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Impact of paving surface material on thermal conditions within a residential building

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Abstract This paper presents the impact of paving surface material on thermal comfort in a residential building. The aim of the study was to demonstrate differences in temperature, measured near a building's walls, depending on their location (relative to the cardinal directions) and the type of paving surface material outside the building (in its immediate vicinity, considering the cardinal directions). The study found differences in temperature values recorded near walls located on the south-west side, which faced a garden and a grassy surface, compared to the temperature of the walls that faced a street with asphalt and concrete paving blocks. It should be noted that the study was carried out in the summer, when the interior of the building was not heated. The facade of the building had not been additionally insulated and retained its original historical form (facade render). The method used in the study consisted of temperature measurements taken near the building's walls using a Steinberg System weather station's sensors. The measurement results supported the hypothesis that wall temperature varies depending on a space's placement relative to the cardinal directions and the surface paving material in the space adjoining the building. The results of the study are presented using line graphs. The study is of scientific value and the results may also be useful in site development planning practice. The thermal conditions are a major factor that affecting the comfort of various types of buildings, including housing.

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Keywords: Thermal comfort; Location; Environmental conditions; Heritage building

Acronyms

PET – physiologically equivalent temperature

1 Introduction

Contemporary trends in architectural and urban design consider the importance of environmental conditions that directly affect the quality of urban areas. Environmental factors that remain in a relationship with architecture and urban solutions directly impact a space's comfort of use. A space's arrangement, the rational placement of objects with well-defined geometries, and the use of construction materials with specific properties, affects the space's microclimate by influencing external temperature, the hygiene of its cross-ventilation, and air humidity. Proving these relationships became the subject of this study, whose objective was to demonstrate that a space's arrangement, namely the use of specific paving materials, can affect the thermal comfort of buildings located adjacent to such a space. Here, it is key to define thermal comfort and its significance. Kowalewski, Kostecka, and Jezierski, citing Klemm [1] defined thermal comfort as a state of the environment in which the human body maintains thermal balance [2].

A spatial planning policy aimed at producing optimal conditions within urban spaces of different character and use should also consider the geometric parameters of external spaces and development density [3]. These phenomena, as noted by Galal, Mahmoud, and Sailor, among others, impact the thermal comfort of urban interiors. They also demonstrated that the way in which a space is arranged, including the use of specific paving surfaces, affects nearby buildings.

Mechanisms for reducing high temperature and its negative impact on the environment were discussed by Lai *et al.* [4]. They noted that changes in urban geometry, increasing the amount of vegetation, the use of cooling surfaces and the introduction of water features into the urban landscape can produce a more temperate urban microclimate. Importantly, the use of specific surfaces is not without significance here. Reflective surfaces lead to higher physiologically equivalent temperature (PET) values in summer. PET is a thermal index derived from the human energy balance. It is well suited to the evaluation of the thermal component of different climate [5].

The results of these observations are significant from the standpoint of spatial planning, and the arrangement of urban spaces and housing areas. This is due to the fact that greenery not only contributes to a place's aesthetic value, but also its microclimate conditions, including thermal determinants. Planners and designers who wish to create thermally comfortable urban spaces can take advantage of this [6].

This study showed that there are differences in temperature depending on the location of buildings next to paved or biologically vital surfaces. Thermal comfort is particularly important in residential buildings intended for permanent occupancy, as well as in street spaces (outside buildings) intended for pedestrians.

Although this research focused on determining temperature changes in a building, in the future it can be extended to analyses of urban interiors. This subject is discussed by Elnabawi *et al.* [7], who studied the temperature perception of users of city street spaces in the hot and dry climate of Cairo, Egypt. Preferences in terms of perceived temperature were rated using a survey from respondents. The analytical results showed that the temperature fluctuations ranged from 23°C to 32°C PET, while the preferred temperatures were 29°C PET in summer and 24.5°C PET in winter. These values are higher than those preferred in a temperate climate zone. It is important to note that how we experience temperature depends on many factors, including, but not limited to, our age, habits, and living conditions [8]. These feelings can therefore vary.

