Analysis of Surface Temperature Measurements over Complex Urban Sites

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Abstract

The aim of this study is to analyse the thermal properties of natural and artificial urban surfaces and the impact of surface colours and shading. Measuring campaigns were conducted in spring and summer (2018–2019) in the district XI of Budapest to determine the surface temperature of various urban materials. The results show that the coolest surfaces are natural covers (water, vegetation), while the hottest surfaces are concrete pavements, asphalt and rubber paving when exposed to direct solar radiation. Moreover, among concrete pavements, light coloured surfaces warm up 5-6 °C less on average compared to dark coloured surfaces. The use of rubber paving may be disadvantageous from the urban climatological point of view, as these surfaces become extremely hot under sunny conditions.

Keywords: surface temperature measurements; concrete pavements; rubber paving; outdoor thermal comfort; Budapest

Introduction

It is a well-known fact that in urban areas, human activities result in special climatic conditions. Urban climate studies nowadays are becoming more and more important as their results can be directly utilized by urban planners (e.g. Nevat et al., 2020), architects (e.g. Beniassadi et al., 2019) and municipal decision-makers (e.g. Zen et al., 2019). In the framework of a long-term cooperation between the Urban Climate Research Group of the Department of Meteorology at the Eötvös Loránd University (Budapest) and the Department of Environment at the Municipality of Újbuda (district XI of Budapest), regular urban climate measurements are carried out in the district XI of Budapest to detect the urban heat island (UHI) effect on different spatial scales.

Measuring campaigns were conducted in July 2018 and later, in May and June 2019 to determine the surface temperature of various urban materials using an infrared thermometer. The purpose of these measurements was to obtain information about the thermal properties of different urban surfaces, objects (covering materials, walls, pavements, etc.) in order to analyse which surfaces are suitable for decreasing and hence mitigating the UHI effect. The impact of the colour of different surfaces and the role of shading are analysed as well.

One of the most often analysed phenomena related to cities is the UHI effect (e.g. Sundborg, 1950; Oke, 1982). The main causes of the UHI-generating heat surplus are associated with the different structure, land cover materials and greenness of urban and rural areas. In addition, heat and moisture release due to human activities plays an important role, too. The effect of this extra warmth on human comfort depends on the season and the climatic location of the city. In the cold season or in a city with a relatively cold cli-

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mate UHI can result in some benefits, e.g. lower heating costs, less icing and fog, better outdoor comfort, etc. In contrast, in the warm season or in a city with a relatively hot climate, urban heat surplus has mostly negative consequences. Human discomfort, heat stress, higher mortality and increased energy demand of air conditioning can be definitely mentioned as the best-known effects (Stewart and Oke, 2012).

To determine the UHI intensity (Mirzaei and Haghighat, 2010), several temperature variables can be used, e.g., regular air temperature measurements from standard meteorological stations (e.g., Oke, 1973) and/or urban climatological networks (e.g. Šećerov et al., 2019), ground-based air temperature measurements using a moving vehicle (e.g., Unger et al., 2000), surface temperature data measured locally with infrared thermometers (e.g. Doulos et al., 2004) or measured remotely from an aircraft (e.g. Ben-Dor and Saaroni, 1997) or calculated from radiation measurements of satellites (e.g., Price, 1979; Nichol, 2005; Pongrácz et al., 2006). The daily cycles of UHI intensities are different when using the different methods as shown by Roth et al. (1989) or Stoll and Brazel (1992) using Vancouver (from British Columbia, Canada), Seattle (from Washington, USA), Los Angeles (from California, USA), and Phoenix (from Arizona, USA) as examples. Thus, it is very important to highlight whether air or surface temperature is used. The air temperature-based UHI intensity reaches its maximum at night (Oke, 1982), while the maximum of the surface temperature-based UHI (SUHI) occurs in the very early afternoon when the incoming solar radiation is the greatest (Vukovich, 1983).

