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Microclimate Mitigation by means of Thermal-energy Storage: A case study in Central Italy

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Abstract

Urban design and local boundary conditions have been detected to significantly affect the local microclimate and, therefore, the environmental quality of urban areas. In this view, the purpose of the present work is to investigate the local microclimate variation in historic districts with respect to the surrounding areas situated in the same temperate climate zone. To this aim, four areas around a historical city center in Italy were monitored during summer 2015 and investigated through microclimate simulation in summer and winter conditions. After the experimental monitoring, that allowed to characterize the main microclimate parameters of each case study area, a calibrated numerical analysis was performed in order to assess the Urban Heat Island (UHI) intensity of the historical district and the implementation passive mitigation techniques. Therefore, the effectiveness of thermal storage solutions as innovative UHI mitigation technique was studied by simulating the implementation of Phase Change Materials (PCMs) within (i) the buildings' walls and (ii) the outdoor pavement of the historic neighborhood. Thermal benefits due to the application of phase change materials were detected both in summer and winter. In summer, the high-capacity PCMs integrated pavement is able to reduce the outdoor air temperature by a maximum of about -0.3 K. On the other hand, in winter, the increased thermal storage potential seems to mitigate the nighttime cooling.

Keywords: *Urban Heat Island, Experimental monitoring, Numerical analysis, Microclimate simulation, Phase Change Materials*

1. Introduction and Motivation

Local microclimate can be significantly altered due to the complex interaction between microclimate parameters and the thermal-optical properties of urban and buildings' surfaces. Urban Heat Island (UHI) represents one of the main microclimate phenomenon able to generate discomfort in urban areas due to the high building density, lack of vegetation, reduced surfaces sky view factor, and convective mixing (Santamouris et al., 2015). Moreover, more than half of the world's population is living in urban settlements. Therefore, the necessity to design efficient, sustainable, and healthy built environments is becoming a crucial issue for both designer and urban planners (Nikolopoulou et al. 2001).

Many UHI mitigation strategies have been proposed over the course of the years, such as green and cool materials (Akbari et al., 2016; Galli et al., 2013; Santamouris, 2014) and tested through experimental and numerical analysis (Allegrini et al., 2015). On the contrary, the use of thermal storage technologies for such purpose (Navarro et al., 2016) as a further outdoor microclimate mitigation strategy is still not very well investigated. However, PCM doped infrared reflective coatings were proved to present lower surface temperatures than common and cool coatings of the same color (Kolokotsa et al., 2013). In particular, peak temperature differences occurred between PCM and common or cool coatings from 7:00 and 10:00 a.m. In this view, some works studied the performance of roofs with PCMs and cool materials to mitigate UHI

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effect. For instance, Roman et al. (2016) performed different thermal energy simulations of cool roof and PCM based roof with varying climatic zones within the United States. In general, increased albedo led to better performance in terms of UHI effect reduction. However, PCM roof showed a heat flux from roof surface to the surrounding environment of 40 % lower than the cool roof technology. By using experimental tests, Chung and Park (2016) analyzed PCM doped cool tiles for roof applications in an artificial environment and showed a decrease of surface temperature and air temperature in the chamber in summer conditions, while an increase of air temperature in winter conditions. Therefore, PCM doped roof reduced the heating penalty of the cool paint in winter. Similarly, Lu et al. (2016) measured the surface temperature and heat flux of a coupled PCM and cool roof in Tianjin of China, which showed a significant effect in decreasing temperature and heat flux peaks. Also heat-harvesting pavements were proposed to mitigate UHI phenomenon in urban environments (Qin, 2015). They seemed to be capable to stay cool and to harness renewable energy. However, such prototypes require further tests on the power output, durability, and lifetime. Moreover, the performance of cool and heat storage pavements was simulated by Qin and Hiller (2014). Increasing pavements albedo was demonstrated effective to suppress the sensible heat and mitigate the UHI effect, while raising the pavement thermal inertia decreased the sensible heat during the daytime but increased this factor at nighttime. On the other hand, no significant results have been found in the assessment of PCMs doped walls for the Urban Heat Island phenomenon mitigation.

Building upon the above mentioned considerations, in this work the local microclimate differences between four areas with different urban configuration and development located in the same climate zone were taken into account. In particular, the historical district of the city of Perugia (Italy) was found to be characterized by a non-negligible Urban Heat Island intensity. Therefore, the capability of innovative thermal storage solutions, i.e. phase change materials, to mitigate UHI phenomenon in the historic district when integrated in different buildings' elements and urban outdoor materials, i.e. external building walls and pavement, was evaluated by means of microclimate calibrated simulation.