Although this issue is not the main subject that the authors explore in this study, it is directly connected to it. The choice of finishing materials, including paving surfaces, significantly affects thermal comfort. With regard to urban interiors, the degree of compactness of development and street canyon parameters are also undeniably important, as demonstrated by Chatzidimitriou and Yannas [9]. Proximity to natural elements also has an effect, as they affect an area's microclimate. The need to design and organise parks in urban spaces was explored by Lili Zhang *et al.* [10]. They pointed out that a park's outdoor thermal comfort is an important factor that can attract people to it and encourage them to stay. Using field meteorological monitoring and surveys, they investigated the outdoor thermal comfort of different types of landscape spaces in urban parks in Chengdu, China, in winter and summer.

The effects of rapid urbanisation, which resulted in a number of environmental problems in cities, were addressed by Ruirui Zhu *et al.* [11]. They stated that such problems include the disruption of thermal comfort and human health. City parks can improve this situation due to the cooling island effect that they produce. Urban parks were also investigated in the context of thermal and acoustic comfort by Negar Mohammadzadeh *et al.* [12]. They noted that the external thermal and acoustic environment are the main factors that influence the overall comfort of an urban space. In the study, they used measurements and surveys to investigate the influence of outdoor thermal comfort on acoustic comfort, with a focus on a plant community located in El Goli Park in Tabriz, Iran.

Although this study did not cover park spaces, it should be highlighted that the immediate vicinity of the building under study features a river and riverside green areas, in addition to an allotment garden complex and park-like cemetery vegetation.

Improving the thermal comfort of urban spaces was also the subject of a study by Mutani *et al.* [13], who saw it as one of the most important challenges that cities must address in the coming years. The aim of their study was to assess the impact of urban variables and to quantify the effect of vegetation on outdoor thermal comfort. Mutani *et al.* compared six neighbourhoods in Turin, Italy, that were characterised by different urban forms, contexts and green spaces. Their findings showed how external thermal comfort varies depending on urban form and greenery.

Zhang and Liu [14], on the other hand, used digital tools to analyse the external thermal comfort of buildings to improve the environment of urban residents. They developed a digital simulation system to facilitate the analysis for assessing the outdoor thermal comfort of buildings in urban neighbourhoods. They also explored whether digital simulation techniques can provide a modelling system for assessing the external thermal comfort of buildings in a continuous and efficient manner. Their findings showed that digital simulation techniques and tools can support the analysis of outdoor thermal comfort by providing 3D models, algorithm-based analysis and visual simulation.

Researchers whose scientific interests revolve around thermal comfort in cities often carry out their research in the centres and public spaces of cities located in hot climate zones, where any increase in temperature is highly perceptible. Such studies were conducted by Kurniati *et al.* [15] in Semarang, Indonesia, by Hirashima *et al.* [16] for Belo Horizonte, Brazil, by Huang *et al.* [17] for Taipei in Taiwan, and by Balogun and Daramola in Akure, Nigeria [18]. Among other things, these research teams identified the need to further develop public spaces to potentially accommodate environmental change.

A research gap between urban climatology and urban design in coastal temperate cities in developing countries was filled by Lamarca *et al.* [19], who studied thermal comfort in urban canyons located in the city of Concepción, Chile, using a multidisciplinary approach that combines morphological, climatic and perceptual factors.

A study of thermal comfort in open urban areas was, in turn, conducted by Vučković *et al.* [20]. They found that thermal comfort in open urban areas can influence medical, sociological, environmental and economic parameters. Therefore, there is a need to establish good thermal comfort in such areas to keep these parameters at an acceptable level.

An interesting aspect of thermal comfort was studied by Urban *et al.* [21], who noted that the external thermal comfort of urban residents is negatively affected by heat waves, which are becoming more frequent and more severe with the ongoing climate crisis. Consequently, assessing outdoor thermal perception and thermal comfort during heat waves has become an important component of successful urban adaptation strategies. The researchers considered an approach to assessing long-term thermal perception that combines features of current approaches (i.e., the use of thermal perception rating scales, the use of questionnaires and the use of photographs that depict sites) and presented a preliminary validation of this approach.

