






Empirical Evaluation of Urban Heat Island Pavements Related. Cagliari Case Study

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Abstract. Worldwide, higher temperatures occur in urban areas (UHI - Urban Heat Island) compared to the surrounding countryside, with a considerable impact on people's health and well-being. Extensive use of paved surface and bituminous materials and human activity heat generation are the major causes of the UHI. The paper points out the importance of bituminous pavements on UHI and reports the empirical evaluation performed in Cagliari (Italy). Using thermal data from the Italian SmartRunway located in Cagliari airport, a fitting empirical model developed for bituminous pavement surface ($R^2 < 0.94$) has been extended to other materials used in the urban context. The model input data are a minimum and maximum air temperature and solar irradiation during the day, and output is the surface temperature. The simplified characterization of different kinds of surfaces covering the cities can be operated through visual analysis of orthophotos or a geodatabase. Combining these data, in the paper is proposed a methodology to build temperature profile along a town cross-section. Finally, a zenithally thermal survey has validated the empirical methodology, with a significant correlation ($R^2 > 81\%$).

Keywords: Urban Heat Island · Bituminous surface · UHI mitigation · Urban warming · Asphalt pavements

1 Introduction

UHI is high-temperature levels in urban centers compared to surrounding rural areas. In the last 15 years, extensive research efforts study UHI (Urban Heat Island) phenomenon. Literature review reports hundreds of investigations [1] related to evaluation, impact, and mitigation, starting in 2000. Mitigation methods include green and blue infrastructure, cool roofs and pavements, urban structures, and the use of vegetation coverage. Some states issued regulations and standards to mitigate the UHI effects, and there is continuous progress to incorporate in the technical codes innovation in construction system, strategies, and research results.

In Italy in 2017, a law on minimum environmental criteria fix the SRI (Solar Reflectance Index) for materials at least 29 to moderate the effect of solar radiation

on UHI [2]. Nevertheless, a lack of general coherence among public administration, academia, companies, and professional operators is a substantial impediment to the implementation and effectiveness of UHI mitigation strategies in urban and regional plans. In general, the pavements capable of reducing thermal field are designed as “cool pavements”. The reduction can be achieved using highly reflective and emissive materials, porous and permeable layers [3]. The “cool pavements”, include both conventional (asphalt and concrete), stone pavement [14], and nonconventional pavements (white-colored course, resin-bonded pavements, a porous superficial layer, and micro surfacing) [3, 17]. Several studies investigated the appreciable cooling of reflective pavements [4–8], but some remark that they can adversely affect drivers such as glare and discomfort due to reflected radiation or the moisture reduction cause higher daytime temperature [9–11].

Recent research [12] remarks that the intensity of UHIs is related to population size and mean annual precipitation and, an explanation for this relationship can be reproduced by introducing in large-scale model population, climate, and UHI intensity. Evapotranspiration and convection efficiency are the main factor that explains differences between rural and urban areas (Fig. 1).

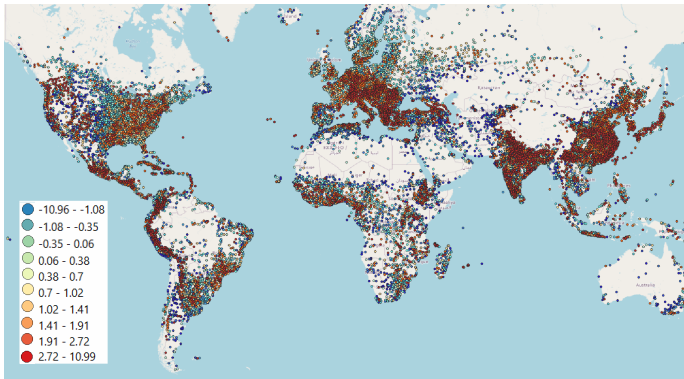


Fig. 1. The intensity of UHI over more than 30,000 world cities according to the model proposed by Manoli, G., Fatichi, S., Schläpfer, M., et al. [12]