Several studies have addressed the possibilities of mitigating the SUHI effect in the last few decades. For instance, Doulos et al. (2004) investigated the role of different materials in cooling outdoor urban spaces. The thermal characteristics of 93 commonly used pavement materials were examined using infrared thermography. They found that the main reason of the observed surface temperature differences is the different albedo of the studied materials, which depends on the colour, the surface texture and the construction material. More specifically, rough and dark coloured surfaces are clearly warmer than smooth, flat and light coloured surfaces. Similar results were obtained by Alchapar et al. (2013), who examined the thermal behaviour of pedestrian pavements, tiles and vertical claddings in a semi-arid city. Qin (2015) summarised the benefits and challenges of using cool pavements to mitigate the SUHI effect. This review article categorised the cool pavements into three main groups: (i) reflective pavements, (ii) evaporative pavements, and (iii) pavements with modified heat storage capabilities, e.g. heat-harvesting pavements. Reflec-

tive pavements are more appropriate in cities with hot and dry summers. Evaporative pavements are permeable or water-retentive surfaces that produce a cooling effect by evaporating the water stored in the pavement layers (Higashiyama et al., 2016). These pavements are more suitable for regions with a rainy and humid climate, where enough water is available. Heat-harvesting pavements stay cool and harness renewable energy at the same time. However, the use of these methods is still in a development phase because of high costs and open questions about efficiency.

In addition to the use of cool surfaces, vegetation cover also plays a major role in optimising urban thermal conditions. For example, Salata et al. (2015) analysed the combined effect of buildings' materials and vegetation on outdoor thermal comfort. They pointed out that high albedo results in lower surface temperatures, which helps to decrease temperatures in indoor environments, but can negatively affect the psychophysical well-being of pedestrians, especially in areas with low sky view factor. Overall, the most effective tool to support thermal comfort in an urban environment with hot climatic conditions is the presence of vegetation, which is able to decrease both air and surface temperature, particularly by the effect of evapotranspiration and by controlling both the incident and reflected direct shortwave radiation. Shahidan et al. (2012) completed model simulations to investigate the combined cooling effect of trees and ground materials in a tropical city. Their results show that three major factors play an important role in the optimal improvement of both indoor and outdoor environment, namely, the increase of tree quantity, higher tree canopy density and cool ground materials. The role of shading was analysed in the study of Vanos et al. (2016) in a special urban environment, namely, in children's playgrounds. Both natural and artificial shade types (i.e. trees and shade sail, respectively) can substantially reduce surface temperature.

The increasing albedo of urban areas certainly affects thermal conditions on the local scale; moreover, it can potentially compensate for the global warming-induced temperature increase. Akbari et al. (2012) simulated the long-term effect of increasing urban surface albedo using a global climate model. They found that the albedo increases of urban areas in the hot and temperate regions of the world by 0.1 results in a slight global cooling, i.e. a decrease of global mean temperature by 0.01–0.07 K, which corresponds to an emission reduction equivalent to 25–150 billion tonnes of CO_2.

As Muller et al. (2013) summarised, most of the in-situ measuring networks consider air temperature and other atmospheric variables, and only a smaller portion of these networks measure surface temperature. For example, Nadeau et al. (2009) analysed the measurements

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during a field campaign in a university campus of Lausanne (Switzerland) from 2006–2007. Although surface temperature was recorded, the main focus of this study was the dynamical processes in an urban environment with special attention to sensible heat flux. Probably the most important example of analysing in-situ measurements of surface temperature involves the Oklahoma MesoNet (Fiebrich et al., 2003), where infrared temperature sensors were used in 89 stations from 1999 to 2001 and revealed several limiting factors, namely, a problem of calibration in cold conditions, the difficult maintenance of remote locations, and the sensors' narrow view (causing limitations in the representation of local conditions). However, the majority of studies (e.g. Lo and Quattrochi, 2003; Rasul et al., 2017, Yavaşli, 2017, Wang et al., 2018) use remotely sensed measurements to analyse and compare surface temperatures in urban environment and rural surroundings, even though only clear sky conditions can be considered. Several

studies used satellite measurements for analysing urban effects in Central Europe. For example, Geletič et al. (2019) compared the SUHI of three cities (Prague and Brno from the Czech Republic, and Novi Sad from Serbia) using surface temperatures derived from LANDSAT-8. Dezső et al. (2005) analysed the SUHI of Budapest and other nine Hungarian cities, while Cheval and Dumitrescu (2015) studied the SUHI of Bucharest (Romania) using surface temperature data derived from MODIS (Moderate Resolution Imaging Spectroradiometer) measurements.

