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Reducing outdoor air temperature, improving thermal comfort, and saving buildings' cooling energy demand in arid cities – Cool paving utilization

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ABSTRACT

Cairo experiences extremely high temperatures, which increase buildings' cooling energy demand. Previous studies found that vegetation raises air temperature in low-density urban areas and has a weak effect on air temperature reduction in high-density urban areas in Cairo. Therefore, this study seeks to investigate the impact of cool paving, as an alternative strategy, on air temperature and buildings' energy demand reduction in urban areas of different densities. Three built-up areas with varying densities of 25 %, 50 %, and 85 % were selected and simulated by using ENVI-met to evaluate the effect of cool paving on air temperature reduction. Then, DesignBuilder model was used to calculate buildings' cooling energy savings resulting from air temperature reduction. This study showed that cool paving can reduce air temperature and buildings' cooling energy in 25 %, 50 %, and 85 % urban densities by 0.5 K – 2.5 %, 0.2 K - 1.4 %, and 0.1 K - 0.2 %, respectively. However, cool paving raised Physiological Equivalent Temperature (PET) in the three areas. Therefore, other scenarios combining vegetation and cool paving are discussed as possible solutions for the dilemma between air temperature and PET reduction. Combining trees with cool paving achieved this balance in the low-density urban area besides reducing cooling energy by 3.2 %.

1. Introduction

Cairo is a megacity that experiences an enormous increase in air temperature up to 40 K during the summertime. Furthermore, research predicts that the number of hot days is likely to increase to up to 200 days annually (Lelieveld et al., 2016). This phenomenon is attributable to massive urbanization and therefore affects air quality and public health negatively (Fu & Weng, 2018; Lelovics, Pongracz, & Bartholy, 2011; Serag, 2014; Wilbey, 2008). Accelerated urban sprawl increased the urban built-up area from 153.29 km^2 to 296.23 km^2 between 1984 and 2015. In addition, green areas were reduced from 374.26 km^2 to 346.12 km^2 during the same period (El-Hattab, A. S.M., & L. G.E., 2018). These factors caused the Egyptian residents to use more air conditioning in their buildings. Accordingly, the sale of air conditioners increased from 54,000 units per year to 766,000 units per year between 1996 and 2010 (CAPMAS, 2008; EEHC, 2008; MTI, 2004). Consequently, electricity consumption increased by 6.3 % annually (Hanna, 2013). This problem has led to chaos in the electricity sector with continuous electricity cut-offs during the summertime (Attia, Evrad, & Gratia, 2012). The increased usage of air conditioning has caused electricity bills, which consume about 40 % of Egyptian residents' monthly income, to rise during the last six years. While Cairo faces a critical problem in the electricity sector due to the extremely high outdoor air temperatures, the stakeholders do not have any innovative strategies to address this issue. The decision-makers tried to solve the problem by advising residents to use energy-saving lamps, which did little to help. The major reason for this crisis is the severe outdoor thermal stress that drives people to use more air conditioning in the buildings (Al-Youm, 2017). Therefore, this study seeks to provide a possible solution to reduce buildings' energy consumption by lowering the outdoor air temperature.

The literature review reported that urban vegetation could reduce outdoor air temperature and therefore buildings' cooling energy demand as well (Calcerano & Martinelli, 2016; Ko, 2018; McRae et al., 2020; Morakinyo, Lau, Ren, & Ng, 2018; Morakinyo, Lau, Ren, & Ng, 2018; Morakinyo, Ouyang, Lau, Ren, & Ng, 2020). However, recent studies carried out in Cairo found that trees and grass raise outdoor air temperature and therefore buildings' cooling energy demand in the

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low-density urban areas as well. Moreover, these studies found that vegetation reduces air temperature and buildings' energy in extremely dense built-up areas by nominal reductions of 0.1 K and 0.2 %, respectively (Aboelata & Sodoudi, 2019, 2020). However, these studies found that urban vegetation reduces Physiological Equivalent Temperature (PET), which is an index of human thermal comfort in outdoor spaces in all areas of different urban densities. Therefore, this study seeks to evaluate the impact of cool paving (as an alternative to urban vegetation) on air temperature reduction, buildings' cooling energy consumption savings, and thermal comfort improving in built-up areas of different densities in Cairo. There have been no studies comparing the effect of cool paving on air temperature and buildings' cooling energy demand in urban areas of different densities in Cairo.

Therefore, the novelty of this study is defined in the following points: -

1 This study aims to fill the research gap on the usage of cool paving to reduce outdoor air temperature and buildings' cooling energy demand in Cairo, with a comparison of effects in areas of different urban densities with the aim of achieving better mitigation than vegetation has yield in previous studies in Cairo.
2 The study aims to find an alternative strategy to the trees and grass that raise air temperature and buildings' energy demand in low-density urban areas in Cairo.
3 This study seeks to find a suitable strategy that could be used to solve the dilemma between air temperature and buildings' energy reduction and improving thermal comfort.

Cool paving is considered an important strategy that can be used to reduce outdoor air temperature, improve thermal comfort, and reduce buildings' cooling energy demand (Carnielo & Zinzi, 2013; Karlessi et al., 2011; Lin et al., 2008; Qin, 2015a, 2015b; Rodenfeld et al., 1995; Santamouris, 2013, 2014; Synnefa, Santamouris, & Livada, 2006). The upcoming section discusses three main issues: -

1 The effect of cool paving on outdoor air temperature at pedestrian level (1.80 m height from the ground).
2 The impact of cool paving on lowering outdoor air temperature in urban areas of different densities.
3 The influence of cool paving on reducing buildings' cooling energy demand.

Firstly, many previous studies showed the effect of cool paving on outdoor air temperature. Computer simulation studies found that the usage of high albedo paving could reduce the air temperature at pedestrian level in Rome, Athens, and Los Angeles significantly by 5.5 K, 5 K, and 2–3 K, respectively (Akbari, 2001; Synnefa et al., 2011). Moreover, cool paving could reduce the air temperature in Greece and Italy moderately by 1.5–4 K (Kyriakodis & Santamouris, 2018; Santamouris et al., 2012). Highly reflective materials could lessen air temperature at 1.80 m height from the ground in Toronto, Brazil, Phoenix, and Malaysia by nominal values of 0.2–0.7 K (Battista & Pastore, 2017; Sen, Roesler, Ruddell, & Middel, 2019; Shahidan, Jones, Gwilliam, & Salleh, 2012; Taleghani & Berardi, 2018). This study seeks to evaluate the effect of cool paving on reducing outdoor air temperature at 1.80 m height from the ground in Cairo.

Secondly, there have been only a few studies investigating the effect of cool paving on outdoor air temperature at the pedestrian level in urban areas of different densities. An assessment of replacing dark asphalt with cool materials conducted via CFD model found that cool reflective paving could reduce air temperature at the pedestrian level in high-density urban areas in Athens and Greece by 1–2 K (Dimoudi et al., 2014; Georgakis, Zoras, & Santamouris, 2014; Tsoka, Tsikaloudaki, & Theodosiou, 2017). Furthermore, some numerical modeling studies found that the effect of cool paving on lowering air temperature is stronger in deep canyons than in wide ones (Xu, Azarijafari, Gregory, Norford, & Kirchain, 2020; Yang, Wang, Kaloush, & Dylla, 2016). Nevertheless, a previous study that used the ENVI-met model and field measurements in South Korea found that cool paving increases air temperature in high-density urban areas (Song & Park, 2015). Contrastingly, some previous studies showed that cool paving should not be applied in canyons of aspect ratio H/W > 1.0 because its effect on air temperature reduction is more efficient in low-density urban areas. The usage of cool paving with and without vegetation does reduce the air temperature in wide canyons by 0.75 K and 3.5–6.4 K, respectively (Alchapar & Correa, 2016; Alchapar, Pezzuto, Correa, & Labaki, 2017; Qin, 2015b). A previous study found that reflective paving could decrease thermal comfort (Physiological Equivalent Temperature, PET) at the pedestrian level (Yang et al., 2016). No previous studies have been carried out in Cairo to investigate the impact of cool paving on air temperature in urban areas of different densities. Therefore, this study aims to fill this research gap and evaluate the possible benefits of using cool paving to lower outdoor air temperature at 1.80 m height from the ground in urban areas of different densities.

Thirdly, there are different studies which showed the effect of cool paving on reducing buildings' cooling energy. Cool surfaces in Los Angeles could lessen the energy usage of air conditioning by 20 % (Akbari, 2001). In addition, various previous studies showed that cool paving can reduce buildings' cooling energy demand by 4–17 % annually (Antonia et al., 2016; Castaldo et al., 2018; Guo, Qiao, Huang, Fang, & Han, 2012; Kolokosta, Giannariakis, Gobakis, Synnefa, & Santamouris, 2018; Pomerantz, Rosado, & Levinson, 2015; Rossi et al., 2016; Wan, Hien, Ping, & Aloysius, 2012). In a simulation of the meteorological and urban parameters in the city of Milan with conventional and high albedo materials, cool paving reduced the cooling energy by 30 % (Falasca et al., 2019). TRNSYS software was used to investigate the impact of high albedo paving in Algeria and found that its usage could reduce buildings' energy by 20–40 % (Hamoudi et al., 2018). A study conducted with the WRF model and the developed energy model (BEM) in Toronto to investigate the influence of high albedo usage on buildings' energy reduction found that it could reduce cooling energy demand by 7–10 % (Jandaghian & Berardi, 2020). A recent study using the UWG model to examine the influence of cool paving on buildings' energy found that it could achieve maximum energy reductions for buildings in high and low-density urban areas (Xu et al., 2020). Changing sidewalk materials by increasing albedo in Greece and Arizona could reduce energy demand annually by 17 % and 11 %, respectively (Kolokosta et al., 2018; Yaghoobian & Kleissl, 2012). This study seeks to estimate buildings' cooling energy savings as a result of reduced outdoor air temperature achieved through the usage of cool paving in Cairo.

To conclude, Cairo is characterized by extremely hot summer days that lead to high rates of air conditioning usage and high electricity bills. Cairo has urban areas of different densities ranging between 25–85 %. Therefore, this study aims to evaluate the effect of replacing dark asphalt with cool paving in urban areas of different densities to improve thermal comfort, reduce outdoor air temperature, and lower buildings' energy consumption.

