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A drainable water-retaining paver block for runoff reduction and evaporation cooling

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ABSTRACT

Water-retaining pavements are optional and effective to mitigate urban heat island as they stay cool by holding rainwater at the surface layer for evaporation cooling. However, excessive rainfall falling on such pavements will overflow and thus contribute to flooding. Here, we report a novel drainable water-retaining paver block for mitigating urban heat island and simultaneously reducing runoff. The albedo, temperature, water-retaining capacity, and outflow sensible heat of this novel paver block were measured and compared with those of a dense block and a pervious block. The permeability of the water-retaining block was also measured to examine whether this paver block can avoid overflow during heavy rain. Our results showed that the temperature of the water-retaining block in the wet condition can be reduced by 13 °C in the daytime and 3 °C at night, which indicates its good performance of cooling the local air temperature. Our results also indicated that the permeability of the water-retaining block is two orders higher than the precipitation rate of heavy rain, which reveals the excellent performance of quickly draining the excessive water in case of heavy rain.

1. Introduction

Asphalt, cement, concrete, and their mixture are widely utilized paving materials for pavements, which cover a high percentage of urban areas (Higashiyama et al., 2016). Paving materials absorb and store most solar energy falling on the surface of pavements during daytime and then release the stored energy as sensible heat to increase the urban air temperature during nighttime (Asaeda and Ca, 2000). Paved urban areas thus decrease the pedestrian thermal comfort by inducing urban heat island (UHI) (Hendel et al., 2018; Imran et al., 2018; Sen and Roesler, 2016; Sun et al., 2018). Various efforts have been made to alter pavement configuration and/or pavement materials to fight against and/or mitigate UHI (Baral et al., 2018; Barthel et al., 2017; Furumai et al., 2008; Hendel et al., 2014, 2015; Qin, 2015; Starke et al., 2010; Takebayashi and Moriyama, 2012; Xie et al., 2018). One of such efforts is to keep pavement cooler than conventional gray pavements (Santamouris, 2013). Experimental results showed that a cool pavement reduces its surface temperature up to 10 °C and cuts the outflow sensible heat flux about 13–30% (Wang et al., 2018). Experimental results also revealed that the cooling provided by cool pavements, when initially wet, can persist more than seven days under the condition without any water supply from rainfall (Liu et al., 2018).

A water-retaining pavement is a promising type of cool pavements. This pavement holds water in the layer close to the pavement surface for subsequent evaporation cooling (Li et al., 2014; Qin and Hiller, 2016). Also, water-retaining pavements can provide the high water availability and a high water amount for evaporation cooling (Qin, 2015). Many studies thus have been conducted to evaluate and/or improve the cooling performance of water-retaining pavements. Ishizuka et al. (2006) used feed pipes and water guide sheets to make pavements wet, which can keep pavement temperatures at as low as 25 °C in summer. Karasawa et al. (2006) found that the temperature drop ranges from 7.7 to 16.6 °C in summer using water-retaining pavements. Yamagata et al. (2008) obtained a temperature drop of 8 °C in the daytime and 3 °C at night with water-retaining pavements. Kinoshita et al. (2012) estimated that the annual electrical saving is 3.46% using water-retaining pavements. Higashiyama et al. (2016) found that the surface temperature can be reduced by 10 °C and this

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temperature drop can further increase if the pavement temperature reaches over 60 °C. Other studies evaluated different materials used for water-retentive fillers in pavements to hold and evaporate water, including allophane and vermiculite materials (Okada et al., 2008), porous geopolymers (Okada et al., 2009), blast furnace slags (Takahashi and Yabuta, 2009), and steel by-products based on a silica compound (Nakayama and Fujita, 2010).

