Experimental Study on the Thermal Characteristics of Urban Mockups With Different Paved Streets

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Research Article

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Abstract

Pavements in urban area absorb more sunlight due to the canyon-like geomorphology of the urban geometry, and store more heat due to the great thermal bulk properties of concrete. Heat released from pavements warms up the urban air, contributing to the urban heat island. Recently, the uses of cool pavements to reduce the pavement temperature as an urban heat island mitigation have gained momentum. Understanding the temperature and solar insolation of a pavement in an urban area is important to adopt the right cool pavement option for the right place. This study measured the temperature of paved streets in an urban mockup for four days in summer. It is found that east-west (EW) streets are the hottest place in an urban area, followed by the intersection, and finally the south-north (SN) street; and that increasing the pavements albedo reduces the pavement temperature effectively. The dark grey pavement in open space is hotter than those in an urban canyon. The heat storage in the building blocks keeps the pavement warmer more than 2^{o}C at nightime. The EW street is exposed to solar insolation for long hours, so it is suitable for preferentially developing of reflective cool pavements.

1 Introduction

Urbanizations are replacing soils and grass surfaces with buildings, pavements, and other sealed surfaces. Buildings and the pavements between two adjacent buildings create a canyon-like geomorphology, which absorbs more sunlight than buildings and pavements in open areas (Aida 1982, Aida and Gotoh 1982, He, Zhao et al. 2019). A great part of the heat stored in pavements and buildings releases as sensible heat to heat up the air in urban areas (Anandakumar 1999, He 2019). As a result, in summer, the air in urban areas and metropolitan areas is significantly hotter than the air in the surrounding rural areas, a well-known phenomenon that is called the urban heat island effect (Phelan, Kaloush et al. 2015, Mohajerani, Bakaric et al. 2017). As pavements typically cover 20–40% land in an urbanized area (Akbari and Rose 2001), the deployment of cool pavements in urban streets has been touted as a strategy for urban heat island mitigation (Santamouris, Synnefa et al. 2011, Akbari and Matthews 2012).

The science and technology of reducing the pavement temperature (i.e., cool pavement) has been well documented. The temperature of a traditional pavement can be cooled by increasing the pavement reflectance (Taha 1997, Akagawa, Takebayashi et al. 2008), by rising the evaporative cooling of the pavement (Hendel, Gutierrez et al. 2016, Wang, Meng et al. 2018), and other techniques that decrease the pavement temperature (Hasebe, Kamikawa et al. 2006, Chiarelli, Dawson et al. 2015). The reflectance of a pavement can be increased by coating the pavement surface with highly reflectance pigment (Feng, Zhong et al. 2012), sealing the pavement with light-colored layers (Tran, Powell et al. 2009), and others(Levinson and Akbari 2002). Increasing the cooling capacity of a pavement can be achieved by developing water-retaining pavements to hold water at the surface layer for subsequent evaporative cooling (Bao, Liu et al. 2019, Wang, Meng et al. 2019). Pavement temperature can be also reduced by harvesting the heat of a pavement for sustainable usages, and by embedding phase-change materials in a pavement to convert the absorbed heat to latent heat rather than sensible heat (Bo, Biao et al. 2011, Jiang, Jin et al. 2019). Details about techniques to reduce pavement temperature can be referred to Santamouris(Santamouris 2013).

However, it remains unknown how to find the right cool pavement options for the right place. Takebayashi and Moriyama (2012) simulated the temperature and solar absorption of an urban street canyon using the Monte Carlo method; they found that reflective pavement is only considered in a street canyon with an aspect ratio (street width to building height) that is greater than 1.5. In practice, the temperature of pavements in an urban canyon is different site-by-site because of the variations of the sky view factor, urban geometry, urban materials, solar radiation, city latitude, etc (Anandakumar 1999). For instance, on a sunny day, the intersection is insolated longer than the other places and thus shall be the hottest place in the urban canyon. The real temperature distribution in the intersection, east-west (EW) street, and south-north (SN) street remains little known. Understaning the temperature distribution in an urban street is important to educate the urban planners to adopt the right cool pavement option for the right place.