2. Methods

2.1. Methodology framework

This study aims to investigate the effect of cool paving on reducing outdoor air temperature, lowering buildings' cooling energy demand, and enhancing outdoor thermal comfort in built-up areas of different densities in Cairo. Therefore, three areas of different urban densities (Tag Sultan 25 %, Zahraa Almaadi 50 %, and Imbaba 85 %) were chosen. Then, the three areas were simulated by ENVI-met v.4.4.4, using the current situation (reference case: conventional asphalt). Each area was simulated by applying a cool paving scenario (stamped light concrete) instead of the conventional asphalt. A comparison between the reference

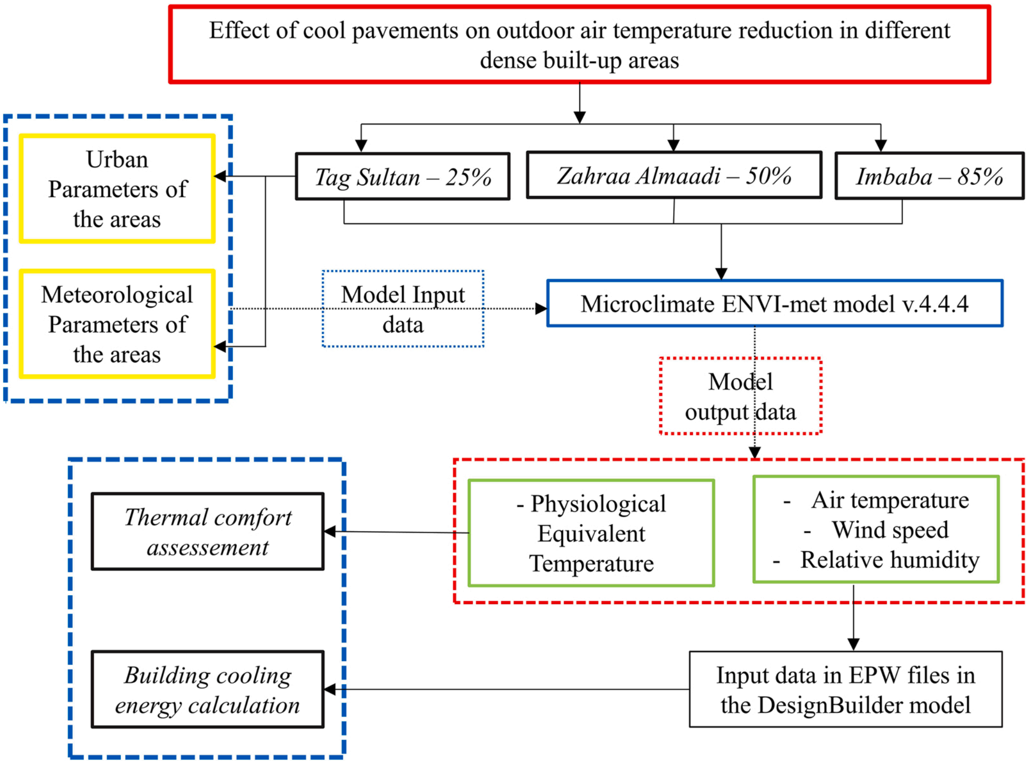


Fig. 1. Research methodology framework.

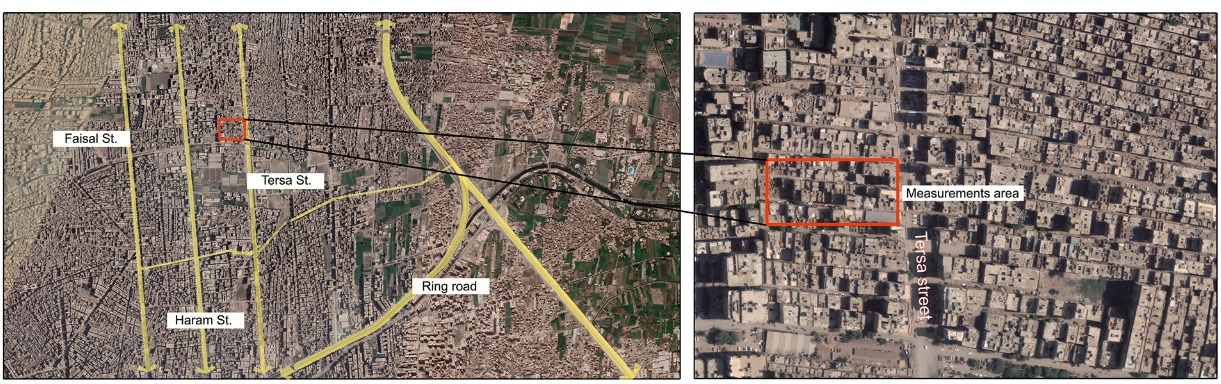


Fig. 2. Micro urban area where meteorological measurements were carried out.

case and the cool paving scenario in terms of outdoor air temperature was carried out to understand the effect of cool paving on air temperature reduction in each urban density. Physiological Equivalent Temperature (PET), which is an index of outdoor thermal comfort, was examined. The ENVI-met outputs of the reference case and cool paving scenarios (air temperature, wind speed, and relative humidity) were used as input data in EnergyPlus weather (EPW) files for the DesignBuilder model. In turn, the DesignBuilder model was used to calculate the cooling energy savings achieved through air temperature reduction. Fig. 1 shows a flowchart summarizing the framework of the methodology.

2.2. ENVI-met model evaluation

Air temperature, wind speed, and relative humidity were measured hourly in a micro urban area in Cairo on 24 August 2018 for 24 h. Fig. 2 shows the area where the measurements were performed. These measurements were carried out from midnight on 24 August 2018 to midnight on 25 August 2018. This day represents a typical hot day in Cairo. The measurements were taken with mobile devices (Appendix A) at 1.80 m height. The measurements were carried out in the middle of this small area. The measurements were taken in this area, which was not one of the three areas investigated, for two reasons. Firstly, the security situation makes working and measuring in Cairo streets very difficult. Secondly, meteorological parameters in most of the areas around Cairo are similar. This area has residential buildings of 60 % urban density, brick and concrete buildings, and streets with an aspect ratio of H/W = 2.

This area was simulated by ENVI-met v.4.4.4 that started running at midnight on 24 August 2018 and lasted 24 h. Moreover, the results of the simulation were cut out at 1.80 m, while the domain size was 100 m × 212 m × 60 m. Table 1 shows the model settings that used nesting grids of 20 m to reduce the numerical problems in the core of the model that can be caused by model borders. The ENVI-met simple forcing method uses hourly air temperature and relative humidity. Therefore, simulated air temperature and relative humidity were compared to the

Table 1
The configuration data of the ENVI-met model of the validation and case study models.

Model validation settings	
Total simulation time (h)	24
Domain size (m)	100 × 212 × 60
Case study models settings	
Total simulation time (h)	30
Tag Sultan area domain size (m)	140 × 200 × 60
Zahraa Almaadi area domain size (m)	130 × 232 × 60
Imbaba area domain size (m)	70 × 100 × 60
General settings of the ENVI-met models	
Simulation day	24.08.2018 – 25.08.2018
Simulation start time (H.H.:MM: S.S.)	00.00.00
Roughness length z_0(m)	0.01
Wind direction (0= from north, °)	315
Wind speed at 10 m above ground (m/s)	2.80
Min. and max. temperature of atmosphere (°C)	23.00 min – 35.00 max.
Min. and max. relative humidity in 2 m (%)	34.00 min – 89.00 max.
Model resolution (m)	2.00 × 2.00 × 0.8
Nesting grids (m)	20
Location	Cairo, Egypt
Latitude and longitude	30.03–31.22

measured parameters. Wind speed at 10 m height (2.8 m/s) was used by considering the average of measured wind speed (1.4 m/s) and the formula of (Bañuelos-Ruedas, Angeles-Camacho, & Rios-Marcuello, 2011). The comparison between measured and simulated air temperature showed an increase in simulated air temperature between 13.00 and 17.00 h. This occurred because the model assumed that the street paving is 100 % asphalt. However, there are tiled spots in front of the residential buildings that are informally and illegally constructed by the residents. These tiles could be cooler than asphalt during the daytime. However, the simulated and measured air temperature and relative humidity curves are almost identical (Fig. 3). Besides, the coefficients of determination (R^2) of air temperature and relative humidity are 0.96 and 0.98, respectively. These values are between 0.89 and 0.99 and are in line with previous studies (Acero & Pascual, 2015; Ketterer & Matzarakis, 2015; Tsoka, Tsikaloudaki, & Theodosiou, 2018). Moreover, the Root Mean Square Error (RMSE) of air temperature and relative humidity are 0.46 K and 3.2 %, respectively (Fig. 3). The previous literature review showed that the common range of RMSE of relative humidity ranges between 2.04 and 10.20 % (Carpio, Marinoski, Triches, Lamberts, & Melo, 2016). Therefore, the model is considered reasonable and reliable.

ENVI-met is a well-known microclimate simulation model widely used for simulating micro-urban areas based on parameters such as buildings, urban surface materials, and landscape elements. It uses local meteorological parameters from boundary conditions or the forcing method that draws on hourly data (Acero & Arrizabalaga, 2018; Crank, Sailor, Ban-Weiss, & Taleghani, 2018; Salata, Golasi, Vollaro, & Vollaro, 2016; Taleghani, Tenpierik, Dobbelsteen, & Sailor, 2014; Yang, Zhao, Bruse, & Meng, 2013). ENVI-met is a well-validated model and has proven reliable in various previous studies (Aboelata & Sodoudi, 2019, 2020; Buccolieri, Maggiotto, & Di Sabatino, 2015; Conry et al., 2015). It can calculate Physiological Equivalent Temperature (PET) directly by using BioMet that refers to outdoor thermal comfort (Aboelata, 2020; Emmanuel & Fernando, 2007). ENVI-met has some limitations because it cannot calculate the anthropogenic heat and indoor thermal comfort.

2.3. Case study areas

Cairo is a very dense city that has extremely hot summers. It is located between 30.06 latitude and 31.25 longitude. Moreover, it has urban areas of different densities that range between 25 % in the newly planned residential compounds or gated communities to 85 % in the informal settlements. Three urban areas of different densities in Cairo (Tag Sultan 25 %, Zahraa Almaadi 50 %, and Imbaba 85 %) were chosen (Fig. 4). The determination method for the urban parameters of each

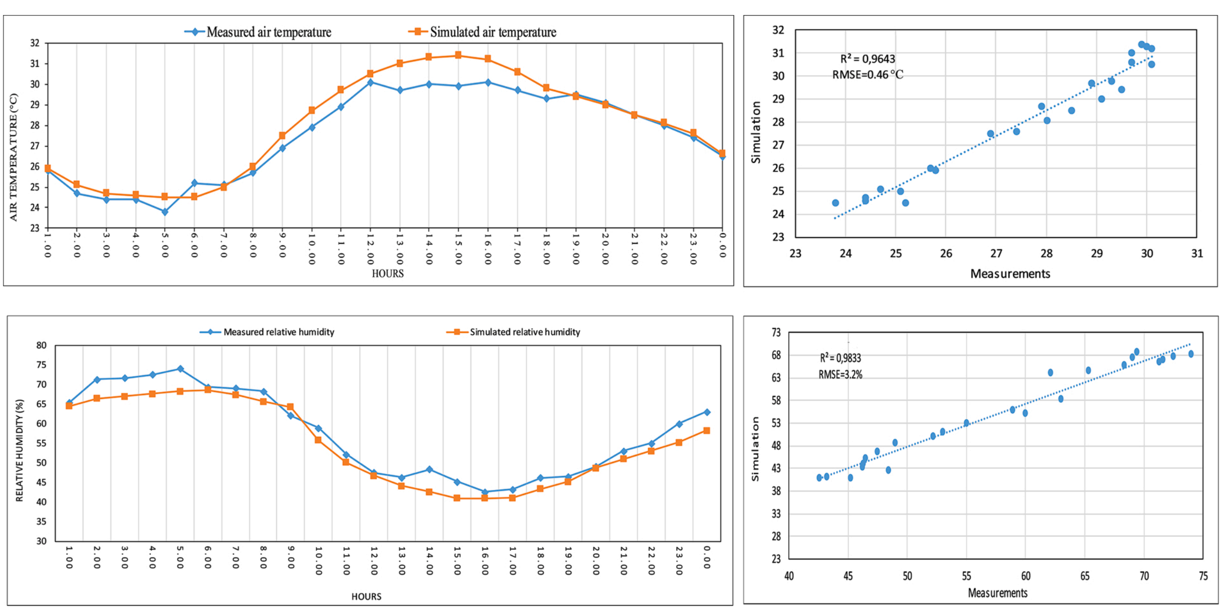


Fig. 3. Simulated and measured air temperature (top figures) and relative humidity (bottom figures).