Even though conventional water-retaining pavements can retain a sizable amount of rainwater for evaporation cooling, they will overflow in case of heavy rain. Considering runoff reduction and UHI mitigation, a water-retaining pavement shall not only store a great amount of water for evaporation cooling but also drain the excessive water for avoiding overflow. Conventional pervious pavements drain water via their internal large pores but fail to hold water for the later water evaporation. Sealing the bottom and sides of a pervious paver block can hold a sizable amount of water (Qin et al., 2018a), but this leads to overflow in case of heavy rain. To circumvent this limitation, this study reports a novel drainable water-retaining paver block for reducing runoff and mitigating UHI. This paver block can retain a great amount of water for evaporation cooling and drain the excessive water for avoiding overflow. To examine the performance of this newly developed paver block, its albedo, temperature, water-retaining capacity, and outflow sensible heat are measured and compared with those of a dense block and a pervious block. The permeability, which determines the capacity to drain the surplus water (Li et al., 2013), is also measured to evaluate the drainable performance of this paver block.

2. Materials and experiments

2.1. Experiment set-up

Experiments were conducted to monitor the hydrological and thermal performances of the new drainable water-retaining pavement. A paver block with 1.04 m × 1.04 m × 0.06 m in width × length × thickness (Fig. 1a) was prepared to represent a typical unit of drainable water-retaining pavements. Qin et al. (2018a) have proposed a water-retaining paver block by sealing four sides and the bottom of typical pervious paver blocks. Different from the block proposed by Qin et al. (2018a), in the current study, the proposed paver block contains five water tubes with the same dimension, as shown in Fig. 1d, four located in four corners of the block and one in the center. The pervious concrete mixture was used as the water-retaining media. Its four sides were sealed by dense mortars (Fig. 1a), which consisted of sands and cement with limestones. Due to the impermeable mortars, the inner dimension of the water-retaining block is 1.0 m × 1.0 m × 0.05 m.

The water tubes were filled with the same pervious concrete mixture as that in the block matrix. The height of the tube was 5 cm, which was 1 cm lower than the thickness of the block. The water tubes were pre-installed; therefore, the bottom of the tubes was not sealed with the impermeable mortars. This allows water to drain out of the block from the tubes when the retained water level exceeds the tubes. To observe the water table in the block during the experiments, a small hole (1.0 cm in diameter) was made at the bottom of the block. A flexible duct was fixed at this hole and then connected to an inclined graduated glass tube (Fig. 1a) to read the water table.

For comparisons, we also prepared a previous paver block with the same size and same mixture protocol as a conventional water-retaining block (Fig. 1b). A dense block was also prepared (Fig. 1c), which has the same size as the other two blocks. All the three blocks were considered as a typical paver block unit and made according to Kevern et al. (2006), in which details of the aggregates mixed with water and cement are tabulated in Table 1. The designed porosity of the pervious mixture for both the water-retaining and pervious blocks was 0.25, which is a typical value for pervious concrete (Tennis et al., 2004). The actual porosity after curing was estimated to be 0.238 according to the measurement procedure and calculations in Montes et al. (2005).

2.2. Thermal parameter measurements

Temperatures and albedos of the three blocks were measured. Their outflow sensible heat to the atmosphere was not measured directly but was calculated based on the measured temperatures. The measurements started from 00:00 a.m., Nov. 2nd, 2018 to 00:00 a.m., Nov. 6th, 2018, lasting 4 days in total.

To record the temperature variation of each block, T-Type thermocouples were used and placed in the center of pavers (see Fig. 1b) at depths of 1 cm, 3 cm, and 5 cm. The detailed set-up of the thermocouples is similar to that in Qin et al. (2018a). A Campbell Micrologger CR3000 was used to record the temperatures at three measured depths simultaneously with an interval of 10 min.

