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Characterization of Urban Surface Materials Through UAV-Based Thermal Imaging and In Situ Data Collection. Two case study in Madrid (Spain).

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Abstract

The urban materials surface interacts with solar energy, and these interactions can significantly influence the thermal environment, contributing to the Urban Heat Island effect. The work presented here responds to the need to better understand the thermal behavior of urban surfaces during the summer period under real conditions of solar exposure. The project focus on analyzing two case studies located in neighborhoods affected by intense Urban Heat Island and social vulnerability, urban overheating rises urban vulnerability. The main objective is to characterize the materials found in the two case studies through high-resolution thermal images from UAVs with ground-based measurements, obtaining values of reflectivity, emissivity and surface temperature. This characterization will help identify how commonly used materials behave thermally and support the proposal of improvements and intervention priorities.

Keywords

Urban heat island, urban overheating, urban vulnerability, microclimate variability, Surface temperature, UAV thermal remote sensing, albedo, emissivity, urban materials.

Highlights (novel results new methods)

Thermal images were obtained using UAVs over two vulnerable urban areas

Thermal emissivity and reflectance were combined with thermal images

Solar exposure and surface orientation are key factors in thermal performance

The findings support the use of UAV data in microclimate-oriented urban design

1. Introduction

The rise in global temperatures has become one of the most serious consequences of climate change, with profound effects on public health and quality of life, especially among the most vulnerable populations. Between the reference period of 1850–1900 and the decade spanning 2011–2020, the global average temperature increased by 1.1 °C, a change unequivocally attributed to human activities. This warming has been accompanied by more frequent, intense, and longer-lasting heatwaves [1]. These developments have been documented thanks to the unprecedented availability and accessibility of climate data [2], contributing to a growing scientific consensus that we are nearing a critical tipping point and are currently facing a climate emergency [3].

In Addition, in urban areas, heatwaves exacerbate the "Urban Heat Island" (UHI) effect [4],[5], a phenomenon that has been extensively studied in hundreds cities globally over several decades using various methods [6]. Furthermore, the combined effects of regional and global climate change are expected to increase global air temperatures, which in turn will amplify the UHI effect during heatwaves [4] [7].

The rise in heat-related morbidity and mortality, linked to both global and local climate change, is deeply concerning [8]. The World Health Organization (WHO) estimates that the warming and changing precipitation patterns driven by human-induced climate change have already caused over 150,000 deaths annually over the past 30 years [9]. Epidemiological data show that 59,114 deaths occurred between 2000 and 2007 during 52 major heat events across the globe [10].

In Spain, in 2004, a daily all-cause mortality monitoring system (MoMo)[11] was created within the framework of the Preventive Action Plan against the Effects of Excessive Temperatures. The system aims to reduce the impact on the population's health resulting from excessive temperatures. The system identifies deviations in observed daily mortality from that expected based on historical mortality series. The latest MoMo summer report published in 2024[12] shows an increase in mortality due to the increase in summer temperatures that year, primarily affecting the population over 74 years of age, the age group in which 90% of the mortality attributable to excessive temperatures was concentrated that year. According to the report, 2024 will see the sixth highest mortality rate attributable to excessive temperatures in summer since records and analyses began (2015-2024).

This problem is exacerbated in highly anthropized environments, coinciding in most cases with large urban environments, since the increase in temperatures described above is added to the heat island effect, the causes of which are varied, primarily resulting from the alteration of natural environments in cities, as urbanization increases worldwide [13], it is essential to understand the linkages between urbanized environments and wellbeing and health.

Material choices can literally “change the (micro)climate” by contributing to the urban heat island effect [14]. The material surface properties interact with solar energy, and these interactions can significantly influence the thermal environment, absorbing heat from the sun (as with concrete and brick), reflecting solar heat gain (as with light-colored surfaces) or transforming solar energy (through on-site power generation and/or living materials such as green roofs). The current moment of climate emergency compels us to take appropriate measures urgently, to propose the most efficient actions and to prioritize measures to improve the built environment. It is mandatory to start by knowing the materials of the urban envelope, their surface properties, and their thermal performance.

Data collection and inspection tasks have traditionally been carried out through street-level fieldwork visits. However, considering the high number of buildings and neighborhoods in need of comprehensive renovation, as well as the urban characteristics of the areas in which they are located, the incorporation of Geographic Information Technologies (GITs) represents a step forward in streamlining and improving inspection activities for project drafting, execution and monitoring of works, as well as for the evaluation of interventions.

In recent years, there has also been growing interest in other emerging information technologies, such as the use of unmanned aerial vehicles (UAVs), commonly known as drones, whose integration with Geographic Information Systems (GIS) is viable, as well as their application into various industries and disciplines with different common objectives, such as, for example, the capture of geospatial data.

UAVs are a valuable tool already used for fire detection [15], to monitor the early responses of plants to different stressors [16], for photovoltaic (PV) plants inspections and maintenance[17], [18], [19], for damage detection in wind turbine blades [20], for volcanic plume measurements [21], for thermal anomaly detection for distributed heating networks [22], for detecting and rating multiple crack-related distresses in airfield pavement systems [23]. Given this enormous variability of the construction industry, UAV technology is expected to become highly invigorated with the help of advanced technologies, which have a high potential in construction and facility maintenance [24].

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Currently, two main types of drones have been developed [25]: multirotor, with great stability, ease of use, and maneuverability, designed to carry different sensors of varying sizes and weights, allowing for more precise flights in smaller areas [26], and fixed-wing drones, which, although they have greater autonomy, allowing them to cover larger surfaces, cannot hover and are more problematic during takeoff and landing [27]. These characteristics make multirotor drones more suitable for detailed urban analysis, where, in many cases, it is necessary to fly the aircraft within the urban canyon.

Both types incorporate GNSS global positioning systems, which, due to centimeter-level accuracy [28], allow for a priori planning and projection of flight plans to efficiently cover the area. Progress in sensor technology includes the miniaturization of advanced cameras designed for UAVs, available with high-resolution hyperspectral and thermal images, which expands the applications of these devices. The development of both technologies, drones and sensors, has been accompanied by a push for software for processing data captured in fieldwork. In this regard, there are photogrammetric applications for the creation of 3D models, point clouds, digital terrain and surface models, orthophotographs, and high-precision cartography. Thanks to these products and their integration into Geographic Information Systems (GIS), geospatial visualization and analysis have been improved [29].

It is essential to consider is the regulatory framework that accompanies these geospatial data capture missions. In Spain the use of drones is regulated by two agencies: the European Union Aviation Safety Agency (EASA), which unifies common standards for all Member States by drafting common rules applicable to all of them [30], and the Spanish State Aviation Safety Agency (AESA), which ensures compliance with civil aviation regulations across all aeronautical activities in Spain, among others. Furthermore, flight and permit management is operated by AENA, through ENAIRE, responsible for airspace control and air traffic management. Everything is regulated by EU Regulations 2019/947 and 2019/945.