Another aspect of the outdoor comfort of urban residents was studied by Ma *et al.* [22], who analysed the temporal effect of urban morphological features on the thermal comfort of pedestrians in the street using the ENVI-met model. Their results showed that the presence of surrounding buildings could cause average PET values on pavements to fall by up to 6.7°C. Hourly PET values also varied significantly with the compactness of a neighbourhood, the height configuration of the surrounding buildings, their forms and architectural composition.

When discussing the state of research concerning the issue investigated, one cannot ignore the work of Lai *et al.* [23], who provided a comprehensive review of current (at the time of writing of this paper) research on outdoor thermal comfort, including benchmarks, data collection methods and models.

On the basis of the literature survey, it should be noted that there is a research gap regarding the influence that paving surfaces (in the urban spaces that constitute the immediate area of a building) may have on the thermal conditions in the direct proximity of a building's walls or inside it building. The hypothesis tested in this study was that the type of paving around a building can affect temperature. The research conducted by the authors was to not only test this hypothesis, but also to demonstrate the following:

- What are the differences in temperature values depending on the type of paving material used?
- What is the impact of biologically vital areas on thermal conditions?

The scope of the study area was therefore clearly delineated; it was not broad. The answers to the research questions listed add to the existing scope of knowledge, which demonstrates their relevance.

To date, research on thermal conditions has mainly been carried out in the public spaces of cities, located in specific climate zones. The literature cited in this study does not reference Polish conditions. In this regard, it is supplemented by a study by Lewińska [24], which is key from the standpoint of the subject under discussion.

This study considered the solutions in the building's vicinity – the use of different paving surfaces outside the building under study, in its immediate surroundings. The surroundings were an important context for the measurements. They consisted of residential development that formed a series of compact buildings and openings located westward of the building investigated. To the north of the building there was an open area. The main research problem was the necessity to take measurements at different times of day, including in the same timeframe. This required systematic analysis as well as constant observation. The problem was minimised by having the research tools continuously powered.

Before commencing with the analysis, it was realised that greenery had a significant impact on the microclimate of the surrounding area. However, the magnitude of the temperature difference near the walls was unknown due to the variety of the paving surfaces used near the building. The aim of the study was to demonstrate that a building's walls display temperature differences depending on their location (relative to the cardinal directions) and the type of paving surface material outside the building (grass lawn, concrete paving blocks and asphalt).

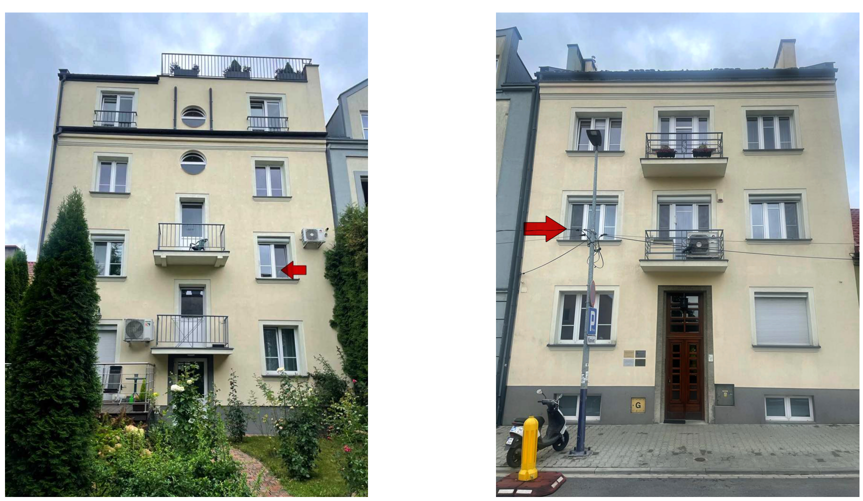
2 Research method

The adopted research objectives – to demonstrate the qualitative influence of the site surface next to a residential building on the temperature in the immediate vicinity of these walls (0.10 m distance), taking into account their exposure relative to the cardinal directions, and to demonstrate the influence of different weather conditions (sunny, cloudy sky, rainy) on temperature changes – required the use of temperature measurements as a research method. Steinberg System weather stations with indoor temperature monitoring screens [25] were used for this purpose. This ensured a high degree of accuracy in the measurements, although it should be noted that this was not required. The main objective was a qualitative rather than a quantitative analysis and to record trends in temperature changes and differences rather than specific temperature values.