To measure the albedo of each block, Kipp&ZoneCMP1 albedometers were used, as shown in Fig. 2. Using such albedometers, the incident radiation and reflected radiation above each block's surface were recorded with respect to time. To ensure that the albedometer receives the radiation from the target block only (may also receive the radiation from the surrounding area), the detector of the albedometer was down-facing according to Mei et al. (2017). The albedo of the measured surface then can be calculated by (Qin

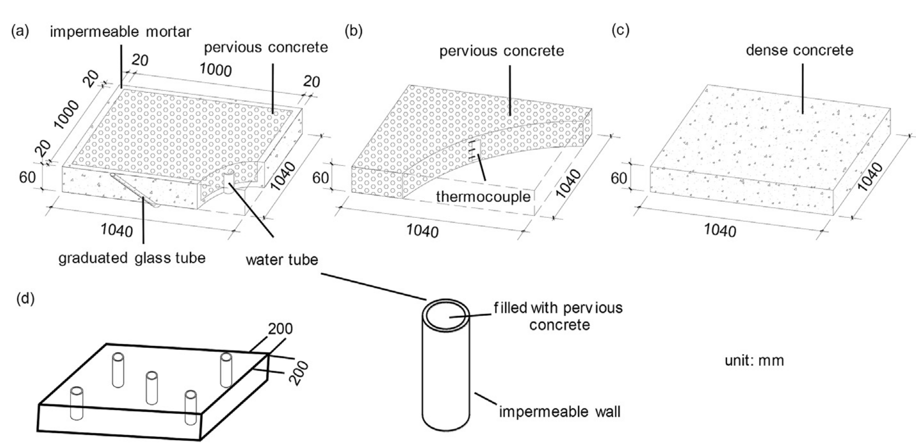

Fig. 1. Prepared paver blocks. (a) Water-retaining block, (b) pervious block, (c) dense block, and (d) configuration of water tubes.

Table 1
Test paver block mixture.

type	1.18–2.36 mm aggregate: 2.36–4.75 mm aggregate: cement: water	4.75–9.50 mm aggregate: cement: water
water-retaining	–	50:10:3
pervious concrete	–	50:10:3
dense concrete	20:30:10:3	–

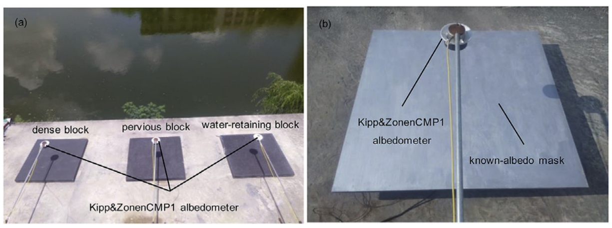

Fig. 2. Albedo measurements: (a) experiment setup and in progress and (b) known-albedo mask measurement.

et al., 2018b)

$$\rho = \frac{I_2 R_1}{I_1 R_2} \rho_{\text{ref}} \tag{1}$$

where I_1 (W/m^2) is the incident radiation of the measured surface, and R_1 (W/m^2) is the reflected radiation of the measured surface; I_2 (W/m^2) and R_2 (W/m^2) are the incident radiation and reflected radiation of the reference surface (i.e., known-albedo mask in Fig. 3b), respectively, and ρ_{ref} is the albedo of the reference surface. To continuously record the incident radiation and reflected radiation, the Campbell Micrologger CR3000, which was used for recording temperatures, was also utilized to store the data measured by the albedometers at a 10-min interval. It is noted that the albedos of the blocks were measured only when the solar zenith angle was less than $\pi/4$. The three paver blocks were painted unicolor.

The surface temperature can be extrapolated on the basis of the monitored sub-surface temperatures for evaluating the outflow sensible heat from the paver blocks. According to the field test results (Hiller and Roesler, 2009), the temperature at any depth can be estimated based on a parabolic curve formulated by

$$T = l + md + nd^2 \tag{2}$$

where l (°C), m (°C/m), and n (°C/m^2) are the regressed coefficients; d (m) is the depth. The origin is the block surface and positive downward. As three temperatures at depths of 1 cm, 3 cm, and 5 cm were measured directly, the surface temperature at $d = 0$ can be estimated. With this surface temperature, the daily accumulative sensible heat can be estimated by (Bentz, 2000)

