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ANALYSES OF URBAN PAVEMENT SURFACE TEMPERATURES

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Abstract. Heat islands are areas that have higher air temperatures than their surroundings. It has been proven that the use of certain types of pavement surface materials contributes to the occurrence of heat islands. The heat island effect is dominant in urban areas, mainly in city centres. To identify potentially favourable pavement surface materials that are suitable for the use on surfaces in urban areas, an extensive analysis of in-place material temperatures was conducted in the city centre of Rijeka (Croatia) during the summer of 2011 and 2012. The measurements included temperatures of pavement surfaces made of asphalt, concrete and stone. The analysis results identified local materials whose use help to reduce or mitigate the effect of additional heating in the urban environment caused by emission of heat from pavement surfaces. In terms of additional heating of urbanized areas, asphalt has proven to be significantly less favourable than other analysed materials. In addition to the materials selected for the use in wearing courses, their characteristics and the microclimates of the locations where they will be placed must be taken into consideration. Among the standard paving materials, in terms of heating and temperature, concrete is more favourable than asphalt because the differences between concrete surface temperatures and air temperatures are significantly smaller than between asphalt surface temperatures and air temperatures. Stone surfaces have proven to be the most favourable. The analysis results presented can be used to establish clear guidelines for using specific materials under specific conditions.

Keywords: pavement, temperature, heat island, asphalt, concrete, stone.

1. Introduction

Pavement surfaces in urban areas are made of various materials, depending on the purpose of the surface in question. Motor traffic surfaces in the urban areas of European cities are usually made of asphalt or concrete and, to a lesser extent, granite blocks. The materials used for pedestrian surfaces are more diverse, and include, in addition to the previously mentioned materials, various types of construction stones and pavers. The effects of different materials used in urban pavement surfaces are important in analysing the causes of heat island occurrence in city centres (Nakayama, Fujita 2010). Heat islands are areas that have higher air temperatures than their surroundings. It has been proven that the use of certain types of pavement surface materials contributes to the occurrence of heat islands (Asaeda, Vu 1993; Doluos *et al.* 2004; Kleerekopera *et al.* 2012). Heat islands occur in urbanized areas in which the use of impermeable pavements prevents the natural circulation of water flow, which results in less aerated water and consequently, higher air temperatures. This effect is especially pronounced in summer, when the temperatures are highest. Analyses conducted in Japan (Asaeda, Vu 1993) demonstrated that the temperatures above paved surfaces are significantly higher during both the day and night than are those above bare soil.

Analyses have also shown that in some cities in the USA, for example, paved road surfaces make up 29% to 44% of the total surface area of city centres and that roof-covered surfaces make up another 20% to 25% (Akbari, Rose 2008). The total contribution of such surfaces to additional heating of a city centre is very significant.

In addition to lowering the quality of life for city inhabitants, high air temperatures during the warmest part of the year also have a negative impact on the environment due to the increase in energy consumption required for air conditioning and the larger CO_2 quantity released into the atmosphere (Akbari *et al.* 1997, 2009; Akbari 2002). Possible ways of preventing these negative effects are the use of materials with favourable thermal characteristics, especially for roof construction (Akbari, Rose 2008) and road surface construction (Doluos *et al.* 2004), what this paper addresses.

Research conducted by Doluos *et al.* (2004) in which the properties of 93 types of commonly used pavement construction materials were analysed under comparable

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insolation conditions demonstrated that for the microclimate conditions considered (Athens, Greece), several of the analysed materials contributed to reducing the heat island effect, reducing electricity consumption and improving thermal conditions in open-space areas. Santamouris *et al.* (2011) analysed special materials that contribute to surface heating reduction and, consequently, reduction of air temperatures. In addition to the aforementioned authors, other prominent authors (Akbari, Matthews 2012; Nakayama, Fujita 2010; Synnefa *et al.* 2008;) have addressed the issues involved in selecting materials whose optical and thermal characteristics have positive effects on the environment.

The parameters that influence the heating of a pavement surface and the air above it are solar emission, solar reflection and thermal emission. When selecting pavement surface materials, it is very important to analyse the solar reflection of any particular material (Akbari, Matthews 2012; Golden, Kaloush 2006). Albedo, or solar reflectance, represents the ability of a surface to reflect short-wave radiation (visible light, for the most part). A higher albedo signifies a greater ability to reflect light. The materials that are commonly used as pavement surfaces absorb from 60% to 95% of solar energy. Albedo values are expressed on a scale from 0, which indicates perfect solar absorption, to 1, which indicates perfect solar reflection. A study conducted by Akbari and Matthews (2012) demonstrated that the use of specific pavement materials with better reflection characteristics and an albedo increase of 0.15 on a 100 m^2 surface results in a reduction of 4 tons of CO_2. A study conducted in Tokyo in 2000 analysed all possible effects of the application of porous pavements on pavement surface temperatures and resulting air temperatures above the pavements. The results (Golden, Kaloush 2006) showed that a reduction in the pavement surface temperature of approx 15 °C results in a reduction of 1–4 °C in the temperature of the air above the pavement at heights of 0.5–1.5 m. The same authors noted the necessity of reducing the temperatures of pedestrian surfaces.

To understand the issues and define solutions for heat island effect mitigation, a good knowledge of the behaviour of pavement surface materials and their reactions in specific microclimate conditions is required.