The goal of this study is to measure the temperature distribution in a typical urban canyon and thus to identify the hottest place of a paved street in the urban canyon. An urban mockup with an aspect ratio of 1.0 (building height to street width) was built up, and the temperature of the paved street in the urban mockup street was measured. Another urban mockup with white streets was setup side by side to conclude if increasing the reflectivity of the paved streets can cool down the pavement effectively. How the heat releasing from the building block affects the temperature of the urban street at night is also studied.

2 Experiments

To measure the temperature of paved streets in an urban canyon, we prepared an urban mockup that consists of a group of cubic concrete blocks. Each concrete block was a hardened dense Portland cement concrete cube with a density of 2350 ± 30 kg/m^3 and a length of 0.15 m on each side. The blocks were arranged as indicated in Fig. 1. The ratio of the building height to the street weight was set as 1.0. The urban mockup, in the top view, was a square consisting of eight cubic blocks at each side. The mockup was placed at a rooftop of a five-floor 18 m-tall building to minimize the shaded effect during the experiment. The building is located at Nanning, Guangxi (longtitude:108.29º, latitude: 22.84º). The roof was a new double-skin roof that has interlocked tiles as the top layer, an 8 cm-thick air layer below the tile as the insulation layer, and a roof deck as the base.The tiles were hardened reinforced concrete slabs with a thickness of 3.0 cm. Details about this roofing structure can be found in Qin et al (2017).

The temperature of typical street sections of the urban mockup was measured. Considering the symmetry of the mockup, we measured the temperature of an L-shape street section that consists of the intersection, north-south street, and the east-west street (Fig. 2). At this section, 42 thermocouples were mounted to the paved street surface to log the local temperature (Fig. 2). To get a representative temperature, each thermocouple was anchored to the upper surface of a 1mm×5mm×5 mm copper plate, the sensor was first attached to the paver surface by thermal grease and the entire thermocouple was covered with aluminum foil. After all thermocouple-mounted plates were anchored, the paved street, the rooftop, and the building wall of the urban mockup were painted unicolor to ensure that the pavement is heated evenly. The painted pigment was selected such that the urban facet has an albedo of 0.30–0.40, which represents the albedo of common concrete surface in a city. After testing the reflectance spectra of a series of pigments and estimating the albedo of the spectra, a gray pigment with an albedo about 0.352 was selected and used to paint the paved street, the rooftop, and the building wall of the urban mockup (Fig. 1). This urban mockup is called gray mockup. The thermocouples and their lines were also painted with consistent color as the entire gray mockup (Fig. 1).

Nearby the urban mockup, for comparison, we used the same pigment to paint an open square with the same size but without concrete block standing. A thermocouple was anchored to the middle of this open square to log the local temperature for representing the temperature of the same pavement in an open area. Above the middle of the open area, an albedometer was leveled at a height of 0.5 m to log the incoming and reflected solar irradiance. The lower pyranometer of the albedometer was assembled with a baffle such that the detector of the pyranometer sees only the underlying mockup. Similarly, above the urban mockup, another albedometer with the same buffer on the lower pyranometer was centered and leveled at 0.5 m height to read the incident solar irradiation and the reflected radiation from the mock. The albedo of the urban mockup and of the slab was estimated according to the method proposed by Qin et al (2018).

Close to these two squares, another urban mockup and another open square were prepared for a comparison side by side (Fig. 1). They had the same geometry as the gray urban mockup and the same cubic blocks as the building, except that the street of this mockup was painted white. The goal was to examine if increasing the reflectivity of the paved street in an urban canyon can effectively cool the street. Only the temperature in the middle of the intersection was measured because of the limitation of the measurement capacity of the data logger. Similarly, the open square was painted white and the temperature in the middle of the square was logged.

Both the temperature and the radiation were logged simultaneously by three Campbell CR3000 loggers in an interval of one minute. To reduce measurement errors of the apparatus, the CR3000 was shaded and the length from the tip of each thermocouple to the CR3000 was the same. The measurement lasted from June 18 to June 22, 2019, a period of partial sunny days without rain. The global horizontal solar irradiance during the measurement is shown in **Appendix A** for reference.