This study aims to analyse in-situ surface temperature measurements carried out in late spring and summer over various surface materials of two specific areas in a district of Budapest using an infrared thermometer. First, the measuring sites and the methodology are described, which is followed by the presentation and discussion of results, and finally, the concluding remarks at the end.

Data and methods

Újbuda is one of the most dynamically developing districts of the Hungarian capital with more than 130,000 inhabitants (HMI, 2019). Overall, the 23 districts of Budapest have a total of 1,752,286 inhabitants, of which almost 8% live in Újbuda, thus forming the most populated district. The geographical location of the district and the measuring sites is presented in Figure 1. The district is characterised by very diverse land use types: both densely and sparsely built-up residential areas, industrial and commercial areas, road and railway traffic nodes are present as well as parks, forests, lakes and rivers. Recently, major real estate developments have taken place in the district.

The measurements were made with a Voltcraft IR-280 infrared thermometer, which has been designed for non-contact temperature measurement. This instrument determines the surface temperature of an object from its emitted infrared energy and its emissivity. The temperature measuring range is from -30 °C to 270 °C.

Our urban climate measurement campaigns were organised in the periods of high solar elevation angles, i.e. in late spring and early summer (more specifically, in July 2018, and in May and June 2019) at two measuring sites. The first site is the largest public park of the district, called Bikás Park (Green Park Site), the second site is a busy transportation centre, one of the most densely built-up squares of the city, namely the Móricz Zsigmond Square (Artificial Covered Site). We selected 37 measuring points at the Green Park Site (Figure 2), and 17 measuring points at the Artificial Covered Site (Figure 3). The detailed list with the name and surface materials of these measuring points

for both sites can be found in Table 1 and Table 2, respectively. The Green Park Site includes several types of surface cover, both natural and artificial surfaces.
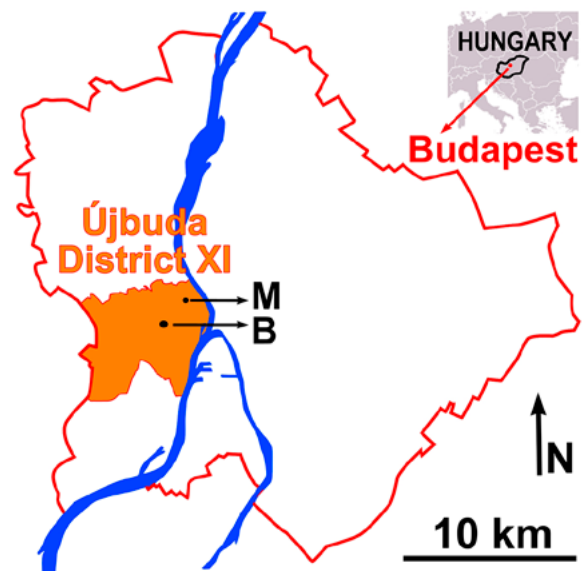

Figure 1. Geographical location of Újbuda (District XI of Budapest) and the measuring sites. M indicates the Móricz Zsigmond Square (Artificial Covered Site), B indicates the Bikás Park (Green Park Site).

The Artificial Covered Site is less diverse in land cover types, and it is dominated by different artificial surface materials (i.e. concrete and asphalt).

