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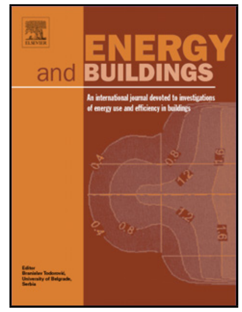

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Thermal Comfort of Pedestrian Spaces and the Influence of Pavement Materials on Warming Up During Summer

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Highlights

Users can not feel small differences in surface temperatures, i.e. less than 3°C.

Small differences in surface temperatures don’t affect user’s thermal comfort.

Surface temperatures of hottest and coolest material differ in range from 8- 22°C.

Different paving materials significantly influence the thermal comfort of pedestrians.

In hot climate users sense the temperature difference between 2-3°C in outdoor space.

Abstract

Public space is very valuable for a variety of community activities. Open public space comfort is one of the main indicators that provide its enjoyability, attractiveness and liveability. Having in mind that the climate conditions and the implemented urban design are influential in providing pedestrian thermal comfort, this study will focus on physical attributes of used pavement materials and their impact when they are exposed to high summer temperatures as well as on thermal comfort of the users of open public spaces. The methods that were used in the analysis include the method of direct surveying of inhabitants, the method of observation and the method of measuring the characteristics of different materials used for pavement in the pedestrian zone. The measuring of the current surface temperature of different paving materials used for pedestrian zone was performed during the summer season (July, August, and September) of 2015 in the central city zone of the city of Niš, with the goal of determining the maximum heating up of horizontal surfaces, i.e. pavements. The survey was done in July 2015 in the main square in Niš. The measuring determined that in the same conditions, various materials yield various maximum temperatures. It was also concluded that the type of material, colour, roughness and shading of an area affect the heating up of pedestrian surfaces. The purpose of this paper is to highlight the complexity of the relationship between microclimate thermal comfort in public open spaces and the measured temperature of the pavement surface, and to emphasize the importance of this relationship in the context of contemporary urban design. The paper presents the case study of pedestrian spaces in the central area of the City of Niš in Serbia.

Keywords: *pavement, surface temperatures, thermal comfort, pedestrian spaces, City of Niš, Serbia*

1. Introduction

Open public spaces are places where civic, cultural and social activities occur. They are stages of public life and a reflection of the interaction between physical, social, political and economic realities. A large part of open public spaces belongs to the so-called pedestrian environment. Urban planning and design that aim to encourage the intensity of pedestrian movement as part of integral urban policy with the aim of developing lively, safe, sustainable and healthy cities, observe pedestrian movement as a twofold character. It is perceived as both a mode of transport and an opportunity for many other activities. This is equally important for strengthening the social function of the urban environment as a meeting place, which contributes to social sustainability and the creation of an open and democratic society (Vukmirovic 2014). Accordingly, all the qualities that have to be assured in order to create good and liveable public spaces need to be applied to the creation of pedestrian spaces.

On the basis of the normative theories in urban design, several frameworks[1] have been defined to establish the criteria and requirements to be met in order to create quality places (Vukmirovic 2013). The majority of these frameworks recognize comfort as one of the most important criteria. Even so, Gehl (2014) notes that architects devote little attention to different aspects of comfort and emphasizes "that so little research is being conducted in this field, as architects influence the lives of so many people. We know more about the comfort and preferred habitats of elephants than we know about what makes people thrive in cities" (Gehl 2014).

[1] Whyte 1988, PPS 2003, PROMPT 2003, Walk21 2006, Bazik and Vukmirovic 2008, Gehl 2010, etc.

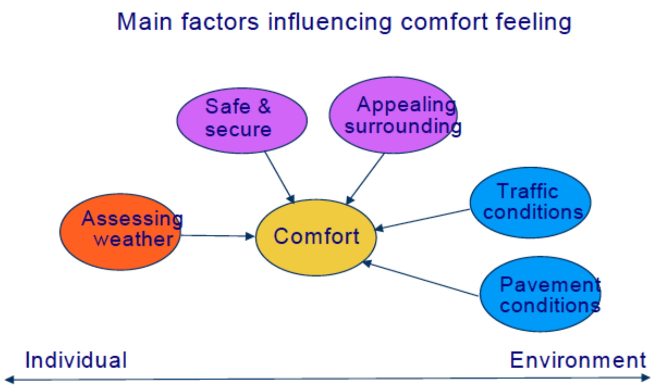

Fig. 1: Main factors influencing the feeling of comfort when walking (Ovstedal and Ryeng 2002)

Based on the results of PROMPT,[2] "comfort for pedestrians is a positive emotional reaction to external surroundings (the walking environment) in different situations, including physical, social and psychological reactions" while "the feeling and degree of comfort is dependent on the *surroundings*, the *situation* and the *individual*" (Ovstedal and Ryeng 2002). Considering the different impacts of the external environment, this complex criterion has different aspects such as thermal comfort, visual comfort, acoustic comfort, tactile comfort, smells, air pollution and allergens, the ease to move and the feeling of security (Ovstedal and Ryeng 2002). The research has also shown that the factors that influence the feeling of comfort when walking are: feeling safe and secure, pavement conditions, lighting conditions, appealing surroundings, weather and traffic conditions (see Fig. 1).

In accordance with this, weather, or more broadly, climate is the most influential factor that determines the level of comfort, particularly thermal comfort of public as well as pedestrian spaces. Nevertheless, many urban designs and renovation processes of public spaces are developed with little consideration for weather and climate factors such as air temperature, air humidity, wind speed and radiation fluxes. However, the relationship between urban design parameters and pedestrian thermal comfort has been the subject of many studies (Golany 1996; Sanaieian, et al. 2014; Jamei and Rajagopalan 2015) such as the influence of city design on wind flow and the reported effective role of ventilation in mitigating the high urban air temperatures and improving thermal comfort (Oke 1982; Kim and Baik 2005) or the

[2] PROMote Pedestrian Traffic in cities – a joint European research effort funded by the European Commission under the Key Action "The City of Tomorrow and Cultural Heritage" of its Fifth Framework Programme "Energy, Environment and Sustainable Development".

effect of urban design strategies on the magnitude of received solar radiation and its influence on pedestrian thermal comfort (Santamouris 2013). However, recent studies (Mendoza, et al. 2012; Li 2012) have focused on investigating the effects of particular elements of public space design and their influence on specific types of comfort with the aim of defining urban design strategies that will be implemented in order to improve the level of comfort of public spaces. The latest assessment of the IPCC (Chapter 8 of Climate Change 2014: Impacts, Adaptation and Vulnerability, the IPCC Working Group II contribution to the Fifth Assessment Report) highlights the limits of what adaptation can do to protect urban areas. Urban areas are the most affected by climate change, and they are facing increasingly negative effects of it. The measurements have shown the increase in temperature in densely built urban areas – heat islands, as well as substantial warming in temperature extremes (Jones, et al. 2009; IPCC 2007).

Serbia belongs to the sub-region of Southeast Europe where a higher temperature increase is forecast compared with the global level. Research has shown that Serbia also experienced a temperature increase in the last century, and that in the last two decades there were 14 years with temperatures above the normal recorded in the period from 1960 to 1985. Three years were designated as distinctly warmer, while the year 2000 was the warmest in the previous century. By the end of the 21st century, this increase will be from 2.2 to 5.1ºC, especially during the summer months (Karadžić and Mijović 2007; Djukic and Stupar 2011).

Considering the planned activities on the expansion of the pedestrian zone in the central core of the City of Niš, different materials used for paving in various stages of expansion and the aspect of thermal comfort that needs to be achieved, the present study is focused on the determination of heating up of the materials commonly used for pedestrian zones at the most intensive solar radiation and maximum air temperatures. Similar studies that can be found in the literature dealt with the following: Asaeda, Vu Thanh and Wake (1996) concluded that the surface temperature, heat storage and its emission to the atmosphere were significantly greater for asphalt than for concrete and bare soil; Doulos, Santamouris and Livada (2004) performed comparative measurements of 93 different materials and measured surface temperature differences of more than 25°C; Rahn et al. (2015) compared the summer daytime surface temperatures of nine different pavement surfaces and grass cover, and found that darker pavements were hotter, more reflective lighter pavements were cooler, and grass was the coolest.