$$\sum H = h_c (T_s - T_a) t A \tag{3}$$

where H (W/m^2) is the sensible heat flux, T_a (°C) is the air temperature, T_s (°C) is the block's surface temperature, A (m^2) is the surface area of the block, t (s) is the time, and h_c (W/m^2·K) is the convective heat coefficient. According to Qin and Hiller (2013), the formulation of h_c with the wind speed is formulated by

$$h_c = \begin{cases} 5.6 + 4v_9 & v_9 < 5 \\ 7.2{v_9}^{0.78} & v_9 \geq 5 \end{cases} \tag{4}$$

where v_9 (m/s) is the wind speed estimated at a height of 9.0 m. The meteorological data was thus needed to calculate h_c. For this purpose, a Davis Instruments 6152 was installed nearby the paver blocks as a weather tower to record the transient air temperature, wind speed, global horizontal solar radiation, and relative humidity (see Appendix) at an interval of 10 min and at a height of 2.0 m. To convert the measured wind speed v_2 to v_9, $v_9 = v_{2.0} \times (9/2)^{1/7}$ can be used according to Qin and Hiller (2013), in which $v_{2.0}$ is the wind speed measured at a height of 2.0 m in the experiment.

2.3. Water-retaining measurements

The water-retaining capacity of the three paver blocks was measured under the same rain event. To control the rain condition, a raining generator was used to ensure that the blocks were under the same raining intensity. If water cannot be retained in the matrix of each block, such water was collected by a bucket under each block through a catchment, as shown in Fig. 3. This bucket was weighted continually and the rate of the weight change for each bucket was calculated. The rain continued until the rate of the weight change was a constant. To evaluate the water-retaining capacity, the water collected by the bucket was recorded and the corresponding water-retaining rate was calculated. The water-retaining rate r_w (kg/m^2) of each block under the same raining condition can be calculated by

$$r_w = \frac{m_{tot} - m_b}{A} \tag{5}$$

where m_{tot} (kg) is the total raining mass, and m_b (kg) is the water mass collected by the bucket.

2.4. Permeability measurements

The permeability of the water-retaining block was measured using the constant water head method. As shown in Fig. 4, a collecting pipe was installed at the bottom of the block as a water outlet. The water drained from the outlet was collected by a bucket placed on a scale, where the collected water was weighted and recorded. To maintain a constant water head, a drain pipe was installed on the plane that is 10 cm above the block surface. Any water above that plane will be drained out. According to Tho-in

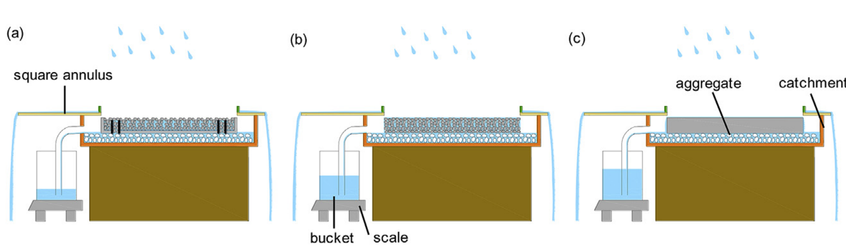

Fig. 3. Water retention measurements: (a) water-retaining block (b) pervious block (c) dense block.

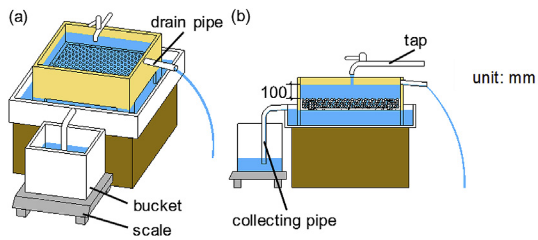

Fig. 4. Permeability measurements: (a) water-retaining block (b) profile view.

et al. (2012), when the volume of drained water Q (m^3) collected during a time interval t (s) is known, the permeability can be calculated by

$$k = \frac{QL}{hAt} \tag{6}$$

where L (m) is the thickness of the block, h (m) is the water head difference, and k (m/s) is the permeability. The side-wall effect can affect the permeability coefficient in the experiments (Sriravindrarajah et al., 2010). To avoid this effect, glass glues were added to the interface between the water retaining paver block and the walls of a water tank for the measurements in Fig. 4a. Due to this treatment, water is only allowed to drain out through five water tubes in Fig. 1a.