The measurements were taken during the day and at night. Therefore, an additional parameter was recorded – brightness (dark, night). This was done as it was recognised that temperature in the immediate vicinity of a building affects a residential space's microclimate. The procedure was carried out in the year 2020 and involved measuring temperatures during the months between and including June and September. The intention behind the study was to conduct measurements during periods with different temperatures.

Measurements were taken throughout the entire day and night at three-hour intervals, using weather stations located outside the building, placed directly at windows on the south-east and north-west sides. The data from the weather stations was collected using a wireless Wi-Fi network with an accuracy of 0.5°C. The measurement sites were placed 0.10 m from the building wall (outside) and were at a height of 6 m from the ground.

The measurements were therefore taken at locations with different insolation conditions (Figs. 1a and 1b). In the vicinity of the building, the



(a) (b)

Figure 1: For caption see next page.

(c)

Figure 1: Study location: (a) garden-facing measurement site, (b) street-facing measurement site, (c) top view of the measurement site location (area: 558 m^2; building footprint: 125 m^2).

surfaces were formed by – on the south-eastern side (sunnier) – low (grass) and medium-height vegetation (conifers), and on the north-western side by a street with an asphalt surface and concrete paving blocks (Fig. 1c). The height of the measurement points above the ground surface was (6 m) due to the nature of the development (this was about 50% of the building's height).

3 Results and discussion

The results of the tests carried out in this study, which consisted of measuring the temperature at the walls of a residential building, were illustrated in graphical form after careful analysis. Series 1, as shown in the charts, includes measurements taken from the south-east, while Series 2 refers to measurements taken from the north-west. The results are shown in Figs. 2 through 8. They include distinct weather periods. One such period lasted four days. This meant 32 pairs of results in this specific measurement period. The remaining periods (6 in total) lasted a week Longer periods offered the opportunity to record greater variation in the weather and thus its impact on the measurements. One measurement period was then represented by 56 result pairs.

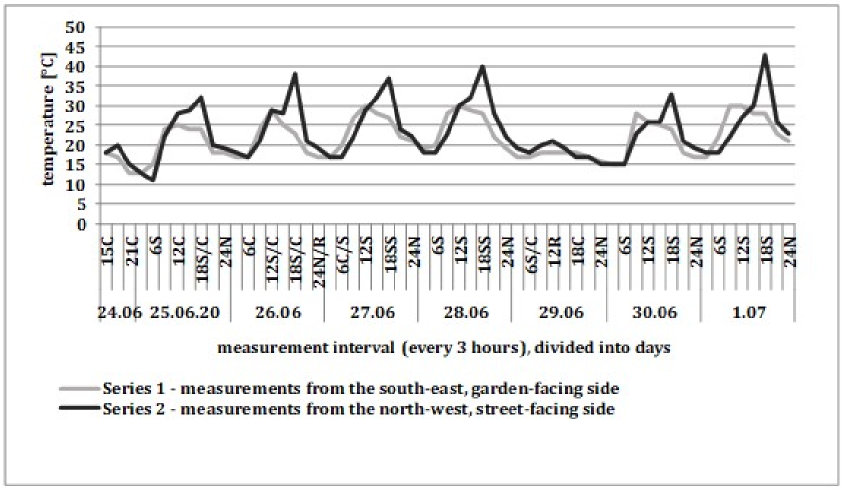


Figure 2: Measurement results for the period between 24 June and 1 July 2020.