2. Pedestrian thermal comfort

Outdoor microclimate, together with safety, accessibility and liveability, is one of the most important qualities of public open spaces and is among the main factors that drive the individual perception and assessment of the place. It is an important factor within the social sustainability of an urban space at the local level, as well as ecological sustainability at the global level, The decision of people whether and when to use public open spaces is primarily influenced by the outdoor microclimate. On the other hand, spatial characteristics as the form, configuration and combination of surface materials influence the urban microclimate (Djukic, Novakovic and Stankovic 2015). However, thermal comfort directly affects the intensity of use of public open spaces and outdoor activities (Chen and Ng 2012, Cortesao et al. 2016). Microclimate characteristics are highly important, as thermal conditions of the environment affect people’s behaviour (Nikolopouloua and Steemers 2003, Nikolopouloua and Lykoudis 2006, Chen and Ng 2012). The relationship between the spatial characteristics and the urban sustainability is often viewed from a particular social, ecological or economic perspective. This paper highlights the link between ecological aspects and social aspects of urban public spaces, which can be simultaneously affected by the same spatial characteristics.

As stated previously, thermal comfort of public spaces is one of the factors that influence different activities of users. The intensity of these activities is inversely proportional to the level of discomfort experienced by the public space users when they are exposed to the climatic conditions. Consequently, minimizing public space thermal discomfort may enhance the liveability of a particular public space during bad weather and temperature conditions.

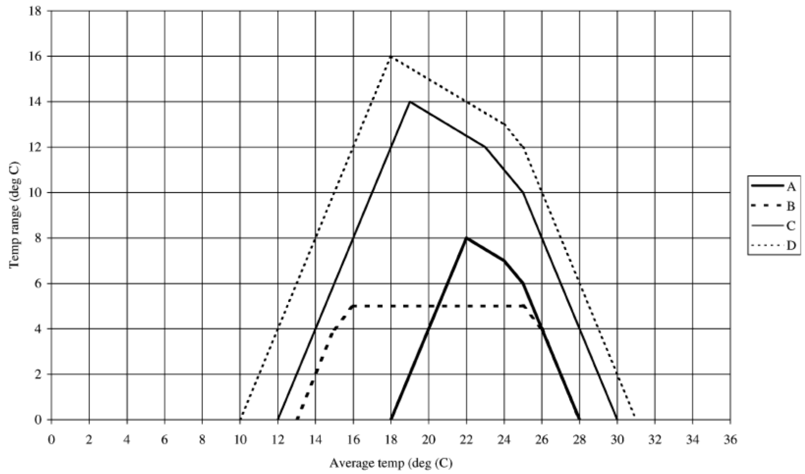

Fig. 2: The comfort triangle with zones for sedentary (A), right comfort (B), indoor circulation (C) and outdoor circulation. (Evans 2003)

On the other hand, thermal comfort is one of the so-called subjective categories, something that "has to do with a person's assessment of the level of stimulation to which his or her body is being subjected" (Lang 1994). In accordance with this and in a situation where the direct examination of the opinion of public space users on thermal comfort is not used, the researches employ general observations that are defined as a zone of comfort, as illustrated in the diagram that defines the comfort zone for outdoor circulations (walking), with appropriate activity levels and typical ranges of clothing levels (see Fig. 2). Evans considers that "users of outdoor spaces are more tolerant of wider temperature fluctuations, clothing insulation levels can vary widely, as in cold conditions they can be increased with overcoats, scarves and gloves, while in summer light clothing can be worn outdoors. Higher outdoor air movement in hot conditions can also extend the comfort zone. Finally, users of outdoor spaces can adjust activity levels over an extended range to compensate for lower or higher temperatures" (Evans 2003).

We also have to take into account what is considered a comfortable temperature for walking in Europe: "temperatures between 16 and 22°C are regarded as the most comfortable for walking. Temperatures between 0 and 15°C are regarded a bit less comfortable than temperatures between 23 and 33°C. Breeze is regarded as more comfortable than strong wind, and sunshine is regarded as more comfortable than snow and rain" (Ovstedal and Ryeng 2002).

Activity	80 W (walking)
Personal data	1.75 m (height), 75 kg, 35 years old, male
Clothing insulation	0.5 Clo (summer clothes)
Emission coefficient of the human body	Standard value 0.97

Fig. 3: Conditions used in the simulation of thermal comfort using the RayMan model for a normal person (Taleghani, Sailor and Ban-Weiss 2016)

Pedestrian thermal comfort could be also understood by calculating the psychological equivalent temperature (PET) using the RayMan model (Matzarakis, Rutz and Mayer 2006; Taleghani, Sailor and Ban-Weiss 2016). This model calculates PET based on the six parameters given for a specific time and location[3]. These parameters include four meteorological and two thermo-physiological parameters: air temperature (°C), mean radiant temperature (°C), wind velocity (ms^{-1}), air relative humidity (%), thermal resistance of clothing (Clo), and level of activity of humans (W) (Taleghani, Sailor and Ban-Weiss 2016). The values given in Fig. 3 represent a normal person walking in summer clothes in a simulated public space.

3. Pedestrian pavements and thermal properties of the materials

Heat is transferred in three ways: by conduction, convection and radiation. Since there is an empty space with no substance (vacuum) between the Sun and Earth, there can be no conduction or convection, so the heat is transferred by radiation. The Sun emits electromagnetic waves that (in the space) transfer the heat. All bodies having the temperature higher than the absolute zero radiate heat, but simultaneously absorb energy imparted by electromagnetic waves. The surface area of the body plays an important role in that. Solar energy enters our atmosphere as shortwave radiation in the form of ultraviolet (UV) rays and visible light, the ground heats up and re-emits energy as long wave radiation in the form of infrared rays. The properties of surface materials, such as reflective capacity

[3] "Activity (a.k.a. metabolic rate) can range from $40 Wm^{-2}$ (sleeping) to $410-505 Wm^{-2}$ (wrestling). Metabolism also depends on personal attributes such as height, weight, age and gender. Clothing insulation, which affects heat exchange between the human body and surroundings, ranges from 0 for a naked person to 1.5 for a person in heavy winter clothes." (Taleghani, Sailor and Ban-Weiss 2016)

of solar radiation (albedo), emissivity and heat absorption capacity, affect the surface temperature and consequently the urban areas temperature. Research shows that albedo and emissivity are the factors with the greatest influence on the surface temperatures of materials (Ferguson, et al. 2008). The albedo of a surface is defined as its hemispherical and wavelength-integrated reflectivity (Taha 1997). Albedo denotes the value from 0-1 which represents the share of reflected solar radiation: 0 - absorbs all incoming radiation, 1 - reflects all incoming radiation. The material albedo values change over time due to fatigue and pollution. Paving materials used in urban areas generally have a lower albedo than areas with vegetation; they reflect less and absorb more sunlight, which naturally results in higher surface and air temperatures. Emissivity determines the amount of long wave radiation emitted by the surface, and as such the surface temperature. As for the emissivity, most of building materials (excluding metal) have high emissivity coefficients (0.8-0.9), which means that they start to radiate heat even if the temperatures rise a bit. The materials used for paving have higher heat storage capacity than the natural materials, which means that the heat emission from these surfaces during night is higher than the emissions from the natural materials (grass, soil, etc.). Green surfaces and trees in particular are additionally cooled through the evapotranspiration process, and in this way, apart from shading, contribute to the lowering of air temperature (Akbari 1992). As opposed to roadways, which are generally covered with asphalt because of its advantages for car and bicycle traffic (smooth and all-weather surface), in the case of pedestrian surfaces, the selection of paving materials is considerably diverse and it is necessary to analyze the material characteristics and choose the most favourable solution in terms of surface heating up and permeability, storm water drainage capacity, durability, maintenance, aesthetics, etc. The choice of materials also affects the thermal comfort and the use of space. Cortesao et al. concluded that “the nature of paving materials and the amount of vegetation are clearly the reason for the remarkably different thermal comfort perceptions and the totally different intensity of use of each space” (Cortesao, et al. 2016).