3 Results

3.1 Temperature of an urban mockup during a day course

The instant temperatures of the representative paved streets in the urban mockup are different place to place (Fig. 3). At the middle day of a day (12:00), the EW street is the hottest place, followed by the intersection, and finally the SN street (Fig. 3a). This order seems reasonable because the EW street is always exposed to sunlight while the SN street always has some parts under shade. Compared to other places, the intersection has a highest sky view factor. Due to this high sky view factor, the intersection drains the absorbed heat faster than both the EW and SN streets. As a result, although the intersection also is exposed to the sunlight as the EW street, it is not the hottest place in the paved street in the urban mockup. Different from the EW street and the intersection, the SN street always has a part of area under shade because the sun rises at the east and sets at the west, making the SN street the coolest place in the paved street in the urban mockup during the middle day.

In the afternoon, the EW street is still the hottest place (Fig. 3b). At 15:00, a half of the NS street has been shaded and the building wall close to the shadow has been shaded for hours. As a result, the west side of the SN street is the coolest place (Fig. 3b), which can be about 3-5^{o}C cooler than the EW street. The east wall of the building along the SN street are facing to the sun, so the place close to the building wall is the hottest place in the SN street. At this time, most part of the EW street is still exposed to sunlight so it stays hot. At the intersection, the hottest spot locates in the south part because some north part of the intersection has been shaded.

At midnight (24:00), the intersection is the coldest place, while the temperature of the NS street is close to that of the EW one. The reason for this phenomenon is that the intersection drains the heat absorbed during the daytime fastest because has a greater sky view factor than both the NS and EW streets. In the urban mockup, the intersection can be about 0.1^{o}C lower than both NS and EW street. In a real urban condition, the building and the street has greater thermal inertia and this temperature difference can be enlarged.

3.2 The daily main temperature of an urban mockup

The daily mean temperature of the paved street in the urban mockup further substantiates that the EW street is the hottest place, followed by the intersection, and finally the SN street (Fig. 4). The temperature difference is about 0.5-1.0^{o}C. The coldest place is the east side of the SN street. This is reasonable because the east side of the SN street is shaded in the morning when the local air temperature is still cool. The intersection is not as hot as the EW street because the intersection has a larger sky view factor and receive a lower amount of heat radiating and reflecting from the building wall. The EW street has almost the same insolation time as the intersection but a lower sky view factor, making it the hottest place in the canyon of the urban mockup.

3.3 Gray pavements in open space are hotter than those in urban mockup

Pavements in the open area are hotter than paved streets in the urban mockup, especially during the daytime. During the daytime, the centers of the intersection, EW street, and NS street of the mockup with the gray pavement are about 3-5^{o}C, 4-6^{o}C, and 6-10^{o}C cooler than the center of the open area with the gray pavement, respectively (Fig. 5). This is surprising because the urban mockup absorbs more sunlight than the pavement in open area due to the sunlight trapping effect of the urban canyon (**Appendix B**). A possible reason may be that the pavement at an open area is directly exposed to sunlight without shade. Another reason is that urban mockup has a greater thermal inertia and thus it has better resistance to temperature rise when it is exposed to sunlight. Due to this thermal inertia, at nighttime, the pavement in an urban canyon is hotter than that in open area because the heat emitted from this pavement and from the nearby cubic blocks is partially captured in the canyon. The difference, however, is much smaller compared to the difference during the daytime.

3.4 Increasing the albedo of paved street reduces temperature effectively

Increasing the albedo of pavements in the urban mockup greatly reduces their temperature. During the daytime, the center of the mockup with the white pavement (T_{imw}) is 5-10$^{\mathrm{o}}$C lower than the center of the mockup with the gray pavement (T_{img}). This difference indicates that increasing the albedo of the paved street in an urban area effectively cools down the street. During the daytime, the temperature at the center of the intersection of the mockup with the white pavement (T_{imw}) shows little to no difference from the temperature at the center of an open area with the white pavement (T_{ow}) (Fig. 6**)**. This minor difference between T_{imw} and T_{ow} means that the albedo of the pavement dominates the pavement temperature, while the urban geometry at this setup plays the secondary role only (Fig. 6). Although we did not measure the temperature at all places in the urban mockup, we can conclude that increasing the albedo of paved streets in an urban area like this urban mockup can decrease the temperature of the street at a degree comparable to the same pavements in open areas.