3. Results

3.1. Water retention capacity

To determine the water retention capacity, the uniform rain continued lasting 20 min and the corresponding precipitation was about 17.8 mm. The rain ceased from 20 min to 40 min. Fig. 5 shows the cumulative water collected by the bucket for each block. For the dense and pervious blocks, there almost has no collected water during the first 3–5 min. However, this period for the water-retaining block is about 10 min, which indicates that the water-retaining block has a lower speed for the water drainage compared to the other two blocks. It is also seen in Fig. 5 that the water volume in the bucket increases with time during 10–20 min for all the blocks first and then tends to remain unchanged after 20 min when the rain ceased. In the period of 20–40 min, the water volume collected from the pervious block also increases because the pervious block fails to hold the raining water. At 40 min, the water volume collected from the pervious block is very close to that from the dense block. However, the water-retaining block has the lowest water volume of 9.64 L among the three blocks, which verifies the water-retaining capacity of this novel block. This can also be supported by the comparison of the water-retaining capacity in Table 2. The water-retaining block has the highest water-retaining of 7.54 kg and the highest water-retaining rate of 6.97 kg/m^2.

3.2. Albedo and temperature

The temperatures were measured under two water conditions. The first period is during 11/02–11/03, in which the blocks were not watered. After that, the three blocks was quickly poured with the same amount of water at 00:00 a.m. on 11/03, in which the water-retaining block was filled with water up to the maximum height of the water tube (see Fig. 6).

Fig. 7 shows the variations of the temperatures measured at three depths. The water-retaining block has the lowest temperature at noon in the dry condition, especially at depths of 3 cm and 5 cm. After each block is watering, it is clearly seen that the measured temperature of the water-retaining block is lower than those of the other two blocks, regardless of daytime and nighttime, as well as the measured depth. The temperature can be reduced by a maximum value of 13 °C in the daytime and 3 °C at night. As time elapses, the temperatures of all the blocks decrease due to the drop in air temperature (see the air temperature in Fig. A1(d) and other meteorological data in Appendix). The results in Fig. 7 confirm that this drainable water-retaining paver block can greatly cool the ambient air temperature via evaporating the retained water. Due to the evaporation, as shown in Fig. 6, the water table decreases during 11/03–11/06. Decreasing the water table from 4 cm to 1 cm takes 39.8 h, where the water evaporation after 1 cm water table becomes slower when compared to that with a higher water table. The total decrease in the water table is about 4 cm during 11/03–11/06. It is known in Section 2.1 that the porosity of the permeable mixture in the block is 0.238. Decreasing 4 cm in the water table during 11/03–11/06 approximately leads to a total evaporation amount of 9.52 kg.

The albedos of the three blocks also vary with time. Fig. 8 presents the typical variations of the albedo. In the dry condition, the albedos of the water-retaining and pervious blocks are very close and about 0.02–0.03 smaller than that of the dense block (Fig. 8a). Since the surfaces of the pervious and water-retaining blocks are rough, the rough surfaces absorb more sunlight than a smooth surface that the dense block has. In the wet condition, the albedos of all the blocks decrease (Fig. 8b) when compared to those in the dry condition. This is because a wet surface looks darker than a dry one due to internal reflections in the moisture layer on a wet surface, leading to a decrease in the albedo. However, this decrease is not significant, about 0.005 for the dense block and 0.01 for the other two blocks.