Therefore, in dry regions is more efficient to increase vegetation cover and albedo, whereas cities in a tropical climate will require innovative solutions. The results of an online survey in 2020 [2] investigate the perceptions of UHI mitigation approaches and, green infrastructure was selected by most respondents ($\approx 90\%$), and at the same time, less than 50% consider cool pavement to be effective (Fig. 2). Green infrastructure and stone pavements are widely used for UHI mitigation and environmental and social benefits [7, 35]. Urban vegetation refreshes cities through evapotranspiration and shading, but few papers [15, 16] quantify the urban vegetation’s cooling effect. It is fundamental to have forecasting models to evaluate different mitigation actions in urban plans and adaptation strategies to climate change. Several investigations proposed a simulation model to predict the surface temperature of the pavements.



Fig. 2. Different types of “cool pavements”: colored, porous (concrete and asphalt), green and stone pavements (Color figure online).

Two linear regression models for predicting the daily minimum and maximum pavement temperatures were developed in 2006 by Diefenderfer et al., using data from Virginia Smart Road [13]. A similar model, developed during the Italian SmartRunway project in 2009 at Cagliari airport, fit empirical data from bituminous pavement surface ($R^2 < 0.98$) over two years [18, 19]. All the models include solar radiation, minimum and maximum ambient temperature, and depth from the surface. Qin [14] in 2015 proposed the following theoretical model

$$T_{s,max} = \Gamma \frac{(1 - R)}{P\sqrt{\omega}} + T_o \quad (1)$$

Where:

Γ = % absorption of the thermal conduction.

R = reflectivity.

I_0 = daily zenith solar irradiation.

w = angular frequency of a sinusoidal wave ($w = 2\pi/24/3600$),

T_0 = constant (period base temperature).

$P = \sqrt{kc\gamma}$ Thermal inertia of the asphalt (k = thermal conductivity, c = heat capacity, and γ = density of the asphalt).

This model addresses the different ways to reduce temperature: increasing reflectivity R (e.g., white coating), increasing thermal inertia P (e.g., dense materials), reducing absorption Γ (e.g., porous materials) and, protection by solar irradiation I_0 (e.g., trees shading). Some authors [20, 21] classify different types of reflective pavements: infrared-reflective paints, coarse aggregates, thermochromic materials and, alternative constituents (i.e., fly ash) and, many studies [22–25] evaluate this reflectance strategy. Porous pavements allow removing heat through evaporative cooling and airflow induced by wind. Phase change materials (PCM) are promising strategies to minimize thermal peaks [26–29]. PCM and various heat-harvesting pavements were also studied to convert the absorbed heat to other forms of energy.

The paper investigates asphalt pavement’s contribution to UHI and proposes a simplified empirical evaluation to estimate UHI pavement’s related effect. Using thermal data from the Italian SmartRunway located in Cagliari airport, a fitting empirical model developed for bituminous pavement surface ($R^2 < 0.98$) has been extended to other materials used in the urban context. The model input data are a T_{min} , T_{max} , and R_s (Solar Irradiation) during the day, and output is the surface temperature during the 24 h. The methodology allows building temperature profiles along a town cross-section. The aerial thermal survey allows validating the methodology, with a significant correlation ($R^2 > 94\%$).

2 Data and Methodology

The structure of the research (Fig. 3) follows five levels:

1. Development of the thermal asphalt model
2. Model extension to different materials
3. Thermal survey and data gathering over Cagliari town
4. Data analysis and model validation
5. Building a cross-section temperature profile along with the town