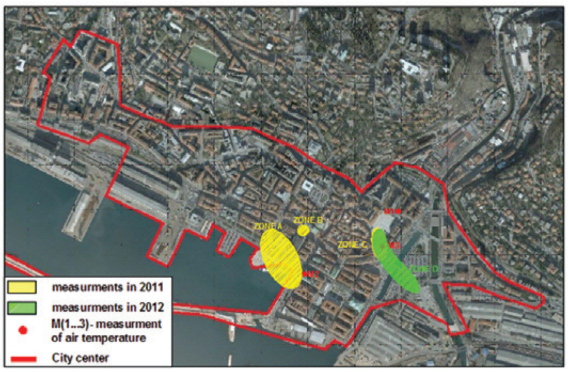

Fig. 1. City centre with measurement zones

To identify potentially favourable pavement surface materials for use on motor and non-motor traffic surfaces in urban areas, an extensive analysis of in-place material temperatures was conducted in the inner city centre of Rijeka (Croatia) in the summer of 2011 and 2012.

The city of Rijeka is situated along the North of the Adriatic coast (14° 26' East, 45° 21' North) deep in the Kvarner Bay. According to Koppen's climate classification, Rijeka is in the moderately warm moist climate (Cf) group. The average annual temperature is 13.5 °C, and the average temperature in the hottest month, July, is 23.3 °C. In the summer of 2012, through August 28th, there were 56 nights in Rijeka with temperatures above 20 °C, which are regarded as "tropical" nights.

During the hottest months of 2011 and 2012, pavement surface temperature measurements were conducted in the inner city area of Rijeka, on pavements made of asphalt, concrete, granite blocks and various types of natural stones. Based on the air and pavement surface temperatures, data were selected that represented parts of whole-day measurements conducted in July and September and measurements conducted during previously determined peak hours.

A surface analysis of the city centre of Rijeka has shown that the city centre is considerably urbanized and that approx 60% of the city centre surface consists of traffic areas and green surfaces. However, it has to be noted that the centre of Rijeka is situated in a very narrow coastal area, which is the reason for its extremely high percentage of lot development. Of the total manmade surface area within the inner city centre, green surfaces cover less than 2%. The city centre area and the locations where temperatures were measured in 2011 and 2012 are shown and marked in Fig. 1. The measurements included temperature measurements of pavement surface materials such as asphalt, concrete and stone, which are the most commonly used materials in pavement surfaces in the centre of Rijeka and other Croatian and even other European cities situated in the same climate belt. Data show that 87% of traffic surfaces in the analysed area in the city centre of Rijeka are made of asphalt, 2% are made of concrete and 9% are paved with various types of stone.

This paper presents part of the results of the analyses of the measurements conducted in 2011 and 2012. The goal was to analyse the behaviour of different pavement surface materials in real locations and under real microclimate conditions. This is the first such study conducted in Croatia, which is a country that has a mostly Mediterranean climate. The analysis results indicate which of the local materials used help to reduce the effect of pavement surfaces on additional heating in the urban environment. Specific material characteristics (colour and texture) identified in previous studies (Doulos *et al.* 2004; Levinson, Akbari 2002; Nakayama, Fujita 2010; Santamouris *et al.* 2011) as being of potential importance to material behaviour associated with solar radiation heating were also analysed. The goal of this study was to assess the behaviour of the materials considered under specific climate and microclimate conditions.

2. Description of the research

Pavement surface temperatures were measured during the summer of 2011 and 2012 in the inner city centre of Rijeka. During the summer of 2011, the measurements were conducted in three micro-locations (Fig. 1):

- on two city roads near the coast: Riva and Riva Boduli Streets – Zone A;
- within the pedestrian Korzo Street – Zone B;
- outside the area in immediate contact with the sea – Jelačić and Klobučarić Squares – Zone C.

The temperature was analysed at 40 marked measurement points, 24 of which were in Zone A, 3 of which were in Zone B and 13 of which were in Zone C. Of the 40 measurement points, 17 were on stone surfaces of different characteristics (in terms of colour, roughness, age), 13 were on asphalt in different locations (traffic lanes, parking lots, pedestrian ways) and in different conditions in terms of surface wear, 9 were on concrete surfaces and 1 was within a green surface. During the measurement period, a total of 35 temperature measurements were obtained. Approx 60% of the measurements were obtained during the previously determined time period during which the highest temperatures typically occur, i.e., between 2:30 pm and 3:30 pm. Two whole-day measurements were conducted during the time period from 6:00 am to 10:00 pm on July 12^{th}, 2011 and September 15^{th}, 2011.

During the summer of 2012, measurements were obtained in 2 locations (Zones C and D, both outside the area of immediate contact with the sea) (Fig. 1). Temperatures were measured at 32 locations, 11 of which were locations in zone C where temperatures were also measured in 2011. The whole day measurement was conducted on July 3^{rd} to 4^{th}, 2012.

An effort was made to conduct the measurements when the weather was dry and stable. The dates of the whole-day measurements were selected based on the weather conditions 7 days prior to measurement (Fig. 2). During the measurements, both in 2011 and 2012, the wind was of very low intensity, average speed during the measurement period was less than 2.0 m/s, this is why was possible to measure and analyse maximum pavement temperatures.

Pavement surface temperatures measured in 2011 at a micro-location Zone A were analysed in detail in a paper by Babić *et al.* (2012).