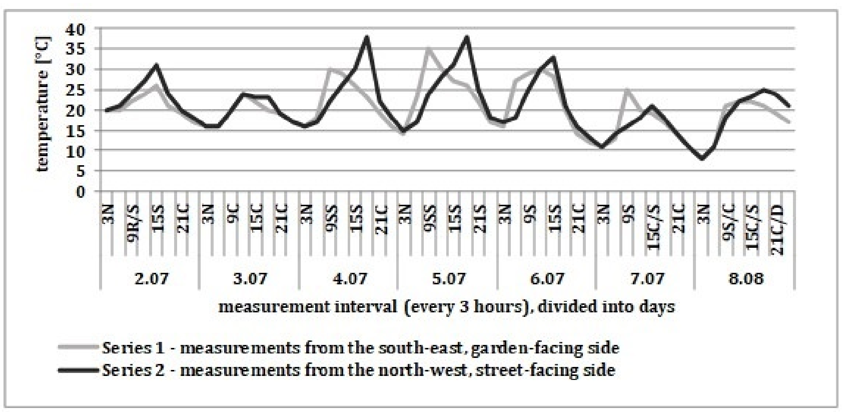


Figure 3: Measurement results for the period between 2 July and 8 July 2020.

The results of the measurements were singular, point readings in terms of duration. They have been presented – for better readability – in the form of jagged lines. The results of the measurements taken on the garden side are shown by the blue line and of those taken on the street side by the red line. The vertices of the lines indicate specific readings, taken every three hours, also during the night, which is indicated by the letter (N). Weather conditions were noted each time. Due to the scale of the drawings, this could not be suitably presented. S (sunny), C (cloudy), D (dusk) and

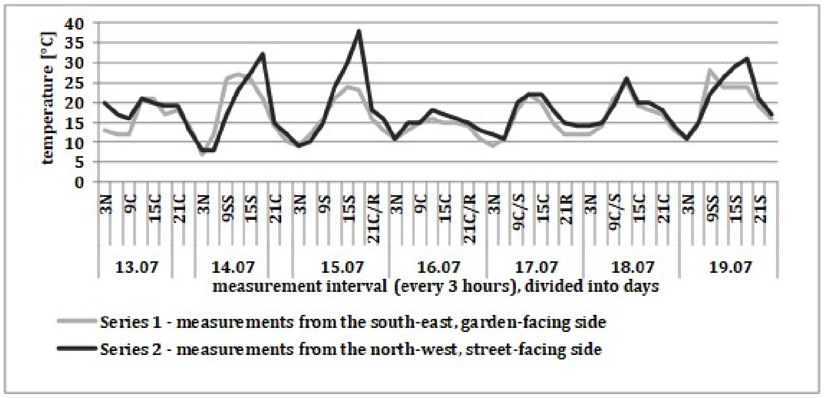


Figure 4: Measurement results for the period between 13 July and 19 July 2020.

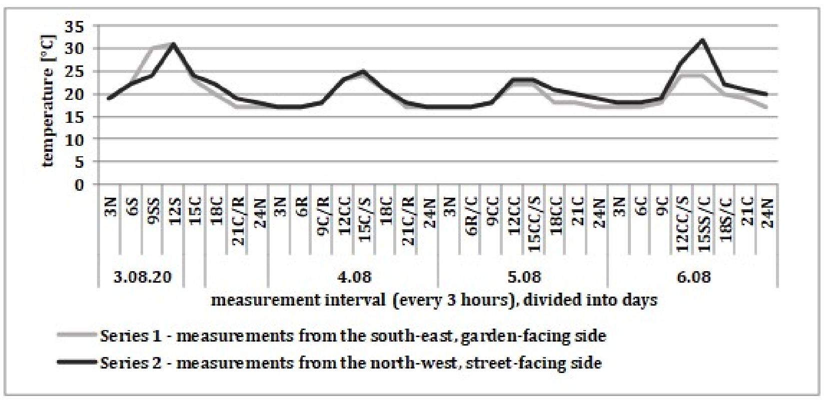


Figure 5: Measurement results for the period between 3 Aug. and 6 Aug. 2020.

N (night), and R (rainy) periods were included. The letters were doubled to indicate severe weather conditions. For example, a designation of (SS) was used for very intense insolation and (CC) was used for very cloudy periods. Three hours is not a long period, but enough for changes in weather to be observed. When the weather did change, a double weather condition marking was used. For example, if there was cloudy and sunny period, a C/S designation was used, with the letter indicating the weather condition that lasted longer being first. For example, the record 6R indicates that it began to rain during the sixth hour of measurement.