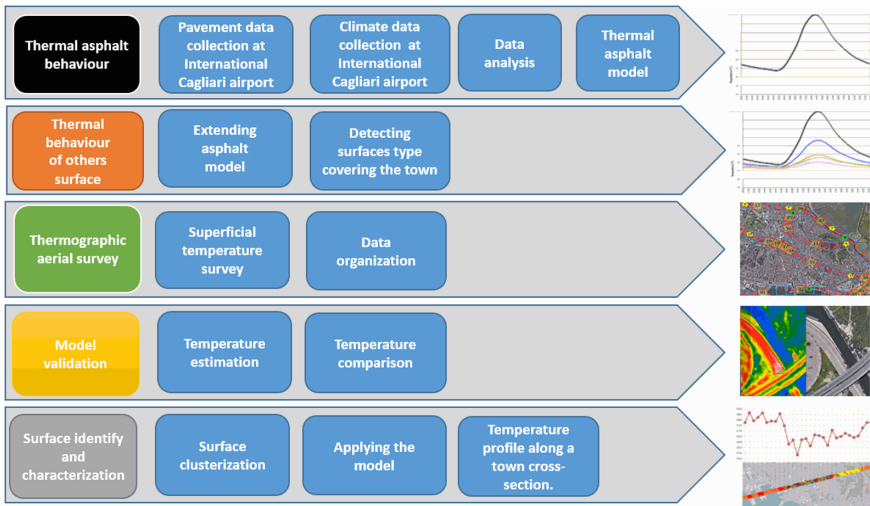


Fig. 3. Structure of the research

2.1 Development of the Thermal Asphalt Model

In 2008 the runway at Cagliari-Elmas International Airport had been reconstructed and, the asphalt pavement of the touchdown area on head 32 was instrumented with a total of 149 instruments: 36 Linear Variable Differential Transformers, 36 pressure cells, four Time Domain Reflectometers, 28 T-thermocouples, and 45 HMA strain gauges (Fig. 4). In particular, the system collected thermal data from April 2009 to December 2011 at regular intervals every 15min, through 2 vertical alignments of T-thermocouples at 14 different depth: 1 cm, 3 cm, 5 cm, 7 cm, 10 cm, 15 cm, 20 cm, 25 cm, 30 cm, 35 cm, 45 cm, 60 cm, 75 cm, and 90 cm.

Figure 5 shows the temperature variability at the top and bottom of HMA layers at Cagliari Airport from May 2009 to December 2010. HMA temperature ranging between 1.2 °C to 56.2 °C at 1.0 cm depth and from 6.2 °C to 42.3 °C at the bottom of the HMA layer (35 cm) with the mean value of 24.7 °C.



Fig. 4. Instrumentation installation at Italian SmartRunway at Cagliari airport

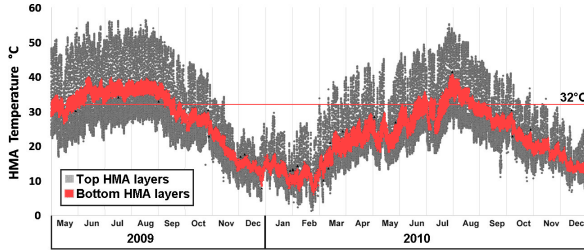


Fig. 5. The temperature of asphalt pavement at Cagliari Airport (2009–2010)

Many approaches have been used to predict the temperature distribution in the HMA layer, such as theoretical, numerical, and statistical methods. The input parameter involves air temperature, solar radiation, wind speed, relative air humidity, heat convection, and heat diffusion. Sometimes the models require complex input, and they are not suitable for practical use. Since 1957 Barber [30] discuss the evaluation of maximum pavement temperatures from weather information to predict pavement temperatures profile, and over the years, many other researchers investigate on temperature distribution in HMA. Only in 2001, some researchers presented models to predict daily temperatures. Park et al. [31] proposed a simple equation to predict temperature inside asphalt layers at any time of the day:

$$T_z = T_{surf} + (-0.3451z - 0.0432z^2 + 0.00196z^3) \sin(-6.3252t + 5.0967) \quad (2)$$

where:

T_z = temperature at depth z (°C).

T_{surf} = temperature at the surface (°C).

z = depth from the surface (cm).

t = time (fraction of day).

