrument and a reliable methodology developed to evaluate the performance of pavement materials under controlled climate conditions. Using the developed GSTM instrument and methodology, LID-based materials and dense-graded asphalt were tested to quantitatively evaluate their ability to mitigate UHI and tropical night phenomena. The experiments were performed under controlled climate conditions, simulating summer climate conditions based on Seoul's TMY data, and were used to evaluate the correlation of the surface temperature of the materials and albedo using porous block specimens of different colors.

According to our findings, LID-based materials have superior performance compared to dense-graded asphalt in mitigating UHI and tropical night events. Especially, the white and yellow porous blocks showed a significant reduction in surface temperature due to higher albedo compared to dense-graded asphalt commonly used for pavement. The greening block showed the highest performance in UHI and tropical night event mitigation because of evaporation of the moisture contained on its vegetation surface. Therefore, expanding green spaces such as green roofs or walls could help to mitigate the effects of the altered thermal circulation present in major cities. Moreover, pavement materials with higher albedo (higher solar radiation reflectance), more evaporation (faster dissipation of heat into the atmosphere), and lower heat capacity (lower surface temperatures), should be preferred for mitigating UHI and tropical night events.

Shin *et al.* (2019) showed that the ambient temperatures of porous/water-retentive blocks were lower than those of conventional blocks, and highlighting the improved UHI mitigation performance of the LID-based materials. Kim *et al.* (2006) showed that the surface temperature of asphalt treated with thermal insulation went down by about 12 °C, and recommended that the effect on the human body should be considered due to the solar radiation reflection properties. Several studies of greening applications of roof and reinforced oil walls have shown that greening has a temperature reduction, temperature maintenance and heating and cooling effect. It is expected that the effect will be greater because the solar radiation will increase in the summer. Based on the results of numerous studies, it is judged that the change from conventional blocks to LID-based pavement materials will contribute to improving the high temperature environment in urban areas (Lee & Lee 2012; Jung *et al.* 2013). However, the porous pavement with point-contact showed a rapid rise in surface temperature as heat was not transferred to the lower part of pavement due to low thermal conductivity. Thus, our future research will be focused on studying the effect of water evaporation on the reduction in surface temperature of pavement materials, along with measurements of material specific property values such as heat transfer and thermal conductivity on surfaces with different pore size distributions.

The data collected in this study is expected to serve as a basic standardized method to evaluate the performance of pavement blocks in mitigating UHI and tropical night events before carrying out testing at empirical demonstration sites. Plus, it could be used as reference data for analyzing the effects of heat accumulated in pavement materials on the urban environment. For changes in road pavement materials, it is necessary to examine the impact on the human body to improve the walking environment of citizens.

ACKNOWLEDGEMENTS

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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