2. Materials and Methods

The research methodology included two main steps. Firstly, the experimental monitoring campaign of four case study areas with different building density, configuration, and vegetation level, i.e. an historical urban district, a more recent urban neighborhood, and two suburban-rural areas, was carried out in the same city, i.e. Perugia (central Italy) during summer 2015. The local microclimate of each area was assessed by means of outdoor microclimate stations. Therefore, the numerical modeling of the historic district (Fig. 1a) was performed to evaluate the benefits achievable in terms of local microclimate by applying innovative passive cooling strategies in order to mitigate the UHI phenomenon.

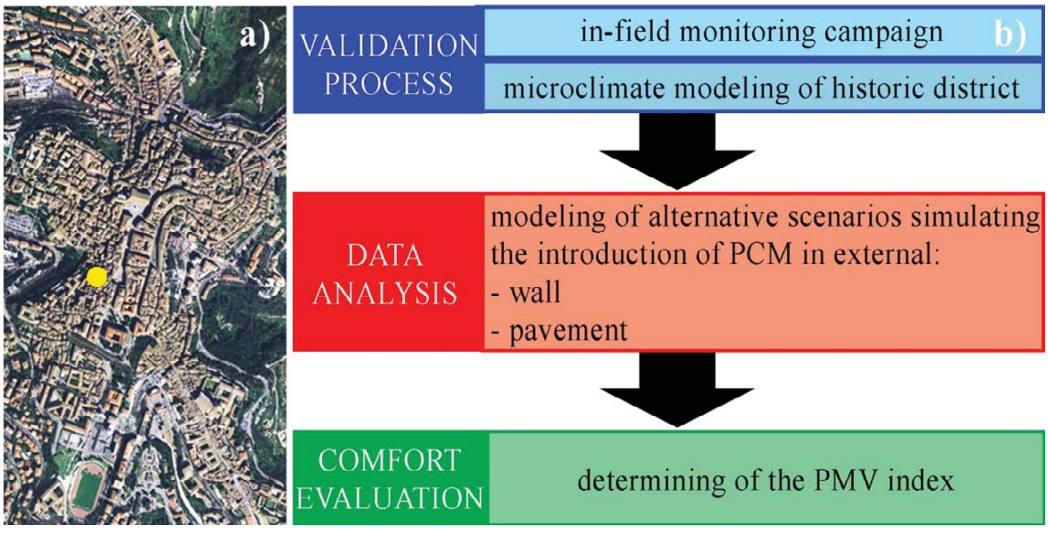


Fig. 1: (a) Position of the modeled area within the historic center of Perugia and (b) scheme of the adopted methodology

The microclimate simulation was carried out by using ENVI-met V4 in order to assess the effectiveness of thermal storage solutions for mitigating the Urban Heat Island phenomenon by preserving the environmental quality of the urban area and the thermal-visual comfort of the pedestrians. More in detail, the integration of Phase Change Materials in (i) the walls of the monitored building and (ii) in the outdoor paving was simulated in order to evaluate the impact of increased thermal capacity of the materials on the local microclimate, both in summer and winter conditions. To ensure the reliability of simulation results, a preliminary phase of validation was conducted. The daily weather profiles were selected from the typical July (July, 15th) and typical January (January, 15th) provided by IGDG TMY (Typical Meteorological Year) for the city of Perugia, built on 1951-1970 period of record (U.S. Department of Energy, 2014). Finally, the simulation results were analyzed in terms of the thermal comfort index PMV (Predicted Mean Vote) (ENVI-met 4, 2015; Fanger, 1972) to assess how the integration of PCMs could affect pedestrian perception of the local urban environment (Fig. 1).

2.1. Modeling and validation process

The simulated area in the historic district is an East-West oriented street, 40 m long with a width varying from 3 to 12 m along its length (Fig. 2). Moreover, between the eastern and western side there is a height difference of 5 m. Buildings in the street are characterized by thick stone walls and outdoor pavements are manly covered by bricks and plates made of *pietra serena* (except for the eastern side recently asphalted) (Fig. 2b), since it is located in the historical center of the city.

ENVI-met V4 was used for the numerical analysis, which is three-dimensional microclimate modeling system designed to simulate the surface-plant-air interactions with a resolution from 0.5 m to 10 m in space and from 1 s to 5 s in time (Huttner and Bruse, 2009). A realistic model of the area was developed and calibrated by using experimentally monitored data, according to the ASHRAE GUIDELINE 14-2002 (ASHRAE, 2005). In order to be representative of the real configuration, the 3D model has a square unit of 1x1 m and a geometrical rotation of 111° North out of the grid. Therefore, it is based on a 30x60x35 grid. The materials used to characterize walls, roofs, and pavements in the reference scenario were selected from the software database and their thermo-physical properties are summarized in Tables 1 and 2.