The tenement house in which the research was carried out is positioned so that exposure time throughout the day would be similar for both the

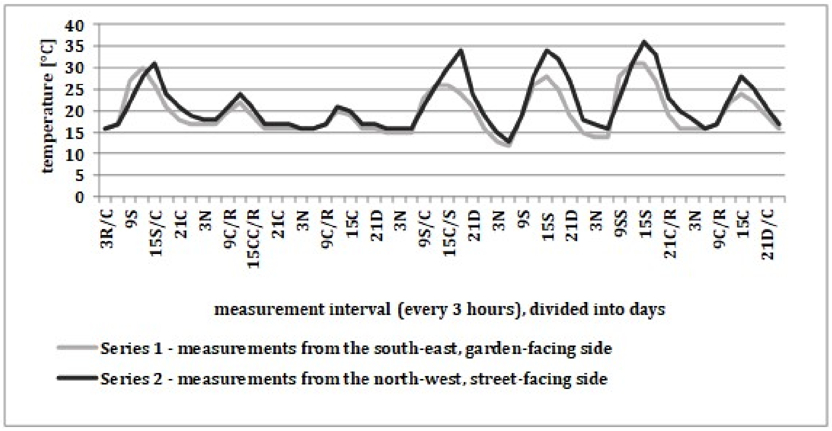


Figure 6: Measurement results for the period between 17 Aug. and 23 Aug. 2020.

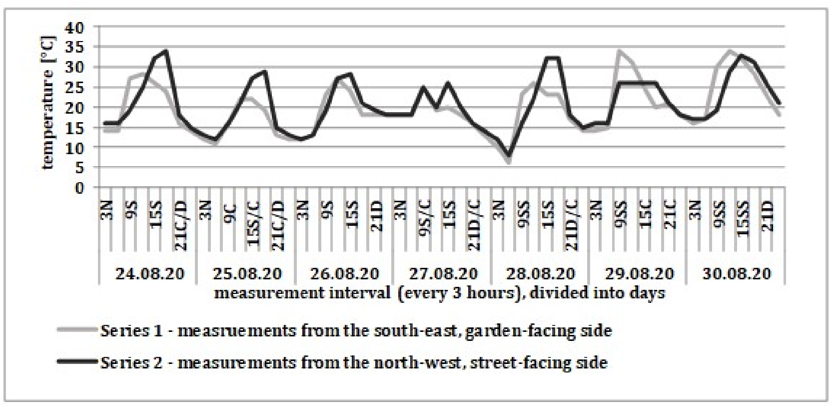


Figure 7: Measurement results for the period between 24 Aug. and 30 Sept. 2020.

garden-facing and street-facing side. Hence, the total heating and cooling times (from evening to morning) of the two walls were also similar. However, these effects, in the form of recorded temperature changes, were different.

The temperature at the wall from the garden-facing side (a lawn) decreased faster than that of the wall from the street-facing side (asphalt and concrete pavement). This is due to the higher proportion of heat emitted from the pavement on the street-facing side. The reported increase was mainly observed on sunny and bright days, with a clear predominance of sunny hours. On rainy and overcast days, the phenomenon was less pronounced.

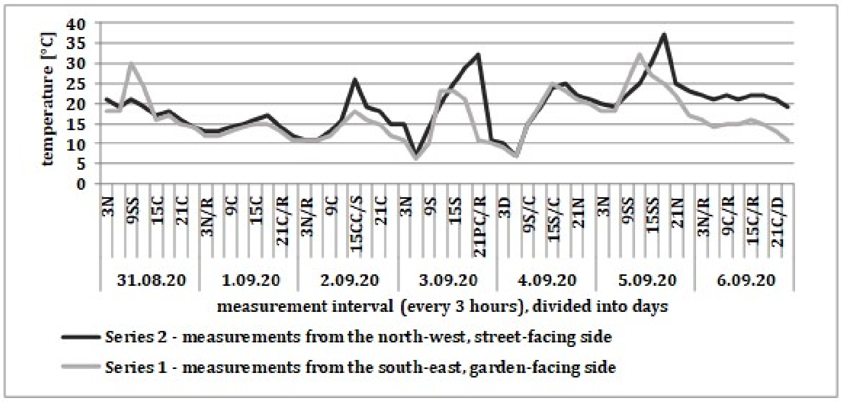


Figure 8: Measurement results for the period between 31 Aug. and 6 Sept. 2020.