The use of UAVs in urban areas is regulated by the need to obtain specific permits, in accordance with a standard scenario (STS), caused by safety restrictions in the event of potential accidents. All this entails the subsequent coordination with authorities, both aeronautical and public safety and mobility, regarding the restriction of pedestrian and vehicular traffic while the drone is in flight [30].

The MateMad Project [31], aims to generate knowledge about the impact of urban surface materials on the habitability and sustainability of cities. The project focus on analyzing neighborhoods affected by intense Urban Heat Island (UHI) and social vulnerability. Citizens capacity to cope with urban overheating depends on age, economic conditions, general health status, conditions and possibilities of the nearby urban environment, social support...etc. Urban overheating rises urban vulnerability [32], the most vulnerable include those who lack resources to privately reduce temperature extremes (such as air conditioning or thermal insulation). Low-income populations primarily reside in poorly insulated homes located in disadvantaged urban neighborhoods that experience significant overheating. Heat stroke can worsen existing health problems and primarily impacts the elderly, children, and outdoor workers; death usually occurs after several days [33].

The work here presented is developed in MateMad Project and responds to the need to better understand the thermal behavior of urban surfaces during the summer period under real conditions of solar exposure. These surfaces receive the highest levels of solar radiation and play a critical role in pedestrian thermal comfort and in the formation of the Urban Heat Island (UHI) effect. The main objective is to characterize the materials found in two case studies through the combination of different technologies, obtaining values of reflectivity, emissivity and surface temperature. This characterization will help identify how commonly used materials behave thermally and support the proposal of improvements and intervention priorities.

This study focuses on level 0, that is, the horizontal surfaces of public spaces such as streets, sidewalks, squares, and courtyards. These are areas where local governments have greater capacity and flexibility to act, as they correspond mainly to public spaces.

By conducting this localized analysis in Madrid, it becomes possible to develop tailored solutions that address specific urban challenges, while also creating a transferable model for other neighborhoods and cities. The insights gained from Madrid can be scaled, adapted, and applied to diverse urban contexts, contributing to broader sustainability goals at the regional, national, and international levels [34].

2. Methodology

In the framework of the MateMad project, data collection follows a multiscale approach, combining various techniques. Previously gathered datasets at both the city and neighborhood levels [26–28] helped identify and justify the selection of the two study areas presented below.

The proposed methodology is applied to vulnerable urban areas in Madrid. The city’s climate is classified as Mediterranean with semi-arid tendencies (Csa-BSk), characterized by hot summers, cold winters, and rainfall concentrated mainly in autumn and spring.

The study follows a five-step process (Figure 1). First, specific areas were selected based on prior analysis. Next, data were collected and processed using UAV thermal imagery and in situ data collection. The third phase involved detailed analysis of the results. Finally, both partial findings and general conclusions were drawn to evaluate the thermal behavior of urban surfaces.

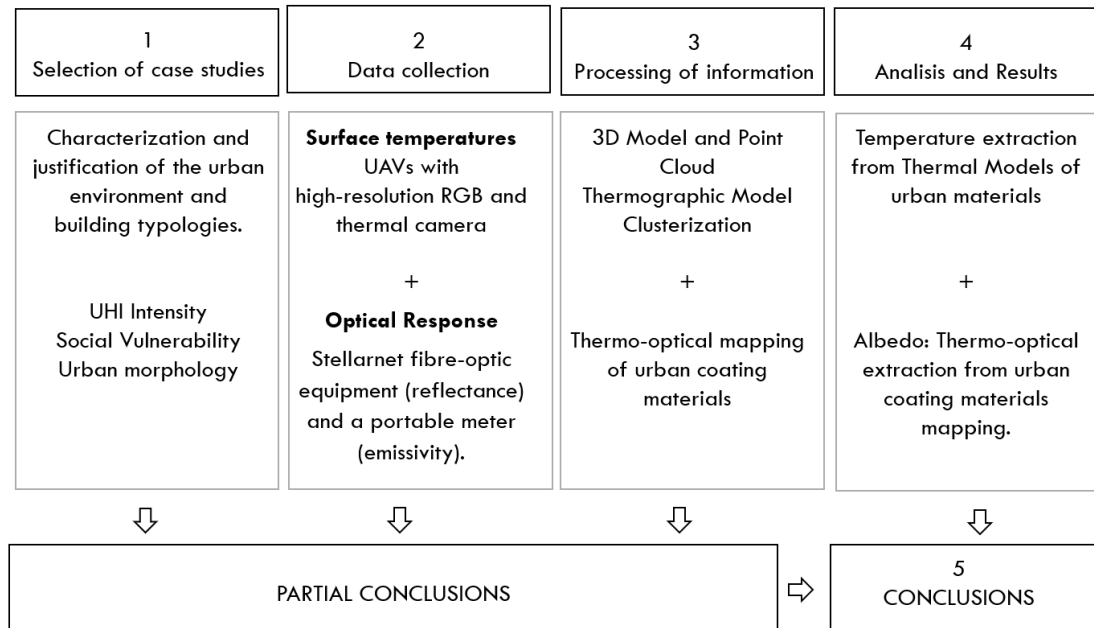


Figure 1. Methodological scheme.

1. Selection of case studies

Among the deteriorated urban areas in Madrid identified for refurbishment, those most affected by intense Urban Heat Island (UHI) effects during the summer have been prioritized. Of the 96 most disadvantaged neighborhoods, 27 have been identified as requiring urgent intervention [35]. While these 27 areas differ in their specific conditions, they are largely

concentrated in the southern outskirts of the city (see Figure 2). The most affected districts include District 13, *Puente de Vallecas*, with nine neighborhoods, and District 12, *Usera*, with five.



Figure 2. Vulnerable urban areas identification in Madrid, Spain (Source: MateMad project)

From these neighborhoods, two specific areas have been selected for study (see Table 1), based on their contrasting urban morphologies, potential for replication and broader applicability, as well as their indicators of social vulnerability.

Table 1. Characterization of the areas of analysis. (Source: MateMad project)

	URBAN FABRIC	URBAN CANYON
San Diego (Puente de Vallecas) Collective Attached blocks (CA)		



2. Data collection

2.1. RGB and Surface temperature UAV.

In this study, a UAV (DJI Matrice 300 RTK) equipped with a high-resolution RGB camera (DJI Zenmuse P1) and a thermal imaging camera (DJI Zenmuse H20T) was used to collect data on surface materials of various elements. The DJI Matrice 300 RTK has a maximum takeoff weight of 9 kg (6.3 kg including batteries and 2.7 kg of payload), with an approximate flight autonomy of 30 minutes and a maximum speed of 17 m/s. The thermal sensor, the DJI Zenmuse H20T, features an image resolution of 640×512 pixels and operates within a spectral band of 8 to 14 microns. Additionally, it is equipped with a 20 MP zoom RGB sensor and a 12 MP wide-angle sensor. The RGB sensor, the DJI Zenmuse P1, offers a resolution of 45 MP

A combination of vertical and oblique flights was employed [36], as this strategy enables highly accurate 3D modeling while minimizing areas with missing data. Vertical flights follow parallel trajectories relative to the terrain, with the sensor's optical axis perpendicular to the surface, resulting in orthogonal images (Figure 3). These flights are primarily used in photogrammetry for the production of orthophotos (which allow for precise measurements), Digital Terrain Models (DTMs), and digital cartography. In contrast, oblique flights are characterized by the sensor's optical axis being inclined with respect to the vertical, generating diagonal views of the terrain.