In this study, surface temperatures were measured with three different "Velleman" – type hand meters. This measurement meter works on the principle of emitting infrared energy to a detector that transforms this energy into an electrical signal that is represented as a temperature on the display screen. To conduct measurements in conditions as similar as possible, a portable block was installed on the measurement meter to ensure a consistent distance (5 mm) between the meter and the surface measured. Prior to recording the measured temperature, 2 control measurements were taken with the same equipment to establish the reliability of using different measurement meters. The mean variation value of a single meter was only 0.1 °C to 0.3 °C, which was judged to be sufficiently reliable. In addition to the temperature, the insolation period of the measurement point was also determined.

The results of the analysis of the temperature measurements obtained for various surface materials are presented in the next section. Special attention was paid to the analysis of temperature measurements of surfaces of the same type but with different characteristics, i.e., colour and pavement surface condition. Pavement temperatures were also compared for the locations in Zone C at which temperatures were measured in both 2011 and 2012.

3. Results of analysis

3.1. Result of analysis of whole-day temperature measurements of different materials

Figs 3 and 4 show the whole-day temperature measurements obtained on July 12^{th}, 2011 and July 3^{rd}, 2012 at the same measurement points in Zone C, outside the area in immediate contact with the sea. The locations include pavement surfaces made of asphalt, concrete and stone and were selected to compare the behaviour of different pavement surface types under similar insolation conditions. The main characteristics of the analysed materials are shown in Table 1.

The charts in Figs 3 and 4 show changes in the air temperature and the temperatures of pavement surfaces made of asphalt, concrete and stone (in this case, marble). The maximum surface temperatures for all types of materials analysed were higher in 2011 than in 2012. This is most likely attributed to the relative humidity, which, according to the official records of the State Weather Bureau, was approx 4% lower in Rijeka on the day prior to the whole-day

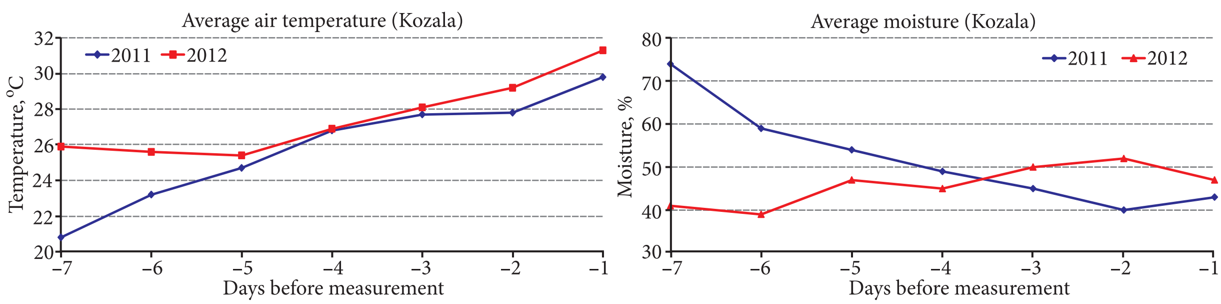

Fig. 2. Weather conditions (temperature and relative humidity) 7 days prior to whole-day measurements in 2011 and 2012

measurement on July 3rd 2012. The air temperatures were higher on the day of measurement in 2012, but they were consistently higher for the 5 days prior to measurement in 2011 (Fig. 2). The wind was of very low intensity so influence of the air flow was not significant for the results.

The material that in both cases resulted in the highest relative surface temperature, due to its albedo and thermal conductivity (Table 1), was asphalt. While the maximum measured asphalt temperature in July 2011 was over 61 °C, in July 2012, it was 57 °C. The analysed materials reached the maximum pavement temperature at approx the same time. An analysis of the measurements obtained in 2011 showed that the mean asphalt temperature was higher than the air temperature by 16.3 °C during the surface insolation period (from 7.00 am to 5.00 pm), while the mean concrete temperature was 14.7 °C higher and the mean stone temperature was 11.9 °C higher.

It is also interesting that, regardless of both the different maximum temperature levels in 2011 and 2012 and the different times of day when the maximum temperatures were measured, the temperature equalization of the various surfaces analysed occurred in both cases during almost the same time period, between 7:00 pm and 8:00 pm. In the period from 5:00 pm to 10:00 pm, the differences