4. Methodology and material

Having in mind the general aim of the research, measuring the microclimate comfort of open public spaces that influence the intensity of the pedestrian movements, as well as the attractiveness of open public spaces at the main square in Niš, the focus is placed on the spatial level of the problem, i.e. pavement, and users' satisfaction with the thermal comfort of open public spaces.

However, the methods used in the analysis are divided into the following three parts: (1) the observation of the study area and direct surveying of inhabitants, (2) the measurement of the temperature of different types of pavements, and (3) the simulation of thermal comfort. The simulation was performed using the RayMan model (Matzarakis, Rutz and Mayer 2006; Taleghani, Sailor and Ban-Weiss 2016) in order to compare the obtained values with those presented in Fig. 4 and with the results of the survey.

Table 3. Thermal comfort ranges for physiological equivalent temperature (PET) [65].

PET (°C)	Thermal perception	Grade of physiological stress
T < 4	Very cold	Extreme cold stress
4 < T < 8	Cold	Strong cold stress
8 < T < 13	Cool	Moderate cold stress
13 < T < 18	Slightly cool	Slightly cold stress
18 < T < 23	Comfortable	No thermal stress
23 < T < 29	Slightly warm	Slightly heat stress
29 < T < 35	Warm	Moderate heat stress
35 < T < 41	Hot	Strong heat stress
41 < T	Very Hot	Extreme heat stress

Fig. 4: Source (Taleghani, Sailor and Ban-Weiss 2016, 5)

Study area

The measuring of surface temperatures was conducted in the centre of the city of Niš, on the main pedestrian surface. The city of Niš is located in the Niš valley, at 43°19′ latitude north and 21°54′ longitude east. The centre of the city, near the central monument, is at 194 m above sea level. Niš has a moderate continental climate with the mean yearly temperature of 11.4°C. The hottest month is July with the mean temperature of 21.3°C, and the coldest month is January with the mean temperature of 0.2°C (see Fig. 5). The City of Niš is the third largest city in Serbia and the regional centre of southern Serbia. Its importance is further increased by the development of the international airport with frequent international flights, which contributes to the increased number of visitors and tourists.

The temperatures of pedestrian surfaces were measured during the summer months of 2015 at the main city public space – the Kralja Milana Square. In the period from June 20 to September 20, the data were collected from the measuring points on the pedestrian surfaces paved with different materials.

Climate data for Niš (1981–2010)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Record high °C (°F)	21.7 (71.1)	25.0 (77)	28.6 (83.5)	33.0 (91.4)	34.7 (94.5)	40.3 (104.5)	44.2 (111.6)	42.2 (108)	38.6 (101.5)	35.0 (95)	29.0 (84.2)	22.2 (72)	44.2 (111.6)
Average high °C (°F)	5.0 (41)	7.5 (45.5)	13.0 (55.4)	18.4 (65.1)	23.8 (74.8)	27.1 (80.8)	29.8 (85.6)	30.1 (86.2)	25.0 (77)	19.3 (66.7)	11.9 (53.4)	6.1 (43)	18.1 (64.6)
Daily mean °C (°F)	0.6 (33.1)	2.4 (36.3)	7.0 (44.6)	12.2 (54)	17.1 (62.8)	20.4 (68.7)	22.5 (72.5)	22.3 (72.1)	17.4 (63.3)	12.3 (54.1)	6.4 (43.5)	2.1 (35.8)	11.9 (53.4)
Average low °C (°F)	−2.2 (28)	−1.4 (29.5)	2.3 (36.1)	6.4 (43.5)	11.0 (51.8)	13.8 (56.8)	15.4 (59.7)	15.4 (59.7)	11.5 (52.7)	7.4 (45.3)	2.6 (36.7)	−0.8 (30.6)	6.8 (44.2)
Record low °C (°F)	−23.7 (−10.7)	−19.3 (−2.7)	−13.2 (8.2)	−5.6 (21.9)	−1.0 (30.2)	4.2 (39.6)	4.1 (39.4)	4.6 (40.3)	−2.2 (28)	−6.8 (19.8)	−14.0 (6.8)	−15.8 (3.6)	−23.7 (−10.7)
Average precipitation mm (inches)	38.8 (1.528)	36.8 (1.449)	42.5 (1.673)	56.6 (2.228)	58.0 (2.283)	57.3 (2.256)	44.0 (1.732)	46.7 (1.839)	48.0 (1.89)	45.5 (1.791)	54.8 (2.157)	51.5 (2.028)	580.3 (22.846)
Average precipitation days (≥ 0.1 mm)	13	13	12	13	12	11	9	8	9	9	11	14	134
Average relative humidity (%)	80	74	66	63	65	65	61	61	69	73	77	81	70
Mean monthly sunshine hours	64.5	93.3	147.8	171.5	220.9	251.2	286.7	274.3	201.9	150.5	85.9	49.4	1,997.7

Source: Republic Hydrometeorological Service of Serbia[24]

Fig. 5: Climate data for Niš (1981-2010). Source: Republic Hydrometeorological Service of Serbia

The main pedestrian zone in Niš is located in the centre of the city, and it is composed of a pedestrian and shopping street (Kralja Milana Obrenovića Street - Pobeda Street) of around 450m in length and a main city square and park (Kralja Milana Square) covering the area of around 0.9ha (see Fig. 6a). The detailed plan for the complex of the Kralja Milana Square in Niš (J.P Zavod za urbanizam Niš 2008) and the current General Regulation Plan for the Mediana municipality foresees the extension of the pedestrian zone so that the surface of the zone amounts to 2.44ha (see Fig. 6b), which represents 0.25% of the Plan area (J.P. Zavod za urbanizam Niš 2015). The plan envisages the expansion zone in a new way, according to the urban plan regulated on the basis of the new urban design competition, but with respect for the competition solutions adopted in 1990 and the actual labour market (see Fig. 7).

a) b)

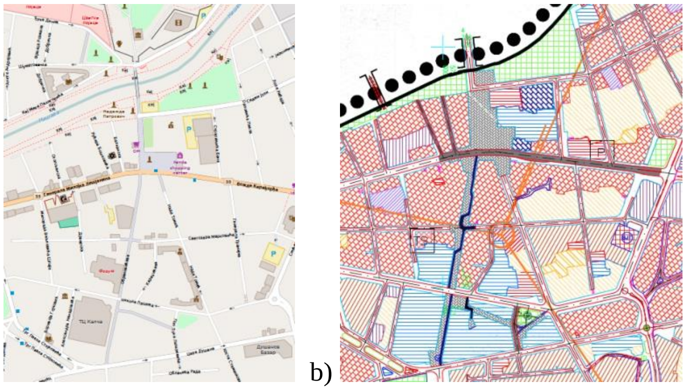

Fig. 6: Pedestrian zone in the centre of Niš: a) existing pedestrian zone (Open Street Map) and b) planned pedestrian zone (J.P. Zavod za urbanizam Niš 2015)

The current proposal for the urban design of the pedestrian zone was obtained at the Yugoslav competition for the arrangement of the Liberation square (Kralja Milana Square) and Pobeda Street in 1990. The urban plan for the development of the pedestrian zone was done on the basis of the first awarded proposal given by Branislav Jovin and Sinisa Temerinski. The first construction phase was finished in 1995. The proposal foresaw the use of granite stone in red, light and dark grey, which was applied in this phase. The second phase of the plan was implemented in 2009, when instead of stone, concrete slabs were applied, in ways that complement the colours and the geometry of the urban design proposal defined during the 1990s.