Fig. 2: (a) View of the street from the western side, (b) different kinds of pavement present in the area, and (d) localization in the plant of the monitoring probes

Tab. 1: Characteristics of the walls and roofs composing the reference scenario

Element	**Albedo [-]**	**Emittance [-]**	**Specific heat [J/kg·K]**	**Thermal conductivity [W/m·K]**	**Density [kg/m^3]**
Walls	0.30	0.90	840	0.86	930
Roofs	0.50	0.90	800	0.84	1900

Tab. 2: Characteristics of the different pavement profiles composing the reference scenario

Pavement profile	Albedo [-]	Emittance [-]	Volumetric Heat Capacity (upper layer) [J/m³·K]	Heat Conductivity (upper layer) [W/m·K]
Brick Road	0.30	0.90	$2.00 \cdot 10^6$	1.00
Basalt Brick Road	0.80	0.90	$2.39 \cdot 10^6$	1.73
Asphalt Road	0.20	0.90	$2.25 \cdot 10^6$	0.90

The data for the calibration were collected through the monitoring campaign during summer 2015. A portable weather station was placed at 15 m height (Pisello et al., 2014) and two Tinytag temperature and relative humidity probes and data-loggers (Pisello et al., 2015) were installed at 2 m above the ground (Fig. 2c). As weather input for the model the following data were used:

- Initial wind speed: value collected from the weather station at 6 a.m., start time of the simulation;
- Wind direction: value prevailing during the three days of the monitoring campaign;
- 24 h air temperature and relative humidity forcing: data collected by the probe located on the South-oriented side (Fig. 2c, point B).

The simulation run for 24 h and the data compared for the calibration were those collected from the North-oriented probe (Fig. 2c, point A) and those extracted from its representative point within the model.

2.2. Modeling of alternative scenarios

Once calibrated the model, alternative scenarios to the reference one, named S0, were developed by analyzing the effectiveness of the application of PCMs at urban level for Urban Heat Island mitigation. Therefore, traditional materials were replaced with high-thermal capacity ones as follows:

- High-thermal capacity walls, i.e. scenario “wall”;
- High-thermal capacity pavements, i.e. scenario “pavement”.

The innovative materials, were selected to be realistically implemented in the case study area, which presents architectural constrains since it is located inside the historical center of the city. In particular, the thermal-storage capability of buildings’ envelope was improved through the application of PCM wallboards. Moreover, pavement’s thermal properties were implemented based on the real necessity to substitute the current asphalted area. Since PCMs dynamic characteristics and behavior cannot be modeled in ENVI-met V4, their modeling was simplified by increasing the materials heat capacity, as summarized in Table 3. Therefore, no specific PCMs’ melting temperature was defined in this analysis. Nevertheless, in the investigated climate, PCMs with melting temperature from 20°C to 25°C are recommended in summer applications for this increase in heat capacity to happen.

Tab. 3: Characteristics of the components modified in each mitigation scenario

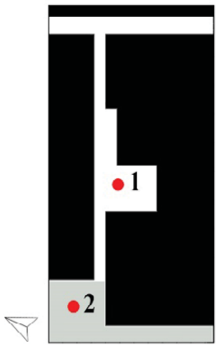
Scenario	Element	Mitigation technique	Properties
wall	Walls	Introduction of PCMs	Specific Heat: 1620 J/kg·K
pavement	Pavement	Introduction of PCMs	Volumetric heat capacity: $3.6 \cdot 10^6$ J/m³·K

The three scenarios, i.e. S0 and the alternative scenarios, were simulated during a representative summer and winter day in the climate context of Perugia, Italy, by using as weather input the TMY weather files for the months of July and January, respectively.

2.3. Outdoor thermal comfort analysis of mitigation scenarios

In order to evaluate the effectiveness of the proposed mitigation strategies, the data obtained as output in the numerical simulation were analyzed in terms of microclimate improvements in the surrounding outdoor area.