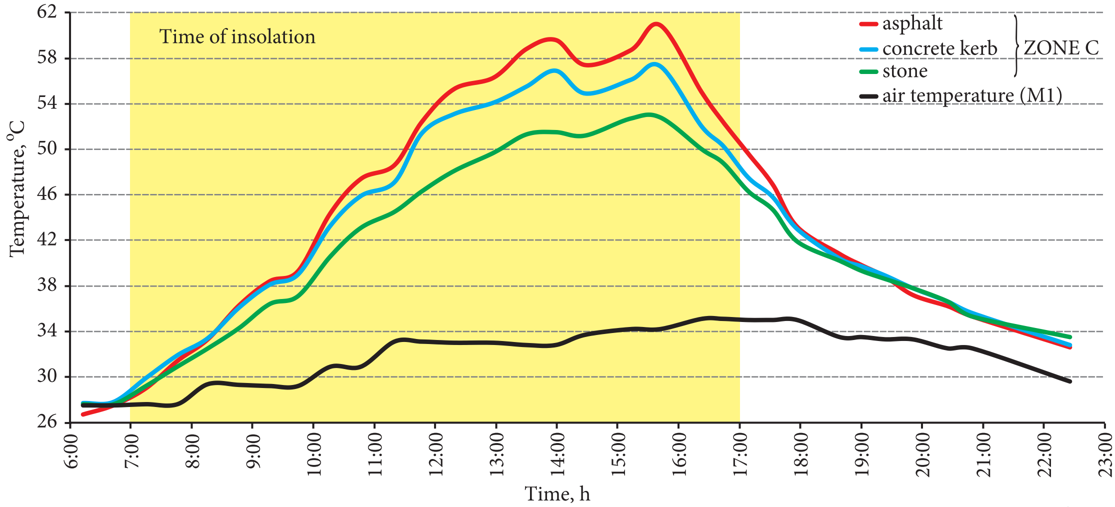

Fig. 3. Whole-day temperature measurements on traffic surfaces made of asphalt, concrete and stone in Zone C (July 12th 2011)

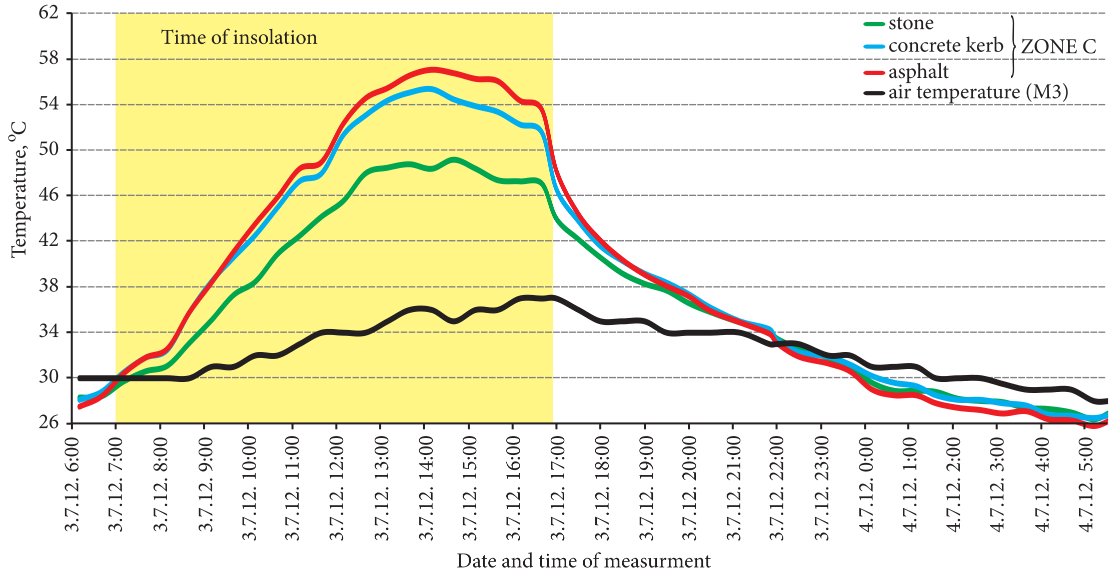

Fig. 4. Whole-day temperature measurements on traffic surfaces made of asphalt, concrete and stone in Zone C (July 3rd 2012)

Table 1. Main characteristics of paving materials

Type of material	Porosity, %	Volumetric weight ρ, kg/m^3	Thermal conductivity λ, W/mK	Albedo
Asphalt	2–9% (porous asphalt 20%)	2100	0.7	0.05–0.20
Concrete	6% (porous concrete 15–20%)	1000–2400	0.35–2	0.10–0.35
Stone	< 1%	2800	3.5	0.07–0.35

in temperature between the pavement surfaces and the air were almost the same for all the materials, which the data from 2011 and 2012 also confirm. According to the data from 2011, the mean difference was 5.8 °C for asphalt and concrete and 5.5 °C for stone. The asphalt temperature tended to drop suddenly, which indicates that asphalt surfaces release a larger amount of accumulated heat into the surroundings in a shorter period of time than do concrete and stone. The higher maximum temperatures of the pavement surfaces in 2011 resulted in the pavement surface temperatures being 2–3 °C higher in July 2011 at 10:00 pm. However, at the same time in 2012, the air and pavement surface temperatures were equalized. For all pavement surface types for which night-time measurements obtained in 2012 were analysed, the surface temperature was higher than the temperature of the surrounding air until approx 10:00 pm, after which the air temperature remained higher than the temperature of the pavement surfaces until approx 7:00 am.

The stone surface was found to be the most favourable for the specific conditions of the measurement locations because the surface temperature of stone was up to 5.3 °C lower than the surface temperatures of the other pavement surface materials. The stone surface temperature was 2.8 °C lower, on average, than the asphalt surface temperature.

In addition to the differences observed in air heating caused by basic material types (asphalt, concrete and stone), significant differences were also noted for the same or similar types of materials, as discussed in more detail below.

3.2. Analyses of asphalt pavement surface temperatures

Asphalt is the dominant material used for traffic surfaces in urban areas in Croatia. In the city centre of Rijeka, which was used as the test area for this traffic surface heating analysis, 87% of the traffic surfaces in the city centre are asphalt surfaces. This was the reason why this study addressed the analysis of the characteristics of this material, which contributes considerably to heating within the city centre.