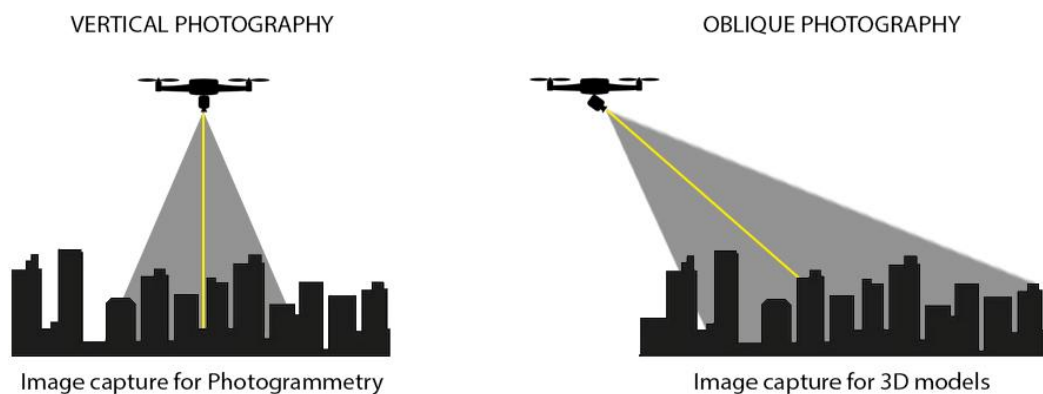


Figure 3. Vertical and oblique flights. Author's source.

Prior to data collection, detailed flight planning was conducted to optimize fieldwork and streamline the photogrammetric processing of the acquired imagery. This included delineating the area of interest, establishing flight paths, determining both frontal and lateral

image overlaps (which must be substantial to avoid data gaps), and defining the flight altitude. Figures 4 and 5 illustrate the delimited flight zones and trajectories for each study area.

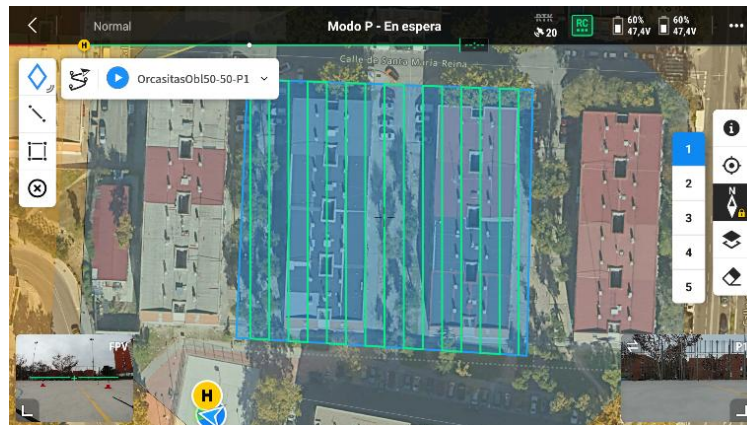


Figure 4. Vertical flight plan for the Orcasur area. Author's source.



Figure 5. Oblique flight plan for the San Diego area. Author's source.

In accordance with regulations governing UAV operations in urban areas, pedestrian traffic was halted or redirected to safe zones during the flights. Motor vehicle traffic was also temporarily suspended during UAV overflights of specific streets, in coordination with Municipal Police mobility officers.

Flights took place at dawn, to minimize the influence of solar radiation on the analyzed surfaces while ensuring sufficient light for capturing RGB imagery. For the San Diego area, flights were conducted on July 24, 2023. The start time was 6:27h, when dry temperature was 23.3°C, wet bulb temperature 13.5°C, relative humidity 32.3%, dew point 5.8°C. The flights end time was 9:30h, when dry temperature was 24.2°C, wet bulb temperature 14.7°C, relative humidity 35.1%, dew point 7.8°C. In the Orcasur area, flights were carried out on July 26, 2023. The start time was 6:30h, when dry temperature was 22°C, wet bulb temperature 14.2°C, relative humidity 42.7%, dew point 8.8°C. The flights end time was 8:11h, when dry temperature was 13.2°C, wet bulb temperature 14.7°C, relative humidity 48.5%, dew point 8.5°C.

The flights in each area were divided as follows:

1. **Vertical and oblique flights using the DJI Zenmuse H20T thermal sensor**, conducted at an altitude of 50 meters above ground level. These flights achieved a Ground Sampling Distance (GSD) of 4.44 cm for the vertical flight and 5.80 cm for the oblique flight.
2. **Facade flights**, also carried out with the DJI Zenmuse H20T thermal sensor. These consisted of vertical trajectories along the street axis and parallel to the building facades,

moving from the top of the facades to the bottom. Special attention was paid to the presence of overhead power lines, for which a prior inventory had been conducted.

3. **A second vertical flight using the DJI Zenmuse P1 RGB sensor**, also at an altitude of 50 meters, achieving a GSD of 0.63 cm.

2.2. Optical Properties with portable equipment.

The field campaign consisted of recording the optical properties of materials identified as being the most frequent finishes in the sample, as well as those with the largest surface area. The surface properties analyzed in this study include solar reflectance (albedo), visible reflectance, and thermal emissivity (ϵ).

- Reflectance was recorded in the wavelength range from 350 to 1700 nm (covering 95% of total solar energy) using portable Stellarnet fibre-optic equipment fitted with a reflectance probe. The equipment consists of a tungsten halogen lamp with a colour equalising filter, a miniature spectrometer covering the wavelength range between 350 and 1080 nm (model BLK-C-SR), and another spectrometer covering an overlapping range from 900 to 1700 nm (model Dwarf Star).
- Emissivity (ϵ) was measured using a portable emissivity meter (ET100 with SOC410 unit) from Surface Optics Corporation, which complies with ASTM E408-19 [35]. The ET100 measures total directional emittance by directing radiation onto a surface in a specific direction and collecting the reflected radiation in all directions. The declared accuracy of the emissivity measurements is ± 0.03 .

3. Data Processing and Analysis

3.1. Thermal mapping of urban coating materials

3.1.1. Image Calibration

The quality and usefulness of thermal images obtained by unmanned aerial vehicles (UAVs) depend mostly on a rigorous radiometric calibration process. This stage is critical to ensure that the surface temperature data accurately represents the actual conditions of the built environment [38] [39]. During the capture campaign, the thermal images were acquired in radiometric format (RAW), which allows all the necessary information to be preserved for subsequent processing and correction [38].

The calibration was based on the use of the ImageJ software [40] and the IRImage plugin [41], which allows digital values (DN) to be converted to absolute temperatures in degrees Celsius [42]. To do this, specific parameters such as the emissivity of the material (usually between 0.87 and 0.92 for urban materials), the reflected apparent temperature, and the camera-object distance, extracted from the flight metadata, were introduced. In addition, reference sensors were placed in the field that recorded in real time the air temperature and relative humidity, essential data for the thermal normalization of the images [38].