The following parameters were considered: air temperature, relative humidity, reflected solar radiation, mean radiant temperature, and the PMV at the pedestrian level (Fanger, 1972), for the outdoor comfort of pedestrians. PMV was analyzed through the PMV Model implemented in ENVI-met (ENVI-met 4, 2015), which is the human thermal comfort model mostly used for indoor applications. In fact, it was originally developed for steady-state indoor situations, but it can also be applied, with limits, to outdoor situations by extending the energy flux related parts of the model with solar and long-wave radiation and allowing wind speeds above an indoor room situation. A comparison between data obtained in the reference and alternative scenarios was performed by analyzing the variation in time during the day of the above mentioned environmental parameters. Time series were extracted at 1.5 m from the ground in two different points selected because of their different characteristics (Fig. 3).



	Location	SVF	Time range when reached by direct solar radiation
Point 1 [x=12, y=28, z=5]	within the urban canyon, above the historical pavement	0.15	12:00-2:00 p.m. in summer, never in winter
Point 2 [x=5, y=8, z=1]	on the western part of the street, above the area originally asphalted	0.51	3:00-8:00 p.m. in summer, never in winter

originally asphalted area

Fig. 3: Positions of the points selected to extract data at pedestrian level

3. Results and Discussion

3.1. Model calibration

The statistical and graphical approach was carried out for the model calibration according to the ASHRAE GUIDELINE 14 (ASHRAE, 2005). The calibration accuracy was evaluated in terms of two statistical indexes, i.e. *Mean Bias Error* (MBE) and *Root Mean Square Error* (RMSE) (ASHRAE, 2005), as reported in Table 4. The maximum gap in terms of both air temperature and relative humidity is reached during the hottest hours of the day, when the software tends to overestimate the outdoor microclimate parameters. According to the obtained results, the model can be considered representative of the real area with good approximation. Therefore, it can be used to simulate which could be the improvements in the outdoor microclimate of the zone due to the application of the selected mitigation strategies.

Tab. 4: Calibration parameters results

Parameter	MBE	RMSE
Air Temperature	0.82 K	1.05 K
Relative Humidity	2.21 %	2.96 %

3.2. Summer analysis

Observations on the experimental monitoring carried out during summer 2015 in the different locations revealed a significant nighttime UHI phenomenon in the two monitored urban areas, with peaks of 2 K and 5 K temperature difference in the recent urban neighborhood and the historical district, respectively, compared to the suburban green area.

Therefore, the alternative scenarios were simulated to assess the possible benefits achievable from the implementation of phase change materials in the built surfaces, i.e. walls and paving, as mitigation technique. Summer results showed the major contribution of the high-thermal capacity pavement, i.e. scenario "pavement". In detail, the high-capacity PCMs integrated concrete pavement is able to reduce the outdoor air temperature by a maximum of -0.31 K in the summer day in point 2 (Fig. 4b). However, in point 1 the high thermal capacity soil effect is negligible in terms of air temperature reduction (Fig. 4a). In fact, at the point with higher Sky View Factor (SVF) the peak air temperature is higher than in point 1 and it is detected two hours before the other one (at 1:00 p.m. instead of 3:00 p.m.). The reason is the different relation between these points and the built environment and the different time-period when they are exposed to direct solar radiation: just two hours for point 1 (from 12:00 p.m. to 3:00 p.m.) and five hours for point 2 (from 3:00 p.m. to 8:00 p.m.). Moreover, point 2 is located above the ground surface covered by asphalt in the reference configuration and, therefore, the effect of the materials' thermal properties improvement is higher. On the contrary, point 1 seems to suffer from the presence of solar radiation, both direct and diffuse, since it is subjected to higher mutual reflections of short way radiations from the surrounding structures. On the other hand, the scenario where increase of specific heat in walls is applied, i.e. scenario "wall", negligible effect is found in both point 1 and 2 during the daytime (Fig. 4). However, slightly better values are reached during the night in both points and in both scenarios, leading to differences up to -0.13 K and -0.26 K (6.00 p.m.), compared to S0, for "wall" scenario in point 1 and 2, respectively. These night-time lower temperature values are due to the less contribution of the built surfaces in the thermal balance determined by lower surfaces' temperatures. As regards the relative humidity trend, it is strictly connected to the one of the air temperature and no significant differences.

