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Waste-Based Concrete for Sustainable Urban Design: Energy and Comfort Benefits across Block Typologies

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Abstract: *Sustainable construction materials are essential for reducing the environmental impact of buildings and enhancing energy efficiency. While the thermal performance of waste-based materials is confirmed by previous studies, their implications at the urban scale remain limited. This study assesses the thermal comfort and energy efficiency of concrete blocks produced from construction waste across three representative urban block archetypes in hot climates. An empirically validated urban microclimate simulation model, supported by experimental field surveys, is used to compare waste-based materials with commercial alternatives. Findings show that using waste-based concrete reduces average mean radiant temperature (MRT) by 1.5 K. Average UTCI improved by 0.5 K in the case of closed court urban block archetype. Indoor cooling energy savings averaged 47%, with consistent reductions across all facades. These results demonstrate the potential of waste-based materials to significantly improve thermal comfort and energy efficiency by moderating heat fluctuations and regulating heat transfer, offering a low-cost sustainable strategy.*

Keywords: Energy efficiency; Sustainable building material; Outdoor thermal comfort; Thermal regulating materials.

1. INTRODUCTION

Waste-based construction materials are increasingly recognized as a key strategy to reduce the environmental impact of buildings [1]. A wide variety of waste streams are currently being explored to develop innovative, sustainable alternatives for different building construction elements. Among these elements, concrete blocks are particularly significant, as they form the core of opaque surfaces in the building envelope, directly influencing the thermal interaction between the building and its surrounding environment [2].

Studies have shown that altering conventional building envelope materials with sustainable, greener alternatives can lead to a reduction in embodied energy and carbon emissions in buildings by over 70% [3]. In addition to reducing environmental impact, recent studies highlight the importance of construction materials made from waste in achieving significant cost savings [4].

Over the past years construction waste from different source including concrete aggregates, glass, wood, fumed silica, and marble dust have been extensively used to fabricate novel construction materials [5]. Such materials are acknowledged for low-density thermal conductivity, which is sufficiently usable for building applications, thereby contributing to the conservation of natural resources and yielding financial savings in terms of construction costs [6]. When tested on a typical residential building, such blocks achieved a reduction in energy consumption of 21.86% for heating loads and 5.24% for cooling loads, compared to traditional concrete blocks. This thermal behavior advantage is consistent with other studies where the use of recycled material aggregates led to decreased thermal conductivity, particularly with increased replacement ratios, because of their greater pore volume, which complies with the relevant code standards [7].

One major concern in this area is the application scale, as most studies tend to assess the performance of waste-based materials at the single-building scale; either through experimental field surveys, numerical calculations or physics-based simulations.

On the other hand, previous research also acknowledged the importance of building façade materials in influencing outdoor thermal comfort on the urban scale [8]. For instance, Zhang, et al. [9] found that using high-albedo façade materials achieved lowering the Physiological Equivalent Temperature (PET) by up to 3.9 K in summer. Ascione, et al. [10], in their review, confirmed the importance of green walls added to building facades in enhancing outdoor thermal comfort. Báez-García, et al. [11] found that green walls can reduce outdoor Mean Radiant Temperature (MRT) by 2.7 K. Additionally, Yoshida, et al. [12] confirmed the effect of different thermal behavior of external wall materials on human sensation due to various outdoor radiation environments.

These findings highlight how wall building materials affect the urban scale. In this respect, the urban block form plays a crucial role in determining the extent of enhancement through building geometries and the layout of buildings in relation to each other [13].

Although the façade material effect is acknowledged at the urban block scale, previous studies on construction materials made from waste are limited to examining and testing performance at the single-building level and indoor energy efficiency without considering potential outdoor implications.

Hence, this study aims to bridge this gap by testing the performance of construction concrete blocks made from waste-based materials at the urban block scale. To provide a comprehensive understanding of the thermal performance implications, the study offers insights into the coupled thermal performance of the material in terms of both outdoor thermal comfort and indoor energy efficiency.

