Albedo impact on the microclimate of courtyards, potential implications on the UHI. A case study in Seville, Spain.

Sebastian Alzate-Gaviria[1], Victoria Patricia Lopez-Cabeza[1], Eduardo Diz-Mellado[1], Carlos Rivera-Gomez[1], Carmen Galan-Marin[1]
[1]Departamento de Construcciones Arquitectónicas I, Universidad de Sevilla, Sevilla, Spain

Abstract

The Urban Heat Island (UHI) effect is a phenomenon that threatens life in cities nowadays. Among other strategies to adapt cities to this phenomenon is the use of the tempering potential of courtyards and changes in the albedo of the surfaces. However, there is little literature about the influence of the albedo on the thermal performance of the courtyard. This research aims to analyze the effect of albedo alteration of the surfaces of a courtyard located in Seville on its tempering potential and the comfort of the users. Besides, it evaluates the accuracy and suitability of the simulation tool ENVI-met, widely used for the simulation of outdoor spaces, by contrasting monitoring and simulation results. It is concluded that high reflectance surfaces reduce the surface temperature by reflecting solar radiation, so they accumulate less heat during daylight hours and release less heat at night, however, the high reflection compromises user comfort.

Key Innovations

- The use of ENVI-met has been validated to analyze the effect of surface albedo on a courtyard's performance.
- Surface albedo has little influence on the air temperature of the courtyard, but it affects surface temperature, Mean Radiant Temperature, and user's comfort in a way that should be considered during the design of these spaces to balance the positive and negative effects.

Practical Implications

For ENVI-met simulations of courtyards, it is enough to model the part of the building surrounding the courtyard.

High albedo is recommended for floor surfaces and medium-range albedo is recommended in walls, to balance the positive effect on temperatures and negative on comfort.

Introduction

The Urban Heat Island (UHI) effect, in which the urban temperatures exceed that of the surrounding rural and suburban areas, occurs due to factors such as high building density, the use of high absorptivity materials, and the scarcity of green spaces, among others. This phenomenon threatens cities, since it increases energy consumption in buildings, deteriorates air quality, and affects people's health (Changnon et al., 1996). High urban temperatures are shown to be related to increased health problems and mortality from cardiovascular and respiratory diseases (Anderson & Bell, 2009). This problem will be worsened by a future of rising temperatures and increasingly frequent heat waves. Therefore, it is necessary to mitigate this phenomenon, a problem that has become a focal point of growing interest in the scientific literature (Rojas-Fernández et al., 2017; Santamouris & Yun, 2020).

Historically, courtyards have been used to adapt to climatic conditions. It is proven that they have a tempering effect that can reduce the energy consumption of buildings and improve comfort (López-Cabeza et al., 2018). Courtyards represent an important strategy in hot climates where it is needed to reduce the high temperatures to cool the indoor spaces. The effectiveness of courtyards will largely depend on its geometry, orientation, and thermal characteristics of the construction materials (Ghaffarianhoseini et al., 2015).

Albedo is the proportion of incident radiation that is reflected, with values between 0 (all absorbed) and 1(all reflected). As a mitigation strategy of the UHI effect, the use of high albedo materials has been studied for a relatively short time. It has been a subject of discussion since some of the scientific literature ensures that these materials reduce the surface and air temperatures by reflecting solar radiation (Kyriakodis & Santamouris, 2018; Santamouris et al., 2012), while others agree that, additionally, they increase the mean radiant temperature (MRT), which compromises people comfort by receiving multiple radiation reflections from high albedo surfaces (Erell et al., 2014; Rosso et al., 2018; Taleghani, 2018a, 2018b). For example, an experiment changing the albedo of pavement from 0.37 (black) to 0.91 (white) in a courtyard caused a reduction of 1.3°C in the air temperature but increased 2.9°C the mean radiant temperature (Taleghani et al., 2014). However, there is not much research about the albedo effect of the surfaces of the courtyard on its performance and users' comfort. This study tries to shed light on that through simulation.

The software used is ENVI-met v4.4.5. This CFD software is one of the most used and most accurate in terms of thermal performance of the outdoor environment, especially on a large scale, and previously validated in many countries (Tsoka et al., 2018). It accounts for wind, solar radiation, soils, and vegetation, among other variables, and it can provide comfort

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indexes. Materials can be defined in all their thermal variables, including albedo. That is why this software is selected.