Fig. 7: Urban Plan of the extension of the pedestrian zone (J.P Zavod za urbanizam Niš 2008)

The presented situation has resulted in the application of a variety of materials for the pavement in the pedestrian zone. Thus a very small area is characterized by a large number of various materials, such as:

concrete tiles, various granite slabs, flagstones in grass, asphalt, and grass. The diversity of materials in one place allowed us to conduct the measuring of temperature of various surfaces which were exposed to almost identical heating conditions. The measuring points were chosen because they are exposed to the sun for the most of the day, except those points which were intentionally chosen as shaded in order to determine differences in temperature of shaded and sunlit surfaces.

Field data collection

According to many authors there is a strong connection between the experiences of thermal comfort of open urban space and type of pavement (Nikolopiulou and Lykoudis, 2006; Taha, Sailor and Akbari 1992; Yilmaz, Toy and Yilmaz 2007; Romero 2001). According to Taylor and Guthrie (2008) there are objective and subjective parameters that influence thermal comfort. Climatic, psychological (thermoregulation) and personal parameters are objective ones, while another group of psychological parameters (such as preference, tolerance, acceptability, motivation and adaptation) belong to the subjective ones. Obviously, the thermal comfort varies from person to person and it is very hard to predict the thermal sensation. However, in this part of the research the focus was on the personal parameters: age, gender, clothing level, user’s activities and position on the square, drink consumption and exposure to the sun.

The observation and survey were done on the same day when the temperature of the different pavements was measured. The analysis was enabled through a method of observation and direct population survey that included 200 inhabitants of Niš. The survey was done in July 2015. It covered the area of the selected square in Niš. Users were questioned at the chosen points with different pavement materials, exposure to the sun and shade and vegetation. The questionnaire comprised six questions regarding: age, gender, thermal comfort in the shade and in the sun, thermal comfort in different points of the square. Three possible answers on the thermal sensation scale were offered to the respondents: hot and uncomfortable, warm and slightly uncomfortable, and comfortable. The survey also included the observation of the users, regarding: clothing level, analysis of drink consumption and level of users’ activity (standing, walking slowly, walking moderately and walking fast).

The measurement of surface temperatures was performed during the summer months (June, July, August and September), more precisely, from June 20 to September 20, 2015. The recording was performed using a thermal vision camera. The measuring plan included various sorts of material of the pedestrian area (granite slabs, granite stone cobbles, asphalt, flagstones in the grass, rustic terrazzo, grass), surfaces of different colours (granite slabs of different colours, lighter and darker asphalt, etc.), surfaces of varying roughness (granite slabs of the same colour and dimensions, but of different roughness). Measurements were performed only during clear days, most of them being in the period between 14:30 and 16:00. This period was chosen after it was found that the temperatures of measured surfaces were the highest then. In addition, “random measurements” at different times of day were performed, as well as two daylong measurements of temperatures with an hour-long break from 06:00 to 22:00, one on July 8 and the other on August 10.

The measurement included fourteen measuring points at the main city square (Kralja Milana Square), on the surfaces intended exclusively for the pedestrians (see Fig. 8 and Tab.1). All measuring points were at the small distance, in the circle having radius of 75 m, exposed to identical microclimatic conditions during the day. Twelve points were exposed to sunlight the whole day (points 1-10, 13 and 14) and two points (11, 12) were intentionally chosen on the surfaces in partial or full shade during the day.

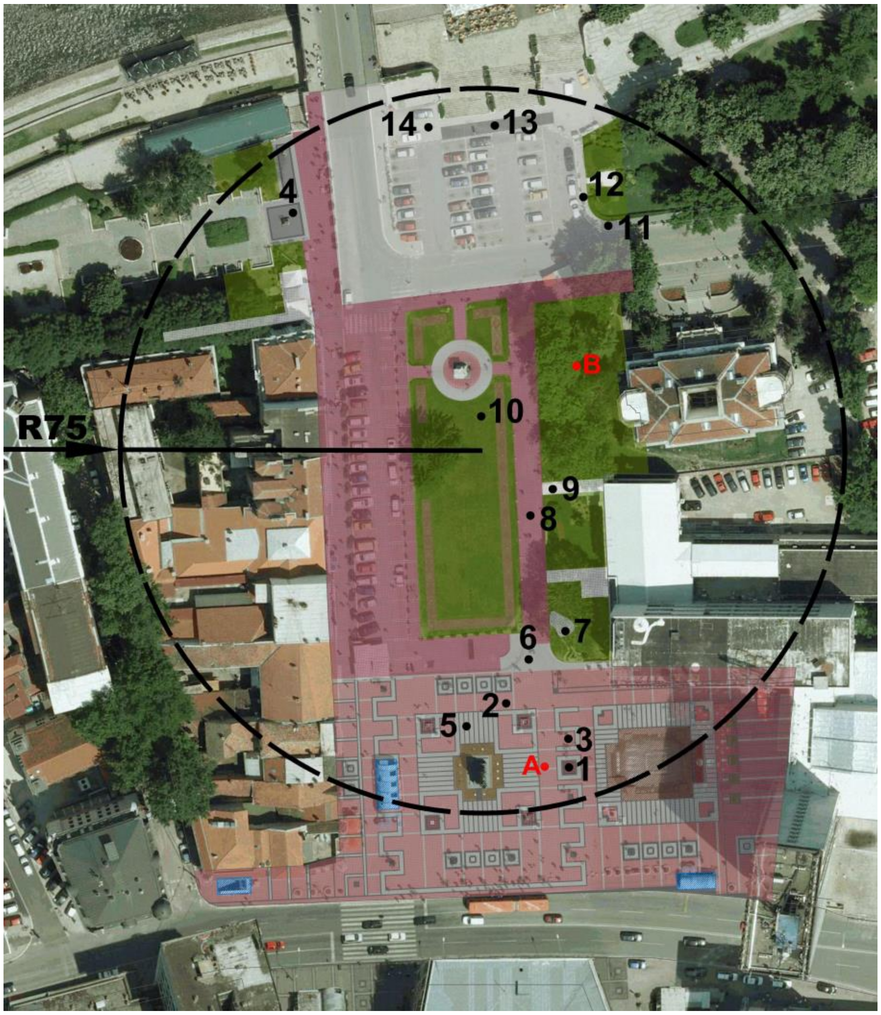

Fig. 8: Position of measuring points

Table 1: Description of measuring points

Points of measurement	**Pavement**	**Surface (m^2)**
Point 1	Red granite - smooth	26.24
Point 2	Red granite - rough	2,498.0
Point 3	Black granite - smooth	864.0
Point 4	Black granite - rough	57.80
Point 5	Grey granite - rough	1,005.83
Point 6	Granite stone cobbles	216.07
Point 7	Flagstones in the grass	17.26
Point 8	Concrete tiles - behaton	2,446.40
Point 9	Concrete tiles - rustic terrazzo	220.17
Point 10	Grass	2,822.3
Point 11	Asphalt shaded	
Point 12	Asphalt partly shaded	
Point 13	Dark asphalt - sunlit	57.32

Point 14	Light asphalt - sunlit	434.52

Equipment and software

The recording was performed using a thermal vision camera E30 (FLIR Systems, Sweden) with the thermal sensitivity of less than 0,1 °C, accuracy ±2% of the detected temperature, and the photograph resolution of 160×120 pixels. During the daylong measurements of surface temperature, measurements of air temperatures were performed using a manual thermometer of the type ODT 0302 (Iskra, Slovenia) with sensitivity ± 0,1 °C and accuracy ±0,05 °C.

Since all measuring points were at a small distance, in the circle with the radius of 75 m, the measurement was performed using one device, and it lasted for 10-20 min for all the marked points, which did not have a considerable impact on temperature variation. Prior to the start of temperature recording, two control measurements of surface temperature were performed using a contact thermometer and a thermal vision camera. It was found that the deviations were small and that they did not exceed 0.1°C. The contact thermometer requires more time for temperature detection, which would increase the time span of temperature measuring to more than an hour, and for that reason the measurement was continued using the thermal vision camera.