The following were considered in the analyses of the influence of different asphalt pavement surfaces:

- asphalt surfaces of different type of traffic surfaces (traffic lanes, lanes for public transport, parking lots A1, A2, A3);
- asphalt surfaces with different degrees of wear (A5 and A6);
- coloured asphalt surfaces (on a pedestrian crossing-A1) (Fig. 5).

The analysis of the influence which asphalt mixture colour, associated with the degree of wear of a surface course (measured at locations A5 and A6), has on the temperature of pavement of a minor city road with less intensive traffic showed that the maximum daytime temperatures of lighter surfaces were up to 1.7 °C lower and 0.6 °C lower on average.

Locations A1 and A2 are situated in a pedestrian crossing at a bus lane. Temperatures were measured on a white-coated surface (A1) and immediately next to it (A2). The data showed that significant differences (up to 7.1 °C) existed in the surface temperatures, which are attributed to the freshly coated surface. The temperature of a white-coated asphalt surface was 3.4 °C lower on average.

Except when there was a different type of relevant vehicle (bus), according to the data analysed, the intended use of a surface had no influence on the surface temperatures recorded. Higher temperatures were expected at locations with heavier traffic loads, such as at location A2 (a bus lane) versus location A6 (a minor road). However, higher temperatures were recorded on a parking lot pavement (A3) and on pedestrian sidewalk (A4). The highest asphalt surface temperature was recorded at a bus stop in Zone C (60 °C), it is attributed to the additional pavement surface heating caused by low-positioned bus engines and suggests another reason (in addition to heating due to solar radiation) for the necessity of using concrete for pavement surfaces for bus stops in urban areas.

The asphalt surface (at a location at which the asphalt surface reached its maximum average daily temperature A3) had an average temperature 21.5 °C higher than the air temperature during the period from 12:00 pm to 6:00 pm, while the maximum difference (reached at approx 3:30 pm) was 24.7 °C. These temperature differences indicate that asphalt contributes significantly to the surrounding air temperature during the period when this material emanates accumulated heat, from 3:30 pm onward. The chart shows that the temperature increases slowly even after 3:30 pm, which indicates that the pavement surface temperature is still contributing to increasing the air temperature.

3.3. Analyses of concrete pavement surface temperatures

Concrete is not widely used in Croatian cities as a material for pavement or pedestrian surfaces. In several American cities analysed (Sacramento, Salt Lake City and Chicago), the percentage of concrete sidewalks is 95% and the percentage of concrete roads and parking lots is 5% (Levinson, Akbari 2002). However, analysis of the Rijeka city centre, based on ortho-photo images, showed that only 2% of the city centre surfaces in Rijeka are covered in concrete. Those are mostly the pavement surfaces of parking lots and, to a lesser extent, pedestrian surfaces along the coastline.

Fig. 6 shows the daily concrete surface temperature changes at different locations in the city centre (3 locations were in Zone A, 2 locations were in Zone C and all measurements were made in 2011). It has to be noted that because concrete makes up a small percentage of the total pavement surface area in the city centre, it was not possible in this study to analyse the impact of concrete surfaces on air temperatures. The lowest temperatures were measured on concrete surfaces of the operational quay (A7 and A8),

	06:02	06:30	07:00	07:32	08:00	08:33	09:02	09:32	10:02	10:34	11:05	11:31	12:00	12:31	13:13	13:45
A1	27.7	27.6	27.8	28.3	28.2	31.6	33.9	36.4	39.2	40,6	43	44.4	46.1	47.6	48.9	49.6
A2	27.8	28.1	28.4	29.3	28.8	33.4	36.4	40.1	42.9	45.9	48.8	49.8	51.6	53.9	55.1	56.7
A3	28.4	28.6	28.9	29.5	31.8	34.9	37.7	40.5	43.7	45.6	48.6	49.3	51.1	53.6	55.8	57.1
A4	27.9	28.3	28.6	28.4	28.9	29.2	29.7	30.3	30.8	31.3	41.9	45.4	48.4	51.4	54.6	56.4
A5	26.1	27.8	27.9	27.7	27.8	28.3	28.4	28.7	29.3	30.4	40.6	43.1	46.5	49.1	51.8	53.6
A6	27.3	27.8	27.8	27.9	27.8	28.1	28.5	28.9	29.3	30.3	42.2	44.3	47.8	50.6	53.3	55.1
T	27.5	27.5	27.6	27.6	29.4	29.3	29.2	29.2	30.9	30.9	33.1	33.1	33	33	32.8	32.8

	14:13	15:00	15:31	16:07	16:36	16:58	17:21	17:46	18:12	18:51	19:15	19:39	20:14	20:39	22:12
A1	50.6	51.3	52.3	50.6	50.6	46.7	44.5	44.4	41.6	39.1	39.6	38.1	36.5	35	33.4
A2	57.4	56.9	58.5	56.8	55.5	50.9	47.8	47.4	44	41	41.5	39.3	37.5	36	34.4
A3	57.7	58.4	58.9	57.9	56.4	53.4	54.3	52.6	50.2	47.2	45.6	43.1	40.8	39.4	36.5
A4	57.3	58.3	59.9	58.2	57.3	53.6	55.1	53	50.9	47.7	46.1	43.3	40.9	38	36.6
A5	55	55.4	57.3	55.1	51.5	49.6	49.2	44.4	41.8	39.7	38.9	37.6	36.2	35.6	33
A6	56.6	56.9	59	56.1	52.7	50.4	50.7	45.1	42.1	39.8	39.1	37.6	36.3	35.5	32.5
T	33.7	34.2	34.2	35.1	35.1	35	35	35	33.5	33.5	33.3	33.3	32.5	32.5	29.6