During the measurement campaign in 2018 (2–5 July), we carried out measurements four times per day at both sites: at 9 am, 1 pm, 5 pm and 9 pm. Weather conditions were ideal for our purposes with calm,
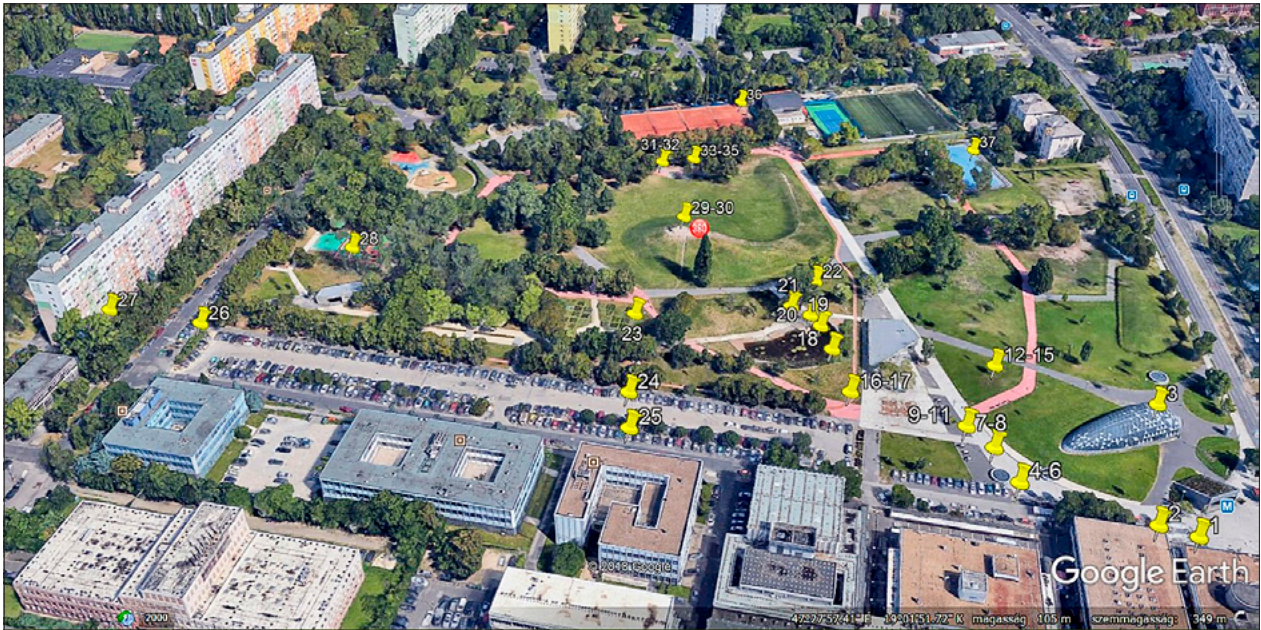
Figure 2. The locations of 37 measuring points (B1-B37) at Bikás Park (Google Earth, 07/2018)

clear, sunny weather, and the time of sunset was 8:43 pm. In the following year, three series of measurements were performed daily at 8 am, 2 pm, and 8 pm. The weather was cloudy with shorter sunny periods in some parts of the campaign. The sunset was recorded at 8:16 pm on 17 May, at 8:23–8:26 pm during 23–26 May, and at 8:36-8:37 during 6–7 June. We measured separately the temperature of the different surfaces exposed to direct sunlight and the temperature of the shaded surfaces if both types occurred at the measuring point. Hence, the role of direct sunlight in surface temperature can be examined.

Figure 3. The locations of 17 measuring points (M1-M17) at the Móricz Zsigmond Square (Google Earth, 07/2018)

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Table 1. The list of measuring points and surface materials at Bikás Park

number	description	surface material
B1	market sign	concrete
B2	pillar in the market	metal
B3	subway station building	glass
B4	dark gray pavement blocks	concrete
B5	red pavement blocks	concrete
B6	gray pavement blocks	concrete
B7	dark gray pavement blocks	concrete
B8	light gray pavement blocks	concrete
B9	bench	wood
B10	bench	metal
B11	table	concrete
B12	statue of Grosics	metal
B13	lawn at the statue of Grosics	plant
B14	lawn under the tree	plant
B15	tree	plant
B16	red rubber paving	rubber+polyurethane
B17	red pavement	concrete
B18	reed	plant
B19	lake	water
B20	lake footbridge	wood
B21	gravel pavement	stone
B22	tree	plant
B23	bare soil	soil
B24	stony asphalt road	asphalt
B25	asphalt road	asphalt
B26	shrub	plant
B27	concrete building	concrete
B28	playground pavement	concrete
B29	statue of Bull	metal
B30	bare soil	soil
B31	grey rubber paving	rubber+polyurethane
B32	red rubber paving	rubber+polyurethane
B33	bicycle handlebars	plastic
B34	metal pipe	metal
B35	public workout equipment	metal
B36	tennis court cover	clay
B37	football field blue rubber paving	rubber+polyurethane