Table 2
Urban parameters of the three urban areas.

	Building materials	Urban density	Street aspect ratio (H/W)	Pavement materials	Pavement colors	Building heights
Tag Sultan	Red bricks -reinforced concrete	25 %	0.3	Asphalt	Dark grey Albedo 0.1	18 m
Zahraa Almaadi		50 %	0.7, 1, and 2			
Imbaba		85 %	4			

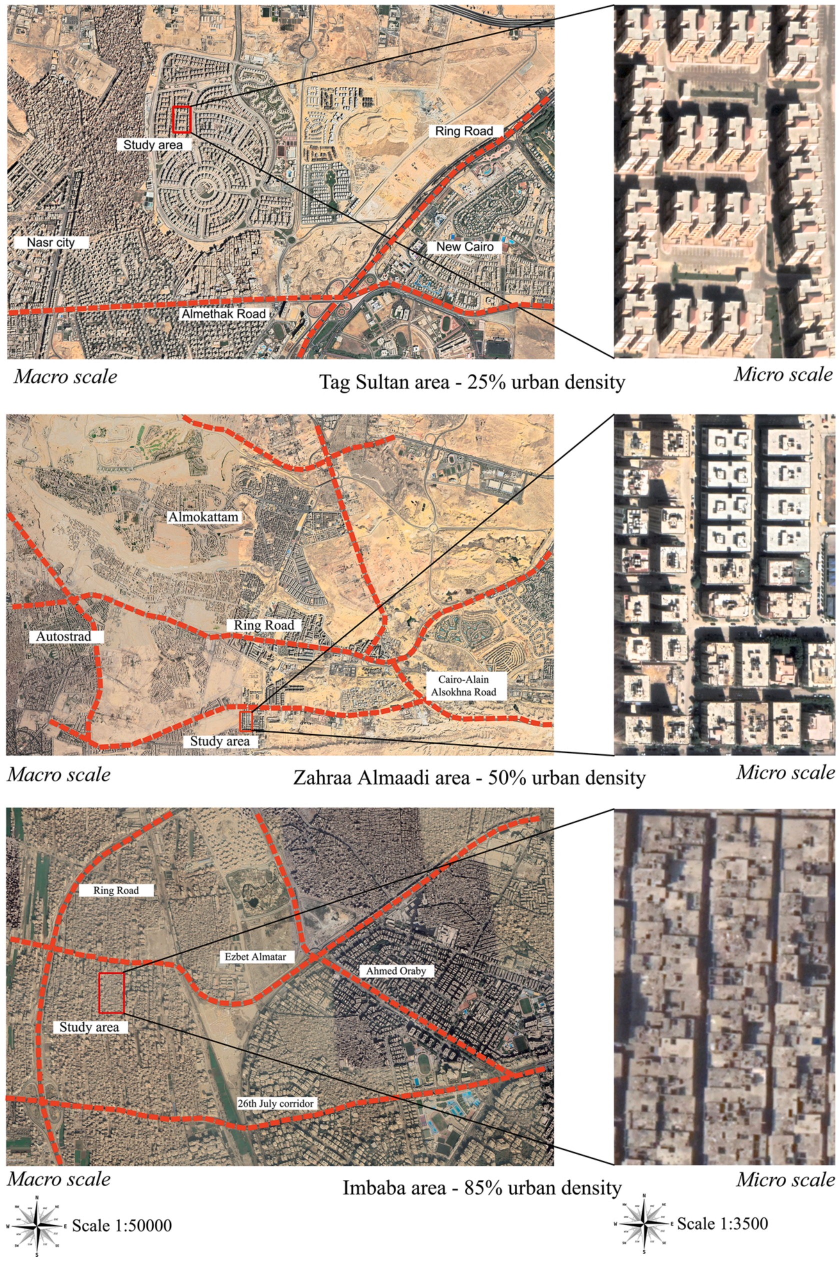


Fig. 4. The three urban areas of different density in Cairo.

Fig. 5. Conventional asphalt materials and the suggested light stamped concrete.

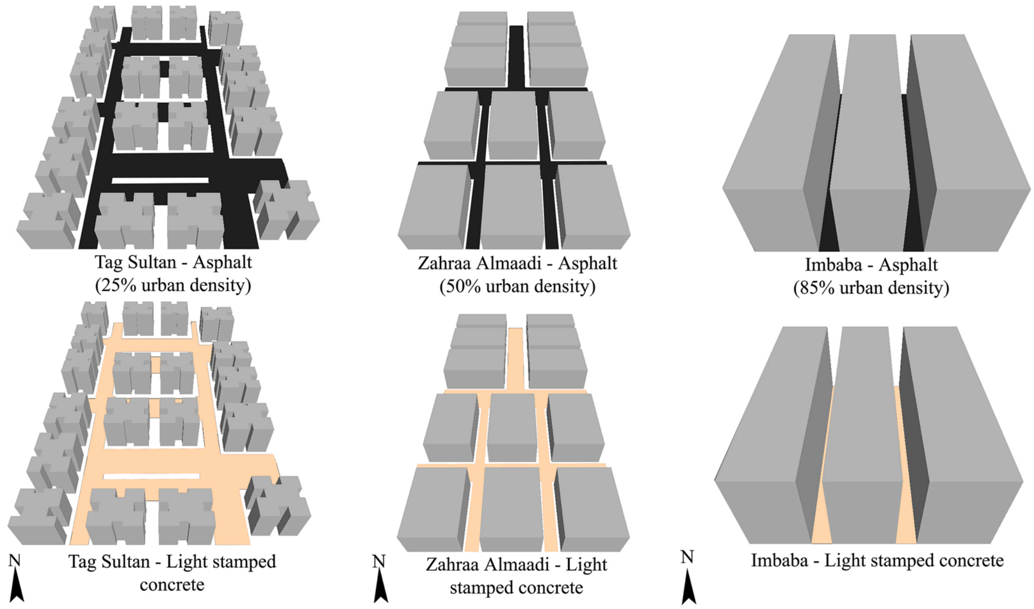


Fig. 6. Reference case and the investigated cool paving scenario in the three urban areas of different densities – ENVI-met 3D models.

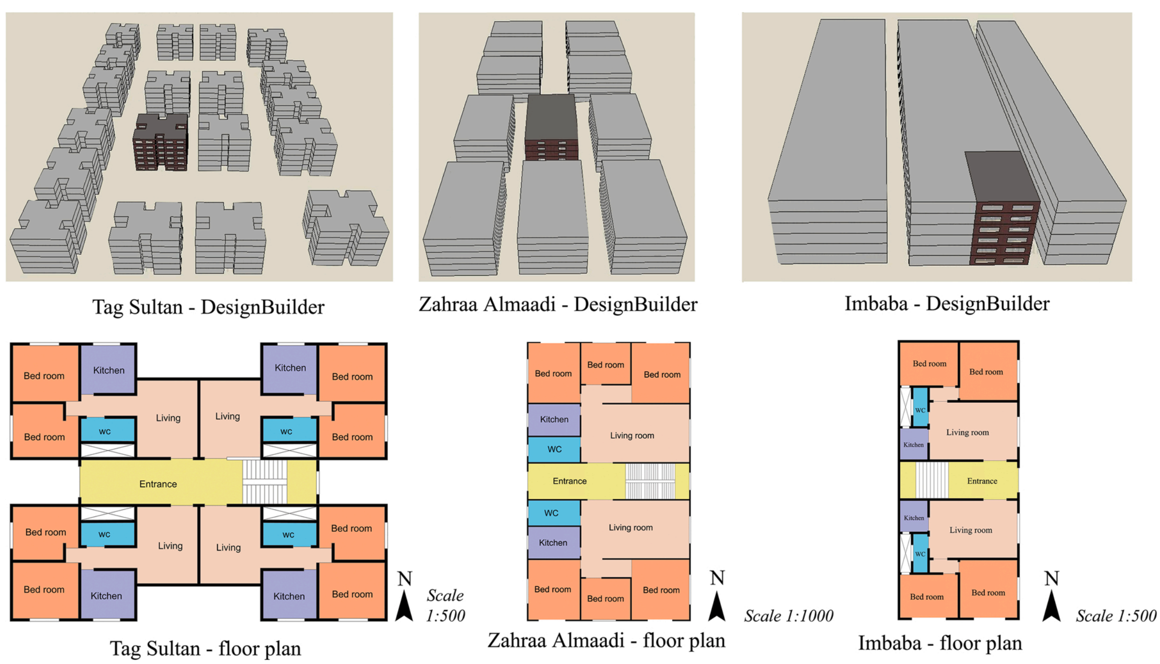


Fig. 7. DesignBuilder model of the three areas and the architectural plans of the residential units.

urban area is described in Appendix B. The urban parameters of the selected three areas are shown in Table 2

2.4. Scenarios design

Most of the previous studies showed that the best outdoor air reduction is achieved by using the highest reflective paving materials (Dimoudi et al., 2014; Falasca et al., 2019; Kolokosta et al., 2018; Yang et al., 2016). This study seeks to investigate the influence of using stamped light concrete instead of asphalt. The two scenarios investigated in the three areas are:

1 Reference case - conventional asphalt of albedo 0.1 and emissivity 0.9. (Fig. 5 – left).

2 Cool paving scenario - stamped light concrete paving of albedo 0.5 and emissivity 0.9. (Fig. 5 – right).

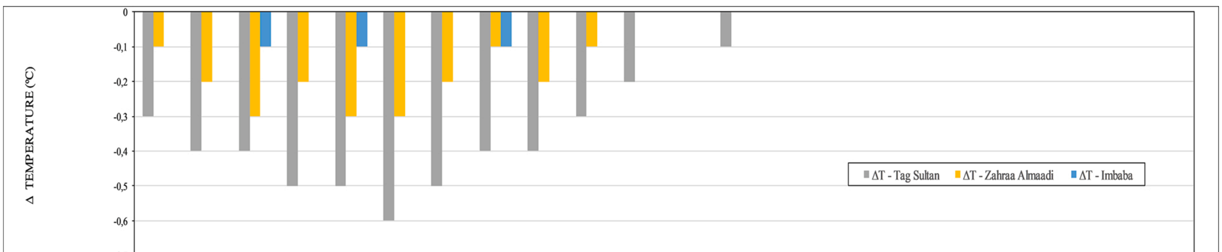
The reason for choosing stamped light concrete is shown in Appendix C. Fig. 6 shows ENVI-met 3D models of the investigated areas and the different scenarios.

2.5. Buildings' energy calculation

ENVI-met modeling concluded some meteorological outputs such as air temperature, wind speed, and relative humidity for each area and both scenarios. These outputs were used in EPW files that could serve as input files in the DesignBuilder model. The EPW files were used to identify the simulation weather data of each scenario. The studied

Table 3
Settings of DesignBuilder simulations.