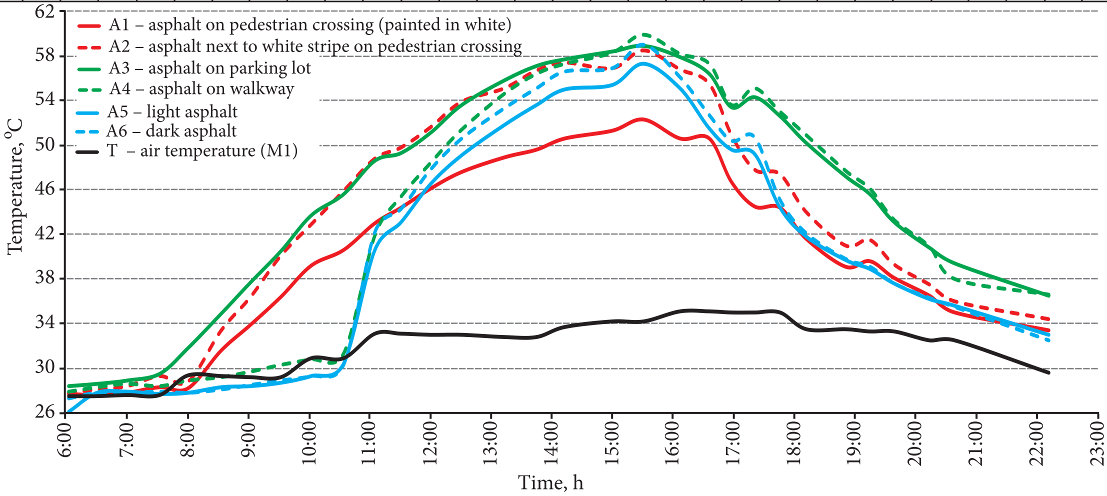

Fig. 5. Whole-day temperature measurements on asphalt surfaces (July 12th 2011)

	06:02	06:30	07:00	07:32	08:00	08:33	09:02	09:32	10:02	10:34	11:05	11:31	12:00	12:31	13:13	13:45
A7	26.8	26.6	27	26.9	27.1	27.3	32.1	35.1	37.7	40.4	42.3	41.1	43.6	44.8	47.1	47.8
A8	26.9	27.2	27.1	27.4	27.4	27.6	32.4	34.9	36.9	39.5	39.8	40.1	42.8	43.9	46.1	47.1
A9	27.7	27.2	27.6	27.7	28.2	28.3	29.3	29.2	29.6	37.8	41.4	43.1	45.1	46.9	49.6	49.9
C1	27.7	27.8	29.9	31.9	33.4	36.1	38.1	39	43.3	45.9	47.1	51.4	53.1	54.1	55.5	56.9
C2	27.6	28.3	29.8	31.6	33	35.2	37.3	39.4	41.6	44.1	45.8	47.5	48.8	50.3	50.7	50.9
T	27.5	27.5	27.6	27.6	29.4	29.3	29.2	29.2	30.9	30.9	33.1	33.1	33	33	32.8	32.8

	14:13	15:00	15:31	16:07	16:36	16:58	17:21	17:46	18:12	18:51	19:15	19:39	20:14	20:39	22:12
A7	48.8	49.8	50.8	49.8	46.7	45.6	47.6	45.4	43.6	41.9	40.3	38.4	35.9	35.1	32.3
A8	47.6	49.1	50.4	49.1	46.4	45.7	47.2	45.4	43.9	42.1	40.8	38.7	36.9	35.9	33.6
A9	51.3	51.9	53.8	51.8	49.3	47.6	50.3	48.1	46	43.5	41.9	39.7	38	36.9	34.3
C1	54.9	56.1	57.3	49.5	50.3	47.5	45.8	43	40.4	39.7	38.9	37.8	36.6	35.6	32.8
C2	51.3	51.6	52.6	50.7	49.1	44.2	41.4	40	38.1	37.6	36.5	36.1	35	34	32.4
T	33.7	34.2	34.2	35.1	35.1	35	35	35	33.5	33.5	33.3	33.3	32.5	32.5	29.6

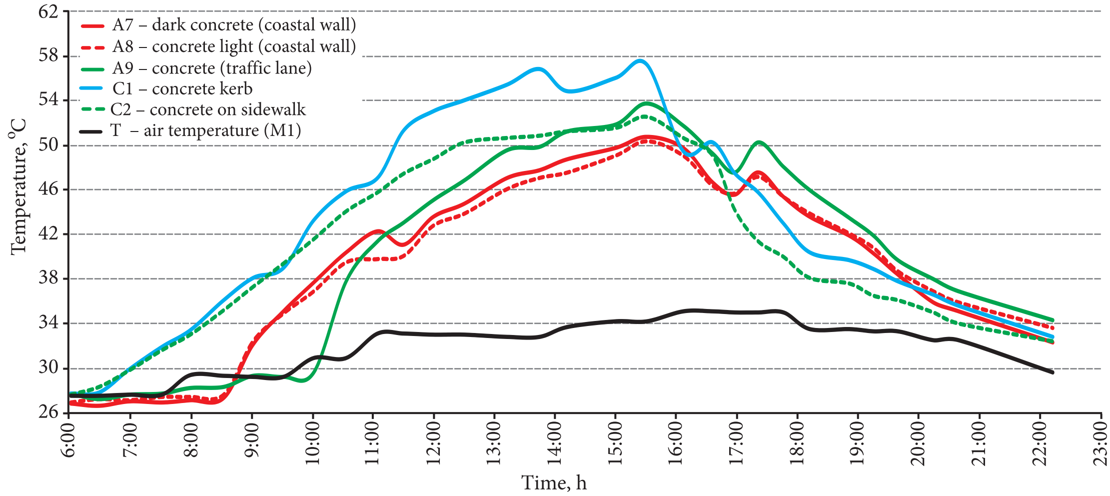

Fig. 6. Whole-day temperature measurements on concrete traffic surfaces (July 12th 2011)