Table 2. The list of measuring points and surface materials at Móricz Zsigmond Square

number	description	surface material
M1	subway station building	glass
M2	bench	wood
M3	Bistro wall	concrete
M4	lawn	plant
M5	tree	plant
M6	reed	plant
M7	dark gray pavement blocks	concrete
M8	red pavement blocks	concrete
M9	blue pavement blocks	concrete
M10	gray pavement blocks	concrete
M11	handrail	plastic
M12	tram rail	metal
M13	asphalt pavement between tram rails	asphalt
M14	road	asphalt
M15	light gray pavement blocks	concrete
M16	bare soil at Allée shopping center	soil
M17	water surface at Allée shopping center	water

Results and discussion

The aims of this study are to evaluate and to compare the thermal properties of different typical surface covers within urban areas. For this purpose, common statistical tools are performed, i.e. box-and-whiskers diagrams to represent the distribution of surface temperature measurements over a specific surface cover, averaging available measurements to compare different types of surface covers, etc.

To study the thermal properties of various materials, first the mean surface temperature of the noon measurements is determined. Figure 4 and Figure 5 show the results for the Green Park Site and for the Artificial Covered Site, respectively. The upper part of the diagrams (positive direction) represents the average surface temperature values of the surfaces exposed to direct sunlight, while the bottom part (nega-

tive direction) shows the average temperatures of the shaded parts of the surfaces. In order to facilitate the comparison, different surface materials are represented by different colours. Both diagrams demonstrate clearly that the coolest surfaces are natural covers, i.e. water or vegetation. Even if the surface is exposed to direct sunlight, and thus, absorbs more radiation than from diffuse sunlight only, their surface temperature remains close to the values in case of shaded conditions (the temperature differences between the sunny and shaded surfaces are mostly around 5 °C). Bare soil warms up more than vegetation when exposed to direct solar radiation, so it is better to plant vegetation than to leave bare soil surface without any vegetation. The hottest surfaces are clearly the sunny concrete pavements, dark painted wood objects, asphalt and rubber paving. Their average surface temperatures exceed 30 °C at noon, and even 40 °C in the case of wood, asphalt and rubber paving. The difference between mean temperatures of sunny and shaded surfaces of each measuring point depends on the properties of the actual surface material. Surface tempera-

tures are relatively high, close to 30 °C, in the case of shaded concrete pavements, while direct solar radiation makes the surface temperatures of concrete higher, up to 30-40 °C. Temperature differences are greater for rubber-paved surfaces, namely, the mean temperatures in the shaded areas are between 20 °C and 30 °C, but these rubber surfaces become extremely hot (over 40 °C) when they are exposed to direct radiation.