	Tag Sultan			Zahraa Almaadi			Imbaba		
Building dimensions	26 × 20 m			25 × 40 m			13 × 15 m		
No. of apartments per building	4 × 6 floors= 24			2 × 6 floors = 12			2 × 6 floors = 12		
External wall area (m^2)	1656 m^2			2340 m^2			948 m^2		
Roof area (m^2)	520 m^2			1000 m^2			195 m^2		
No. of split units in the building	48			24			24		
Air-conditioned area (m^2)	Apartment	Floor	Building	Apartment	Floor	Building	Apartment	Floor	Building
	40	160	960	135	270	1620	36	72	432
Building orientation	E-W								
The name of weather files	EGY_Cairo.Int.Airport.ETMY.epw								
Simulation period	24 August – 25 August 2018								
HVAC	Split with no fresh air								
Lighting	Compact fluorescent and led units								
Setpoint	25 °C								
Roof U-value W/m^2k	1.39								
Walls U-value W/m^2k	2.54								



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔT - Tag Sultan	-0,3	-0,4	-0,4	-0,5	-0,5	-0,6	-0,5	-0,4	-0,4	-0,3	-0,2	0	-0,1	0	0	0	0	0	0	0	0	0
ΔT - Zahraa Almaadi	-0,1	-0,2	-0,3	-0,2	-0,3	-0,3	-0,2	-0,1	-0,2	-0,1	0	0	0	0	0	0	0	0	0	0	0	0
ΔT - Imbaba	0	0	-0,1	0	-0,1	0	0	-0,1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Reference case - Tag Sultan	23,6	24,1	25,4	26,6	27,6	28,7	29,2	29,6	29,9	29,8	29,5	28,9	28,6	28,1	27,4	26,9	26,4	25,9	25,4	25	24,8	24,3
Cool paving - Tag Sultan	23,3	23,7	25	26,1	27,1	28,1	28,7	29,2	29,5	29,5	29,3	28,9	28,5	28,1	27,4	26,9	26,4	25,9	25,4	25	24,8	24,3
Reference case - Zahraa Almaadi	22	22,3	23,2	23,9	24,6	25,3	25,7	26	26,3	26,3	26,2	26	25,9	25,7	25,4	25,2	25	24,7	24,5	24,3	24,2	24
Cool paving - Zahraa Almaadi	21,9	22,1	22,9	23,7	24,3	25	25,5	25,9	26,1	26,2	26,2	26	25,9	25,7	25,4	25,2	25	24,7	24,5	24,3	24,2	24
Reference case - Imbaba	20,7	20,8	21,2	21,5	21,9	22,2	22,5	22,8	23	23,2	23,4	23,5	23,6	23,7	23,7	23,8	23,8	23,8	23,8	23,8	23,8	23,8
Cool paving - Imbaba	20,7	20,8	21,1	21,5	21,8	22,2	22,5	22,7	23	23,2	23,4	23,5	23,6	23,7	23,7	23,8	23,8	23,8	23,8	23,8	23,8	23,8

Fig. 8. Difference between the air temperature of the reference case and the cool pavement scenario in the three areas (ΔT = cool paving scenario – reference case).

building in each area was simulated by using the DesignBuilder model v.8.9, taking into consideration its urban context, orientation, and building materials. This step was carried out to calculate building cooling energy demand in each area for the reference case and cool paving scenarios. The model run lasted 24 h, starting on 24 August and lasting until 25 August 2018. Fig. 7 depicts the architectural plans and the DesignBuilder model of the simulated three buildings in the three districts, while Table 3 shows the settings of DesignBuilder simulations.

ENVI-met and DesignBuilder models uses the ray-tracing method to calculate solar radiation and shadowing. This method can calculate radiation velocity, absorption characteristics, and reflectivity. DesignBuilder estimated the reflected solar radiation by considering the three reflection types; beam to beam, beam to diffuse, and diffuse to diffuse following (Yang, Zhao, Bruse, & Meng, 2012). DesignBuilder defined the albedo of ground surfaces by assuming a homogenous ground albedo in all scenarios. The trees were simulated in DesignBuilder as component blocks by defining their physical design (i.e., tree height, trunk height, and crown diameter) following the same parameters in ENVI-met. Tree canopies' solar transmissivity was defined and scheduled according to each season. Due to the extremely hot weather, the residents rarely open windows, therefore natural ventilation was not active during air conditioning occupying. Besides, the natural ventilation is active in DesignBuilder when the air temperature in indoor spaces is higher than the outside air temperature that does not occur during summertime. The model used split units with no fresh air based on residents keeping the windows closed while using air conditioning. However, the residents tend to use the newly developed devices that able to eliminate bacteria inside rooms with positive and negative ions and use plasma cluster to self-clean. The model used the infiltration rate of 0.7 ac/h that represents the unintentional air flow through buildings' fabric caused by gaps and cracks.

3. Results

3.1. Air temperature

Results were determined by estimating the mean average of the air temperature of the whole domain at 1.80 m height. In the daytime, the results show that the cool paving scenario (light stamped concrete) reduced outdoor air temperature by the maximum hourly mean average reduction of 0.5 K in the low-density urban area (25 % urban density). Moreover, it reduced air temperature by a mean average of 0.2 K in the high-density urban area (50 % urban density). However, it reduced air temperature by 0.1 K for just three hours per day in the extremely dense urban area (Imbaba 85 %) as shown in Fig. 8. These results confirmed that cool paving can achieve the maximum effect on lowering outdoor air temperature in low-density urban areas and wide canyons. This result is attributable to the relationship between the surface temperatures (that are related to incident solar radiation) and outdoor air temperature reduction. Low-density urban areas have wide canyons that are more exposed to incident solar radiation. The wide sky view leads to higher surface temperature when using asphalt. In contrast, the cool paving reflects more solar radiation in wide canyons than in deep ones that are already shaded by building walls. The usage of cool paving could cool the canyons' surface, leading to lower air temperature (Appendix D). In the nighttime, the usage of cool paving does not have any effect on air temperature reduction in the three areas due to the absence of solar radiation. Fig. 9 depicts a comparison between the air

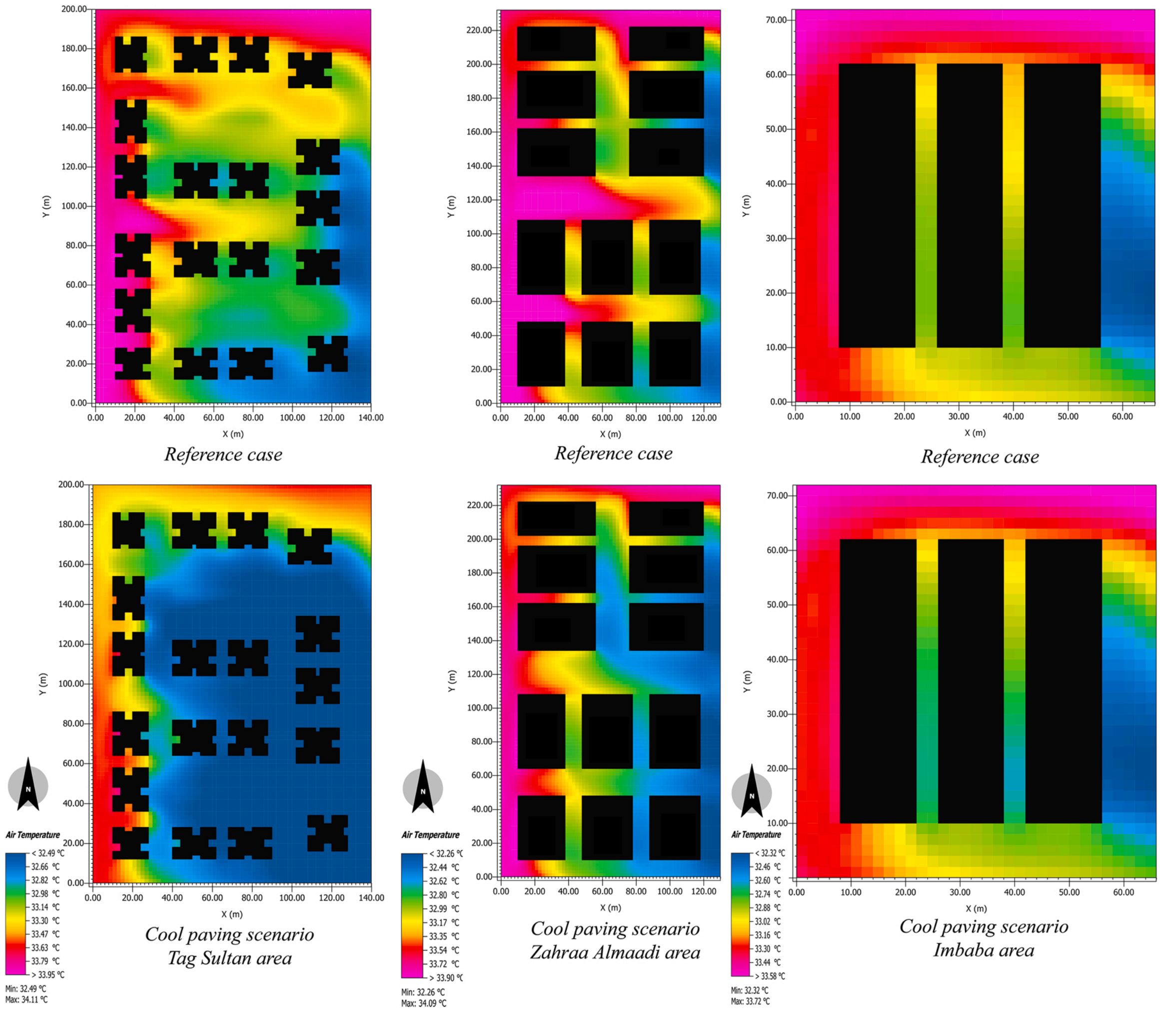
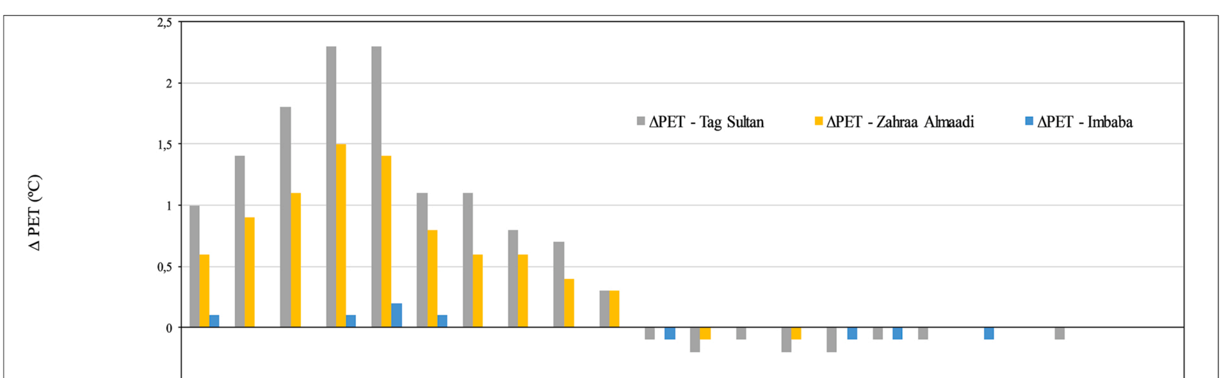


Fig. 9. ENVI-met thermal maps of the air temperature for the reference case and cool pavement scenarios in the three areas at 3.00 p.m..