In order to mitigate the UHI effect, this study aims to analyze the influence of the surfaces' albedo of the courtyard (both floor and walls) on its thermal performance and users' comfort. Through simulation, the air temperature, surface temperature, MRT, and Physiological Equivalent Temperature (PET) comfort index are analyzed to provide recommendations for an adequate selection of materials in courtyards in a specific case in Seville, Spain.

Methods

This study's workflow is structured as shown in Figure °1. First, the selected case study was monitored. Temperature, relative humidity, and surface temperature were recorded in different albedo configurations of the courtyard. Some of these data were used to calibrate the software used, ENVI-met v4.4.5. Once validated, the software was used to simulate different scenarios of the courtyard, trying different albedo values for walls and the floor of the courtyard. Finally, the results of air temperature, surface temperature, MRT, and user comfort are discussed. For the analysis of user comfort, the Physiological Equivalent Temperature is used since it has become an accepted index to analyze comfort in outdoor environments (Matzarakis et al., 1999).

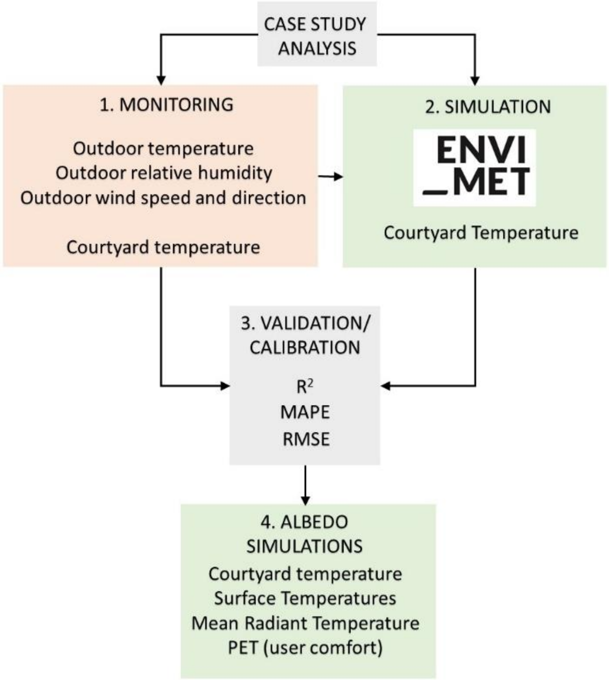

Figure °1: Workflow

Case Study

The selected case study is a courtyard located in an educational building in Seville (37°17′01″N 5°55′20″O, 7m asl), in the south of Spain. Seville is located in a Csa zone according to Koppen classification (Kottek et al., 2006), which is characterized by warm and dry summers and mild winters.

The building is divided into different rectangular blocks of one or two floors, organized by courtyards, which provide light and natural ventilation, one of them being our case study. The building is detached from any other building. It was refurbished in 2017 and the new construction is characterized by white-coated walls and dark roofs.

The case study courtyard is located in the building in Figure 2 and represented in Figure 3. It is 5.2 x 6.9 meters and has a minimum height of 5.0 meters. We defined the aspect ratio (AR) as the proportion between the height and width of the courtyard as shown in eq.1:

$$AR = Height/Width \qquad (1)$$

Applying equation 1, the AR of this courtyard is 1.00 in the long direction and 0.7 in the opposite one.

The courtyard has three walls with large windows lighting an internal corridor, and the rest of the walls are coated with white paint. The southwest façade has a green wall installed, as shown in Figure 4. The floor of the courtyard consists of white gravel.

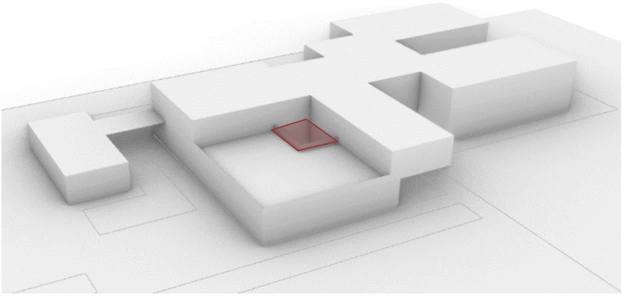

Figure 2. Model of the building. In red, the courtyard.