Many other researchers propose to estimate daily maximum and minimum HMA temperature [32–34] based on the daily solar radiation (R_s), air temperature (T_a), and depth from the surface (z). Using climate data at Cagliari-Elmas Airport for 315 days in 2010, these models can predict maximum pavement the observed temperature with reliability between $72.2\% < R^2 < 91.7\%$. Figure 6 shows regression between measured and predicted temperatures at 3 cm, 20, and 35 cm deep during the warm season.

The model proposed in this paper first estimates the daily minimum and maximum temperature of HMA through a regression analysis of climate data provided by C.O.Met. (Italian Ministry of Defence - Air Force - Operational Centre for Meteorology). The

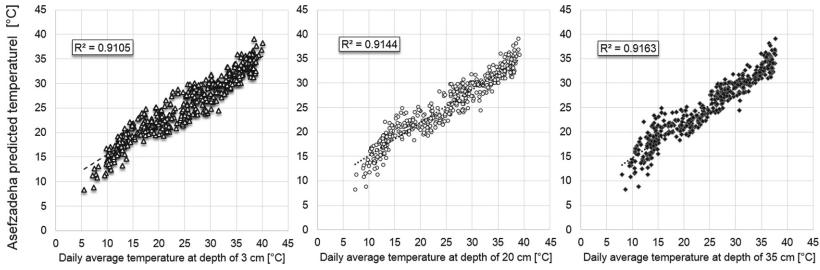


Fig. 6. Predicted versus Cagliari Airport measured HMA temperatures at a depth of 3 cm, 20, and 35 cm during the warm season.

multiple regression based on daily minimum and air temperature and solar radiation give the daily minimum and maximum temperature of HMA with $R^2 = 92\%$. This result has been obtained on a regular day, characterized by no clouds and wind. The assumption allows avoiding high variability during the seasons and the local peculiarity (i.e., buildings shadow and wind tunnel effect in the urban streets). The best-fit equations obtained for the regular day are:

$$T_{Daily-min} = 1.2097 + 0.6754T_{air-min} + 0.37642R_s \tag{3}$$

$$T_{Daily-max} = 10.4875 + 0.6864T_{air-max} + 0.5674R_s \tag{4}$$

where:

- $T_{Daily-min}$ = daily minimum temperature of HMA (°C).
- $T_{Daily-max}$ = daily maximum temperature of HMA (°C).
- $T_{air-min}$ = minimum temperature of air (°C).
- $T_{air-max}$ = maximum temperature of air (°C).
- R_s = total daily solar irradiation (MJ/m²).

Considering the periodical trend of daily temperature, a Fourier series development of the phenomenon over the day is very effective. In the research, a high correlation was observed between predicted and measured values. Stopping the development of the Fourier series at the first four terms, R^2 has always been greater than 94.5%

$$T_{surf} = a_0 + \sum_{n=1}^{\infty} (a_n \cos n\omega t + b_n \sin n\omega t) \approx \dots \tag{5}$$

$$\dots \approx a_0 + a_1 \cos \omega t + b_1 \sin \omega t + a_2 \cos 2\omega t + b_2 \sin 2\omega t$$

where:

- a_0 = mean daily temperature $T_{Daily-med} = (T_{Daily-max} + T_{Daily-min})/2$.
- $a_1 = T_{Daily-min} - T_{Daily-med}$.
- $b_1 = T_{Daily-max} - T_{Daily-med}$.
- $a_2, b_2 = 2^\circ$ order coefficient.
- ω = angular frequency of a sinusoidal wave ($\omega = 2\pi / 24/3600$).

2.2 Model Extension to Different Materials

A simplified approach is implemented to extend the model validated to HMA to others covering materials. The analysis comprises asphalt (HMA), light and dark roofs, concrete, stone material, vegetation, and unpaved areas. In addition, since the city of Cagliari have numerous water surfaces and lagoons, the thermal response of a water surface 2.0 m deep was also considered. In order to extend the model, several daily measurements have been performed in different conditions and areas with the simultaneous presence of asphalt and other covering materials (Fig. 7). Comparing the thermal response of the different surfaces with respect to asphalt allows resizing the proposed model for other materials.