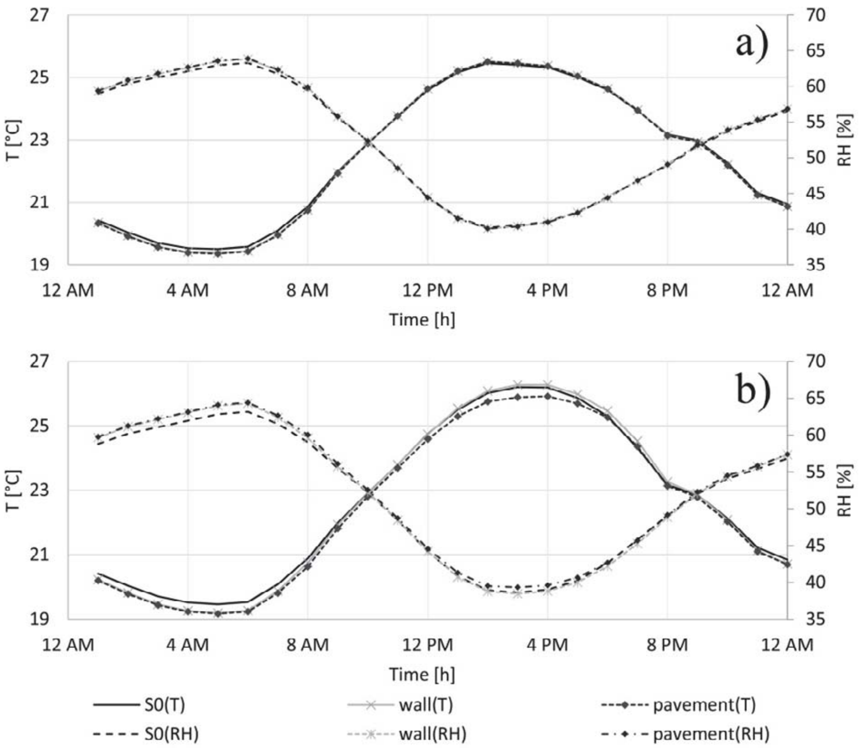


Fig. 4: Simulated air temperature and relative humidity hourly profiles in (a) point 1 and (b) point 2 in the different scenarios during the summer day

The reflected solar radiation and the mean radiant temperature were also analyzed (Fig. 5). It is interesting to notice that the trend of the MRT assumed in point 2 shows two peaks (Fig. 5b), differently from point 1 showing just one peak (Fig. 5a). This is due to the presence of direct solar radiation that occurs at different times in the two selected locations. In point 1, the peak coincides with the maximum values of reflected solar radiation (around 1:00 p.m.), while in point 2, a first relative peak is detected due to the maximum value of the reflected radiation and an additional one is achieved at 3:00 p.m., when the point is reached for the first time from the direct radiation. Conversely from the previous results, negligible differences between the mitigation scenarios and S0 are found in terms reflected solar radiation in point 2, while a significant increase is found in "pavement". Moreover, an increase of MRT is found in "pavement" with a maximum of +2.18 K at 3:00 p.m. and +2.28 K at 2:00 p.m. in point 1 and 2, respectively.

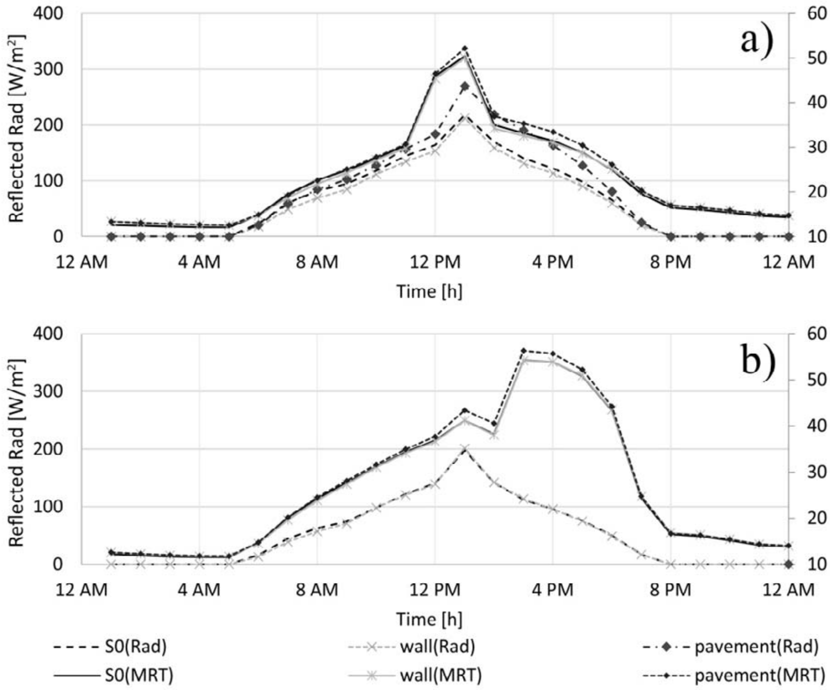


Fig. 5: Simulated mean radiant temperature and reflected solar radiation hourly profiles in (a) point 1 and (b) point 2 in the different scenarios during the summer day