3.5 Heat storage in the building blocks warms the pavement at night

In Fig. 6, at nighttime, the center of the intersection (T_{imw}) is about 2$^{\mathrm{o}}$C warmer than the center of the pavement in the open area (T_{ow}). The difference, T_{imw}-T_{ow}, starts from 18:00 (sunset) and ends at 6:00 (sunrise) in the next day. During the time spell, there is no solar irradiation and both pavements have the same emissivity. As a result, the leading reason to the difference, T_{imw}-T_{ow}, is that the pavement in the mockup absorbs the heat emitting from the cubic blocks. From sunset to sunrise, the difference is almost the same, which indicates that the heat in the block is not exhausted during this time span. As the thickness of a real building wall is almost the same as the thickness of the cubic blocks in the urban mockup, we can conclude that the building wall can make pavement at the center of intersection 2$^{\mathrm{o}}$C warmer. As the center of the intersection in the mockup has the largest sky view factor and thus the least view factor to the building wall, one can further imagine that the heat released from the building wall warms the pavement in urban area more than 2$^{\mathrm{o}}$C.

4 Discussion

The urban mock-ups used in this study are different from a real urban morphology, the experiments were carried out with an urban mock-up by a uniform building height to reach a universal conclusion of the albedo and temperature of an urban canyon, although the building height in reality is not uniform and the building shape is not necessarily cubical. The ratio of building height to street width is different and varies in space. All these differences affect the albedo of the real urban morphology surface. Nevertheless, although the urban mock-up of 2.2×2.2 m^2 used in the experiment is much smaller than the size of a real city, it is much larger than the wavelength of the incident radiation so the diffraction can be ignored(Qin, Tan et al. 2016). The authors do believe the proposed model is useful because the parameters that dominate the albedo and temperature of an urban canyon are research-able and controllable in the mockup.

The experiment above demonstrates the albedos and temperatures of paved streets, and pavement in open areas. The albedo varies with time and has a nadir near solar noon, an observation is in accordance with the observations of(Masaru and Aida 1982, Akbari, Levinson et al. 2008). During sunny days, the albedo of the gray urban mockup is about 0.10–0.15 lower than that of the gray pavement slab in the open areas, this is because the photons reflected from an urban mockup surface are partially intercepted by the other surfaces, resulting in multiple reflections, which increase the absorption and decrease the albedo.

As expected, the pavement temperature in the center of the urban mockup is much lower than that of the open area. A crucial aspect is the multiple reflections of solar radiation in urban canyons. This finding is consistent with (Garcia-Nevado, Duport et al. 2021), who attributed the actual effect of inter-reflections within the canyon that leads to a radiative trapping phenomenon. In this study, the experiment time is on June 18–22. At this time spell and at the Tropic of Cancer, the sun is rightly above the experiment location. As a result, the EW street is exposed to sunlight during the daytime for long hours and shows a higher temperature than NS street. At other dates, the solar position is different so the sunlight falling on the paved street will be different. However, as the daytime temperature of the paved street is directly related to the solar insolation and its duration, it is more reasonable to develop reflective pavements in a street that is exposed to sunlight for a longer time. The positive results in the current study indicate that reflective pavement emerges as an attractive option to reduce the temperature of paved street as an urban heat island mitigation. In next study, we will explore the impact of different canyon geometries, concrete blocksizes, urban-block spacing, and pavement colors (i.e., albedo of paved streets) on the pavement temperature through an entire year.

5 Conclusion

This study side-by-side measured the temperature of paved streets in two urban mockups and measured the temperature of two paved slabs with the same color as the paved streets. It is found that in an urban street near the Tropic of Cancer, the hottest place is the EW street, followed by the intersection, and finally the SN street. On a partially sunny day, the daily mean temperature at the center of the EW street can be 3-5^{o}C hotter than that of the SN street. The reason is that the EW street has the longest duration of sun insolation. Therefore, the EW street is the most suitable place to develop reflective cool pavements as a strategy for urban heat island mitigation. Our measurement shows that increasing the albedo of pavements in the urban canyon can effectively cool down the pavement (about 5-10^oC). In addition, it is found that after a partially sunny day, the heat released from the building block can keep paved streets about 2^oC hotter than the pavements in the open air at nighttime.