In the next steps of this study we focused on the thermal differences among the same types of surface covers, so we investigated the role of the colours in case of the concrete paving. For this purpose, four measuring points are selected from the Móricz Zsigmond Square that are close to each other with similar micro scale environments, but different colours. Measuring point M15 is covered by light grey pavement blocks, M10 is grey, M8 is red and M9 is blue. Figure 6 compares the distribution of the surface temperature measurement values of these selected points using a box-and-whisker diagram chart. (All available measurements are used in this analysis whether sunny or shaded.)
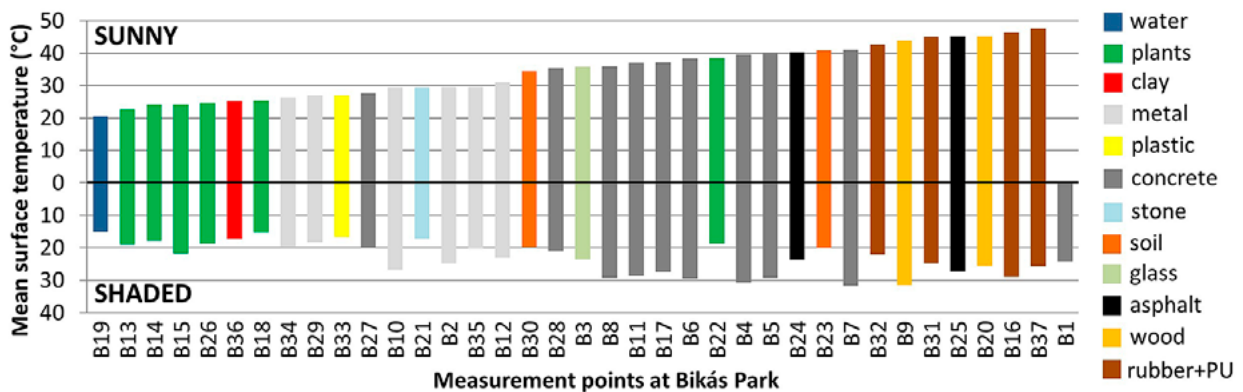

Figure 4. Mean surface temperature of measurements around noon at measuring points in Bikás Park. Colours indicate the surface materials of the points. The upper part of the diagram (positive direction) represents the sunny, while the lower part (negative direction) represents the shaded measurements at the same point
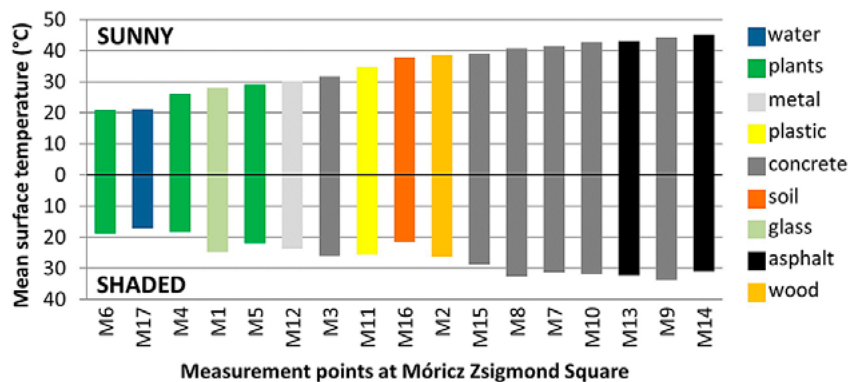

Figure 5. Mean surface temperature of measurements around noon at measuring points in Móricz Zsigmond Square. Colours indicate the surface materials of the points. The upper part of the diagram (positive direction) represents the sunny, while the lower part (negative direction) represents the shaded measurements at the same point

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The light grey pavement clearly shows the lowest temperature values, then, overall, the grey surface is warmer, the red is slightly warmer, and the blue pavement is the hottest. This sequence of temperature ranges clearly suggests that light coloured concrete covers are much better than dark coloured concrete covers from the point of view of how they affect the near-surface atmospheric layers where people can be found. The reason behind this behaviour is certainly the albedo (and consequently, the portions of reflected and absorbed radiations) of the different coloured concretes, i.e. light colours reflect more radiation than dark colours. As the temperature values of sunny surfaces are substantially higher than the temperature of shaded surfaces, the sub-median range of the entire distribution represents the shaded measurements, whereas the above-median range includes mainly the sunny measurements. Despite having more measurements for shaded conditions than sunny conditions, the asymmetry of the distribution shows a positive skewness towards higher temperature. This implies that the variation of sunny temperatures is greater than the variation of shaded temperatures.