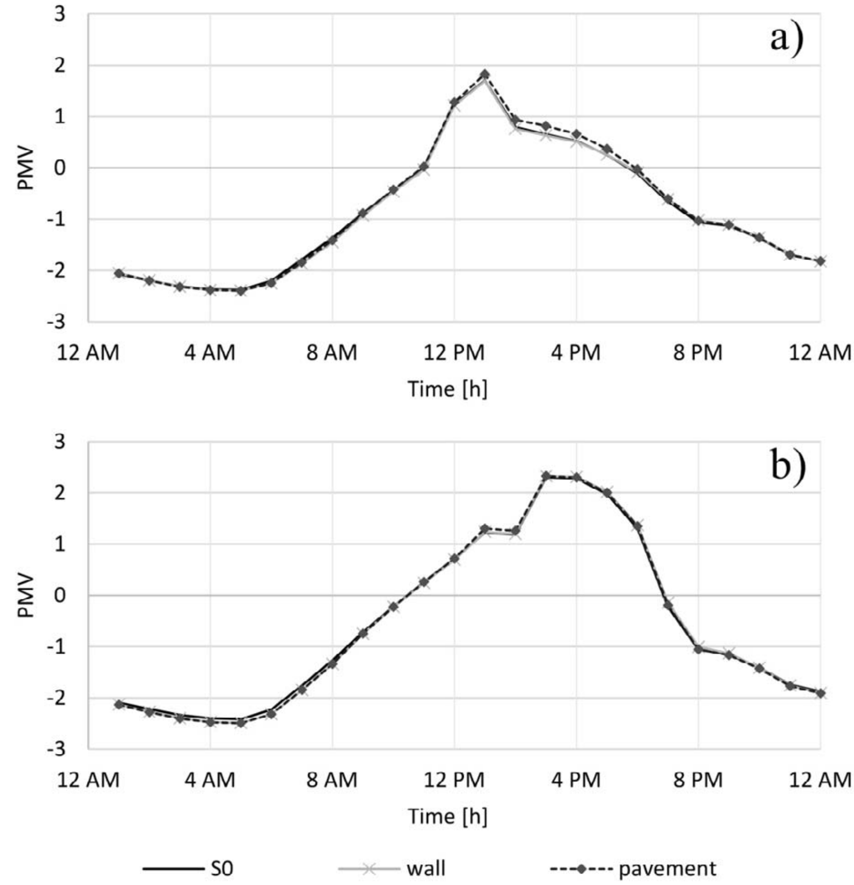


Fig. 6: Comparison between all the simulated scenarios in terms of PMV daily trend at pedestrian level in (a) point 1 and (b) point 2 during the summer day

As regards the pedestrians' comfort analysis (Fig. 6), the PMV was evaluated by imposing a clo (static clothing insulation) equal to 0.5. The resulting PMV values vary from a minimum of about –2.4, achieved before the sunrise, and a maximum of +1.8 and +2.3 (scenario "pavement") for point 1 and point 2, respectively. However, negligible variations in terms of PMV are found between the different scenarios, due to the small temperature difference.

3.3. Winter analysis

Although the proposed mitigation techniques were proposed to improve the outdoor microclimate conditions of the selected area during the hottest season (in order to mitigate the Urban Heat Island phenomenon), their effect during winter was also analyzed. The aim is to evaluate if the thermal comfort could be enhanced also in the cold season.

During the winter day, the increased thermal storage potential of the built surfaces leads to the mitigation of the night cooling (Fig. 7). Air temperature data extracted in point 2 (i.e. SVF = 0.51) are subjected to greater variations compared to the ones in point 1 (i.e. SVF = 0.15). In fact, the outdoor air temperature in point 2 increases up to +0.23 K and +0.32 K in scenario "wall" and "pavement", respectively, compared to S0 (Fig. 7b). On the other hand, lower improvements are detected in terms of air temperature from 11.00 a.m. to 4.00 p.m. All in all, scenario "pavement" seems to be the most effective strategy in winter conditions, when increasing the outdoor air temperature and, therefore, reducing the relative humidity.