Although reflective pavements have been advocated as possible solutions to reduce the urban surface temperature, there has been sparse information to understood the effect of solar reflective coatings on pedestrians. Future experiments are expected to assess the thermal impacts of albedo increase on pedestrians and to long-term observe temperatures of paved street in different regions to reach a universal conclusion on the use of reflective pavement as an urban heat island mitigation.

Declarations

Acknowledgments

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Data availability

All data included in this study are available upon request by contact with the corresponding author.

Credit Authors Statement

Kanghao Tan: Writing-original draft. Pei yuan WEI: Field measurement. Junsong WANG: Data analysis and plotting. Yinghong Qin: Project administration, Writing-review & editing, Supervision.

Conflicts of Interest

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal’s policies, and we believe that neither the manuscript nor the study violates any of these. There are no conflicts of interest to declare.

Ethics approval and consent to participate

The experimental site and materials here are neither privately owned lands nor protected areas. No specific permits were required for our research.

Consent to Publish section

Not applicable.

Symbols	
R	Albedo
T	Temperature, ^oC
T_{img}	Temperature at the center of the intersection of the mockup with gray pavement, ^oC
T_{emg}	Temperature at the center of the east-west pavement of the mockup with gray pavement, ^oC
T_{smg}	Temperature at the center of the south-north pavement of the mockup with gray pavement, ^oC
T_{imw}	Temperature at the center of the intersection of the mockup with white pavement, ^oC
T_{emw}	Temperature at the center of the east-west pavement of the mockup with wray pavement, ^oC
T_{smw}	Temperature at the center of the south-north pavement of the mockup with wray pavement, ^oC
T_{og}	Temperature at the center of theopenarea with gray pavement, ^oC
T_{ow}	Temperature at the center of the openarea with white pavement, ^oC

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Figures

Figure 1

Two urban mockups with a 2.2m×2.2m square were setup side by side for comparing the temperature of paved streets with different colors.