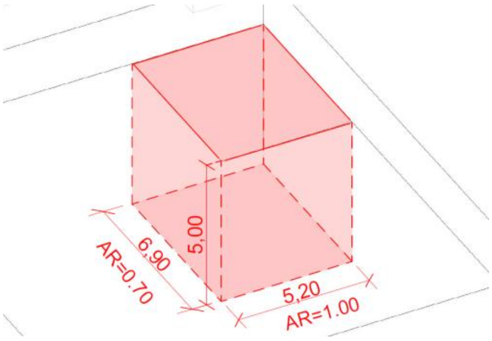

Figure 3. Dimensions of the courtyard.

Figure 4. Green facade in the case study courtyard.

Monitoring

The monitoring campaign took place during the hot seasons of 2017 and 2018, that is, before and after the installation of the vegetal façade. One day of each campaign is selected to be simulated for the validation and calibration of the software. The variables recorded are dry bulb temperature and relative humidity inside the courtyard, using TESTO 174H data loggers, and wind speed and direction, relative humidity, and dry bulb temperature in the outdoors, through a weather station model PCE-FWS 20. The sensors inside the courtyard are located at 1 m above the floor, in order to record the temperature at users' height. They have been placed in the south-east façade, to avoid direct solar radiation on them. Sensors are protected with a ventilated shield to avoid overheating due to solar radiation. Table 1 shows the characteristics of the instruments used.

The selected days to be simulated are the 3rd of October 2017 and the 14th of August 2018. In both cases, the maximum outdoor temperature reached similar values, around 37ºC.

Table 1: Technical data of the measurement instruments

Sensor	Variable	Accuracy	Resolution
TESTO 174H	Dry bulb Temp.	±0.5 °C	0.1 °C
	RH	±0.1%	2%
PCE-FWS 20	Dry bulb Temp.	±1 °C	0.1°C
	RH	±5%	1%
	Wind	±1 m/s	-

Simulation

The software ENVI-met is used to evaluate the courtyard in different configurations through simulation. This section describes all the simulation parameters.

The model's geometry for the simulation is described in Table 2 and displayed in Figure 5.

Table 2: Simulation model geometry properties

Number of grid cells	55, 61, 20
Size of the cells (m) (x,y,z)	1x1x1 Telescoping factor 12%. Start at 10 m height.
Nesting grids	4
Model rotation out of grid north	45

The model used for the simulations represents just an important part of the building around the courtyard, but not the whole building, in order to optimize the simulation time. Tests with the reduced model have been contrasted with the whole building and the results have been similar enough. This statement is done after the comparison of the statistical variables used in this paper. The two models provided the same R^2 value, and only 0.01 difference in RMSE and 0.09% in MAPE. The simulation time, on the other hand, was twice. Based on this, we confirmed that the reduced model was the best option to find a balance between accuracy and time optimization.

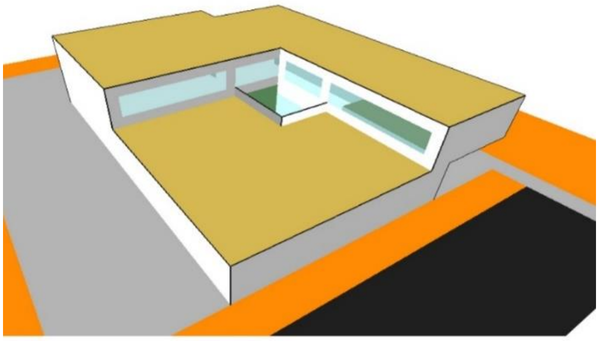

Figure 5: Simulation model.

The software is calibrated using monitoring data. The recorded wind speed and direction, dry bulb temperature, and humidity are used as inputs for the simulation, and courtyard temperature is the output that is compared to the monitored temperature to validate the software. Two different test configurations are performed: One before the green façade was installed (T1) and the other one after the installation (T2). The materials used are from ENVI-met's library, modifying the albedo and reflectivity values according to literature. The green façade has been modelled as only vegetation added to an existing wall. The main input variables of the simulations are in Table 3. All the simulations start three hours before the day that is being analyzed in order to discard the first hours that may provide inaccurate results.