By doing this, thermal biases related to the physical characteristics of the sensor and the surrounding environment are eliminated, ensuring that the temperature readings correspond to the conditions of the materials that were recorded [42].

3D Model and Point Cloud Generation

The 3D point cloud urban area was reconstructed using photogrammetric algorithms applied to high-resolution RGB images captured during UAV flights. This workflow involved three main steps: image capture, georeferencing, and point cloud reconstruction [43]. To obtain an accurate RGB Point Cloud, point matching techniques between thermal and RGB images were

used to find image point correspondences. This enabled the creation of a dense point cloud that accurately represents the volumes and surfaces of the urban area [44] [45].

Once the point cloud was obtained, the previously calibrated thermal information was integrated onto it, projecting the temperature values onto the 3D points using geometric recording algorithms. The result is a georeferenced thermal model, in which each point contains spatial coordinates (X, Y, Z), color attributes (RGB) and a scalar surface temperature value [43] [38]. This combination of data provides a solid basis for urban energy analysis, detection of thermal anomalies, and evaluation of heat island mitigation strategies[43] [45].

Below (figures 6, 7, 8 and 9) are the results of the orthophoto obtained from point clouds generated in the visible and infrared spectrum:

Study Case2: Orcasur



Figure 6. RGB Orthophoto obtained from Point Cloud.
Own elaboration

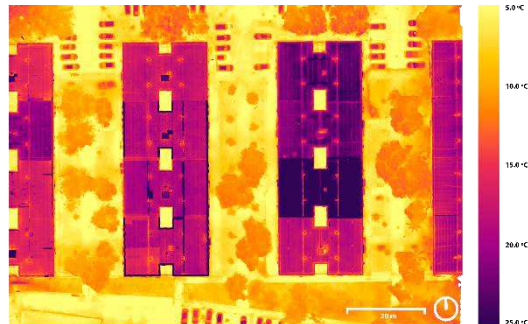


Figure 7. Thermal Orthophoto obtained from Point Cloud.
Own elaboration

Study Case 1: Vallecas



Figure 8. RGB Orthophoto obtained from Point Cloud.
Own elaboration

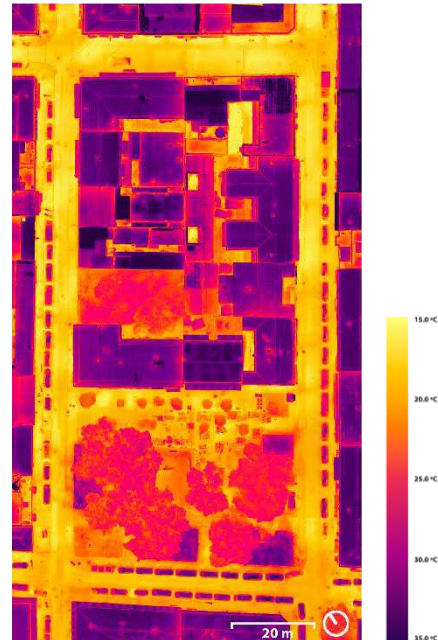


Figure 9. Thermal Orthophoto obtained from Point Cloud.
Own elaboration

3.1.2. Thermographic Model Clusterization

With this approach, the point cloud was segmented considering only the materials present in the soil plane, such as asphalt, concrete pavement, tiles, pavers, gravel or other types of

pavements. The classification was carried out by combining the urban finish maps, previously generated by GIS, and the chromatic information of the RGB point cloud, which made it possible to accurately identify the different materials captured during the flights. The validation of this classification was completed with visual inspections on site.

Once the materials were identified, thermal clustering was applied by surface temperature ranges, which allowed visualizing and comparing the absorption, accumulation, and heat retention capacity of each one. To facilitate its spatial interpretation, a coded nomenclature was established according to location and orientation (e.g., "Street 2 (S2)", "Canyon 1 (C1)", "Plaza (Q)"), and sequential labels were assigned to each type of material.

Once the materials of the model were classified, the average temperature values for each homogeneous sector were extracted. Statistical analysis algorithms were applied to extract the average temperature of each section.

3.2. Thermo-optical mapping of urban coating materials

To measure thermo-optical properties of public space urban materials a mapping of surface finishes was carried out during MATEMAD Project [31]. The method for developing this map (figure 10) consisted of field visits to identify urban coatings, parallel work with GIS databases and the collection of in situ experimental data on the physical characteristics of the materials found at the study cases [46].

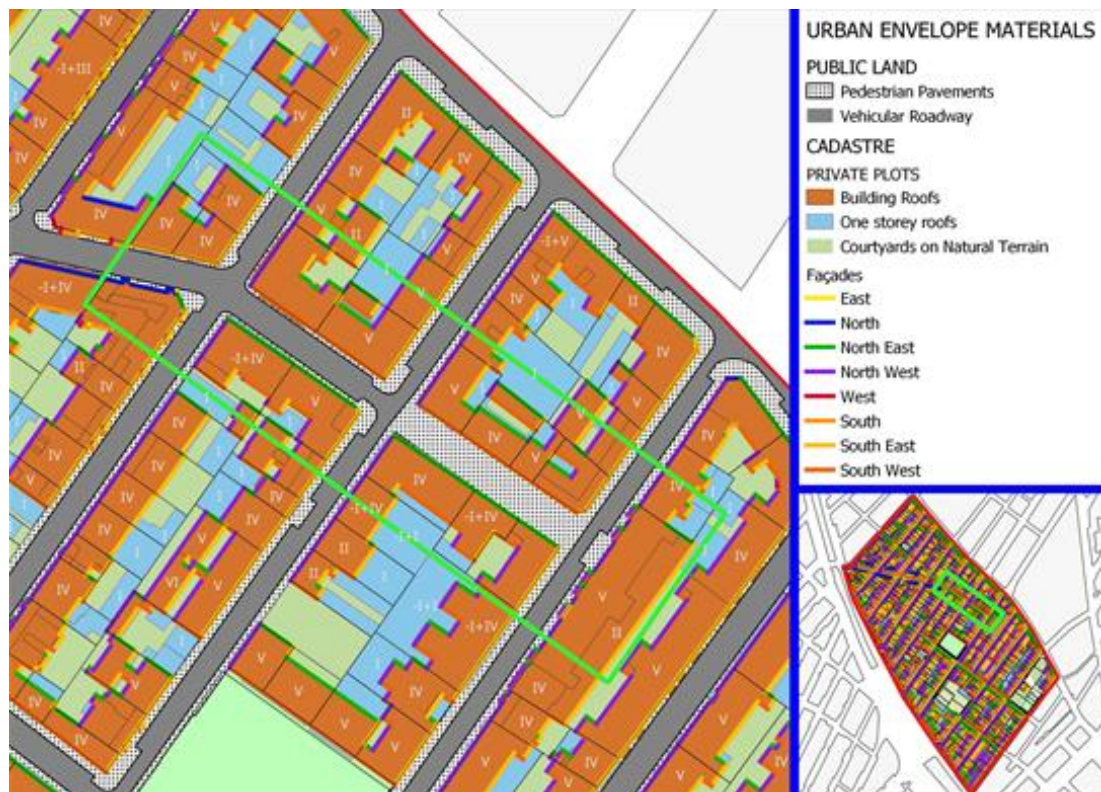


Figure 10. Urban envelopes map of Picazo district [25]

The surface area of the urban envelope was quantified using open-source geographic information and geoprocessing tools within a GIS environment. Vector cadastral data was employed to extract the geometric information of private plots [47]. This information was classified according to the elements of the urban envelope: floors, roofs and facades. The roofs are counted separately for buildings and low-rise constructions inside the courtyards of urban blocks. Facades were categorized into the ground floor (commercial plinths) and the

rest of the façade [48]. Public land information was categorized into pedestrian areas, squares, sports areas and roadways for road traffic [48].