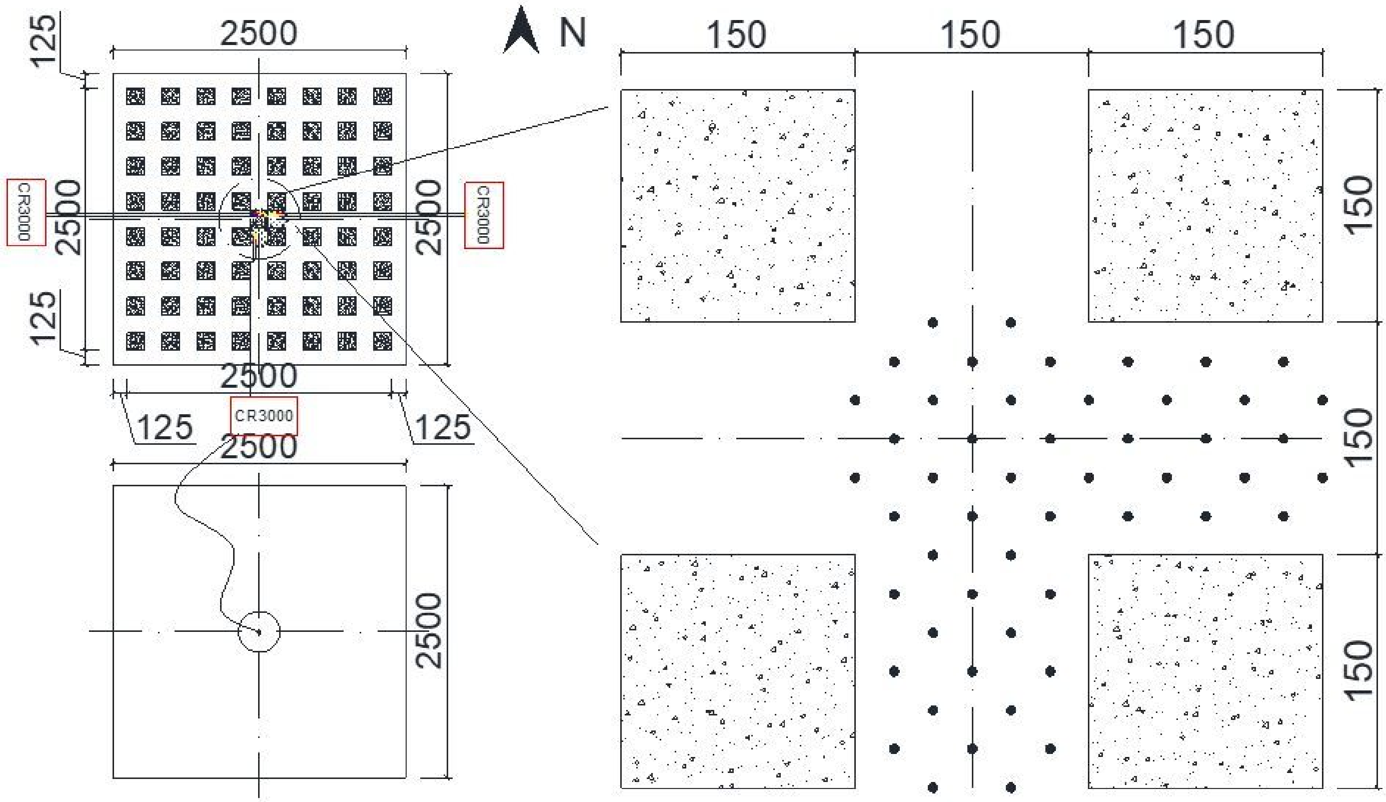

Figure 2

Places attached with thermocouples to log the local temperature. Note: black dots at the right magnified panel are thermocouples.

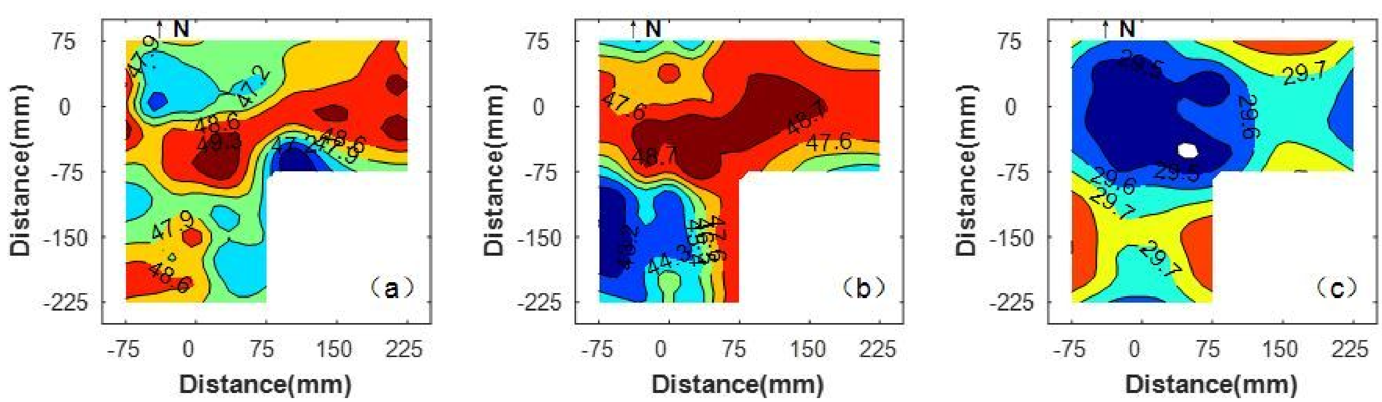

Figure 3

Surface temperature at the gray streets of the mockup on June 21. (a) 12:00; (b) 15:00, (c) 24:00.