Table 3: Main input variables for ENVI-met validation.

	T1	T2
Start Simulation Day (DD.MM.YYYY)	13.08.2018	02.10.2017
Start Simulation Hour (hh:mm)	21:00	
Total Simulation Time (hours)	28	
Wind Speed at 10 m (m/s)	0.79	0.96
Wind direction	225° (SW)	90° (E)
Roughness Length (m)	0.01	
Air temperature (min - max) (ºC)	20.7 – 38.4	22.0 – 37.0
Relative Humidity at 2m (min-max) (%)	19.0 – 89.0	29.0– 60.0
Initial Soil Temperature (ºC)	19.85	
Initial Soil Humidity (%)	50	

Once validated and calibrated, the software is used to simulate different albedo configurations in the courtyard. These simulations share the same input variables, and they are described in Table 4. The characteristics of the materials used are described in Table 5.

Table 4: Input variables for the albedo simulations.

Start Simulation Day (DD.MM.YYYY)	19.07.2020
Start Simulation Hour (hh:mm)	21:00
Total Simulation Time (hours)	28
Wind Speed at 10 m (m/s)	1.59
Wind direction	45° (NW)
Roughness Length (m)	0.01
Air temperature (min - max) (ºC)	23.6 – 44.4
Relative Humidity at 2m (min-max) (%)	44.4 – 74.8

Initial Soil Temperature (ºC)	19.85
Initial Soil Humidity (%)	50

Table 5: Materials' properties for the simulations

Materials			Albedo	Emissivity
WALLS	M1	Beige brick	0.40 (Mat Santamouris, n.d.)	0.90 (Yaghoobian & Kleissl, 2012)
	M2	White coating	0.70 (Taha et al., n.d.)	0.91 (Taha et al., n.d.)
	M3	Green facade	0.30 (Djedjig et al., 2016)	0.95 (Djedjig et al., 2016)
	M4	Dark coating	0.10 (Oke, 1992)	0.93 (Oke, 1992)
	V	Windows	0.05	0.90
FLOORS	P1	White gravel	0.38 (M. Santamouris et al., 2011)	0.93 (M. Santamouris et al., 2011)
	P2	White concrete	0.85 (Taha et al., n.d.)	0.96 (Taha et al., n.d.)
	P3	Dark concrete	0.03 (Taha et al., n.d.)	0.87 (Taha et al., n.d.)

The combination of materials used in each simulation is shown in Table 6. There are two groups of simulations. One keeping the existing materials for the walls and changing the albedo of the floors (F) and another group keeping the existing floor and changing the albedo of the walls (W). Figure 6 displays the model of the courtyard and the material used in each surface for the different simulations.

Table 6: Materials utilized in each simulation

Name	Description	Walls Materials	Floor Materials
F 1	White floor	M2 + M3 + V	P2
F 2	Dark floor	M2 + M3 + V	P3
F 3	Grey floor	M2 + M3 + V	P1
W 1	White walls	M2	P1
W 2	Dark walls	M4	P1
W 3	Beige walls	M1	P1

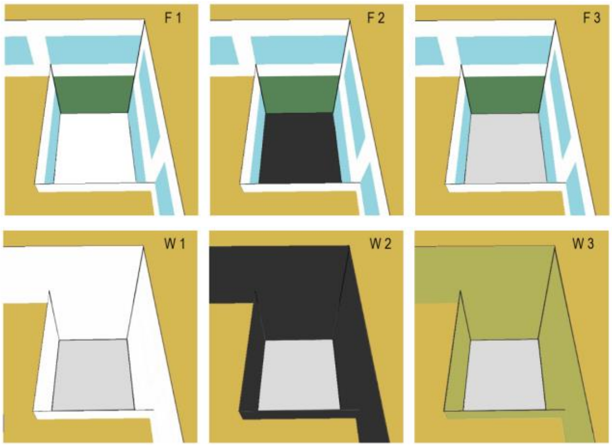

Figure 6: Model of the courtyard. The colors represent the material of the surfaces.