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔPET - Tag Sultan	1	1,4	1,8	2,3	2,3	1,1	1,1	0,8	0,7	0,3	-0,1	-0,2	-0,1	-0,2	-0,2	-0,1	-0,1	0	0	-0,1	0	0
ΔPET - Zahraa Almaadi	0,6	0,9	1,1	1,5	1,4	0,8	0,6	0,6	0,4	0,3	0	-0,1	0	-0,1	0	0	0	0	0	0	0	0
ΔPET - Imbaba	0,1	0	0	0,1	0,2	0,1	0	0	0	0	-0,1	0	0	0	-0,1	-0,1	0	-0,1	0	0	0	0
Reference case - Tag Sultan	35,6	39,7	42,3	43,9	45	48	48,7	48,7	46,4	42,3	33,4	28,7	27,5	26,6	25,1	23,9	23,1	22,2	21,4	20,7	20,3	19,7
Cool paving - Tag Sultan	36,6	41,1	44,1	46,2	47,3	49,1	49,8	49,5	47,1	42,6	33,3	28,5	27,4	26,4	24,9	23,8	23	22,2	21,4	20,6	20,3	19,7
Reference case - Zahraa Almaadi	31,7	36,1	38,9	41,8	43,6	46,8	47	46,8	44,4	39,9	32,9	28,3	27	26,1	24,5	23,4	22,6	21,8	21	20,2	19,9	19,3
Cool paving - Zahraa Almaadi	32,3	37	40	43,3	45	47,6	47,6	47,4	44,8	40,2	32,9	28,2	27	26	24,5	23,4	22,6	21,8	21	20,2	19,9	19,3
Reference case - Imbaba	31,2	33,9	37,4	41,7	51,7	48,9	49,7	48,7	46,3	39,3	34,3	28,8	27,6	26,8	25,7	24,7	23,9	23,2	22,4	21,7	21,4	20,8
Cool paving - Imbaba	31,3	33,9	37,4	41,8	51,9	49	49,7	48,7	46,3	39,3	34,2	28,8	27,6	26,8	25,6	24,6	23,9	23,1	22,4	21,7	21,4	20,8

Fig. 10. Difference between the PET of the reference case and cool pavement scenario in the three urban areas of different densities (Δ PET = cool paving scenario – reference case).

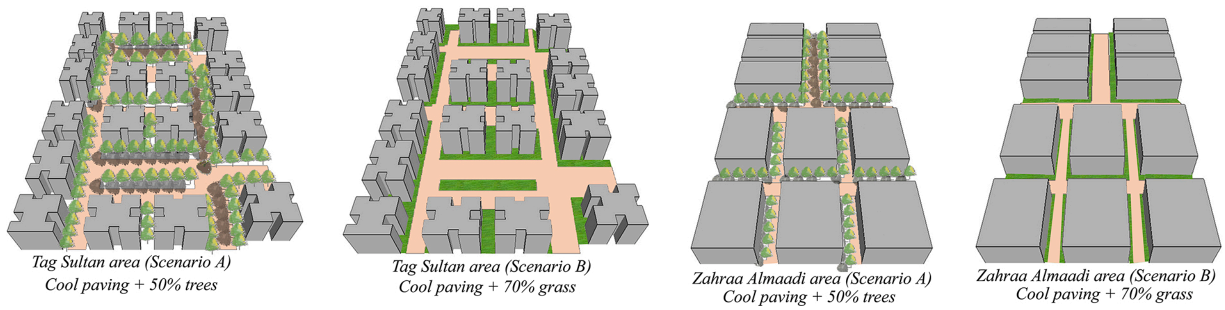
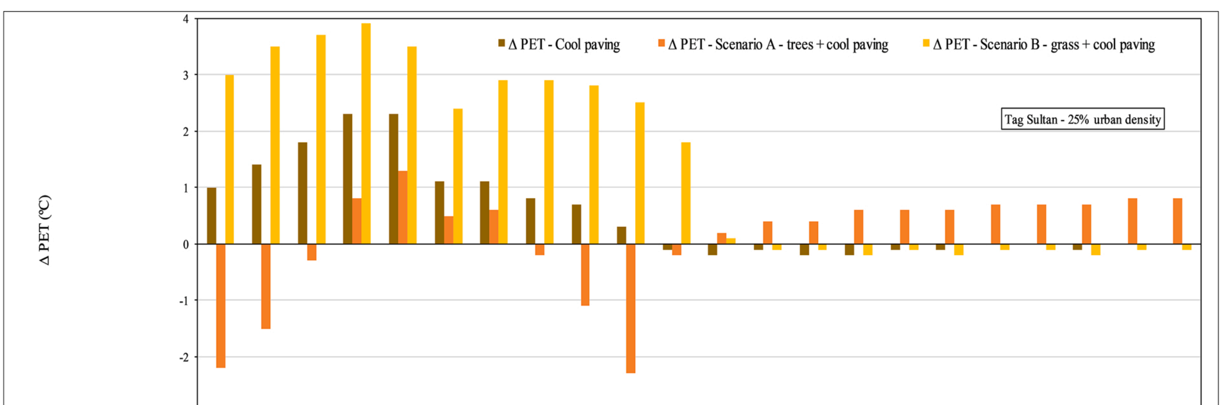


Fig. 11. Combining cool pavements and vegetation scenarios in Tag Sultan (low urban density) and Zahraa Almaadi (high urban density) areas.

temperature of the reference case and the cool paving scenarios based on thermal maps at 3:00 p.m.

3.2. *Physiological equivalent temperature – PET*

Physiological Equivalent Temperature (PET) is a biometeorological parameter that represents how humans perceive thermal conditions in outdoor spaces (Gomez, Perez Cueva, Valcuende, & Matzarakis, 2013; Krüger, Rossi, & Drach, 2017). The PET was calculated by using the ENVI-met BioMet, which can calculate PET directly based on atmosphere outputs. The results of PET were determined by estimating the mean average of the PET for the whole domain at 1.8 m. In the daytime, results show that the usage of cool paving has a detrimental effect on PET and thermal comfort at the pedestrian level. Moreover, the effect of cool paving on PET is related to urban density and the aspect ratio. Cool paving raised PET by the maximum mean average increase in the low-density urban area (Tag Sultan 25 %) during the daytime by 1.3 K. Meanwhile, it increased the mean average of PET in the high-density urban area and the extremely dense urban area (Zahraa Almaadi 50 % and Imbaba 85 %) by 0.8 K and 0.2 K, respectively (Fig. 10). The negative effect of cool paving on PET is related to reflected shortwave radiation which is shown in Appendix E. Therefore, cool paving reduced air temperature significantly in the three areas however it increased PET and diminished thermal comfort. The next section investigates new scenarios combining vegetation and cool paving to improve thermal comfort (PET).



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
Δ PET - Cool paving	1	1,4	1,8	2,3	2,3	1,1	1,1	0,8	0,7	0,3	-0,1	-0,2	-0,1	-0,2	-0,2	-0,1	-0,1	0	0	-0,1	0	0
Δ PET - Scenario A - trees + cool paving	-2,2	-1,5	-0,3	0,8	1,3	0,5	0,6	-0,2	-1,1	-2,3	-0,2	0,2	0,4	0,4	0,6	0,6	0,6	0,7	0,7	0,7	0,8	0,8
Δ PET - Scenario B - grass + cool paving	3	3,5	3,7	3,9	3,5	2,4	2,9	2,9	2,8	2,5	1,8	0,1	-0,1	-0,1	-0,2	-0,1	-0,2	-0,1	-0,1	-0,2	-0,1	-0,1
Reference case	35,6	39,7	42,3	43,9	45	48	48,7	48,7	46,4	42,3	33,4	28,7	27,5	26,6	25,1	23,9	23,1	22,2	21,4	20,7	20,3	19,7
Scenario A	33,4	38,2	42	44,7	46,3	48,5	49,3	48,5	45,3	40,00	33,2	28,9	27,9	27	25,7	24,5	23,7	22,9	22,1	21,4	21,1	20,5
Scenario B	38,6	43,2	46	47,8	48,5	50,4	51,6	51,6	49,2	44,8	35,2	28,8	27,4	26,5	24,9	23,8	22,9	22,1	21,3	20,5	20,2	19,6

	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
Δ PET - Cool paving	0,6	0,9	1,1	1,5	1,4	0,8	0,6	0,6	0,4	0,3	0	-0,1	0	-0,1	0	0	0	0	0	0	0	0
Δ PET - Scenario A - trees + cool paving	-0,1	0,6	1,2	1,3	1,3	0,5	1	0,7	0,2	0,1	0,6	0,3	0,5	0,5	0,6	0,6	0,6	0,6	0,6	0,7	0,6	0,6
Δ PET - Scenario B - grass + cool paving	3,8	4,7	5,1	5	4,4	2,7	3,3	3,3	3,4	3,8	2,4	0,3	0,2	0	0	0	0	0	0	0	0	-0,1
Reference case	31,7	36,1	38,9	41,8	43,6	46,8	47	46,8	44,4	39,9	32,9	28,3	27	26,1	24,5	23,4	22,6	21,8	21	20,2	19,9	19,3
Cool paving	32,3	37	40	43,3	45	47,6	47,6	47,4	44,8	40,2	32,9	28,2	27	26	24,5	23,4	22,6	21,8	21	20,2	19,9	19,3
Scenario A	31,6	36,7	40,1	43,1	44,9	47,3	48	47,5	44,6	40,00	33,5	28,6	27,5	26,6	25,1	24	23,2	22,4	21,6	20,9	20,5	19,9
Scenario B	35,5	40,8	44	46,8	48	49,5	50,3	50,1	47,8	43,7	35,3	28,6	27,2	26,1	24,5	23,4	22,6	21,8	21	20,2	19,9	19,2

Fig. 12. Differences in PET between the reference case, cool pavement scenario, Scenario A, and Scenario B.
(Δ PET = suggested scenario – reference case).

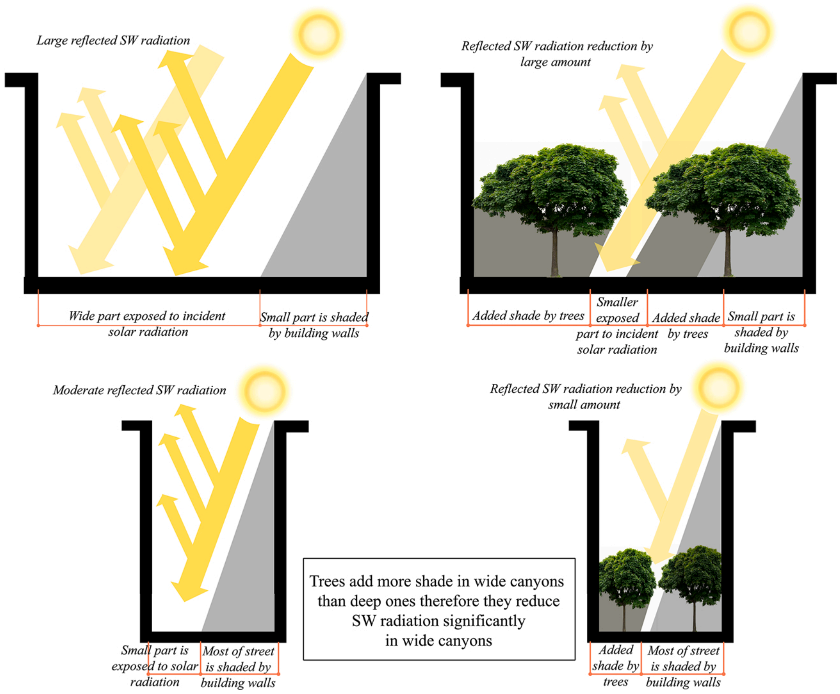
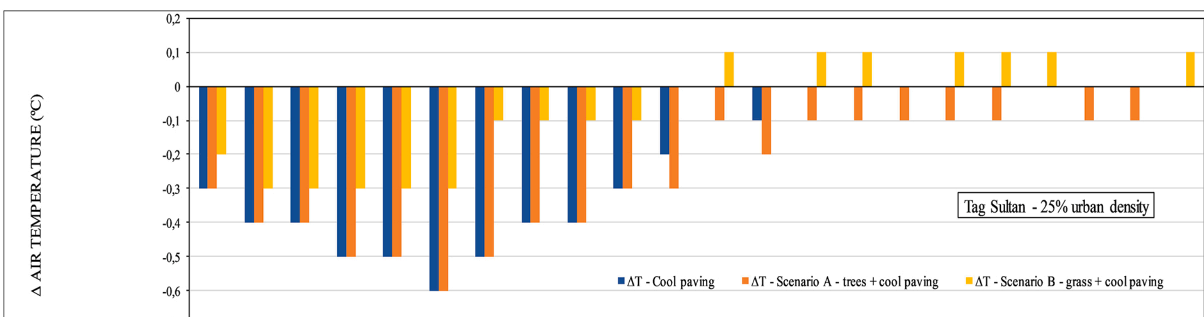


Fig. 13. Comparison between the effect of trees on increasing shade and reducing reflected SW radiation in low- and high-density urban areas.