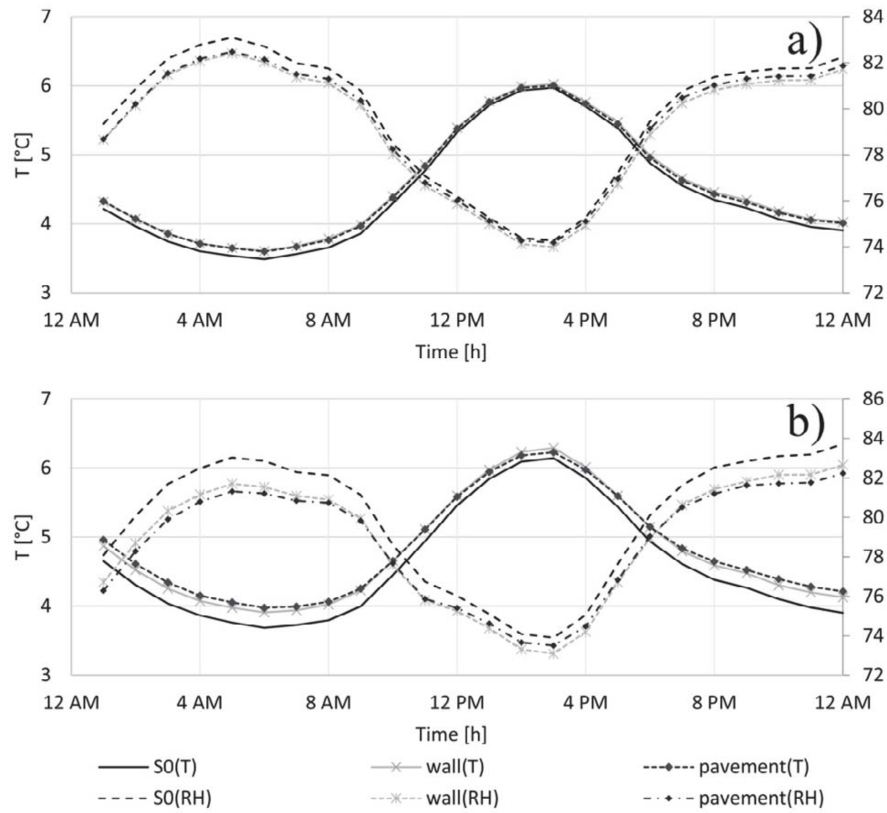


Fig. 7: Simulated air temperature and relative humidity hourly profiles in (a) point 1 and (b) point 2 in the different scenarios during the winter day

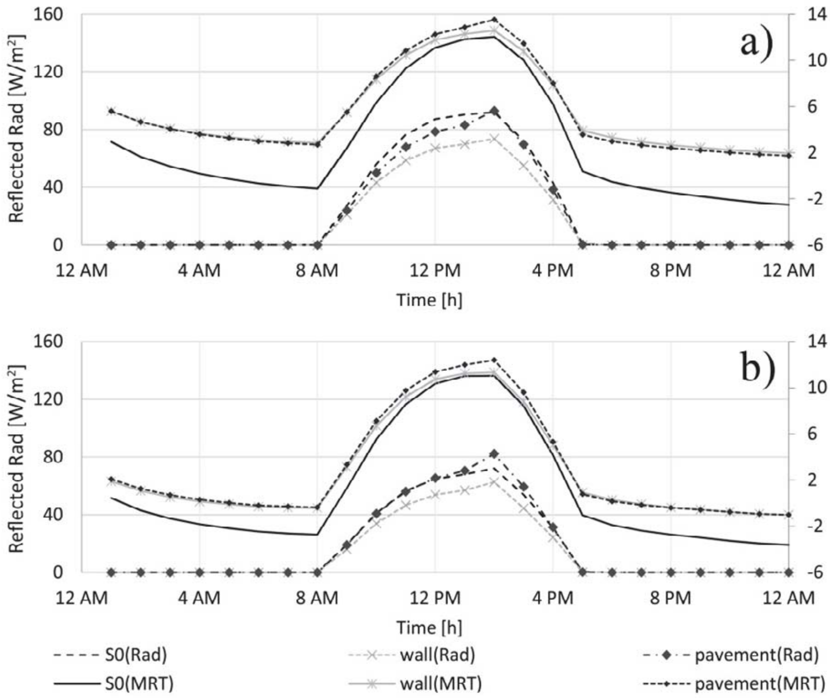


Fig. 8: Simulated mean radiant temperature and reflected solar radiation hourly profiles in (a) point 1 and (b) point 2 in the different scenarios during the winter day