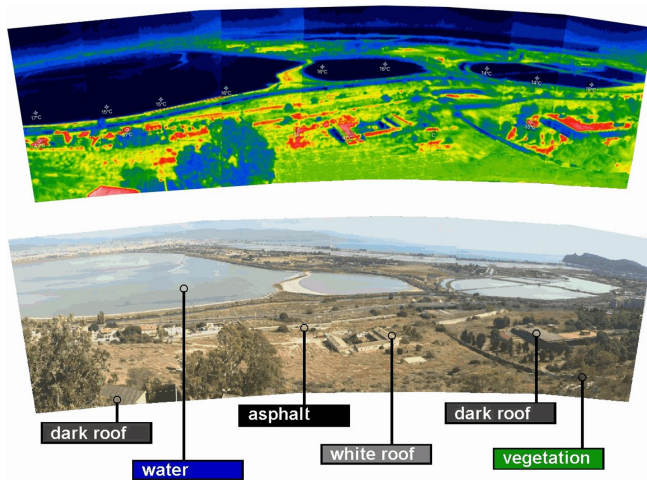


Fig. 7. Thermal measurements in areas with the simultaneous presence of asphalt and other covering materials.

The following Table 1 shows the linear combination coefficient to predict maximum and minimum daily temperature for different materials.

2.3 Thermal Survey and Data Gathering over Cagliari Town

In order to validate the proposed methodology and analyze the UHI phenomenon over the city of Cagliari, an aerial survey was carried out on October 17, 2017, at 4.00 PM.

During the flight, a thermal video was recorded. Twenty images were extracted, relating to different areas of Cagliari, significant since covered by large surfaces of the different materials considered. Figure 8 shows the flight plan, for a total length of 70 km, with a speed of 80 knots (148 km/h) and an altitude of 300 m. The areas analyzed are highlighted with red boxes (250 x 250 m).

The flight was performed in clear-sky conditions in the afternoon, with an air temperature of about 20 °C and low wind speed (11 km/h).

Table 1. Linear combination coefficient of the model

	$T_{Daily-min}$			$T_{Daily-max}$		
	$l_1 + m_1 T_{air-min} + n_1 R_s$			$l_2 + m_2 T_{air-max} + n_2 R_s$		
	l_1	m_1	n_1	l_2	m_2	n_2
Asphalt	10.4875	0.6864	0.5674	1.2097	0.6754	0.3764
Dark Roof	10.461	0.640	0.469	1.196	0.644	0.320
White roof	8.462	0.631	0.366	1.195	0.612	0.258
Concrete	8.155	0.622	0.360	1.189	0.615	0.266
Stone	7.136	0.420	0.321	1.190	0.603	0.261
Vegetation	0	1	0	0	1	0
Water	0	1	1	0	1	1
Unpaved	7.050	0.380	0.321	1.209	0.615	0.306

**Fig. 8.** Thermographic aerial survey over Cagliari

3 Results

3.1 Data Analysis and Model Validation

The twenty areas recorded in the aerial flight were analyzed using both the municipal cartography's orthophotos and the survey on the sites. Figure 9, on the top, shows the results and analysis for zone 20 and Zone 3: temperature distribution on the left, surface type at the centre and, orthophoto on the right. Each area has been segmented into the different types of surfaces present, associating each one with the corresponding thermal

images of the fly survey. The surface classification includes the materials type, their color intensity, and coverage area. Next, through a calculation code developed in Matlab R16, the temperature values of the surfaces of each thermal image were extrapolated, and the weighted average of these values in the respective areas was calculated. Figure 9 reports two examples of the areas analyzed.