Based on these finish maps, the urban materials present in the study areas are identified, and an on-site inspection is then carried out. During this inspection, measurements of the thermo-optical properties of the surface finishes are taken using specialized instruments (as previously described).

The incorporation of the thermo-optical properties of urban envelope materials enables the calculation of an approximate theoretical urban albedo. This is achieved by weighting the solar reflectance values of the various ground coatings that make up the urban surface. Such information is also valuable for the calibration and refinement of energy models.

4. Results and discussion.

4.1. Result of thermal mapping of urban coating materials.

Figures 11 and 12 allows to establish the relationship between urban materials and surface thermal distribution of public space in San Diego (Vallecas), the correspondence between both allow to clearly identify how visual information is transformed into analytical data for thermal study. In figure 11 the urban surface has been divided into material categories differentiated by color code:

- Asphalt (dark grey): used on the roadway of perimeter streets, it is the dominant surface for road traffic.
- Sidewalk 1 (light grey): represents sections of sidewalk with standard square pavement of gray concrete.
- Sidewalk 2 (very light grey): identifies a different type of sidewalk, a rectangular concrete paving stone in grey.
- Pavement 1 (light blue): continuous paved surfaces with square-shaped tiles, associated with pedestrian or recreational areas.
- Sand (light yellow): Soft areas of sand or gravel.
- Grass: grassy areas.
- Vegetation (contoured green): woodland with a projected canopy, delimiting areas of natural shade within the urban area.
- Vehicles (black): corresponds to the spaces occupied by vehicles parked on the margins of public roads.
- Others (pink): small surfaces without a defined classification, which could include street furniture or various artificial elements.

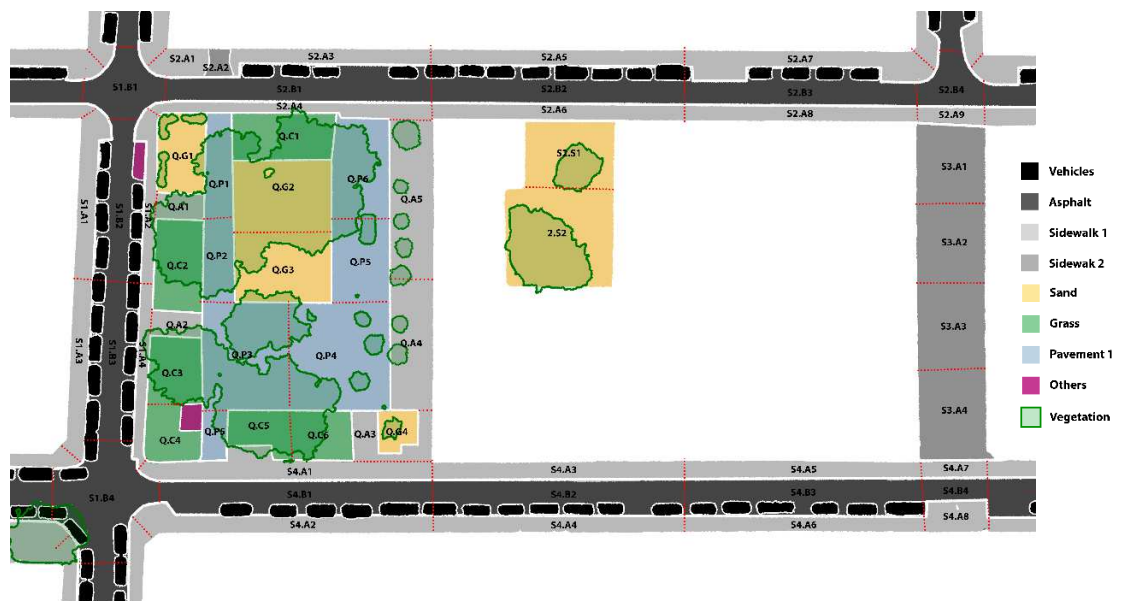


Figure 11. Numbering of Classified Materials

Figure 12 shows the spatial distribution of surface temperatures. The color palette, which goes from dark violet (colder areas) to yellow (warmer areas), reflects the thermal range between approximately 22 °C and 35 °C. The warmest areas are concentrated on the edges of streets and asphalted surfaces, while the lowest values are in areas with vegetation cover or light pavements. This information is complemented by the thematic classification image, which allows to identify which material category corresponds to each area analyzed.

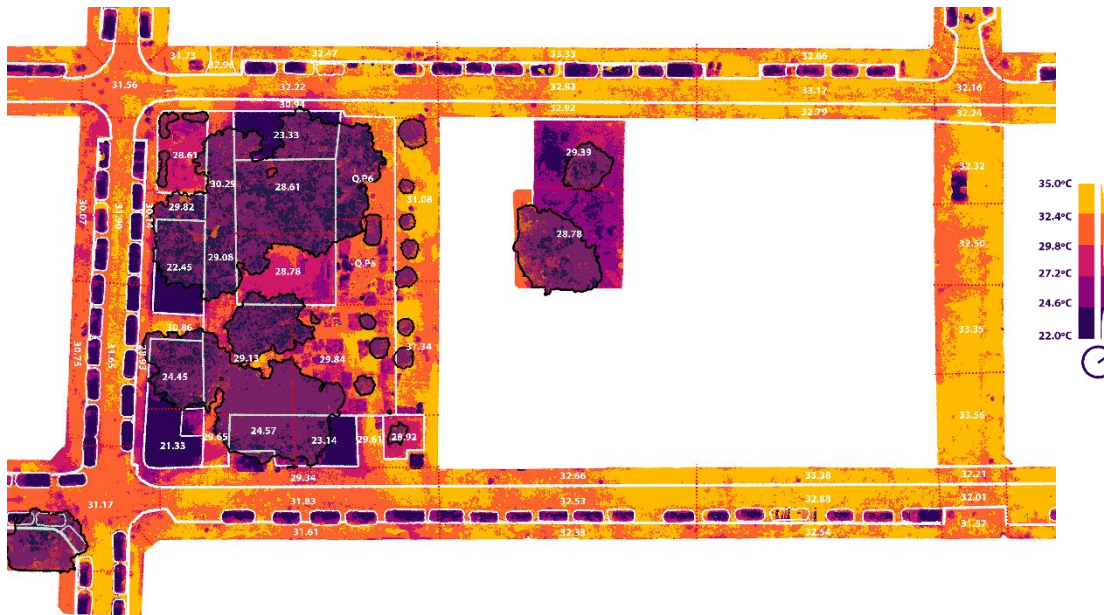


Figure 12. Average temperatures per section

Next, in table 2 the relationship between the thermal model, the classification of materials, and the tabulated data of average surface temperature by type of material and location is presented.