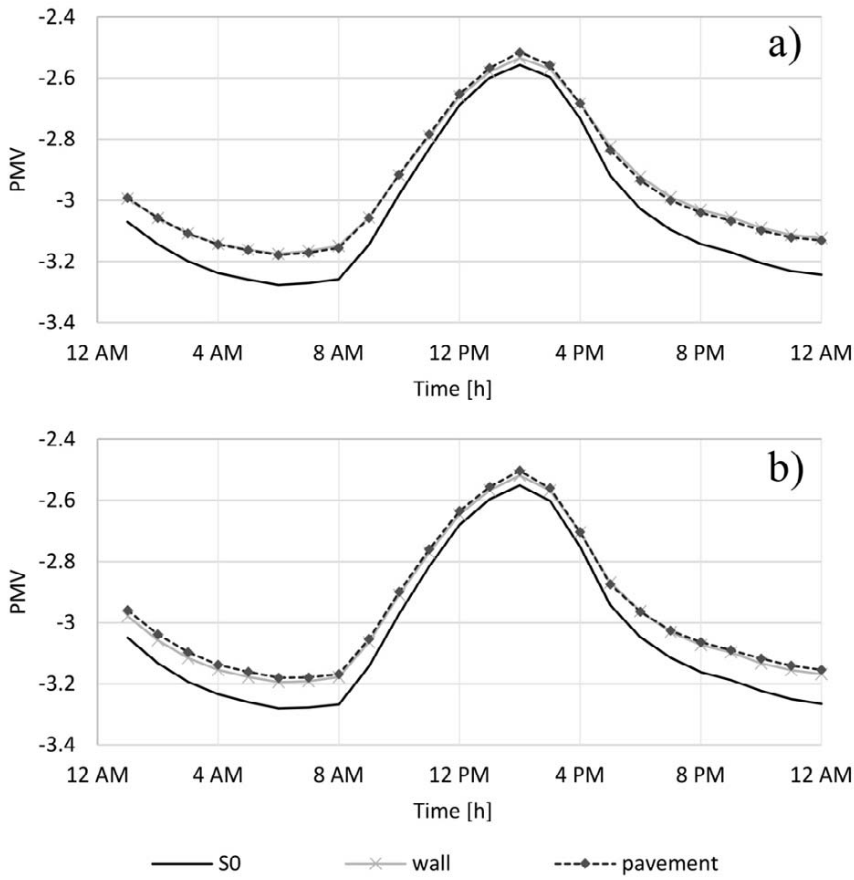


Fig. 9: Comparison between all the simulated scenarios in terms of PMV daily trend at pedestrian level in (a) point 1 and (b) point 2 during the winter day

Opposite behavior was detected in terms of mean radiant temperature, since greater modifications were obtained in point 1, the one presenting the lower value of SVF (Fig. 8). In fact, during the day both the points are not reached by direct solar radiation, due to the lower height of the winter sun, and, therefore, the effect of mutual reflectance between built surfaces has a stronger impact on the MRT. In general, the increased surfaces' heat capacity is able to significantly increase the MRT in the two analyzed points, with a slightly greater performance of pavement's included PMCs. In particular, after the sunset (i.e. from 5:00 p.m.) the effect of the applied mitigation actions provides a MRT increase up to +4.47 K and +2.60 K for "wall" and +4.25 K and +2.56 K for "pavement" at midnight, in point 1 and 2, respectively.

The PMV was evaluated also for winter conditions, by imposing a cloth resistance of 1.2 clo (Fig. 9). In general, improvements in terms of PMV are detected to be very low. However, it is interesting to notice that the PMV in the two mitigation scenarios is higher during the coldest hours of the day with respect to the reference scenario, showing a mitigation effect of the proposed strategies.

4. Conclusions

Microclimate variations due to local phenomena such as Urban Heat Island are nowadays very well acknowledged. This paper investigated the UHI in different areas belonging to the same climate zone with particular attention to the its intensity in a historic district. Therefore, the analysis of the impact of different boundary conditions on the local microclimate at neighborhood level was performed through coupled experimental and numerical analysis. The numerical analysis of the historical urban scenario, presenting the worst microclimate conditions, was performed in order to assess the effectiveness of thermal storage solutions, i.e. PCMs integration within building walls and outdoor pavements, as UHI mitigation measures in improving the thermal quality of the environment at neighborhood-urban scale.

The experimental campaign showed a significant nightly Urban Heat Island in the dense urban historic area compared to the other suburban areas. Therefore, the numerical analysis showed the non-negligible role of thermal storage strategies in mitigating outdoor air temperature both in summer and winter at local scale. In summer, the high-capacity PCMs integrated pavement appears to reduce the peak outdoor air temperature, while in winter PCMs are able to mitigate the nighttime cooling. Moreover, the MRT is improved under winter conditions when high thermal capacity materials are used.

The work demonstrated the importance of the relation between the built environment's characteristics and its microclimate. It was proved that the accurate analysis of the local boundaries conditions produces non-negligible findings supporting the realistic simulation of the urban environments.

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