Table 2. Main characteristics of stones used for paving in the city centre of Rijeka

Group of stone	Type*	Porosity, %	Water absorption capacity, %	Volumetric weight ρ, kg/m³	Thermal conductivity λ, W/mK
Marble	Kanfanar Dalmatinski dolit Rasotica Rozalit	< 1% (dense)	0.1%–0.3% (very small)	2600–2900 (heavy)	2.0–2.6
Granite	Rosso porinho Dark impala	0.4%–1.5% (dense to low porosity)	0.1%–0.9% (very small to small)	2600–2800 (heavy)	1.6–3.4

*according to *HRN EN 12440:2000 Denomination of Natural Stone*

	06:06	06:35	07:07	07:38	08:08	08:38	09:06	09:36	10:06	10:39	11:10	11:37	12:05	12:36	13:17	13:50
A10	27.8	27.9	27.7	27.8	27.8	28.1	28	28.4	30	29	29	29.9	36.5	37.7	41.1	43.5
A11	27.7	27.6	27.4	28	27.8	28.6	28	28.3	30.1	28.9	28.9	30.1	39.1	42.3	46.2	49.6
C8	27	27.1	27.9	30.4	31.3	32.6	34.6	36.8	39.1	41	43	44.4	45.8	47.7	48.6	49.1
C9	27.6	26.4	26.3	29.5	31.8	33.6	33.5	38.2	41.1	43.8	46.9	48.3	50.1	52.1	53.1	54.1
C10	27	27.1	26.4	28.2	28.7	30.8	36.3	39.4	41.9	44.9	47.1	49.4	51.3	53.4	54.8	49.8
T	27.5	27.5	27.6	27.6	29.36	29.3	29.2	29.2	30.9	30.9	33.1	33.1	33	33	32.8	32.8

	14:20	15:04	15:37	16:14	16:39	17:02	17:26	17:52	18:18	18:56	19:19	19:44	20:19	20:45	22:18
A10	44.9	46.3	48.4	48.4	46.8	45.6	47.4	46.1	45	43.4	42.3	40.5	38.8	37.6	34.7
A11	49.9	51.8	53.9	53.5	50.7	48.4	50.7	49.6	47.4	44.1	42.1	40.6	38.9	37.4	34.6
C8	50.3	50.8	51.4	44.4	43.6	42.2	41.1	40	39.1	38.1	37.2	36.4	35.4	34.3	32.8
C9	54.7	55.2	56	45.6	44.2	43	42.3	40.3	39.8	38.6	37.3	36.7	35.8	34.7	32.7
C10	45.4	42.5	41.8	39.7	39.4	38.8	38.3	37.3	35.7	35.3	34.7	34.3	33.6	33	31.8
T	33.7	34.2	34.2	35.1	35.1	35	35	35	33.5	33.5	33.3	33.3	32.5	32.5	29.6

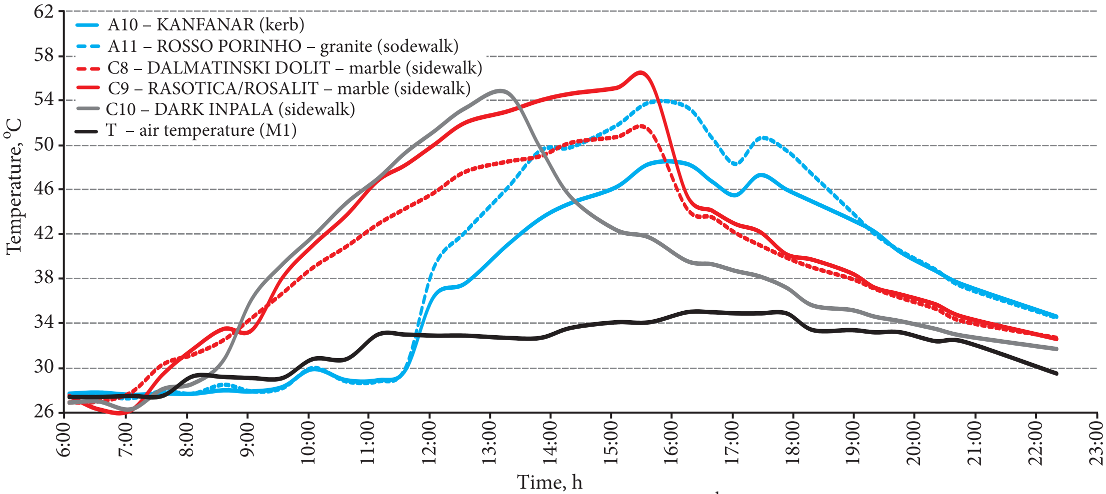

Fig. 7. Whole-day temperature measurements on stone pedestrian surfaces (July 12th 2011)

where, just as with other materials, the lighter surfaces had the lowest temperatures (up to 1.3 °C lower and 0.2 °C lower on average). In comparison to the locations farther from the coastline (C1 and C3), the recorded concrete surface temperatures were up to 11.3 °C lower and were 3.8 °C lower on average. These differences mostly attributed primarily to the influence of the sea nearby. The same difference is also evident in the temperatures measured at location A9 (parking lot concrete pavement), which is situated approx 10 m from the quay (average difference of 1.1 °C).