3.3. Sensible heat

The daily cumulative sensible heat discharging from each block

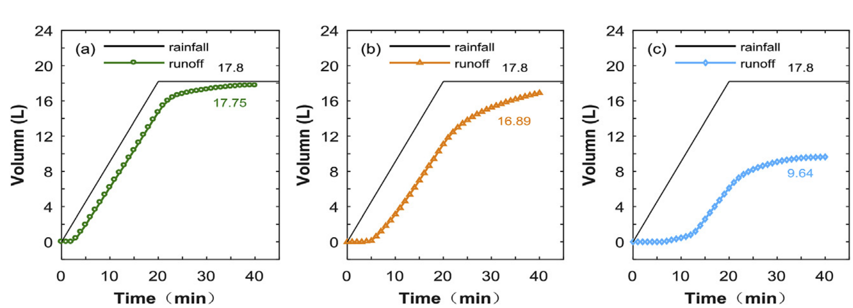

Fig. 5. Cumulative water collected by the bucket from: (a) dense block, (b) pervious block (c) drainable water-retaining block.

Table 2
Comparison of the water-retaining capacity.

samples	total raining water (kg)	water-retaining amount (kg)	water-retaining rate (kg/m^2)
water-retaining block	17.8	7.54	6.97
pervious block		0.78	0.72
dense block		0.05	0.05

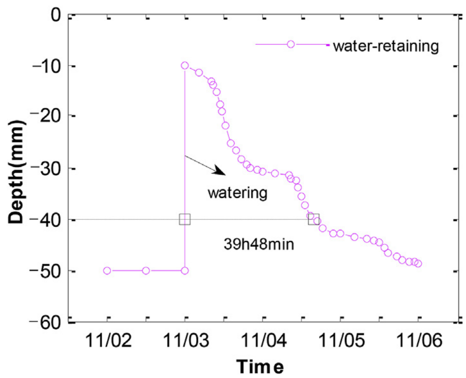

Fig. 6. Water depths observed from the water-retaining paver block.

was calculated with Eqs. (2) and (3) based on the meteorological data monitored at the experimental site (see Appendix). As shown in Fig. 9, the cumulative sensible heat releasing from the pervious block in the dry condition is almost equal to that from the dense block, while the cumulative outflow sensible heat from the water-retaining block is slightly smaller than that of the other two. In the wet condition, it is clearly seen that the cumulative sensible heat discharging from the water-retaining block is much smaller than that of the other two. On 11/04 and 11/05, the cumulative sensible heat releasing from the water-retaining block even becomes negative, which indicates that this drainable water-retainable block extracts heat from the surrounding air while the other two blocks discharge heat to the air. Therefore, this new block, when wet, can

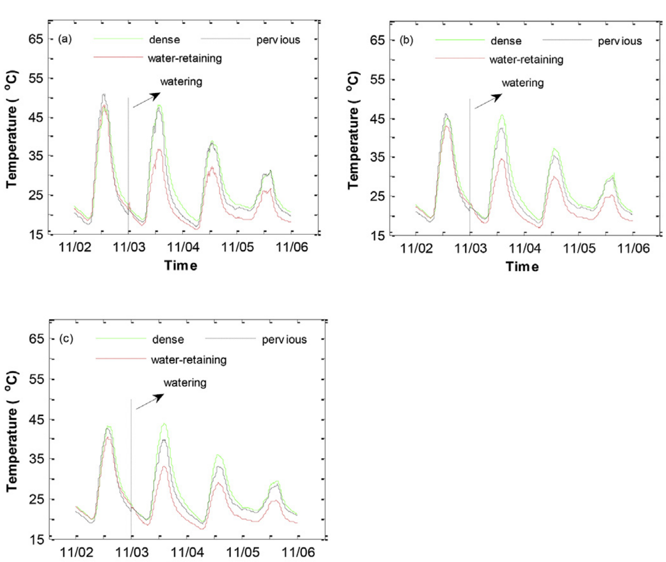

Fig. 7. Variations of the temperatures of the paver blocks measured at different depths: (a) 1 cm, (b) 3 cm, and (c) 5 cm.