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔT - Cool paving	-0,3	-0,4	-0,4	-0,5	-0,5	-0,6	-0,5	-0,4	-0,4	-0,3	-0,2	0	-0,1	0	0	0	0	0	0	0	0	0
ΔT - Scenario A - trees + cool paving	-0,3	-0,4	-0,4	-0,5	-0,5	-0,6	-0,5	-0,4	-0,4	-0,3	-0,3	-0,1	-0,2	-0,1	-0,1	-0,1	-0,1	-0,1	0	-0,1	-0,1	0
ΔT - Scenario B - grass + cool paving	-0,2	-0,3	-0,3	-0,3	-0,3	-0,3	-0,1	-0,1	-0,1	-0,1	0	0,1	0	0,1	0,1	0	0,1	0,1	0,1	0	0	0,1
Reference case	23,6	24,1	25,4	26,6	27,6	28,7	29,2	29,6	29,9	29,8	29,5	28,9	28,6	28,1	27,4	26,9	26,4	25,9	25,4	25	24,8	24,3
Cool paving	23,3	23,7	25	26,1	27,1	28,1	28,7	29,2	29,5	29,5	29,3	28,9	28,5	28,1	27,4	26,9	26,4	25,9	25,4	25	24,8	24,3
Scenario A	23,3	23,7	25	26,1	27,1	28,1	28,7	29,2	29,5	29,5	29,2	28,8	28,4	28	27,3	26,8	26,3	25,8	25,4	24,9	24,7	24,3
Scenario B	23,4	23,8	25,1	26,3	27,3	28,4	29,1	29,5	29,8	29,7	29,5	29	28,6	28,2	27,5	26,9	26,5	26	25,5	25	24,8	24,4

	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
ΔT - Cool paving	-0,1	-0,2	-0,3	-0,2	-0,3	-0,3	-0,2	-0,1	-0,2	-0,1	0	0	0	0	0	0	0	0	0	0	0	0
ΔT - Scenario A - trees + cool paving	-0,1	-0,1	-0,2	-0,1	-0,2	-0,2	-0,2	-0,1	-0,1	-0,1	0	0	0	0	0	0	0	0	0	0	0	0
ΔT - Scenario B - grass + cool paving	0	0	-0,1	0	-0,1	0	0	0,1	0,1	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,3	0,2	0,2	0,2	0,2
Reference case	22	22,3	23,2	23,9	24,6	25,3	25,7	26	26,3	26,3	26,2	26	25,9	25,7	25,4	25,2	25	24,7	24,5	24,3	24,2	24
Cool paving	21,9	22,1	22,9	23,7	24,3	25	25,5	25,9	26,1	26,2	26,2	26	25,9	25,7	25,4	25,2	25	24,7	24,5	24,3	24,2	24
Scenario A	21,9	22,2	23	23,8	24,4	25,1	25,5	25,9	26,2	26,2	26,2	26	25,9	25,7	25,4	25,2	25	24,7	24,5	24,3	24,2	24
Scenario B	22	22,3	23,1	23,9	24,5	25,3	25,7	26,1	26,4	26,5	26,4	26,2	26,1	25,9	25,6	25,4	25,2	25	24,7	24,5	24,4	24,2

Fig. 14. Difference between air temperature of the reference case and cool pavement scenario, Scenario A and Scenario B (ΔT = suggested scenario – reference case).

Table 4
Buildings' cooling energy reduction in the three urban areas of different densities.

	Tag Sultan – low-density urban area (25 %)			
	Building cooling daily consumption kWh	Daily savings kWh	Daily savings Money (LE/€)	Daily savings (%)
Reference case	523.91 kWh	17.17 kWh	LE 30.9 /€1.7	3.2 %
Scenario A – cool paving + trees	506.74 kWh			
Cool paving	510.41 kWh	13.5 kWh	LE 24.3/€1.35	2.5 %
	Zahraa Almaadi – high-density urban area (50 %)			
Reference case	580.34 kWh	8.63 kWh	LE 15.5 /€0.8	1.4 %
Cool paving	571.71 kWh			
	Imbaba – very high-density urban area (85 %)			
Reference case	108.15 kWh	0.28 kWh	LE 0.5 /€0.02	0.2 %
Cool paving	107.87 kWh			

4. Combined vegetation and cool paving scenarios

The usage of cool paving reduced the air temperature in the three areas by various values. Conversely, the cool paving raised PET values higher than the reference case, thereby diminishing the thermal comfort in outdoor spaces. Therefore, this study found a critical dilemma between reducing air temperature (which affects buildings' cooling energy demand) and improving outdoor thermal comfort as measured by PET. The next section will investigate two additional scenarios in the two areas (Tag Sultan, 25 % urban density, and Zahraa Almaadi, 50 % urban density). These two scenarios combine urban vegetation (trees and grass) with cool paving. These two new scenarios were not tested in Imbaba (85 % urban density) due to its extreme compactness. At four meters wide, Imbaba streets are very narrow and do not have either sidewalks or enough spaces for planting. These scenarios were investigated as an attempt to improve PET in addition to reducing the outdoor air temperature. These two scenarios are: -

1 Scenario A (cool paving + 50 % trees from sidewalks).
2 Scenario B (cool paving + 70 % grass from sidewalks) (Fig. 11).

Appendix F shows vegetation ratio estimation method and vegetation specifications.

4.1. Physiological equivalent temperature (PET)

Results show that the Scenario A (50 % trees + cool paving) reduced PET during the daytime by mean average of 1.3 K except for four hours between 11:00 a.m. and 2:00 p.m. in the low-density urban area. Although this scenario raised PET higher than the reference case between 11:00 a.m. and 2:00 p.m., its PET mean average value is less than reference case by 0.4 K during daytime as shown in Fig. 12. Adding trees to cool paving could reduce reflected SW radiation more than the cool paving scenario alone due to the shade effect. This effect is stronger in wide canyons due to their high exposure to solar radiation than in deep canyons, which are partially shaded by their building walls as shown in Fig. 13. Scenario A raised PET during the nighttime due to heat trapped by tree canopies. Scenario B (cool paving + grass) raised the mean average of PET higher than the other two scenarios (cool paving and cool paving + trees) during daytime. Using the high albedo paving (0.5) and high albedo grass (0.25) without shading increased the rate of reflected SW radiation by the maximum difference (200 W/m^2) compared to the other scenarios, as shown in Appendix G. Therefore, this scenario cannot be evaluated as suitable for improving PET in low-density urban areas. When considering the mean average of PET during the day for the three scenarios, Scenario A (cool paving + trees) is the best scenario at improving PET because the average of its PET equals the PET average of the reference case (33.3 K). Nevertheless, Scenario A achieved good results during daytime hours, which is very important for pedestrians. Meanwhile, the cool paving scenario and Scenario B (cool paving + grass) raised the daily mean average of PET higher than the reference case by 0.5 K and 1.4 K, respectively. Regarding Zahraa Almaadi (50 % urban density), results show that neither Scenario A nor Scenario B improved PET (Fig. 12).

4.2. Air temperature

In the low-density urban area, results show that Scenario A (cool paving + trees) reduced air temperature during the daytime by a mean average of 0.5 K, which is the same reduction as the cool paving.

At the same time, it reduced air temperature more than the cool paving scenario by an average mean of 0.1 K during the nighttime as shown in Fig. 14. This result is due to the positive effect of the trees on lowering surface temperature thanks to dense shade patterns in wide canyons. Scenario B (cool paving + grass) reduced air temperature more than the reference case by a mean average of 0.3 K during daytime and no reduction during nighttime. Nevertheless, the effect of Scenario B on air temperature reduction is still weaker than the cool paving scenario and Scenario A.

In the urban area with 50 % density (Zahraa Almaadai), the cool paving scenario achieved the greatest air temperature reduction of all scenarios as it reduced air temperature by a mean average of 0.2 K during daytime. Meanwhile, Scenario A (cool paving + trees) reduced air temperature in the same district more than the reference case by a mean average of 0.1 K. Therefore, the cool paving is the most effective scenario at air temperature reduction in the high-density urban area (50% urban density). Scenario B (cool paving + grass) reduced air temperature more than the reference case by 0.1 K during just two hours in daytime. Besides, it raised air temperature in Zahraa Almaadi (50 % urban density) more than the reference case by a mean average of 0.1−0.2 K daily due to the relative humidity effect. Recent studies in Cairo found that grass could raise outdoor air temperature due to the relative humidity effect in wide canyons. Grass is planted above humid loamy soil that is exposed to sun radiation more than in deep canyons. Therefore, the evaporation process could reduce relative humidity in the wide canyons. Besides, grass can absorb the humidity from the air in the wide canyons (Aboelata, 2020; Aboelata & Sodoudi, 2019, 2020). These factors reduce relative humidity and therefore increase air temperature due to the inverse relationship between air temperature and relative humidity. The previous studies that evaluated the effect of grass on air temperature reduction in Cairo found that grass could raise air temperature during the daytime and the nighttime (Aboelata and Sodoudi, 2019, 2020). However, Scenario B achieved the same daily mean average air temperature of the reference case in Tag Sultan area due to the large cool paving area than used in 50% urban density. Scenario B (cool paving + grass) reduced air temperature during the daytime in low-density urban area. This effect is due to the impact of cool paving that reduced air temperature by a mean average of 0.5 K, counteracting the influence of grass increasing the air temperature. Therefore, Scenario B (cool paving + grass) reduced air temperature in low-density urban areas by a mean average of 0.2 K during the daytime. In the area with 50 % urban density, Scenario B (cool paving + grass) reduced air temperature during the daytime for just two hours, which is a weak effect compared to the low-density urban area. This impact is a consequence of the weaker effect of cool paving usage in the area with 50% urban density than in the low-density urban area. Scenario B (cool paving + grass) could raise air temperature during the nighttime due to the relative humidity mechanism and the absence of the cool paving effect on air temperature reduction.

5. Buildings' cooling energy reduction

One building in each area was simulated by using DesignBuilder and taking into consideration the method mentioned in paragraph 2.6. Therefore, the comparison was carried out between the reference case, cool paving scenario, and Scenario A (cool paving + trees) in the Tag Sultan area (25 % urban density). Additionally, the reference case was compared to the cool paving scenario in high- and extremely high-density urban areas (50 % and 85 % urban density) because these scenarios achieved the maximum air temperature reduction.

Results show that Scenario A and cool paving scenario could reduce building cooling energy demand in the low-density urban area (Tag Sultan 25 %) by 17.17 kWh (3.2 %) and 13.5 kWh (2.5 %) on a typical summer day, respectively. Furthermore, the cool paving scenario could reduce building cooling energy demand in the high-density urban area (Zahraa Almaadi 50 %) by 8.63 kWh (1.4 %) on a typical summer day. Due to the very weak effect of cool paving on air temperature reduction in the extremely dense urban area (Imbaba 85 %), the cool paving scenario reduces building cooling energy demand by 0.28 kWh (0.2 %) daily (Table 4).