Based on the detailed test results, the average temperature measured was higher at the garden-facing wall. Similarly, the average of the lowest daily temperature values and the average of the highest temperature values was also lower at the garden-facing wall. This further demonstrates the effect of the heat emitted from the asphalt and concrete pavement on the temperature at the wall on the street-facing side.

4 Final conclusions

This study demonstrates the significant impact of paving surface materials in the vicinity of a heritage building on the temperature of its external walls that were heated by sunlight. This is particularly important in the case of buildings with historical value, given the constraints on altering their structural systems and also in the choice of building materials, including insulation.

Based on an analysis of the measurements taken using Steinberg System weather stations, which were also equipped with indoor temperature monitoring screens, it can be concluded that the heat emission of the heated asphalt and concrete pavement – relative to the grassy surface – results in temperatures near the wall remaining higher for a longer period, as well as slower cooling. This regularity (property) is more pronounced the more sunny the weather (sunny or slightly cloudy days). It should be noted in this regard that the measurements were taken at a height of 6 m above the ground and not directly at ground surface level. Had they been taken at ground level, the regularities observed would have become even more pronounced.

Naturally, the temperature at the free-standing wall (masonry) on the garden-facing side was higher before midday, due to its south-east orientation, as well as the ground surface – a biologically vital area. In contrast, the temperature at the street-facing facade wall was higher in the afternoon (south-west orientation). What is important is that there was a greater temperature rise at the wall on the street-facing side and that the temperature remained high for longer. This was due to the accumulation of heat by asphalt. There was little difference between the garden-facing wall (gassy surface) and the street-facing wall (asphalt) on rainy and very cloudy days. The street and pavement surface would then heat up much less and thus emit much less heat. It was the cardinal directions that affected temperature changes the most during this time.

The analysis of the measured data made it possible to draw mainly qualitative conclusions and to identify trends regarding the influence of the paving on the temperature of the façade of a historic building (without thermal insulation) and its thermal comfort inside.

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References

[1] Klemm P.: *General Construction*. Arkady, Warszawa 2005 (in Polish).

[2] Kowalewski G., Kostecki I., Jezierski W.: *Assessment of thermal comfort in the single-family residential building after its thermal-modernisation*. Civ. Environ. Eng. **8**(2017), 2, 67–73 (in Polish).

[3] Galai O.M., Mahmoud H., Sailor D.: *Impact of evolving building morphology on microclimate in a hot arid climate*. Sustain. Cities Soc. **54**(2020), 102011. doi: 10.1016/j.scs.2019.102011

[4] Lai D., Liu W., Gan T., Liu K., Chen O.: *A review of mitigating strategies to improve the thermal environment and thermal comfort in urban outdoor spaces*. Sci. Total Environ. **661**(2019), 337–353. doi: 10.1016/j.scitotenv.2019.01.062

[5] Matzarakis A., Mayer H., Iziomon M.G.: *Applications of a universal thermal index: physiological equivalent temperature*. Int. J. Biometeorol. **43**(1999), 76–84.

[6] Huang T., Li J., Xie Y., Niu J., Ming Mak Ch.: *Simultaneous environmental parameter monitoring and human subject survey regarding outdoor thermal comfort and its modelling*. Build. Environ. **125**(2017), 502–514. doi: 10.1016/j.buildenv.2017.09.015

[7] Elnabawi M.H., Hamza N., Dudek S.: *Thermal perception of outdoor urban spaces in the hot arid region of Cairo, Egypt*. Sustain. Cities Soc. **22**(2016), 136–145. doi: 10.1016/j.scs.2016.02.005

[8] Amindeldar S., Heidari S., Khalili M.: *The effect of personal and microclimatic variables on outdoor thermal comfort: A field study in Tehran in cold season.* Sustain. Cities Soc. **32**(2017), 153–159. doi: 10.1016/j.scs.2017.03.024

[9] Chatzidimitriou A., Yannas S.: *Street canyon design and improvement potential for urban open spaces; the influence of canyon aspect ratio and orientation on microclimate and outdoor comfort.* Build. Environ. **38**(2017), 85–101. doi: 10.1016/j.scs.2017.05.019