Results

Monitoring results and software validation

Results of the monitoring campaign are contrasted to the first group of simulations (T1 and T2) in order to calibrate and validate the use of the software. The recorded data confirms the tempering potential of the courtyard in hot days, as shown in Figure 7. the difference between the monitored outdoor and courtyard temperatures is known as thermal delta (TD), defines in Eq.2:

TD = Outdoor temperrature – Courtyard temperature (2)

It can be seen that in T1, the TD is up to 5.3ºC, and it rises to 6.2ºC in T2, an improvement that can be caused by the installed vegetal façade, although it is also possible that the higher outdoor temperature is increasing the tempering potential of the courtyard.

The simulation results for both days follow a similar pattern. During the night and the morning, the simulated courtyard temperature matches the recorded way with high accuracy. However, in the afternoons, the simulations overestimate the temperature of the courtyard up to 4 ºC. Despite that, the software is able to simulate the tempering effect of the courtyard.

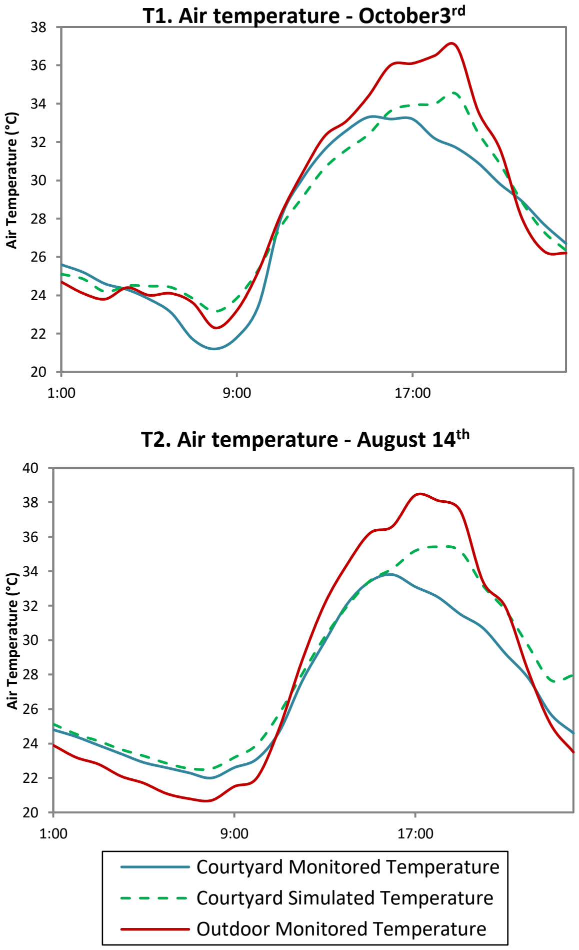

Figure 7: Monitoring and simulation results for validation. Top: T1: without vegetal facade. Down: T2: With vegetal facade installed.

In order to evaluate the accuracy of the results provided by the software, the statistical parameters calculated are the Root Mean Square Error (RMSE), the coefficient of determination (R^2), and the Mean Absolute Percentage Error (MAPE). The closer the RMSE is to 0, R^2 to 1, and MAPE to 0, the more accurate the simulation is. Table 7 shows the results of these parameters for each test simulation. With these results, the software was validated.

Table 7: Quantitative evaluation of the simulations for validation.

	Date	RMSE (°C)	R^2	MAPE
T1	2017 - Oct 3	1.26	0.92	3.90%
T2	2018 - Aug 14	1.59	0.94	4.02%

Floor albedo variations

Figure 8 shows the results of changing floor albedo simulations. It can be seen that air temperature is higher in the dark floor scenario than in the others in the morning hours. The white color scenario shows the lowest air temperature. However, the difference between the maximum and minimum temperatures of the different scenarios at peak time is only 0.2ºC.