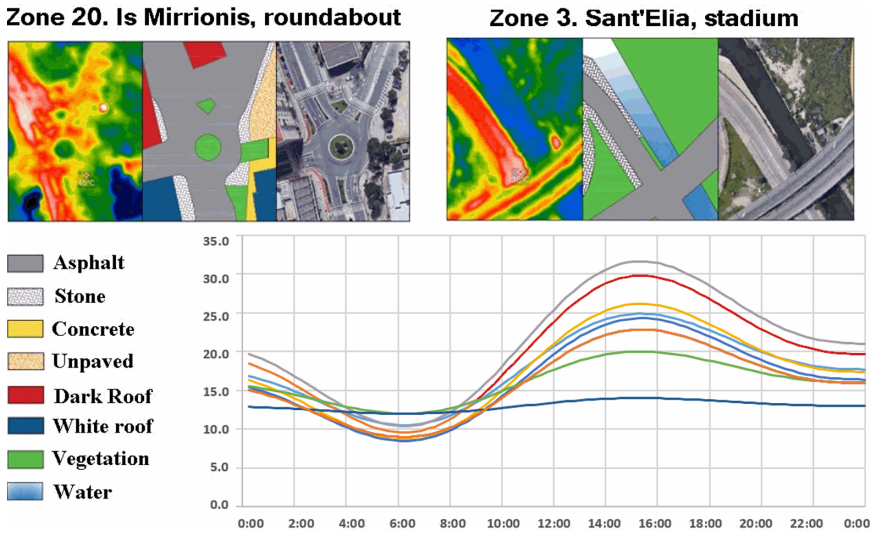


Fig. 9. Two examples of the areas analysed (on the top: temperature distribution on the left, surface type at the centre and, orthophoto on the right) and daily estimated temperature for different materials (on the bottom).

The histogram in Fig. 10 shows higher temperature values for asphalt road pavements and dark roof, which during the survey assume a mean temperature close to 30 °C. Concrete and stone have similar values, lower than those of asphalt by about 4 °C. Vegetation have the lowest temperature values of about 10 °C. The model extension show limited correlation for water surfaces.

3.2 Building a Cross-Section Temperature Profile Along with the Town

The proposed method allows estimating the temperature profile through any cross-section of the urban centre. By extending the section to the more peripheral and rural areas, it is possible to highlight the urban effect of heat islands. The estimation is based on the segmentation of the cross-section of the urban center into cells, evaluating the surface extension of the various covering materials. Inputting data $T_{\text{air-min}}$, $T_{\text{air-max}}$, R_s , and hour of the day in the model, the temperature of each covering surface is calculated. The mean temperatures of each surface, weighted regarding the extension of the surfaces, allow attributing an average temperature value to each cell.

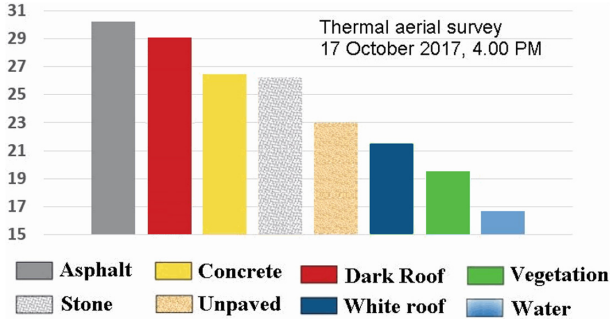


Fig. 10. Temperature distribution on a different surface (October 17 2017, 4:00 PM)

A good correlation ($R^2 = 0.81$) was found between the weighted temperature values predicted by the model and that measured in the aerial thermal survey for the 20 cells considered. Figure 11 shows the cross-section and estimated temperature profile, evaluated in four different situations: typical winter and summer, early morning and afternoon.