[10] Zhang L., Wei D., Hou Y., Du J., Liu Z., Zhang G., Shi L.: *Outdoor thermal comfort of urban park — A case study.* Sustainability **12**(2020), 5, 1961. doi: 10.3390/su12051961

[11] Zhu R., Zhang X., Yang L., Liu Y., Cong Y., Gao W.: *Correlation analysis of thermal comfort and physiological responses under different microclimates of urban park.* Case Stud. Therm. Eng. **34**(2022), 102044. doi: 10.1016/j.csite.2022.102044

[12] Mohammadzadeh N., Karimi A., Brown R.D.: *The influence of outdoor thermal comfort on acoustic comfort of urban parks based on plant communities.* Build. Environ. **228**(2023), 109884. doi: 10.1016/j.buildenv.2022.109884

[13] Mutani G., Todeschi V., Beltramino S.: *Improving outdoor thermal comfort in built environment assessing the impact of urban form and vegetation.* Int. J. Heat Technol. **40**(2022), 1, 23–31. doi: 10.18280/ijht.400104

[14] Zhang Y., Liu Ch., *Digital simulation for buildings' outdoor thermal comfort in urban neighborhoods.* Buildings **11**(2021), 11, 541. doi: 10.3390/buildings11110541

[15] Kurniati R., Kurniawati W., Dewi D.I.K., Astuti M.F.K.: *Measurement of thermal comfort in urban public spaces Semarang, Indonesia.* Pertanika J. Sci. Technol. **29**(2021), 3, 1371–1395. doi: 10.47836/pjst.29.3.01

[16] Hirashima S.Q.D., Ferreira D.G., De Assis E.S.: *Thermal comfort description of urban structure types.* In: PLEA 2018: Smart and Healthy within the Two-Degree Limit (Proc. 34th Int. Conf. on Passive and Low Energy Architecture, Dec. 10–12, 2018) Vol. 3, 1105–1106. The Chinese University of Hong Kong, Hong Kong 2018.

[17] Huang Ch., Tsai H., Chen H.: *Influence of weather factors on thermal comfort in subtropical urban environments.* Sustainability **12**(2020), 5, 2001. doi: 10.3390/su12052001

[18] Balogun I.A., Toluwalase M.: *The outdoor thermal comfort assessment of different urban configurations within Akure City, Nigeria.* Urban Clim. **29**(2019), 100489. doi: 10.1016/j.uclim.2019.100489

[19] Lamarca C., Qüense J., Henríquez C.: *Thermal comfort and urban canyons morphology in coastal temperate climate, Concepción, Chile.* Urban Clim. **23**(2018), 159–172. doi: 10.1016/j.uclim.2016.10.004

[20] Vučković D., Jovic S., Bozovic R., Džamić V., Kićović D.: *Potential of neuro-fuzzy methodology for forecasting of outdoor thermal comfort index at urban open spaces.* Urban Clim. **28**(2019), 100467. doi: 10.1016/j.uclim.2019.100467

[21] Urban J., Pikl M., Zemek F., Novotny J.: *Using Google Street View photographs to assess long-term outdoor thermal perception and thermal comfort in the urban environment during heatwaves.* Front. Environ. Sci. **10**(2022), 878341. doi: 10.3389/fenvs.2022.878341

[22] Ma X., Leung T.M., Chau C.K., Yung E.H.K.: *Analyzing the influence of urban morphological features on pedestrian thermal comfort*. Urban Clim. **44**(2022), 101192. doi: 10.1016/j.uclim.2022.101192

[23] Lai D., Lian Zh., Liu W., Guo Ch., Liu W., Liu K., Chen Q.: *A comprehensive review of thermal comfort studies in urban open spaces*. Sci. Total Environ. **742**(2020), 140092. doi: 10.1016/j.scitotenv.2020.140092

[24] Lewińska J., *City climate. Threat, Resources, Shaping,* Instytut Gospodarki Przestrzennej i Komunalnej, Oddział w Krakowie, Kraków 2000 (in Polish).

[25] https://manuals.expondo.com/10030583 (accessed 18 June 2020).