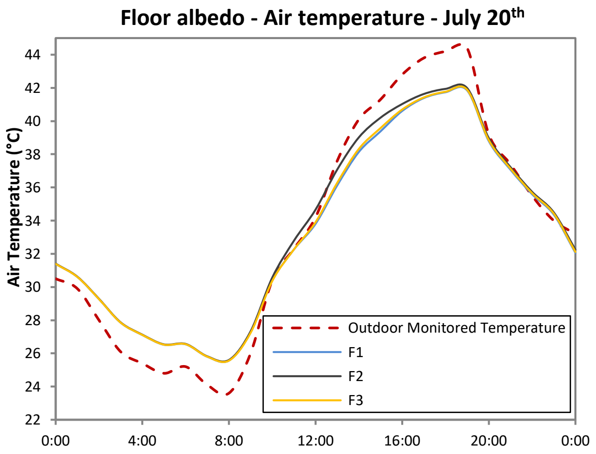

Figure 8. Air temperature in floor albedo simulations.

The surface temperature of the floor shows clear differences in the scenarios, as shown in Figure 9. The lowest temperatures are obtained from the white color scenario (31.8ºC) and the dark color reaches the highest temperature, up to 55.5 ºC. The grey color scenario falls in the middle. This tendency is maintained throughout the day.

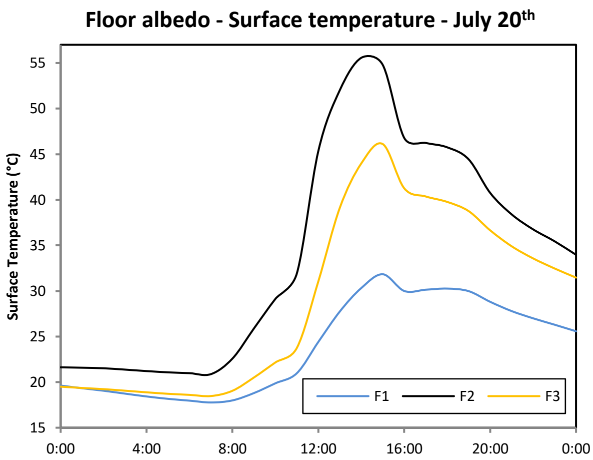

Figure 9. Floor surface temperature in floor albedo simulations.

Figure 10 shows that differences in mean radiant temperature at 1.5 m in the middle of the courtyard are imperceptible among the three scenarios.

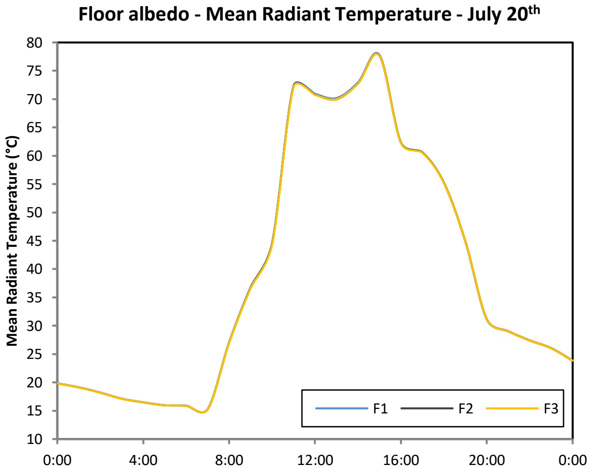

Figure 10. MRT in floor albedo simulations.

PET results have also minimal differences among scenarios. This is related to the importance of MRT and air temperature on PET. This is seen in Figure 11.

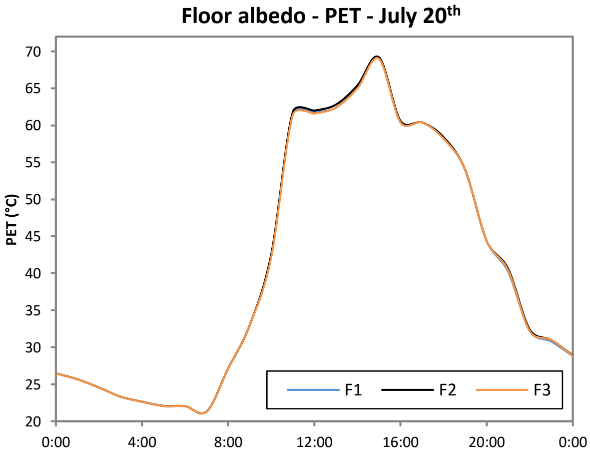

Figure 11. PET in floor albedo simulations.