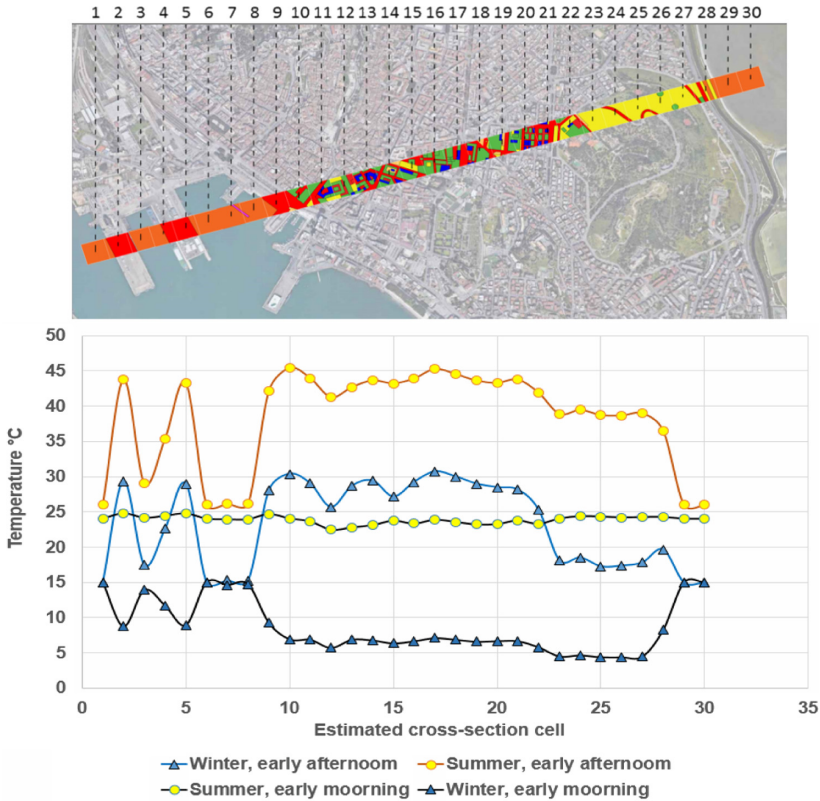


Fig. 11. Cross-section and the estimated temperature profile.

4 Conclusions and Remarks

In urban areas, temperatures are increasingly higher than in the surrounding rural areas. The well-known phenomenon (UHI - Urban Heat Island) has several negative consequences on cities' energy balances and people's health and well-being. Many urban climate change adaptation plans include UHI reduction strategies. The wide use of bituminous materials for road paving is one of the leading causes of UHI due to the thermal properties, mainly high absorbent and low solar reflection index.

The paper proposes an original methodology for the empirical evaluation of UHI, calibrated on Cagliari (Italy), and highlights the importance of bituminous pavements. The authors outline some mitigation strategies to reduce global warming. Main mitigation strategies comprise "cool materials" for the urban context surfaces: roads, parking, squares, dirt field, and buildings. The reduction of asphalted surfaces would significantly benefit since, in medium latitudes, they reach temperatures up to 65 °C. Knowing the thermal behavior of materials in the actual condition is crucial to promoting "cool materials" on roofs and pavements.

An empirical model of the surface temperature of the bituminous pavement ($R^2 < 0.98$) was developed in the research. The model has been extended to other materials used in the urban context of Cagliari. For the development of the model were the thermal data of the Italian SmartRunway and the climatic data of the Cagliari airport.

The input data are the minimum and maximum temperatures and solar radiation forecast for the day, and the output is the surface temperature on the pavement. All-day experimental surveys of the temperatures of different materials highlight a behavior very similar to that of bituminous surfaces. The substantial difference is the magnitude of the minimum and maximum peaks. Therefore the rescaling factors were calculated, extending the model to the other materials.

Following a section of the city of Cagliari was divided into cells, identifying the areas of the covering materials, using the available orthophotos. At specific times of the day, the temperatures predicted for these materials were weighted to the calculated average value. Finally, a zenithally thermal survey has validated the empirical methodology, with a significant correlation ($R^2 > 81\%$).

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