2. MATERIALS AND METHODS

The methodology of this study is outlined in Fig. 1. It begins with the modeling and characterization of the study area using climatic data from Borg El Arab, Alexandria, located at 30°51'57.94"N, 29°34'59.98"E. Urban block typologies were then identified and assigned. For the selected typologies, the study evaluates each block twice; once using traditional commercial concrete blocks, and again using concrete blocks manufactured from construction waste. The second phase involves the empirical validation of the simulation model through field measurements obtained from an on-site survey. Finally, the study conducts a coupled indoor–outdoor assessment, analyzing both energy demand and outdoor thermal comfort, to provide a comprehensive evaluation of the thermal performance of the two block types.

2.1 Urban Block Archetypes (UBA)

Since the urban block form is widely recognized as a vital controller of the thermal behavior of buildings, previous research has extensively addressed this area by offering insights into how changes in urban block configurations influence both indoor energy use and outdoor comfort [14]. For example, Jareemit, et al. [15] found that block form optimization can reduce energy use intensity varied by 58.4%, CO_2 emissions by 44.3% and solar energy production intensity spanned by 7.5%.

Block configuration includes a range of parameters such as built-up area, floor area ratio, average height, and sky view factor, each of which affects thermal performance differently [16]. Among the various typologies of urban blocks, previous research has highlighted the pavilion/dot pattern, slab, and closed courtyard as major typologies employed in different contexts and under varying climate conditions [17].

Hence, this study employs these three typologies as representative Urban Block Archetypes to test the performance of the waste-based material. Figure 1 shows the generic forms of the three block typologies.

2.2 Construction blocks material characterization

This study tests the performance of two distinct types of concrete construction blocks (see Fig. 3).

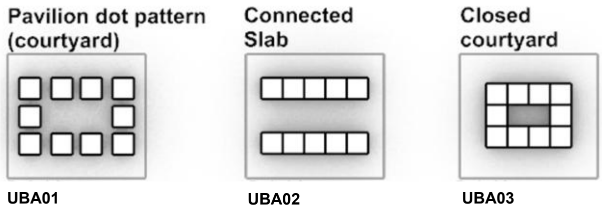

Fig. 1. Generic models of selected Urban Block Archetypes (UBA).

2.2.1 *Traditional Commercial Blocks*

These blocks represent the conventional concrete units commonly used in construction and manufactured in accordance with international standards. Their thermal and mechanical properties conform to the specifications provided by the Chartered Institution of Building Services Engineers (CIBSE). The mix design comprises standard raw materials cement, river sand, and gravel with no recycled or waste components included.

2.2.2 *Construction Waste-Based Cement Blocks (CWCB)*

These blocks were specifically engineered for this research and underwent extensive laboratory testing to evaluate both thermal and mechanical performance, following the methodology developed by Kuoribo, et al. [18].

As outlined in Table 1, CWCBs incorporate composite waste materials as substitutes for traditional raw ingredients. The substitutions include:

- Fumed silica and marble dust replacing cement,
- Fine wood and crushed glass replacing natural sand,
- Recycled concrete aggregates substituting coarse gravel.

These modifications result in a total replacement ratio of approximately 85%, representing a significant shift toward sustainable construction practices [7].