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Walls albedo variations

Air temperature results for changes in wall albedo are similar to changes on the floor. They are displayed in Figure 12. The dark wall presents the highest air temperature, while the light one the lowest. However, these differences are small, only 0.2ºC at peak temperature, reaching 42.1 ºC in W2 and 41.9 in W1.

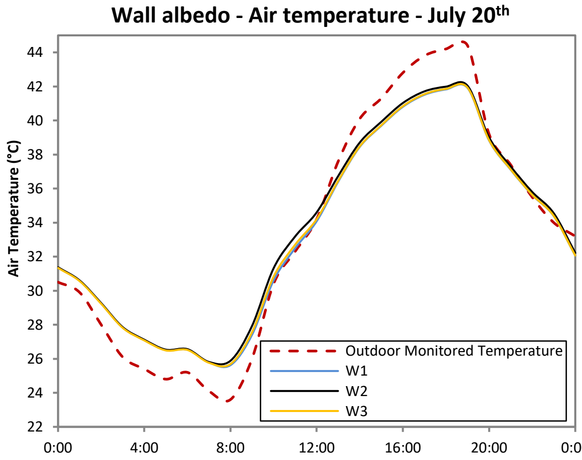

Figure 12. Air temperature in wall albedo simulations.

In Figure 13, the surface temperature of the floor is shown in the different simulations. Although in this second group of simulations the albedo of the floor is not changed, the albedo of the wall is affecting the solar radiation that is reflected to the floor, thus, its temperature varies. It can be seen that the W3 scenario provides the lowest temperature, 45.5ºC at the peak, and the high albedo scenario presents the highest peak temperature, 46.6ºC at its peak.

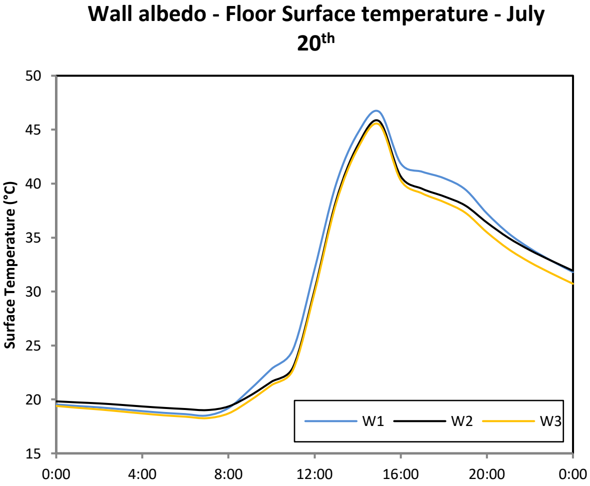

Figure 13. Floor surface temperature in wall albedo simulations.

Figure 14 shows that the highest MRT is 79.1ºC and occurs with the highest albedo. This means that the reflected radiation from the walls is affecting the MRT of the courtyard. In this sense, the lowest MRT occurs with the lowest albedo in the walls, which is 74.8ºC. However, at night, the tendency is the opposite. The highest MRT occurs with the lowest albedo in the walls. This is because they have a higher temperature affecting the MRT, but it is less important than in the morning hours, with only a 1.5ºC difference among them.

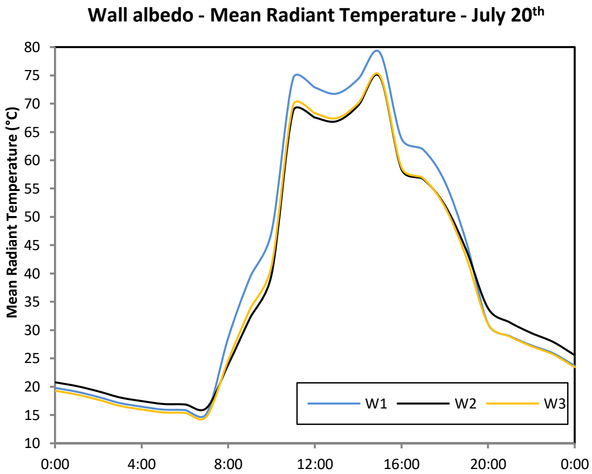

Figure 14. MRT in wall albedo simulations.

PET is an outdoor comfort index highly affected by the MRT, which is why the tendency is the same as before. In Figure 15, the highest values are provided by the high albedo simulation. During the night, it is the low albedo that provides the highest values.