Table 2. Average temperatures per material in San Diego

Material	Street 1 S1	Street 2 S2	Street 3 S3	Street 4 S4	Square Q
Sidewalk	29.97	32.47	32.93	31.96	30.54
Asphalt	31.57	32.60	-	32.31	-
Grass	-	-	-	-	23.21
Gravel	-	-	-	-	28.93
Pavement	-	-	-	-	29.65
Sand	-	26.56	-	-	-

Figure 13 represents the image resulting from the thematic classification process of materials in Orcasur (Usera), this classification of materials together with the information obtained from the thermal point cloud is represented in figure 11. As previously (in San Diego), the urban surface has been divided into material categories differentiated by color code:

- Vehicles (black): Vehicle parking areas, located at the top of the image. They can generate thermal accumulation due to their metallic surface and low reflectance.
- Asphalt (dark grey): main roads and roads, with a high degree of solar absorption and low reflectance, which makes them urban heat sources.
- Sidewalk (light grey): sidewalk pavements with a standard concrete finish, with medium reflectance.
- Sand 1 and Sand 2 (light yellow and beige): soft or semi-soft surfaces (sand, loose aggregate), with variable thermal characteristics. They are distributed in longitudinal strips on both sides of the blocks.
- Sport pavement (light blue): area paved with sports cladding, located in the lower left corner of the image, with organic base material.

- Pink pavement: a small area of decorative pavement, also located at the bottom, close to the pavement.
- Vegetation (green): masses of trees and meadows that provide natural shade and heat attenuation, distributed in the central courtyards between blocks and along the road perimeter.



Figure 13. Numbering of Classified Materials

Figure 11 shows the spatial distribution of mean surface temperatures in the Orcasur study area, using a color palette ranging from dark violet (colder areas) to yellow (warmer areas), with values ranging from approximately 19 °C to 27 °C. This representation is complemented by Figure 14, where each spatial unit has been classified and numbered by material typology, which allows correlating the thermal behavior with the properties of each surface.

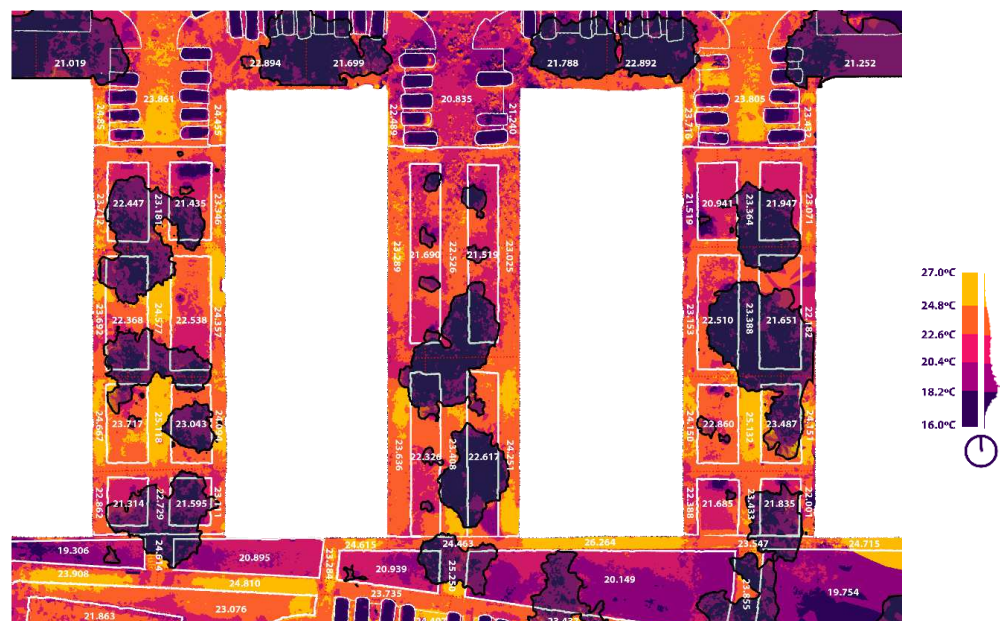


Figure 14. Average temperatures per section

Next, in table 3 the relationship between the thermal model, the classification of materials, and the tabulated data of average surface temperature by type of material and location is presented.

Table 3. Average temperature per material in Orcasur.

Material	Canyon 1	Canyon 2	Canyon 3	North	South
	C1	C2	C3	N	S
Sidewalk	23.79	23.36	23.16	22.60	24.35
Asphalt	-	-	-	22.83	24.50
Gravel	22.31	22.04	22.11	-	20.21
Pink Pavement	-	-	-	-	23.08
Sport Pavement	-	-	-	-	21.86

4.2. Results of thermo-optical mapping of urban coating materials.

Firstly, tables 4 and 5 present the results of the in-situ measurements of the optical properties of the pavement materials found in the study areas (San Diego and Orcasur).

Table 4. Thermo-optical properties for paving materials measured in situ in San Diego

Material	Material family	Visible Reflectance	Solar Reflectance	Emissivity
Sidewalk (cobble)	Cement-based	0,14	0,17	0,90
Sidewalk (cobble)	Cement-based	0,21	0,23	0,91
Sidewalk (light grey cobble)	Cement-based	0,17	0,21	0,90
Sidewalk (beige cobble)	Cement-based	0,18	0,20	0,90
Asphalt	Bituminous	0,16	0,18	0,88
Asphalt	Bituminous	0,15	0,17	0,90
Asphalt	Bituminous	0,15	0,16	0,90
Sidewalk (white)	Cement-based	0,56	0,56	0,87
Sidewalk (old white)	Cement-based	0,29	0,31	0,89
Sidewalk (black)	Cement-based	0,16	0,16	0,90
Sidewalk (red)	Cement-based	0,20	0,22	0,88
Sidewalk (old pink)	Cement-based	0,21	0,25	0,89
Sidewalk (pink)	Cement-based	0,43	0,50	0,88

Table 5. Thermo-optical properties for paving materials measured in situ in Orcasur