As Figure 4 shows, the hottest points in the measurement series are the rubber-paved surfaces exposed to direct radiation. This paving material has lately become very popular in the design of playgrounds, running tracks and sport fields. Various technologies exist for producing these types of surfaces; the most often-used technology consists of the following two main processes, (i) splitting small pieces of vulcanised rubber, and then, (ii) gluing them together with various polyurethane or latex materials. The use of these surfaces has several advantages. For instance, rubber-paved surfaces reduce the risk of injury, it is easy to keep them clean, and they have a modern look. However, from the urban climatological point of view, the use of these covers may also be disadvantageous due to their thermal properties. In addition, volatile organic compounds (VOCs) can be released from these surfaces, and the total emis-
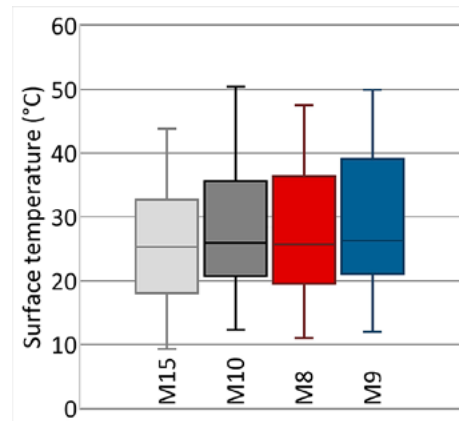

Figure 6. Surface temperature distribution of concrete pavement surfaces of different colours at Móricz Zsigmond Square. The box-and-whisker diagram includes the minimum and the maximum (bottom and upper end of the whiskers, respectively), the lower and upper quartiles (bottom and top of the box, respectively) and the median (line inside the box) of all the available data. The colours of the pavement blocks: M15 – light grey, M10 – grey, M8 – red, M9 – blue.

sion flux is correlated to the track surface temperature (Chang et al., 1999).

In the last part of this study we focus on these rubber-paved surfaces to evaluate their behaviour in the measuring sites. Figure 7 shows all temperature values for four measuring points covered by rubber paving located at Bikás Park (this surface cover type cannot be found at Móricz Zsigmond Square). The rubber paving materials are similar in these measuring points, but their colours are different, namely, B16 and B32 are red, B31 is grey, and B37 is blue. Sunny and shaded measurements are compared in this analysis, so different symbols are used for them in the diagram. Evening measurements mostly resulted in data for shaded conditions with very few exceptions. In addition, measurements with sunny conditions are missing on some days (e.g. 23.5.2019) due to cloudy weather. Summer is well-known for hot periods that can be even more severe in the urban environment. Extreme surface temperatures
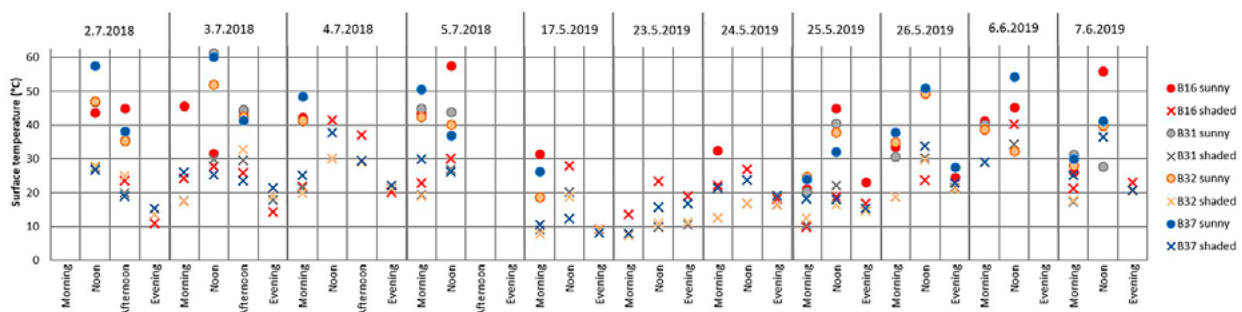

Figure 7. Surface temperature measurements of different rubber-paved surfaces at Bikás Park measuring site. Circles and crosses represent temperatures at sunny and shaded points, respectively. The colours of the rubber surfaces are as follows: B16 – red, B31 – grey, B32 – red, B37 – blue

can appear during this period of the year, especially in calm, sunny weather conditions. The highest temperature of the present campaigns was measured on 3.7.2018 when the temperature of the grey rubber paving reached 61.2 °C shortly after noon. Figure 7 clearly shows that there is a distinct difference between sunny and shaded surface temperature values. Shaded temperatures generally remain within tolerable temperature range, they exceed 30 °C in a few cases only. In contrast, sunny surfaces are often extremely warm (above 40 °C). These extreme temperatures have a negative impact on human comfort, so the usability of the facilities (playgrounds, sport fields) covered with this artificial material is strongly limited.