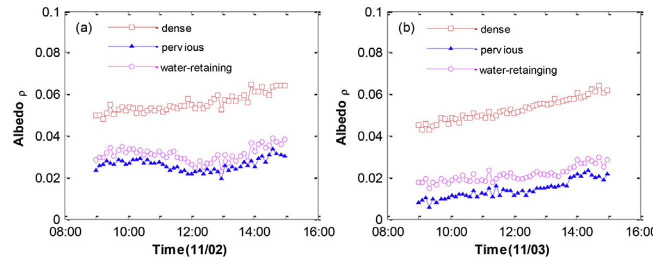

Fig. 8. Variations of the albedo for each block during: (a) dry condition and (b) wet condition.

neutralize the sensible heat in the air for attenuating the urban heat island effect.

3.4. Permeability

The permeability determines whether a water-retaining paver block can drain the retained water quickly or not for avoiding overflow (Li et al., 2013), especially during a heavy rain event. Table 3 shows the permeability of the water-retaining block calculated with Eq. (6). Based on three measurements, the average permeability was found to be 1590 mm/h, which is three orders higher than the precipitation rate of 9.9 mm/h for moderate rain (Glickman and Zenk, 2000) and two orders higher than the precipitation rate of 50.4 mm/h for heavy rain (Glickman and Zenk, 2000). The high permeability found from the water-retaining block reveals the excellent performance of draining the retained water quickly during a heavy rain event for avoiding urban flooding.

4. Discussions and further work

The water-retaining paver block with water tubes can further advance the water-retaining paver block proposed by (Qin et al., 2018a) because the excessive water infiltrates through this new drainable water-retaining block to subsoils. In the meantime, this new structure does not hurt the evaporative performance because a sizeable amount of water can still be held by the block. As shown in Figs. 7 and 9, the water-retaining block with the new structure performs very well for cooling the local air temperature. Therefore, compared to the previous one (Qin et al., 2018a), the water-retaining block embedded with water tubes is more advanced, which can be widely used in cities for reducing runoff and mitigating UHI simultaneously.

In addition, the mechanical performance of this advanced paver

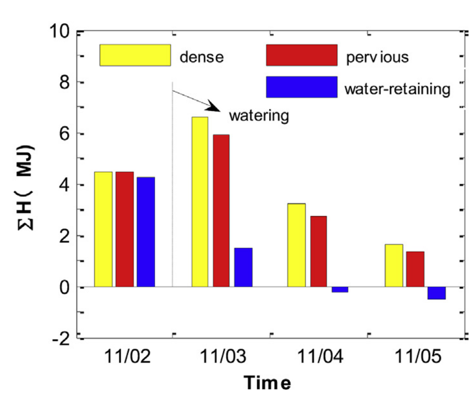

Fig. 9. Daily cumulative sensible heat releasing from the three blocks.

Table 3
Results of the permeability.

Sample	Density (kg/m^3)	Average k (mm/hr)	t (s)	Q (m^3)
water-retaining block	2024	1.59×10^3	60	4.80×10^{-2} 4.69×10^{-2} 4.85×10^{-2}

block may be better than that of the pervious paver block. According to Joshaghani et al. (2017), the compressive strength and flexural strength of typical previous concrete samples at 28 days are 6–9 MPa and 1–4 MPa, respectively. The aggregate size, the water/cement ratio, and the aggregate/cement ratio adopted in this study for casting the pervious mixture in the water-retaining paver block are almost the same as those in Joshaghani et al. (2017). Therefore, it is estimated that the compressive strength and flexural strength of the pervious mixture used for the water-retaining paver block are 6.6–6.9 MPa and 1.7–2.7 MPa, respectively. Because five water tubes are embedded in this water-retaining paver block and also the bottom and four sides of this paver block are sealed with dense mortars, as shown in Fig. 1a, this structure could increase the mechanical strength of the water-retaining paver block to some extent so that its mechanical performance could be better than that of the pervious paver block in this study that has been widely used for light-load pavements.