Material	Material family	Visible Reflectance	Solar Reflectance	Emissivity
Sidewalk (beige)	Cement-based	0,38	0,43	0,90
Pink pavement (a)	Cement-based	0,29	0,32	0,89
Pink pavement (b)	Cement-based	0,24	0,27	0,89
Pink pavement (c)	Cement-based	0,23	0,25	0,89
Pink pavement (d)	Cement-based	0,16	0,18	0,90
Sand 1	Arid	0,26	0,29	0,92
Asphalt	Bituminous	0,12	0,14	0,90
Sidewalk (beige)	Cement-based	0,26	0,27	0,89
Sidewalk (red) (a)	Cement-based	0,19	0,22	0,90
Sidewalk (red) (b)	Cement-based	0,19	0,20	0,90
Sidewalk (red) (c)	Cement-based	0,23	0,24	0,90
Sidewalk (black)	Cement-based	0,19	0,17	0,89
Sidewalk (grey)	Cement-based	0,20	0,19	0,89
Sport pavement (blue)	Organic-based	0,18	0,23	0,90
Sport pavement	Organic-based	0,44	0,47	0,90
Sand 2	Arid	0,25	0,29	0,92

It can be observed that the materials generally have low reflectance values, below 0.25, which translates into high energy absorption in sun-exposed areas. Light-colored pavements show somewhat higher values (white, beige, pink), with the highest reflectance being 0.56 for the polished white tile. The lowest values are found in asphalt pavements used for roadways (with reflectance values ranging from 0.14 to 0.18), absorbing up to 86% of the incoming radiation. Aged materials show reflectance values well below those of their original condition. For example, the polished white tile exhibits the highest solar reflectance in the sample, with a value of 0.56, which drops to 0.31 in its aged state. The new pink tile shows a value of 0.50, which decreases to 0.25 when it becomes dirty and degraded.

As for emissivity, the results are very consistent, ranging from 0.87 to 0.92 across the entire sample of pavements.

Figures 15, 16, and 17 show an aerial photograph of the study area in the Orcasur neighborhood, along with the solar reflectance (top) and emissivity (bottom) maps of its pavements.



Figure 15. Mapping of the thermo - optical properties of urban surface materials. Aerial view of pavements in Orcasur district.



Figure 16. Mapping of the thermo - optical properties of urban surface materials. Measures of solar reflectance of pavements in Orcasur district



Figure 17. Mapping of the thermo - optical properties of urban surface materials. Aerial view and measures of emissivity of pavements in Orcasur district

By combining map surface information and surface optical property values, it is possible to calculate the albedo for the study area. The final value for San Diego (0.27) is obtained by averaging the solar reflectance values of each material weighted by the urban land surface occupied (Table 6).

Table 6. Calculation of average pavements albedo for the case study area in San Diego.

Area function	Surface (m2)	Albedo
Sidewalk	5.856,02	0,21
Cobble	3.958,39	0,21
Black	1.897,63	0,21
Road	2.149,76	0,17
Asphalt	2.149,76	0,17
patios	530,19	0,29
Sand	323,69	0,29
Unknown	206,50	-
Square	2.047,20	0,32
Cobble	382,69	0,21
Sand	849,63	0,29
White pavement	710,85	0,56

Pink pavement	104,03	0,50
AVERAGE VALUE	10.583,16	0,27

Figure 18 shows the spatial distribution of materials in the public space. The area with the highest absorptance corresponds to the asphalted areas.

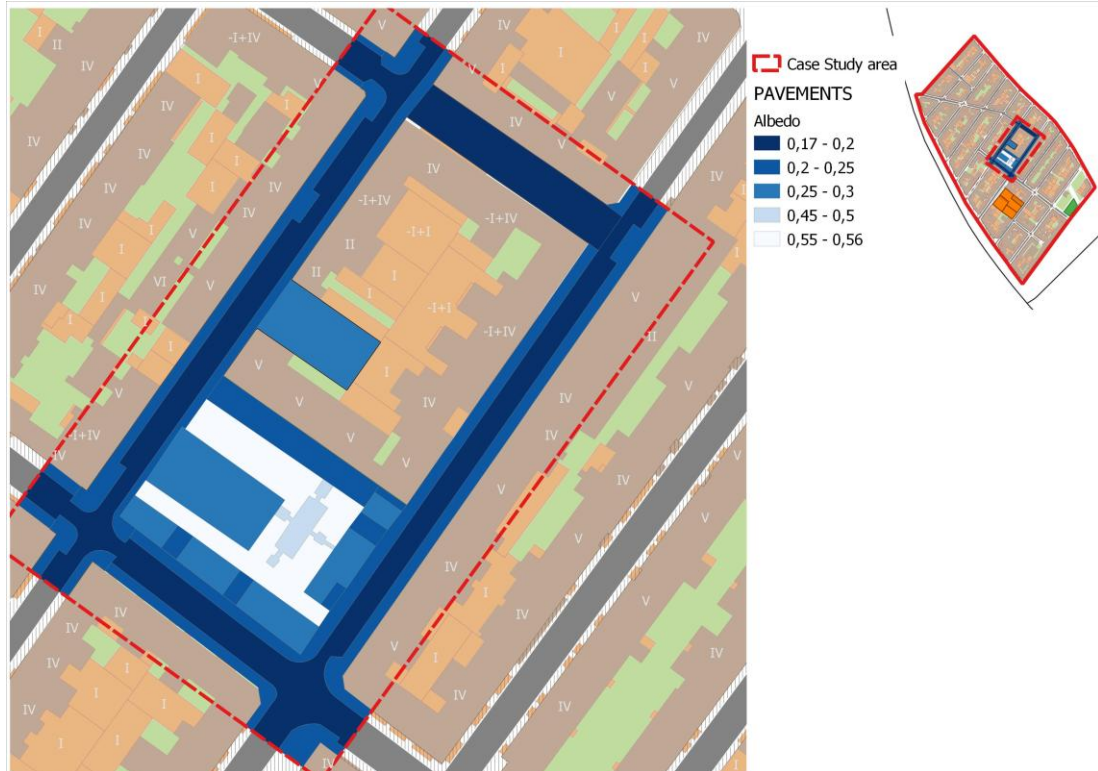


Figure 18. Solar reflectance of pavements in the Picazo neighbourhood case study

Results of combining thermal images with in situ measures.

The relationship of temperature differences between materials and with their albedo in both areas is gathered in table 7 and 8.

Table 7. Comparison of albedo and surface temperature of pavements measured in situ in Picazo

Material	Average temperature (°C)	Average Albedo
Sidewalk (cobble)	31,57	0,21
Asphalt	32,16	0,17
Grass	23,21	- (no mesure)
Gravel	28,93	0,29
Pavement (white)	29,65	0,56
Sand	26,56	0,29

Table 8. Comparison of albedo and surface temperature of pavements measured in situ in Orcasur

Material	Average Temperature (°C)	Average Albedo
Sidewalk	23,45	0,21
Asphalt	23,66	0,17
Gravel and Sand	21,66	0,29

Pavement (Pink)	23,08	0,47
Sport Pavement	21,86	0,23

The thermal analysis reveals material- and space-based differences in surface temperature between San Diego and Orcasur study sites that closely reflect urban material optical and physical characteristics.