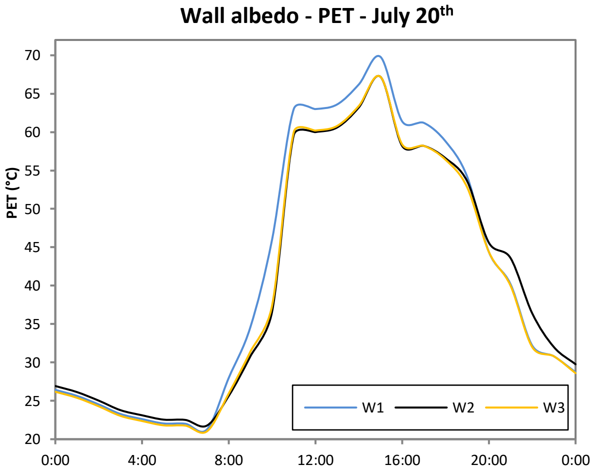

Figure 15. PET in wall albedo simulations.

Discussion

The air temperature results suggest that, in general, the higher the albedo of the surfaces of the courtyard, the lower the air temperature. However, the effect is not very important, only around 0.2ºC when the temperature in the courtyard is at its peak. In contrast, the effect on the surface temperature is significant, reaching a 25ºC difference between the dark and the light albedo (Figure 9). From the results, we have seen that high albedo pavement reflects a higher proportion of solar radiation, so it does not keep the heat, reaching lower surface temperature than lower albedo surfaces.

Another important aspect that has been revealed is that the albedo of the floor surfaces does not have any important effect on the mean radiant temperature inside the courtyard, while the albedo of the walls does, up to 5ºC

(Figure 14). Given the little influence of floor albedo on air temperature and MRT, the changes in the floor albedo do not have an important influence on the PET index, very influenced by those variables. It is the wall albedo that has a larger influence, thus, the use of very high albedo on walls, although beneficial to slightly reduce air and surface temperatures, may be detrimental to the user's comfort. The higher influence of walls albedo than floor albedo on the MRT of the courtyard may be also due to the larger surrounding surface that they have.

The surface temperature results also show the influence of changing the albedo of one surface on the temperature of others. Figure 13 shows that the high albedo of walls produces a floor temperature 2ºC higher than the medium albedo for the walls. Accordingly, a higher reflection from the walls increases floor temperature.

Walls with high albedo reflect solar radiation affecting user's comfort, while a low albedo in the walls absorb radiation and increase surface temperature and air temperature. Therefore, in walls of enclosed spaces similar to our case study, it is convenient to use materials with a medium-range albedo to equilibrate both phenomena.

Conclusion

In this paper, the software Envi-met has been assessed to study the effect of the albedo of surfaces on the microclimate of a semi-outdoor space. A courtyard in the city of Seville has been monitored to compare the results with the simulation and calibrate the software. Then, different configurations of albedo in walls and floor have been simulated.

The results show that the albedo has a low influence on the air temperature of the courtyard (0.2ºC). A higher effect has been recorded in the validation simulations, where a change in one wall into a green wall caused a higher thermal delta (0.9ºC difference). This was accurately simulated by the software.

The influence of albedo on the temperature of the surfaces is high (25ºC), as well as the mean radiant temperature of the courtyard (5ºC), affected by reflected solar radiation and surface temperature radiation. The albedo of the walls is especially important, being the floor less influent.

Taking the results into account, the recommendations for designers are that in floor surfaces the highest the albedo, the better the tempering effect of the courtyard, and the higher comfort. However, for the walls, the albedo recommended is a medium-range albedo, to avoid high reflections that affect adversely the comfort of users and the increase of temperature of the surfaces.

This study is limited to changes on albedo, not on the material of the surfaces. This means that it can be easily translated into a change in the surface color or painting. Further studies should also consider variations on the material characteristics and different kinds of construction.

These conclusions stem from one case study and results can only be extended to cases with similar geometry and climatic conditions. Thus, this study should be improved with other cases with different geometries and climates in order to corroborate the results. Further studies should also elaborate on the implementation of other strategies to improve the tempering potential of courtyards in relation to the albedo, such as shading.

Acknowledgments

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