Due to the significant similarity between August days in Cairo, this study could assume that the monthly money savings in low-, high- and extremely high-density urban areas would total LE 927 (€51.5), LE 465 (€25.8), and LE 15 (€0.8), respectively. Moreover, the construction cost of 1 m^2 of stamped concrete equals LE 130 (€7.2), while the price of 1 m^2 of asphalt equals LE 400 (€22). Therefore, using cool paving could achieve significant benefits at various levels: -

1 This strategy could achieve economic benefits for the government through use of cheaper materials on the roads.
2 This strategy could achieve economic advantages for the residents by reducing their electricity bills.
3 Cool paving could create environmental benefits by reducing outdoor air temperature and improving thermal comfort.

6. Discussion

Cairo, as one of the hot arid cities, is characterized by an extremely hot summer that has led to enormous use of air conditioners in indoor spaces, increasing the price of electricity. There is a significant lack of studies that examine the influence of cool paving on air temperature in Cairo. Moreover, a few recent studies in Cairo found that trees and grass raise the air temperature in the wide spaces while they reduce air temperature by nominal values (0.1–0.2 K) in the deep canyons (Aboelata & Sodoudi, 2019, 2020; Aboelata, 2020). Therefore, this study aims to investigate the impact of cool paving on reducing air temperature at the pedestrian level, enhancing thermal comfort, and reducing buildings' cooling energy demand in urban areas of different densities in Cairo. The results showed that cool paving is an effective strategy that could reduce air temperature significantly, and this result is in line with the results of the previous studies (Efthymiou, Santamouris, Kolokotsa, & Koras, 2016; Kyriakodis & Santamouris, 2018; Noro & Lazzarin, 2015; Santamouris et al., 2012; Yinfei, Shengyue, & Jian, 2015). Furthermore, the results of this study agree with previous studies (Alchapar & Correa, 2016; Qin, 2015b), which showed that cool paving achieved better air temperature reduction in the low-density urban areas than in high-density urban areas. The results of this study showed that the cool paving scenario could reduce the air temperature in the extremely dense built-up areas by 0.1 K, which differs from previous study results (Georgakis et al., 2014) that showed that cool paving could reduce air temperature in the deep canyons by 1 K. Although cool paving has a very weak effect on air temperature reduction in the extremely high-density urban area, it did not increase the air temperature as reported in previous study results (Song & Park, 2015).

The results of this study showed that combining grass with cool paving (Scenario B) in the 50 % dense urban area has a nominal effect on air temperature, reducing air temperature by a mean average of 0.1 K for just two hours during daytime. The effect of Scenario B is not in line with the results of previous studies, which showed that the same scenario could reduce air temperature by 3.5–6.4 K (Alchapar et al., 2017). The results of (Xu et al., 2020) showed that cool paving could reduce the air temperature in high-density urban areas more than in low-density urban areas, which does not agree with the results of the current study.

The new insight of this study is the new model that suits low-density urban areas with wide canyons and an aspect ratio less than 1.0 in Cairo. Previous studies that aimed to evaluate the impact of trees on thermal stress found that trees increase the air temperature in low-density urban areas (Aboelata & Sodoudi, 2019, 2020; Aboelata, 2020). This study found that cool paving is a great alternative strategy that could be used in low-density urban areas to reduce outdoor air temperature and solve this problem. Nevertheless, the cool paving strategy raised PET due to the increase of reflected SW radiation. Meanwhile, the previous recent studies in Cairo found that trees achieved the strongest PET reduction in the low-density urban areas (Aboelata & Sodoudi, 2019, 2020; Aboelata, 2020). Therefore, this study found a new model that can be used in the low-density urban areas to solve this dilemma between air temperature reduction and PET maintenance in Cairo and similar environments. Combining cool paving and 50 % trees (Scenario A) can at least keep the daily mean average of PET at the same level as the reference case. Moreover, Scenario A reduced PET significantly during daytime hours, which are very important to pedestrians. Furthermore, Scenario A (cool paving + trees) could reduce the air temperature by a mean average of 0.6 K, which is greater than the impact of trees as reported in the previous studies in Cairo (Aboelata, 2020; Aboelata & Sodoudi, 2020). Although cool paving increases PET and diminishes thermal comfort due to the increase of radiative flux absorbed by pedestrians' clothes, especially in low-density urban areas, it can be used because the pedestrians' albedo is greater than 0.7 according to (Qin, Liang, Tan, & Li, 2019). The results of previous study can enrich this study's results by highlighting the importance of pedestrians' albedo while using cool paving.

In high-density urban areas (50 %), the cool paving strategy is recommendable for reducing air temperature and buildings' cooling energy demand regardless of PET improving. The cool paving scenario could reduce outdoor air temperature by a daily mean average of 0.2 K. In the extremely dense built-up areas (85 %), which are informal settlements, the cool paving strategy has a weak effect on air temperature and buildings' cooling energy reduction.

Scenario A (cool paving + trees) can reduce building cooling energy demand by 3.2 % daily, which is significant savings compared to the effect of trees in such areas in Cairo (2020; Aboelata, 2020). Trees could raise air temperature and buildings' energy in this urban setting. Therefore, combining cool paving with trees can solve this problem. The usage of cool paving in the high-density urban areas (50 %) can lead to reducing buildings' energy demand by 1.4 % daily. This saving is higher than the reductions achieved by the usage of trees in the same urban density in Cairo, which was 0.5 % (Aboelata & Sodoudi, 2019, 2020). Cool paving can reduce buildings' energy in the extremely dense built-up areas by 0.2 % daily. This reduction is equal to the savings achieved by the trees in the high-density urban areas (Aboelata & Sodoudi, 2020). However, it is considered an acceptable reduction ratio in these areas where it is impossible to plant trees due to scarcity of public spaces. These savings that range between 1–4 % on a typical summer day are in line with previous study results (Antonia et al., 2016; Rossi et al., 2016; Wan et al., 2012).

7. Conclusion

This study aimed to investigate the effect of using cool paving in urban areas of different densities on reducing outdoor air temperature, lowering buildings' cooling energy consumption, and enhancing thermal comfort. Furthermore, it aimed to suggest a suitable mitigation strategy that could be used in the low-density urban areas to solve the dilemma between reducing air temperature and improving PET or thermal comfort. The results of this study have enabled the conclusion of some design guidelines and recommendations that could be used by stakeholders and landscape architects to reduce outdoor air temperature at the pedestrian level, improve thermal comfort, and reduce buildings' cooling energy demand in arid cities.

More precisely:

1 Using cool paving such as light stamped concrete combined with 50 % trees from sidewalks is recommendable in low-density urban areas (25 %) to reduce air temperature and buildings' energy consumption without diminishing thermal comfort (PET) in outdoor spaces.
2 If decision-makers and urban planners seek to reduce outdoor air temperature and buildings' cooling energy demand in the high-density urban areas regardless of improving PET, they can use just cool paving instead of conventional dark asphalt in the roads.
3 Cool paving can be used in extremely dense built-up areas which lack open spaces that can be planted.

The results of this work can help decision-makers, landscape architects, and urban planners understand how to reduce outdoor air temperature, improve outdoor thermal comfort, and reduce buildings' cooling energy demand in summer in Cairo and cities with similar meteorological and urban conditions.

Declaration of Competing Interest

The author reports no declarations of interest.

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Appendix A

Experimental instruments

The device on the left in Fig. A1 is a multifunction hygrometer PCE-WB 20SD that was used to measure air temperature with an accuracy of ±0.6 °C and resolution of 0.1 °C. This device was used to measure relative humidity with an accuracy of ±3% RH and a resolution of 0.1 % RH. This instrument can measure air temperature between 0–50 °C and relative humidity between 5–95 %. The device on the right in Fig. A1, German Testo (Testo 410 high precision) anemometer was used to record wind speed with a resolution of ±0.01 m/s and accuracy of ±3%.

Fig. A1. Mobile devices that were used in field measurements.

This instrument can record wind speed between 0.7 and 42 m/s.

Appendix B

Urban parameters of each area identification method

The urban density of each area was determined by using the AutoCAD program to calculate the total location area. Then, the areas taken up by buildings and outdoor spaces were calculated. The buildings' area (footprint) was divided by the total site area to estimate the urban density of the area. The street aspect ratios were determined by calculating street width and building heights. Street width was determined by using GoogleEarth and AutoCAD, while a field visit was used to determine building heights. The other urban parameters, such as building materials and material colors, were determined by field observation. Areas selected to represent the various commonly occurring different urban densities in Cairo were low, high, and extremely high urban densities along with different street aspect ratios (H/W) with wide, deep, and extremely deep canyons.

Appendix C

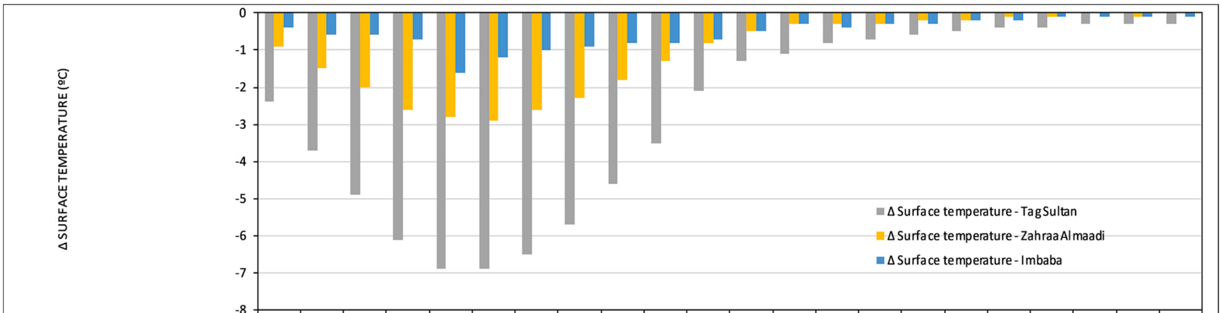
Reasons for choosing stamped light concrete

Stamped concrete was selected for comparison to dark asphalt because it is considered the most used pavement materials in the newly developed urban areas. It is used widely in any new development because it has many advantages such as a short construction period, high resistance to weather conditions and friction, color variety, and low cost. This strategy could be applied in smaller streets, residential compounds, and internal neighborhood streets.