The simulation of thermal comfort

The results of the measuring of surface temperatures show that the greatest differences in surface temperatures are between the surfaces that are exposed to the sun all day and the shaded surfaces. Therefore, the simulation of thermal comfort was performed for: point A which is exposed to the sun during the whole day, and point B which is in the shade all day (see Fig. 8). Meteorological parameters for July 8, 2015, were used in the simulation (see Tab. 2). RayMan calculates thermal indices PMV, PET and SET by using personal data: height: 1.75 m, weight: 75.0 kg, age: 35 a, sex: m, clothing: 0.9 clo, and activity: 80.0 W.

Table 2: Meteorological parameters for 08th of July of 2015

	07:00	11:00	14:00	17:00	20:00
Air temperature (°C)	22.8	29.6	35.3	36.2	27.3
Relative humidity (%)	64	51	32	42	53

Wind velocity (m/s)	0.0	0.0	0.8	0.8	0.8
Cloud cover (octas)	0	1	1	0	0

5. Analysis and discussion of measurement results

Figure 9 shows the measurement results of air temperature and the chosen materials in the course of the entire measuring period. The chosen materials are those prevalently found in the pedestrian zone (concrete tiles - behaton, red granite and asphalt), the hottest material (black rough granite), and grass as the coolest surface. The air temperature during the measuring period ranged between 15°C in the morning and 37°C in the hottest part of the day. The temperature of the hottest material (black rough granite) ranged between 26.2 and 60.8°C, so that the difference of air temperature and the hottest material was between 11 and 24°C. The smallest differences between the air temperature and the hottest surface were found in early morning hours, while the largest differences were found at the hottest time of the day.

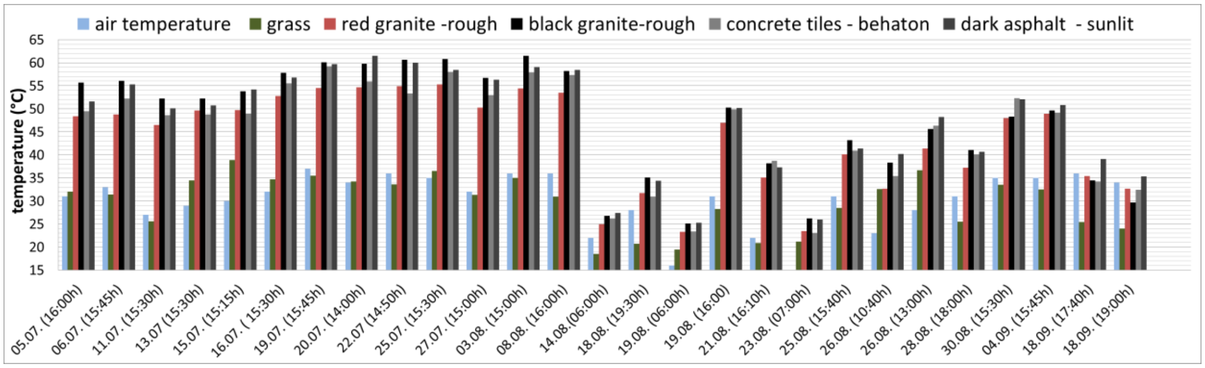

Fig. 9: Temperatures of air and the chosen materials in the course of the entire measuring period

After the daylong measuring of temperatures had confirmed that air and surface temperatures were the highest in the period between 14:30-16:00, a large number of measurements were conducted in this part of the day with the goal to determine the maximum surface heating up. In this part of the day, the air temperature varied in the range from 27°C to the maximum of 37°C (Δt=10°C). The calculation of the mean maximum air and surface temperatures was performed during the entire measuring period from July 5 to September 15 (whole period temperatures - WPT) (see Fig. 10) and during the hottest part of the year from July 15 to August 15 (hottest period temperatures - HPT).

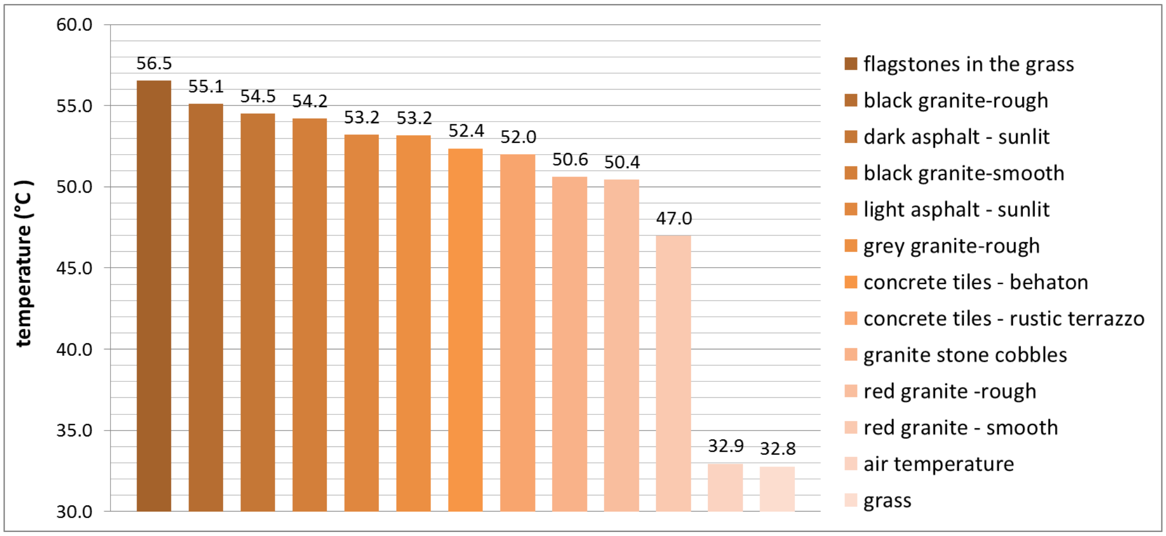

Fig. 10: Mean maximum temperatures of surfaces for the entire measuring period 5th July-18th Sep.2015

The highest temperatures were achieved by natural stone laid in grass (WPT-56.5°C, HPT-60.7 °C), however, since such sort of pavement has no large share on the pedestrian surfaces, this material was not considered. Black rough granite was assumed as the hottest material (WPT-55.1°C, HPT-59.4°C), followed by asphalt (WPT-54.5°C, HPT-58.8°C), other sorts of granite surfaces (grey and red granite) and concrete surfaces (rustic terrazzo and behaton tiles). The lowest temperatures, as expected, were reached by the grass surface WPT-32.8°C and HPT-34 °C, which was lower than the mean maximum air temperature (WPT-32.9, HPT - 35°C).

Impact of colour on surface temperature

The impact of colour on heating up is visible when comparing the temperatures of point 1 (red granite-smooth) and point 3 (black granite-smooth). The observed granite tiles have the same thickness, finish and same heating conditions, but different colour. Fig. 11 comparatively displays the temperatures of red and black smooth granite for the entire measuring period. The temperature of black granite was on average 7.2°C higher than the temperature of red granite–the average temperature of black granite in the entire measuring period was 54.2°C, and of red granite 47°C. The differences in temperature are the smallest in the early morning hours and in the evening after sunset, when the difference was 1.5-2.4 °C, while at the hottest part of the day (14:00-16:00h) this difference ranged between 5-11°C (see Fig. 11) The impact of the colour on the surface temperature is also visible at points 13 and 14 (dark and light asphalt), which are positioned at a very short mutual distance on asphalts of different mix designs. The measured temperatures of dark asphalt were on average 1-1.5°C higher than the temperatures of light asphalt (mean temperature of dark asphalt in all performed measurements was 47.4°C, and of light asphalt, 46.1°C).