3.4. Analyses of different natural stone pavement surface temperatures

In this study, surface temperatures were analysed for two large natural stone groups that are commonly used for paving of pedestrian surfaces: marble and granite. Both are characterized as low-porosity materials with little or very little water absorption capacity (Table 2). Because stone has traditionally been used as a construction material in the Mediterranean and recently has also been used as a material for pedestrian zone surfaces, the analysis included all types of stone pedestrian surfaces in the city centre of Rijeka.

The data comparison shown in Fig. 7 can be made if the temperatures of those of the stone pavement surface locations shown are compared for identical insolation conditions, i.e., A10 versus A11 and C8 versus C9. Analysis of the temperatures of the marble (A10) and granite (A11) surfaces showed that marble is a more favourable material for pavement surface construction from a surface heating point of view. During the hottest period of the day (from 12:00 pm to 3:00 pm), the temperatures of the marble surfaces averaged 6 °C lower than those of the granite surfaces. Granite heats up and cools much faster than marble because of its higher thermal conductivity, which makes it less favourable for use as a pavement surface material from the perspective of its influence on heating.

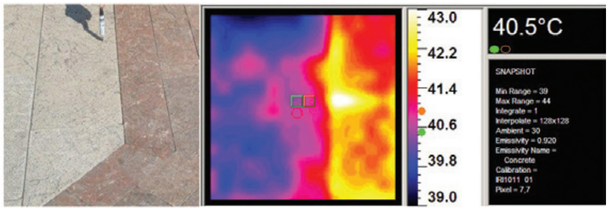

Fig. 8. Infrared images of different stone types (C8 and C9)

Based on a comparison of temperatures of two marble surfaces at the same micro-location and under the same insolation conditions (C8 and C9), the conclusion is that there are significant differences in heating of pedestrian surfaces even for the same stone type. In this case, the stone colour is obviously the reason for the different temperatures: the stone at location C9 (to the right in Fig. 8) is darker in colour than the stone at location C8. Although the surfaces are stones of the same type at the same micro-location, the marble temperature at location C9 is, on average, 1.6 °C higher than the marble temperature at location C8.

4. Conclusions

1. The paper presents the results of analyses of measurements of pavement surface temperatures in the city of Rijeka (Croatia) in 2011 and 2012. The measurements were conducted in the inner city centre during the summer months at real micro-locations to determine the effects of locally used materials on air heating under conditions of maximum annual temperatures and maximum insolation periods. The analyses included all the materials commonly used for wearing courses (asphalt, concrete and stone). From among these, the materials that are most favourable for pavement surfaces under the given conditions were identified. Use of these favourable materials will mitigate the heat island effect, which has been observed predominantly in modern city centres, including Rijeka, due to urbanization.

2. The results of the analyses of measurements obtained during a longer period in the summer of 2011, whole-day measurements obtained in 2011 and whole-day and whole-night temperature measurements obtained in the summer of 2012 show that, in terms of the additional heating of urbanized areas, asphalt is significantly less favourable than the other materials analysed. Asphalt surfaces proved to be unfavourable at all of the analysed locations and microclimate conditions (temperature, relative humidity, water body surfaces).

3. The results of this study also show that there are differences in the air heating effect even among asphalt surfaces, what is also true with the other analysed materials, namely, concrete and stone. Asphalt with a worn-out surface, lighter in colour than freshly placed asphalt, has shown better heat island mitigation properties than freshly placed asphalt. The beneficial effect of a lighter-coloured surface can also be obtained by using aggregate whose grains are of a lighter colour.

4. Among the standard paving materials, in terms of their heating and temperature contributions to the surrounding air, concrete is more favourable than asphalt: for the same conditions, the differences between concrete surface temperatures and air temperatures were up to 2 °C lower, on average, than the differences between asphalt surface temperatures and air temperatures. The asphalt temperature tended to drop suddenly, which indicates that asphalt surfaces release a larger amount of accumulated heat into the surroundings in a shorter period of time than do concrete and stone.

5. Stone surfaces were found to be the most favourable. Under the same insolation conditions, the average difference between stone surface temperatures and air temperatures were approximately 4.5 °C lower than the average difference between asphalt surface temperatures and air temperatures. Among the stone surfaces analysed, marble, especially lighter-coloured marble, was found to have better heat island mitigation properties than granite.

6. The analysis results, presented in this paper, pointed out the advantage of detailed analyses of specific pavement surface materials under specific conditions in urban areas. The favourability of various pavement surface materials, in terms of their thermal characteristics and albedo, has become an imperative criterion in selecting materials for urban traffic surfaces, especially surfaces meant for pedestrian traffic and especially in locations with high average summer temperatures and where the occurrence of heat islands is becoming more prominent. A systematic analysis of this issue is recommended.

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