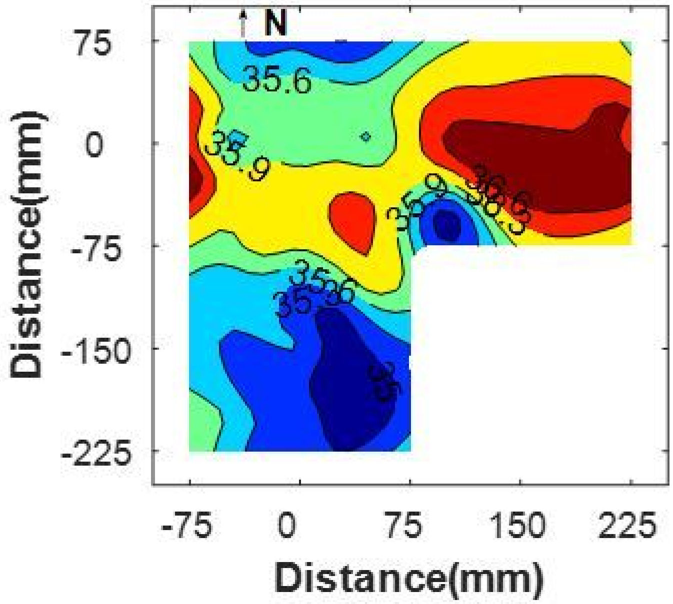

Figure 4

Mean daily surface temperature of streets of the urban mockup on June 21, 2019.

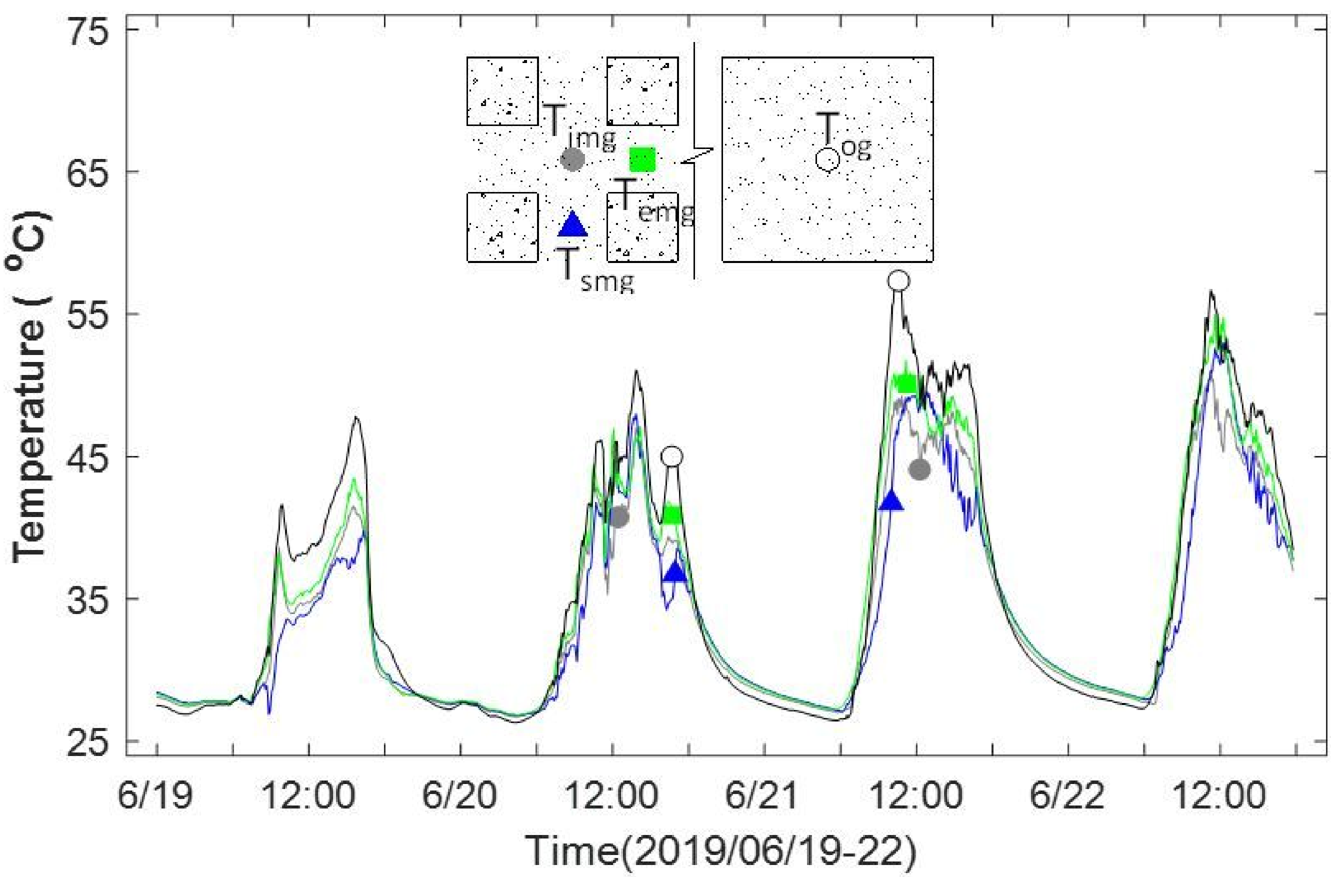

Figure 5

Typical daily temperature series of representative positions in the urban paved street vs in the pavement at an open area.