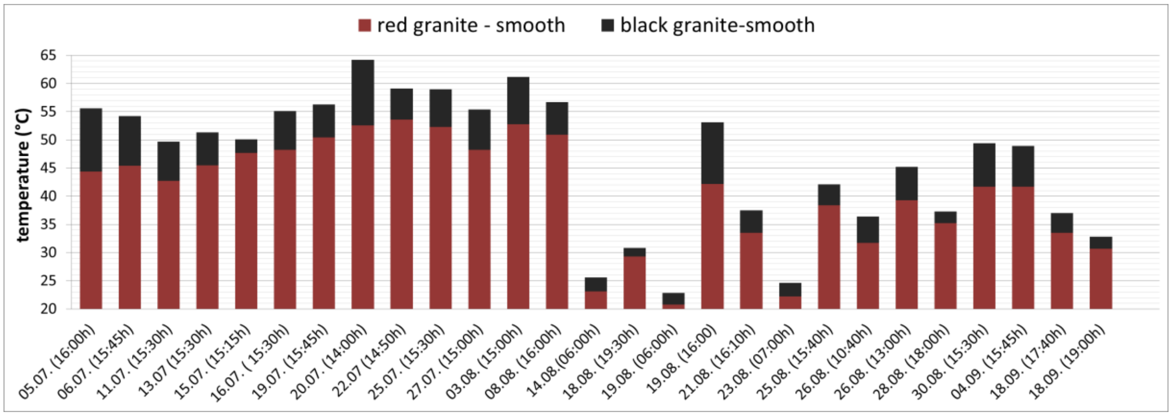

Fig. 11: Differences of temperatures of red and black granite in summer season

Impact of roughness on surface temperature

Measurements indicated that the same materials (type of material, thickness, colour), but of a different finish - roughness, achieved different maximum temperatures. The temperature of rough granite was 2-8°C higher than the temperature of the smooth one (see Fig. 12). A rough texture decreases albedo compared to that of smooth texture; it increases the possibility that a reflected beam strikes the same surface again and is absorbed, so a rough surface will have a higher temperature than a smooth one (Taha, Sailor and Akbari 1992).

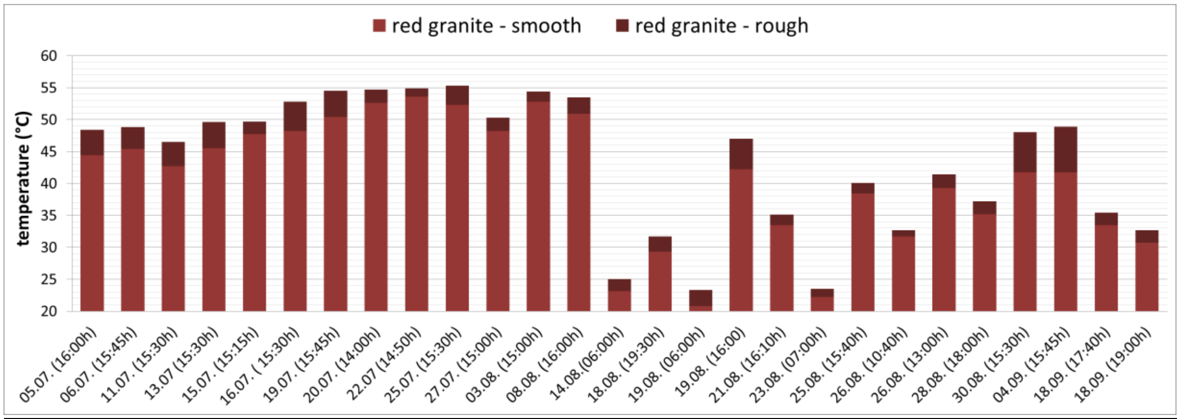

Fig. 12: Differences of temperatures of smooth and rough red granite in summer season

Impact of shading on surface temperature

In order to determine the effect of shading on the surface temperature, asphalt temperatures were measured in four different points, one being in the shade almost the entire day (point 11); the other being in the shade during one part and in the sunlight during the other part of the day (point 12); and two points exposed to direct sunlight almost the whole day (point 13 - dark asphalt and point 14 -light asphalt). The daylong measurement indicated that the temperatures of points in the daylong shade, or partial shade, ranged between 2-20°C, which was 4.5-25.8°C lower than the temperature of dark asphalt exposed to sunlight the whole day. The daylong temperature measuring indicated that the temperature of point 11, which was in the shade most of the day, in the hottest part of the day was 11°C lower than the temperature of the hottest asphalt (point 13 - dark asphalt in sunlight). The morning and evening measurements indicated that the temperature of points exposed to the sun during the entire day was higher than the temperature of points in the shade, both at the start of measuring (first measurement at 6:00) and after the sunset (last measurement at 22:00). The temperature of the points exposed to sunlight the whole day, gradually rises during the day with the constant difference in temperature from 0.8-2.4°C between dark and light surfaces (see Fig. 13). In the case of the points in the shade, there is a notable abrupt rise and fall of temperature depending on whether the point is in the shade or in the sunlight – e.g. the temperature of point 11 (almost in daylong shade) rose in the period between 8:00 and 9:00, and then remained unchanged in the period between 10:00 and 14:00 when it started to rise and reached the maximum around 15:45, after which it cooled down until the final temperature. It is interesting to notice that the temperatures of surfaces that were exposed to sunlight the entire day, even after nocturnal cooling down, remained higher than the temperatures of the surfaces which were shaded or partly shaded during the day.

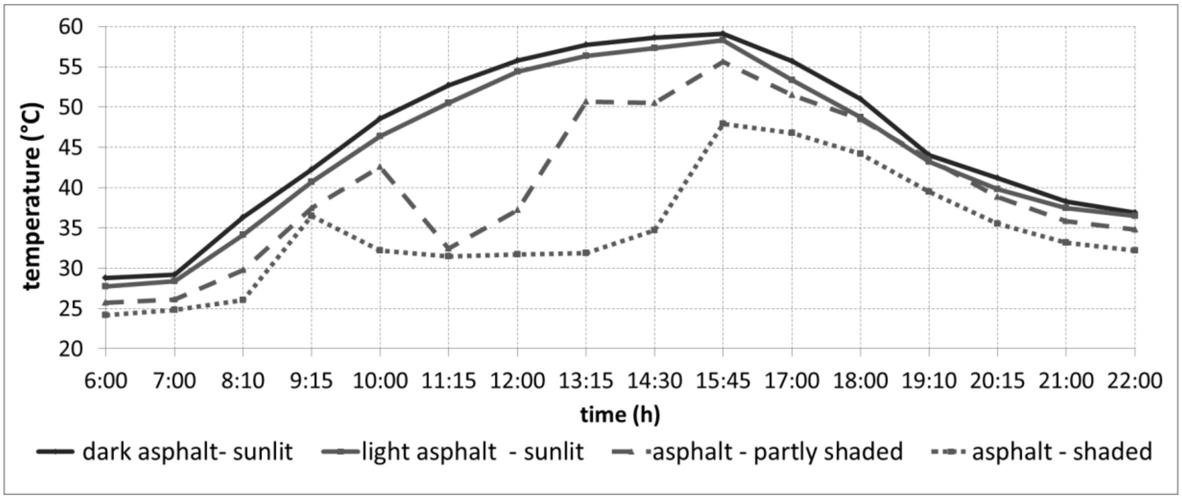

Figure 13: Daylong measuring of temperature of asphalts of different colors and shade

Thermal comfort

Results of the observation and survey

The identified types of users were: children (up to 15 years of age), adolescents (15-25), adults (25-65) and elderly/pensioners (more than 65). According to the survey there were: 10% of children, 22% of adolescents, 43% of adults and 25% of pensioners. The first two groups tolerated higher temperature at the square more easily, while the adults complained about thermal conditions and the elderly claimed that they were unable to cope with thermal conditions.

During the survey, there were 62% of women and 38% of men in the square. According to the results, women felt cooler than men. Three possible answers on the thermal sensation scale were offered to the respondents: hot and uncomfortable, warm and slightly uncomfortable, and comfortable. 54% of men felt hot and uncomfortable, 37% warm and slightly uncomfortable and 9% comfortable. At the same time, 49% of women felt hot and uncomfortable, 40% warm and slightly uncomfortable and 11% comfortable.