Asphalted roads that are readily distinguished in the class map as dark perimeter bands exhibit the highest temperatures of any material. In San Diego, these surfaces (particularly Calle 3 and Calle 4, locations S3 and S4) exhibit average temperatures ranging from 31.17 °C to 33.56 °C. In Orcasur, asphalted locations (B.01 to B.03) exhibit slightly lower temperatures ranging from 23.80 °C to 24.49 °C. These surfaces also appear in intense orange colors in the thermal images due to low reflectance and intense solar absorptiveness with their low albedo values (≈ 0.17), further validating their role as main collectors of warmth in urban areas.

Sidewalks, designated as Sidewalk 1 and Sidewalk 2, also reach elevated temperatures, particularly in San Diego. Aged in lots as A.01 to A.09, these pavement types frequently reach temperatures near asphalt levels with maxima up to 33.56 °C, particularly in sun-exposed southeast-facing locations. In Orcasur, sidewalks (A.01 to A.13) exhibit wider thermal ranges from 21.01 °C to 26.26 °C with good orientation and control of shadows. South-facing locations (e.g., A.03) exhibit highest temperatures while shadowed locations facing the north (e.g., A.01) exhibit clear coolness. The sidewalks appear in intermediate pink, orange, and fuchsia hues in the thermal images. Their quite low albedo (≈ 0.21) explains their thermal similarity with asphalt pavement surfaces, particularly in sun-exposed locations.

Instrumented surfaces, that is, paved surfaces such as pedestrian paths and plazas, have moderate thermal characteristics. Pavement 1 (areas P.01 to P.05) in San Diego measures average temperatures between 29.08 °C and 30.29 °C. In Orcasur, pink pavement (PR.01) measures 23.07 °C while the sports pavement (PR.02) measures 21.86 °C, indicating more effective thermal efficiency. The surfaces appear in pink to light violet shades on the thermal maps indicating an intermediate thermal class that is cooler than asphalt but warmer than shaded or vegetated surfaces. The thermal variation between pavement types is due to their surface finish as well as their albedo with lighter pavement such as pink tiles (≈ 0.47) reflecting more radiation and retaining less warmth.

Transition area gravel industries exhibit a range of moderate warmth behavior. In San Diego (G.01 to G.04), gravel surfaces reach 28.61 °C to 29.39 °C temperatures, slightly less than asphalt surfaces but nonetheless demonstrate to hold appreciable warmth. These appear in soft orange to fuchsia hues. In Orcasur (G.01 to G.08), gravel locations, ranked in light yellow, exhibit colder mean temperatures of 20.94 °C to 23.71 °C, depending primarily on degree of compaction as well as shade. On the thermal images, they appear in light purple or pink hues, cooler than asphalt and sidewalk, but warmer than vegetated surfaces. The intermediate albedo of gravel and sand (≈ 0.29) allows for a moderate absorptivity for warmth, with a resultant surface temperature less than asphalt but more than vegetation.

Green sites indicate lowest surfaces for both study locations. In San Diego (Q.C1 to Q.C6), vegetated sites show surface temperatures between 21.33 °C and 24.57 °C and tend to be located in interior blocks with frequent vegetative shade. On thermal maps, they show dark

purple hues. In Orcasur, vegetated sites, circumscribed in green on classifying map surfaces, show even lower temperatures with minimums between 19.31 °C and 20.14 °C. The study confirms vegetative cooling of urban microclimate. The effect is bolstered by a naturally elevated albedo and evapotranspirative nature of vegetated surfaces. Loose soil surfaces in San Diego (S.01 and S.02), with intermediate temperatures of 26.14 °C and 26.97 °C, appear between vegetated surfaces that record higher temperatures yet exhibit better thermal characteristics than paved or gravel surfaces. In the thermal maps, they represent intermediate colors between light orange and pink. The relatively moderate albedo value of sandy surfaces lies behind their thermal characteristics that expose them thermally between vegetated surfaces and urban surfaces.

There is a recurrent pattern that is evident with decreasing albedo surfaces for increased surface temperatures. This pattern remains true for all material types with one exception being white tiles whose temperature recordings cannot be determined with certainty due to frequent shading.

5. Conclusions

Through coupling UAV thermal images with ground measurements, a more accurate and subtle urban surface temperature determination is attainable. This research approach makes urban climatology more practical by providing useful material heat storage data and surface response. This data is extremely useful for urban heat island (UHI) adaptation and mitigation planning measures, selection of reflective or cool surfaces, as well as sustainable cities planning.

Optical properties such as emissivity and albedo greatly influence urban surfaces' thermal behavior. Accurate characterization of these parameters is instrumental for reliable thermal mapping and energy balance computation. It will further reduce the gap between predictions and measurements.

The results demonstrate that surface temperature variations across urban materials are closely linked to their optical properties, primarily emissivity and albedo. Materials such as asphalt and concrete exhibited higher thermal retention, aligning with previous urban heat island (UHI) literature. In contrast, surfaces with higher reflectivity, such as vegetation, showed lower thermal signatures. These findings reaffirm the critical role of material selection in urban design and its impact on local microclimates and, therefore, in the health and quality of life of people.

The use of UAVs in urban areas is still complex, nevertheless UAVs have the ability to comprehensively characterize urban environments, as well as offer a flexible, efficient, and high-resolution platform for monitoring complex these areas, surpassing some limitations of satellite or fixed ground-based methods.

Accurate surface temperature measurements require proper calibration of UAV thermal data using in situ observations as well as adequate flight scheduling to consider aspects related to weather, time of day and urban security. Emissivity correction, atmospheric adjustment, and surface validation are critical steps in the workflow.

Urban envelope material thermo-optical property integration enables an approximate urban albedo theoretical computation that is usable for calibrating and refining energy models. It can also benefit finishing material producers with data for them to adjust their products due to evolving demands caused by global warming.

Factors such as time of day, atmospheric conditions, and ground variability could also impact accuracy in thermal measurement. Technical expertise is also required to be able to interpret data effectively.

Whereas a clear inverse connection between albedo and surface temperature was pronounced under conditions of heavy thermal loading, this relation tends to decrease with decreasing ambient as well as surface temperatures. Where it is colder, material thermal inertia of surfaces, humidity of surfaces, or shade conditions may assume more significant roles in differential temperatures of surfaces. This nuance must be borne in mind while making inferences or while designing mitigation measures under changing seasonal conditions.

However, the approach is not without qualifications. Data obtained with thermal cameras is subject to variability with atmospheric conditions (e.g., wind speed, humidity) and time of day that affect surface heat fluxes. Scalability and time resolution are also limited due to the labor-intensive nature of obtaining in-situ data. Future studies could focus on applying radiative transfer models, auto-estimation of emissivity or machine-learning techniques in order to allow for wider generalizability and practical use of this method for urban climate monitoring.

Overall, this combined approach forms a helpful instrument for urban planning specialists, climatologists, together with policy decision-making authorities who aim for rehabilitating or planning thermally strong and healthy cities amidst climate change and urbanization.

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Data availability statement

"All data generated or analyzed during this study are included in this published article".

Declaration of AI-assisted technologies in the writing process.

During the preparation of this work the authors used ChatGPT only during the writing process in order to improve the readability and language of the manuscript.

After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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