Embedding water tubes in the water-retaining block may raise the construction cost if too many water tubes are needed or the structure for embedding tubes is too complicated. This, however, can be resolved by designing a standard mold for manufacturing paver blocks. Another concern is the optimal structure of the water-retaining paver block to ensure the maximum evaporation and quick drainage. In this study, five water tubes were embedded in the block, four close to the corners and one in the center. As illustrated in Section 3.4, the permeability with five water tubes is two orders higher than the precipitation rate of heavy rain, which indicates that there still has a large room to improve the block structure with water tubes in the future work. For example, the number of water tubes could still be reduced to save the cost. The height of water tubes may further be increased to allow the paver block to retain more water. Increasing the porosity of the bock could also help increase the water retention during a rain event. Manufacturing a thicker block can also retain a greater amount of water for evaporation cooling. Therefore, further research can be placed on the above considerations to optimize this water-retaining paver block for improving its performance of reducing runoff and mitigating UHI simultaneously.

5. Conclusions

This study proposes a novel drainable water-retaining paver block for reducing runoff and mitigating urban heat island simultaneously. To evaluate the performance of this paver block, the thermal parameters for mitigating urban heat island, including the albedo, temperature, water-retaining capacity, and sensible heat, were measured and compared with those of a dense block and a pervious block. The permeability of the water-retaining block was also measured to examine whether this paver block can avoid urban flooding during heavy rain. Our results clearly showed that the temperature of the water-retaining block in the wet condition is distinctly lower than those of the dense and pervious blocks, regardless of daytime, nighttime, and the measured depth, which indicates the good performance of the water-retaining block for cooling the local air temperature. It was also found that the permeability of the water-retaining block is three orders higher than the precipitation rate of moderate rain and two orders higher than the precipitation rate of heavy rain, which reveals the excellent performance of draining the retained water quickly during heavy rain for avoiding urban flooding. Therefore, this new drainable water-retaining paver block retains a great amount of water for mitigating urban heat island and meanwhile drains any excessive water quickly for avoiding urban flooding.

Acknowledgement

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Appendix

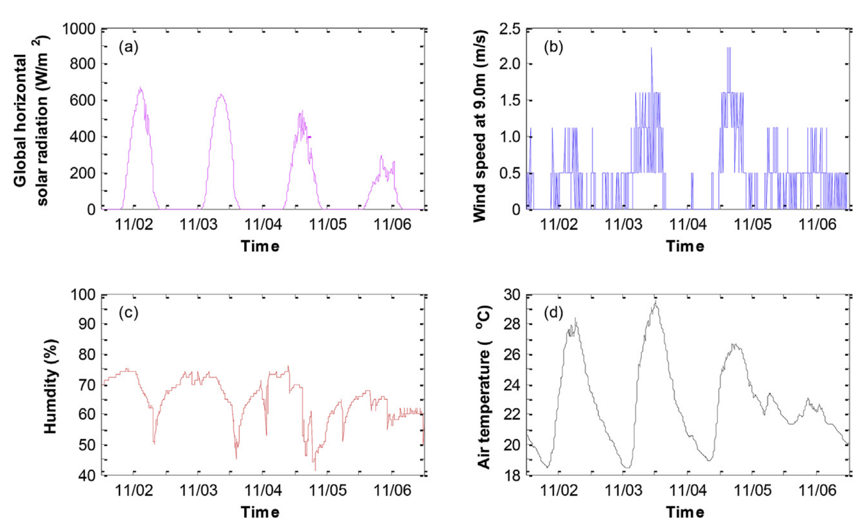

Fig. A1. The meteorological data monitored at the experimental site on 11/02–11/06, 2017. (a) Global horizontal solar radiation, (b) wind speed, (c) humidity, (d) air temperature.2

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