Appendix D

Effect of cool paving on surfaces temperature

The cool paving reduced the surface temperature by the maximum mean average reduction of 5.1 K in the low-density urban area during the daytime. Meanwhile, it reduced surface temperature in the high-density urban area (50 %) and the extremely high-density urban area (85 %) during the daytime by a mean average of 2.1 K and 1.1 K, respectively. More reduction of surface temperature in the wide street



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0	1	2	3	4	5
Δ Surface temperature - Tag Sultan	-2,4	-3,7	-4,9	-6,1	-6,9	-6,9	-6,5	-5,7	-4,6	-3,5	-2,1	-1,3	-1,1	-0,8	-0,7	-0,6	-0,5	-0,4	-0,4	-0,3	-0,3	-0,3
Δ Surface temperature - Zahraa Almaadi	-0,9	-1,5	-2	-2,6	-2,8	-2,9	-2,6	-2,3	-1,8	-1,3	-0,8	-0,5	-0,3	-0,3	-0,3	-0,2	-0,2	-0,1	-0,1	0	-0,1	0
Δ Surface temperature - Imbaba	-0,4	-0,6	-0,6	-0,7	-1,6	-1,2	-1	-0,9	-0,8	-0,8	-0,7	-0,5	-0,3	-0,4	-0,3	-0,3	-0,2	-0,2	-0,1	-0,1	-0,1	-0,1
Reference case - Tag Sultan	26	29,1	32,2	35,3	37,8	38,9	38,9	38,2	36,7	34,6	32,2	30,3	29,2	28,3	27,6	26,9	26,3	25,7	25,2	24,7	24,3	23,9
Cool paving - Tag Sultan	23,6	25,4	27,3	29,2	30,9	32	32,4	32,5	32,1	31,1	30,1	29	28,1	27,5	26,9	26,3	25,8	25,3	24,8	24,4	24	23,6
Reference case - Zahraa Almaadi	22,9	24,5	26	27,8	29,3	30	29,9	29,6	28,7	27,7	26,6	25,6	25	24,6	24,2	23,8	23,5	23,1	22,8	22,5	22,3	22,1
Cool paving - Zahraa Almaadi	22	23	24	25,2	26,5	27,1	27,3	27,3	26,9	26,4	25,8	25,1	24,7	24,3	23,9	23,6	23,3	23	22,7	22,5	22,2	22,1
Reference case - Imbaba	20,7	21	21,2	21,5	22,9	22,8	22,5	22,5	22,5	22,5	22,3	22	21,7	21,6	21,4	21,3	21,2	21,1	20,9	20,8	20,8	20,7
Cool paving - Imbaba	20,3	20,4	20,6	20,8	21,3	21,6	21,5	21,6	21,7	21,7	21,6	21,5	21,4	21,2	21,1	21	21	20,9	20,8	20,7	20,7	20,6

Fig. D1. Difference between surface temperature of the reference case and the cool pavement scenarios in the three areas (Δ surface temperature = cool paving scenario – reference case).

aspect ratios means more reflectance of the incident solar radiation and greater air temperature reduction. Fig. D1 shows the differences between the surface temperature of the reference case and the cool paving scenario in the three areas.

Appendix E

Effect of cool paving on reflected SW radiation and PET

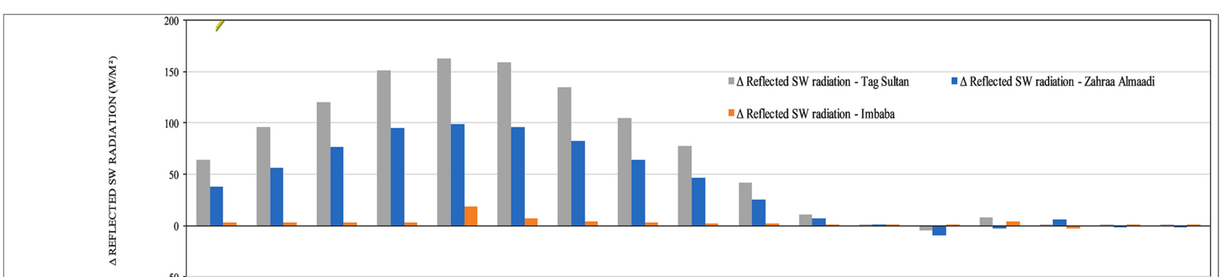
High albedo paving in the wide canyons reflects a higher volume of heat than in the deep canyon. This mechanism increases thermal stress at the pedestrian level during the daytime. Therefore, the cool paving reflects more heat, which increases PET at the pedestrian level. The reflected heat is called reflected short-wave radiation and represents the major volume of energy that raises PET more than the reference case. Besides, cool paving increased reflected SW radiation in the low-, high-, and extremely high-density urban areas during daytime by mean average of 110 W/m^2, 65 W/m^2, and 3 W/m^2, respectively (Fig. E1). In contrast, cool paving does not have any impact on PET during the nighttime in the three areas. The absence of reflected SW radiation during the night explains why cool paving has no effect on PET.

Appendix F

Vegetation ratio estimation method and plant specifications

The 50 % tree ratio was determined by calculating half the area of the sidewalk. Then, the required number of trees was estimated by dividing half of the sidewalk by half of the tree canopy (the tree area which grows above sidewalks). The grass scenario was designed by considering 70 % of the area of the sidewalks. The vegetation cools the urban spaces by providing shade and evapotranspiration. Evapotranspiration depends on the tree foliage that absorbs and converts the energy to latent heat; therefore, the modeling considered the plant irrigation. The shade is achieved by tree canopies that reduce reflected short-wave radiation (Kotzen, 2003; Shahidan, 2015). The ratio of the investigated trees and grass was suggested based on previous study results that were carried out in Cairo (Aboelata & Sodoudi, 2019, 2020; Aboelata, 2020) and found that 50 % trees and 70 % grass have the best effect on PET enhancing.

Furthermore, the tree species which was used in the modeling is the Ficus microcarpa tree with a height and canopy of 9.0 m. The tree albedo, foliage transmittance, and leaf weight are 0.5, 0.3, and 100 g/m^2, respectively. The type of grass used is Paspalum vaginatum grass, which



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0
Δ Reflected SW radiation - Tag Sultan	64,1	96,2	120	151,3	162,5	158,6	135	104,9	77,2	41,8	11,1	0,12	-4,6	7,5	0,9	1,5	0,8
Δ Reflected SW radiation - Zahraa Almaadi	38,3	56,8	76,8	94,8	99,2	95,9	82,9	64,3	47,1	25,6	7,1	0,1	-9,7	-2,7	6,4	-2,1	-2
Δ Reflected SW radiation - Imbaba	2,9	3	3,1	3,2	18,6	7	3,9	3,5	2,4	2,5	1,6	0,1	1,6	3,9	-2,4	0,4	0,5
Reference case - Tag Sultan	192,6	271,8	333,9	390,4	423,2	418,8	391,1	336,7	256,6	161,6	66,5	0,16	4,6	1,3	3,9	1,1	3,2
Cool paving - Tag Sultan	256,7	368	453,9	541,7	585,7	577,4	526,1	441,6	333,8	203,4	77,6	0,28	0	8,8	4,8	2,6	4
Reference case - Zahraa Almaadi	189,8	267,3	322,6	387,7	424,9	421,9	392,2	337,5	261	167,2	70,7	0,2	9,7	4	1,7	7,1	6
Cool paving - Zahraa Almaadi	228,1	324,1	399,4	482,5	524,1	517,8	475,1	401,8	308,1	192,8	77,8	0,3	0	1,3	8,1	5	4
Reference case - Imbaba	225,6	279,3	329	371,6	381,1	416,2	403,4	357,9	289,8	203,2	98	0,1	2,2	2,9	3,6	4,6	3
Cool paving - Imbaba	228,5	282,3	332,1	374,8	399,7	423,2	407,3	361,4	292,2	205,7	99,6	0,2	3,8	6,8	1,2	5	3,50

Fig. E1. Reflected SW radiation due to the usage of cool pavements in the three urban areas of different densities.
(Δ Reflected SW radiation = cool paving scenario – reference case).

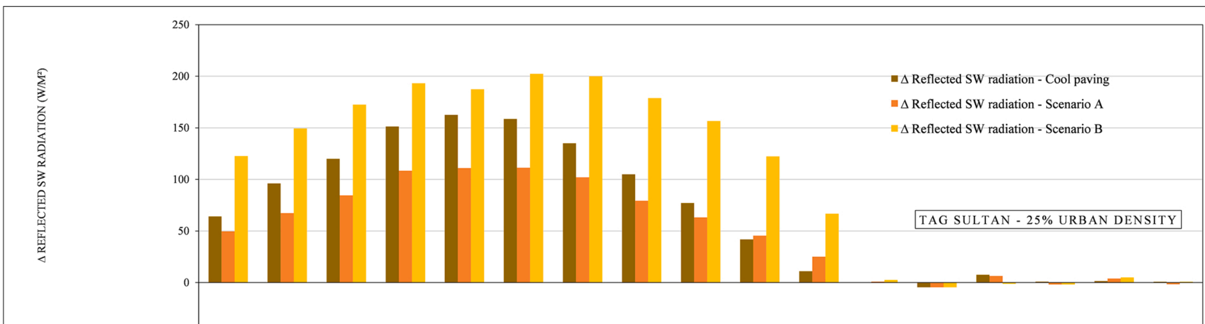
Fig. F1. Vegetation species that were chosen in the additional scenarios.

is a groundcover of a deep green color. It is used in public spaces and has a fibrous root system of 8–10 cm long (Fig. F1). In comparison, the albedo of the grass is 0.25. These species were used in the modeling because they are common types in Cairo (Elmasry, 2014).

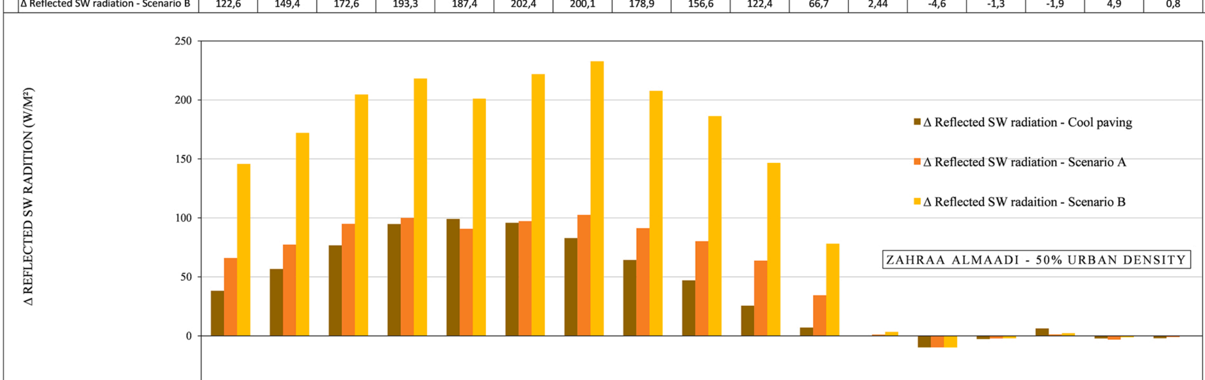
Appendix G

Reflected SW radiation of cool paving scenario and combined vegetation and cool paving scenarios

See Fig. G1.



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0
Δ Reflected SW radiation - Cool paving	64,1	96,2	120	151,3	162,5	158,6	135	104,9	77,2	41,8	11,1	0,12	-4,6	7,5	0,9	1,5	0,8
Δ Reflected SW radiation - Scenario A	49,6	67,3	84,6	108,4	111,1	111,4	102,1	79,3	63,2	45,5	25	0,84	-4,6	6,4	-1,8	3,9	-1,7
Δ Reflected SW radiation - Scenario B	122,6	149,4	172,6	193,3	187,4	202,4	200,1	178,9	156,6	122,4	66,7	2,44	-4,6	-1,3	-1,9	4,9	0,8



	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	0
Δ Reflected SW radiation - Cool paving	38,3	56,8	76,8	94,8	99,2	95,9	82,9	64,3	47,1	25,6	7,1	0,1	-9,7	-2,7	6,4	-2,1	-2
Δ Reflected SW radiation - Scenario A	66	77,4	95	100	90,8	97,2	102,6	91,3	80,3	63,8	34,4	1,2	-9,7	-2,1	1,3	-3,1	-1
Δ Reflected SW radaition - Scenario B	145,7	172,1	204,6	218,2	201,1	221,9	232,8	207,7	186,3	146,6	78,1	3,4	-9,7	-2	2,3	-1,1	0

Fig. G1. Difference between reflected SW radiation in the reference case and the cool pavement scenario, Scenario A, and Scenario B (Δ Reflected SW radiation = suggested scenario – reference case).

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