Regarding the positions of the users in the square, the respondents could not feel the difference between the parts covered with black granite, dark asphalt, light asphalt and grey granite, but they could feel the difference in temperature between those materials and concrete tiles – behaton, granite stone cobbles and red granite cobles. The difference in thermal sensation was even higher in comparison with grass or the parts next to the river Nišava. However, the parts of the square which were in shade were more comfortable than the ones which were more exposed to the sun. 75% of the respondents stated that they felt more comfortable in the shade, while 15% felt uncomfortable both in the sun and in the shade.

There were no remarkable differences in the clothing level between users, although it was noticed that the elderly were more likely to wear more clothes and usually wear shoes instead of sandals. Most of the users that belonged to the first three groups wore short sleeves blouses or sleeveless blouses, shorts, skirts, dresses, sandal or sneakers, while the 45% of the group of elderly wore long sleeved shirts and blouses, dresses, trousers, vests and shoes.

Several types of users' activities were recognized in the square: standing, walking slowly, walking moderately and walking fast. Only 6% of users were standing (probably waiting for someone) in the shadow, no one was standing in the sun, 20% were walking slowly, 60% were walking moderately and 14% were walking fast. Most of the people who were walking moderately belonged to the group of adults.

Results of simulation

The simulation was done in two points. Point A is in the middle of the city square and exposed to sunlight almost during the whole day, while point B is located under the tree canopy and shaded from 08:00 to 16:00 (see Fig. 14 and Fig. 15). Surface temperatures (Ts) at point A are higher than surface temperatures at point B, which corresponds to the results of the measurement. Differences in temperature range from 2°C early in the morning, then 12° at in the afternoon (14:00), to as much as 20°C at 11:00. The surface temperature of point B is higher than temperature of point A at 17:00, when point A is shaded and point B is exposed to sunlight, which emphasizes the impact of shading on surface temperature.

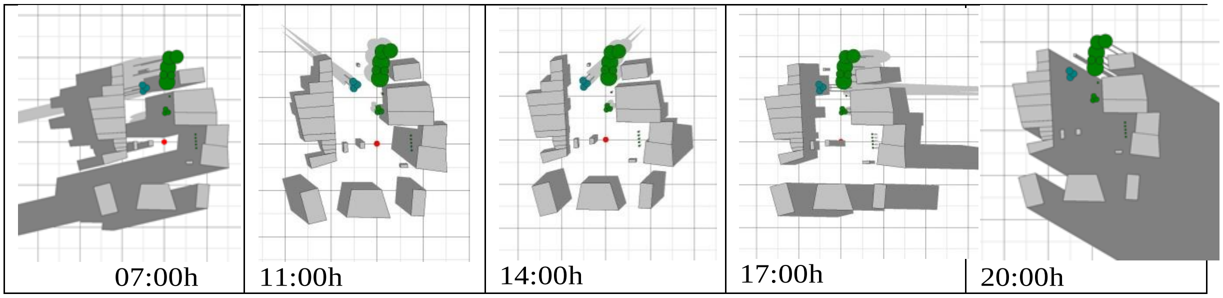

Fig. 13: Top view of environmental obstacles and their shadows on the ground

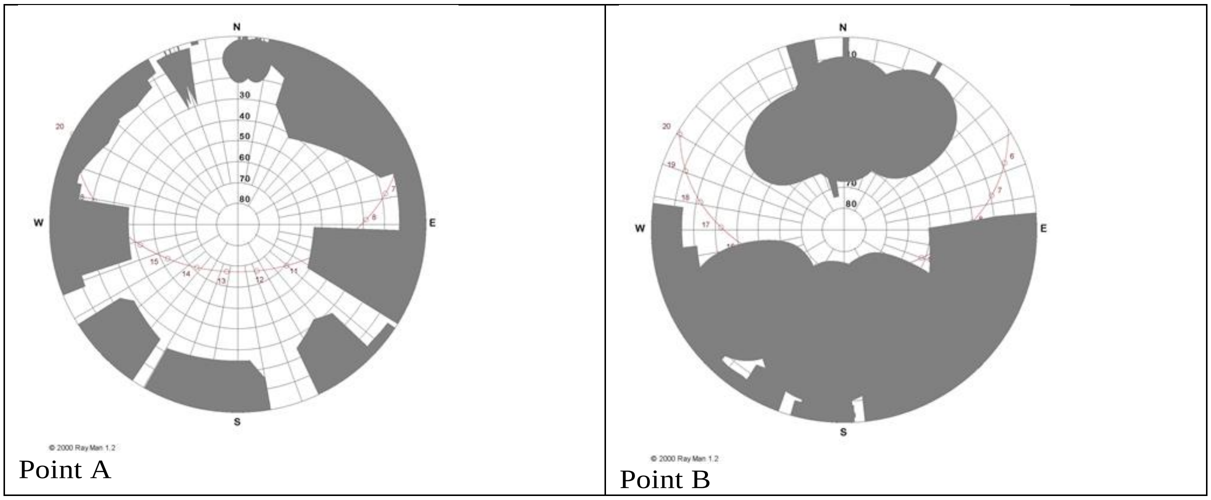

Figure 15: Diagram of sun orbit and horizon limitation in cylinder coordinates

The results of simulation show the difference in physiologically equivalent temperature (PET) for unshaded and shaded spaces. Although PET values for both points exceed 41°C for the period from 11:00 to 17:00 indicating extreme heat stress (see Fig. 4), PET values for point B are almost 5-10°C lower than PET values for point A at 11:00 and 14:00, when point B is shaded (see Fig.15)This corresponds to the results of the survey, which indicate that users feel more comfortable in the shade than in the areas exposed to the sun.

Table 3: Results of thermal comfort simulation for point A and point B; Gact - actual global radiation, Sact – actual direct radiation, Dact – actual diffuse radiation, Ts – surface temperature, Ta – air temperature, Tmrt - mean radiant temperature PMV - Predicted Mean Vote, PET-Physiologically Equivalent Temperature, SET-Standard Effective Temperature

Time	Point	Gact W/m^2	Sact W/m^2	Dact W/m^2	Ts °C	Ta °C	Tmrt °C	PMV °C	PET °C	SET °C
07:00	A	286	168	118	32.1	22.8	41.2	2.2	35.1	28.8
	B	227	147	81	30.7	22.8	37.7	1.9	32.8	27.2

11:00	A	720	549	171	55.3	29.6	62.5	5.0	51.7	40.6
	B	191	0	191	35.7	29.6	49.7	3.7	42.8	34.6
14:00	A	653	485	167	52.0	35.3	62.9	4.8	48.7	38.5
	B	179	0	179	39.3	35.3	52.3	4.0	43.3	34.6
17:00	A	138	0	138	38.2	36.2	46.8	3.9	41.5	33.4
	B	255	168	88	42.3	36.2	49.8	4.1	43.0	34.5
20:00	A	0	0	0	30.3	32.0	26.4	1.9	29.6	24.5
	B	0	0	0	30.9	32	28.6	2.1	30.5	25.2

General overview of the results

Results of the observation and survey showed that the respondents cannot feel small differences in surface temperatures (for example between parts covered with black granite and dark asphalt) and that these do not affect their comfort, but that they feel greater differences surface temperature (between dark asphalt and red granite cobles). Differences in surface temperatures range from 8°C between the hottest and the coolest material (black rough granite and red smooth granite) to 22°C between the hottest material and grass. Differences in temperature of light and dark materials at the hottest part of the day range from 5-11°C, while the temperature of rough surface is 2-8°C higher than the temperature of smooth surface. The greatest differences in temperature are between surfaces exposed to sunlight and shaded surfaces and they range between 2-20°C. The results of simulation also showed that the temperature (Ts) of the shaded surface is 2-20°C lower than the temperature of the unshaded surface. Previous research has shown that air temperature is the dominant factor to the overall comfort (Stathopoulos, Wu and Zacharias 2004). Considering the sensitivity to the difference in temperature determined by the survey and measured differences in surface temperature, it can be concluded that different paving materials significantly influence the thermal comfort of pedestrians. Although previous studies state that people can sense the temperature difference between 1-2°C (Lstiburek 2002; Hoppe 2002), this research concludes that in a hot climate users can sense the outdoor temperature difference between 2-3°C.