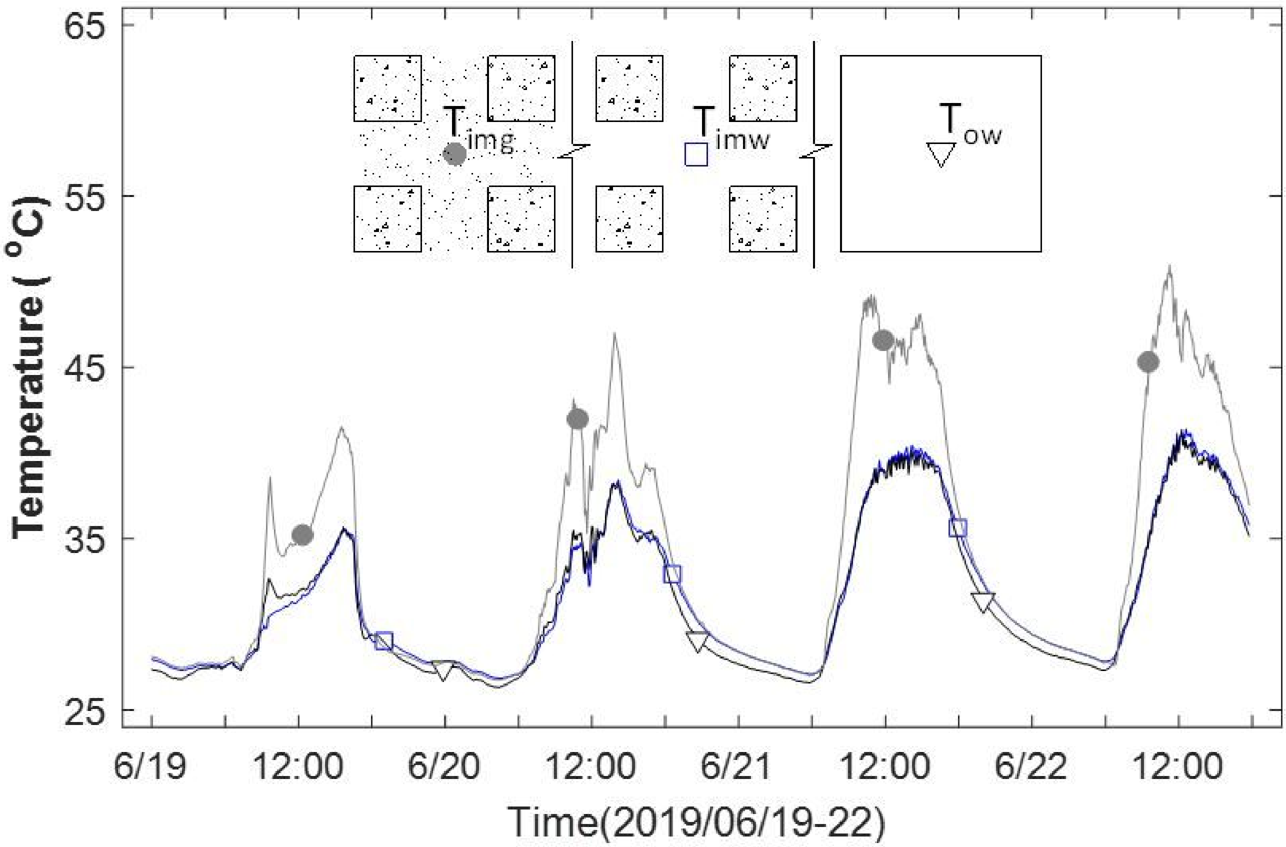

Figure 6

Typical daily temperature series of central positions in the two urban paved street vs in the white pavement at an open area.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Appendix.docx