Conclusion

In the framework of a cooperation between the Urban Climate Research Group of the Department of Meteorology at the Eötvös Loránd University and the Department of Environment at the Municipality of Újbuda, measuring campaigns were conducted in July 2018 and in May and June 2019 to determine the surface temperature properties of different natural and artificial urban materials using a Voltcraft IR-280 infrared thermometer. The measurements were carried out at two measuring sites: (i) in the largest public park of the district, called Bikás Park (with 37 measuring points), (ii) in the commercial and public transportation centre of the district, called Móricz Zsigmond Square (with 17 measuring points). On the basis of the compiled database, a detailed statistical analysis was performed to investigate the thermal properties of various urban surfaces, e.g. pavements, walls, street furniture, sport facilities, water and plant surfaces.

In this period of the year, extremely high surface temperatures can occur, especially when the surface is directly exposed to sunlight. The average surface temperature measurements around noon exceed 40 °C in the case of dark painted wood objects, asphalt and rubber-paved surfaces with sunny conditions. In the case of most materials, shading reduces the surface temperature substantially, and consequently, potential thermal stress above these surfaces is decreased effectively.

The coolest surfaces are natural covers, i.e. water and vegetation surfaces. Bare soil surfaces are slightly warmer, which highlights that the planting of vegetation can provide climatic benefits, and overall, it will improve human comfort.

Substantial temperature differences can often be detected among similar surface covers within the same type of materials. Surface colours definitely influence the thermal properties; thus choosing the appropriate colour can effectively reduce the surface temperature. The analysis focusing on the concrete paving blocks with different colours shows that the average surface temperature of light grey surfaces is 5-7 °C lower than the average temperature of darker colours. The difference is more pronounced when the surfaces are exposed to direct sunlight. The reason behind this behaviour is probably the albedo of the different coloured concretes, i.e. light colours reflect more and absorbs less radiation than dark colours. The presented analysis clearly highlights that it is recommended to use light coloured paving blocks instead of dark pavements.

During the measurement series, the highest temperatures (over 50 °C) were measured at rubber paving-covered sport facilities and playgrounds, in sunny conditions. This material is very popular because its use has many benefits. Our study showed that the extensive use of these surfaces has a negative impact on the urban climate. These surfaces warm up so much during sunny summer days that the facilities covered with this material become practically unusable due to their extremely hot surface. In the case of this surface material, shading plays an important role as it can effectively control and reduce the warming of rubber paving-covered surfaces. More specifically, during daytime, the shaded parts of these surfaces are often 20-30 °C cooler than the sunny surfaces. Therefore, it is highly recommended to use other, natural materials with better thermal properties, e.g. sand and grass for playgrounds. Wherever the alternate natural cover is not possible for any reason, and this rubber paving material is chosen to cover the surface due to its advantageous properties, it is essential to provide potential shading and protect the surfaces from direct sunlight as much as possible, e.g. by planting trees with sufficient foliage around the facilities.

Surface temperature substantially influences the temperature of the near-surface atmospheric layers, and consequently, the overall human comfort. Our study showed that the adverse effects of the urban climate can be effectively mitigated (i) by selecting appropriately the covering materials, (ii) by increasing the proportion of natural vegetation and water surfaces, and (iii) by appropriate shading of surface covers with less advantageous thermal properties.

It is important for urban planning and development professionals to be aware of the role of different surfaces, colours and shading, and to take into account urban climatic factors when making a new investment. Taking the suggestions derived from our results into account can effectively contribute to a more comfortable, healthy and sustainable urban environment.

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