More than half of the respondents stated that they felt hot and uncomfortable in the open public space, and more than one third felt warm and slightly uncomfortable, although most of them were properly dressed and had a bottle of water. The absence of shade in the square combined with pavement surface materials was perceived as a discomfort during the hot summer day for most of the respondents. The comparison of the survey results and the simulation results showed matching between simulated and perceived thermal comfort. 75% of the respondents stated that they felt more comfortable in the shade. At the same time simulated PET values for shaded areas were lower than values for unshaded areas. In addition, most of the respondents felt comfortable on the grass.

Similar studies have shown that barely shaded locations (high sky view factor) are uncomfortable in summer (Lin, Matzarakis and Hwang 2010). In a survey conducted in Szeged (Hungary), Kantor and Unger (2010) concluded that in warmer conditions (even in autumn, after the long warm season) visitors chose a position in penumbra or shade. They also concluded that with the increasing amount of global radiation (clear sky) and at higher PET ranges greater portion of visitors stay in the grassy sector (Kantor and Unger 2010). Nikolopoulou and Lykoudis (2007) conducted the study of use of outdoor spaces in a Mediterranean urban area (Athens, Greece) and concluded that temperature and solar radiation are dominant parameters in relation to the use of space, because high temperatures contribute to discomfort and people prefer staying in shaded areas at higher temperatures.

Mitigation and adaptation strategies

The building sector is one of the largest energy end-use sectors. Buildings consume 40% of global primary energy and contribute to CO2 emissions in excess of 30% (Costa, et al. 2013), which makes a larger proportion of the total energy consumption than both industry and transportation (Yang, Yan and Lam 2014). Almost 50% of the energy consumed in buildings and 10–20% of the total energy consumption is used for HVAC systems (Costa, et al. 2013). As previously mentioned, Serbia belongs to the sub-region of Southeast Europe where a higher temperature increase is forecast compared with the global level. Niš is surrounded with

Belgrade, Sofia and Skopje, cities with the highest predicted temperature increase by 2100 according to the Climate Central projections (Kahn 2017), which means the energy consumption for air conditioning in Serbia will rise. Research has shown that there is a strong correlation between indoor thermal comfort and outdoor temperatures (Raja, et al. 2001; de Dear and Brager 2002; Yang, Yan, and Lam 2014), especially when outdoor temperatures are warmer, i.e. higher than 12.7°C (Nguyen, Schwartz and Dockery 2014). Yang et al. (2014) reported that in naturally ventilated buildings even 90% of the variations in the neutral temperature could be explained by the changes in the mean outdoor temperature. Considering this, it can be concluded that the use of appropriate paving materials and greenery (turf areas and trees) affects not only outdoor thermal comfort, but also contributes to the improvement of indoor thermal comfort and helps reduce the energy consumption for HVAC systems.

Recent research has focused on different mitigation and adaptation strategies both at the city and building level. Appropriate street orientation and urban corridors are proposed solutions for better urban ventilation (Santamouris and Kolokotsa 2015). Green areas preservation, strategic landscaping (ibid.), green and blue infrastructure planning and green roofs are some of the adaptation and mitigation strategies already incorporated in planning regulations and practice in some European cities (Carter 2011). Solar control systems, which include shading devices such as pergolas, tents, canopies, etc. and tree shading, reduce the radiant temperature of materials and improve outdoor thermal comfort. Trees planted close to a building reduce 70 to 85% of the radiation incident on building facades, and temperatures in the area around the trees are significantly lower than those in non-shaded areas (Papadakis, Tsamis and Kyritsis 2001). Results of thermal comfort simulations for open spaces in Italy (Noro and Lazzarin 2015) and Greece (Dimoudi, et al. 2014), which have similar climatic conditions as Serbia, showed that use of cool materials for open areas, together with other mitigation strategies such as: extensive use of vegetation, shading, use of water installations, can significantly reduce outdoor air temperature. “That temperature reduction have a big influence on the microclimate of the area, the thermal comfort of people in the outdoors spaces but also it will affect indoor conditions and buildings' cooling loads" (Dimoudi, et al. 2014). The latest mitigation and adaptation strategies include the use of Low and Zero Carbon Technologies and innovative materials such as: phase changing materials (Kim, et al. 2017), cool coatings, chromotropic and photocatalytic coatings, both for buildings and outdoor spaces (Santamouris and Kolokotsa 2015).

6. Conclusions

Outdoor thermal comfort is one of the crucial factors for providing a successful open public space, especially in the regions with warm and hot summers. However, paving has numerous functions in the cities and often covers more than 30% of the entire urban area within the city. It can cover pedestrian pathways as well as heavy traffic roadways, which must be taken into account when selecting materials. The pavement temperatures in the summer months are significantly higher than those of air and turf areas.

Since there is "a significant lack of information on the way microclimatic issues affect the use of open spaces, along with subjective data for evaluation of comfort conditions in outdoor spaces", as stated by Nikolopoulou and Lykoudis (2007), the undertaken field survey provided important insights into the validity of combining the used methods. Furthermore, by comparing the thermal comfort of the users and measured temperatures in the selected open public space, it can be concluded that both objective and subjective parameters are included in the research. The results indicated that heating up of pavement surfaces has a considerable impact on heating up of the surrounding air and thermal comfort of pedestrians. Previous studies also showed that covering soil and permeable surfaces with non-permeable materials that absorb heat dramatically increases surface and air temperatures (Santamouris and Kolokotsa 2015) and that there are differences in air temperatures over different paving materials (Tan and Fwa 1992). Black rough granite proved to be the hottest material in the course of measuring, which indicates the important effect of colour and surface texture on the heat properties of the material. For this reason, when choosing the pavement material, special attention must be paid to the choice and usage of light and smooth materials.

The findings from the survey and observation suggest that the users cannot feel small differences in surface temperatures that are less than 3°C and that they do not affect their thermal comfort. Differences in temperature measured between the hottest and the coolest material (8°C), the hottest material and grass (22°C) and between shaded and unshaded areas (20°C) are noticeable and affect the users' thermal comfort. Unlike other researches that report similar gender distribution in open public space 60-65% female and 35-40% male (Kantor and Unger 2010; Nikolopoulou and Lykoudis 2007) but don't consider differences between male and female thermal sensation (Nikolopoulou and Lykoudis 2007, Cortesao, et al. 2016) or suggest there are no significant gender-dependant differences in thermal sensation (Kantor and Unger 2010), the results of the survey presented in this paper show that women are more heat-tolerant, i.e. under the same heat conditions women feel cooler than men. Furthermore, the study shows that urban planners' choice of new paving materials has a negative impact on urban environment and thermal comfort. In accordance with this, thermal comfort must be considered as a very important element in urban design proposals in order not to create a situation where people would not spend time in the public spaces, caused by inadequate temperature conditions.

The findings of the research concerning the influence of material and shade on the users' thermal comfort can be used in the construction of new public spaces and in the reconstruction of existing spaces to improve their thermal characteristics. Since shading proved to be very important for outdoor thermal comfort, when designing public spaces, the height of surrounding buildings and summer Sun path must be considered to provide better shading during the summer days.

Besides the improvement of outdoor thermal comfort the use of cool paving materials together with appropriate use of green areas and other mitigation and adaptation strategies can significantly contribute to the improvement of indoor thermal comfort. The significance of the research is reflected in linking objective and subjective parameters and checking the validity of software for the simulation of outdoor thermal comfort. Further research should include more features of the open space (shape, size, share of paved and green areas, arrangement of green areas and trees, presence of water surfaces, etc.) and features of surrounding buildings (height, building materials, building functions and regime of use, manner of air conditioning, etc.) when calculating indoor or outdoor thermal comfort. A comparison of different software characteristics and their combination should be used to obtain more accurate results of thermal comfort simulations, as suggested by Perini et al. (2017).

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