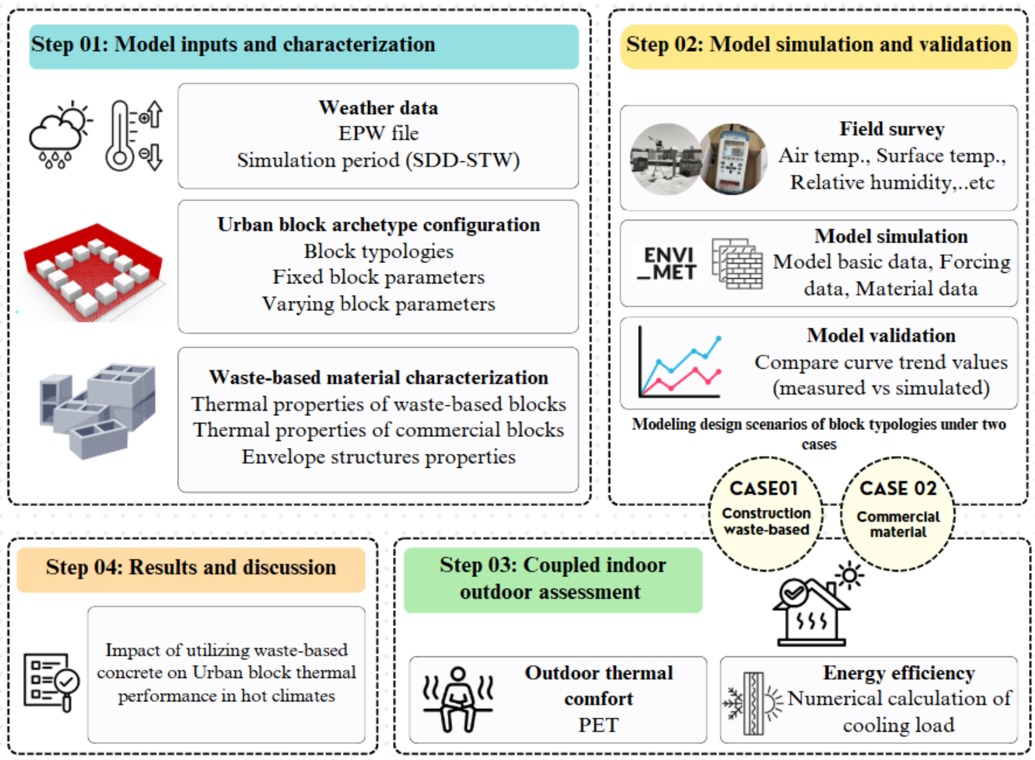

Fig. 2. Research Methodology.

Table 1. Specifications of two different types of construction blocks.

Density kg/m^3	**Open Pores** %	**Compressive strength** MPA	**Thermal conductivity** W/m.K
Commercial standard block			
2183	6.54	46.70	1.655
Construction waste block			
1684	11.11	13.75	0.723

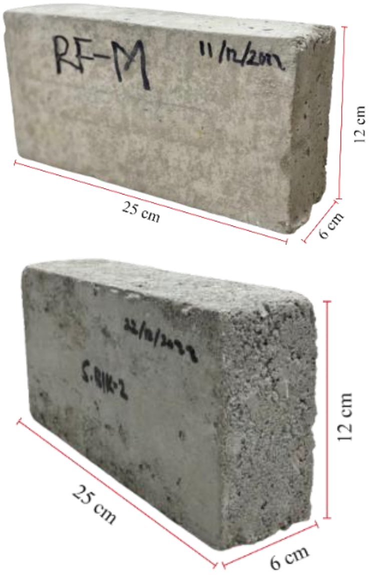

Fig. 3. Two identically sized concrete blocks constructed using a conventional commercial mix and a recycled construction waste mix.

2.2.3 Experimental evaluation of waste based concrete blocks

To evaluate the effect of waste-based concrete blocks on outdoor thermal performance, an empirical experimental setup was employed to estimate the specific heat capacity of the blocks. A key factor influencing the thermal performance of construction materials, especially in outdoor conditions, is the specific heat of the material mixture. Two scaled-down prototype rooms were constructed: one using typical commercial concrete blocks and the other using waste-based blocks. Both rooms were exposed to identical heat and solar radiation conditions. As a result, both types of blocks received the same amount of solar energy input. This allows the temperature difference between the inner and outer wall surfaces to be used as an indicator of the heat stored versus the heat transmitted through the material.

Given that the typical commercial concrete block has a known specific heat capacity of 840 J/kg·K, the specific heat capacity of the waste-based concrete blocks can be estimated by comparing the inner and outer surface temperature differences of the two rooms under these same test conditions. The estimation is carried out using the following formulas.

$$Q = mc\Delta T \qquad (Eq.\ 1)$$

$$c\_{waste} / c\_{typical} = \Delta T\_{typical} / \Delta T\_{waste} \qquad (Eq.\ 2)$$

Where:

(Q) *is Heat absorbed (J),* ***(m)*** *is Mass (kg),* ***(c)*** *is Specific heat capacity (J/kg·K)* ***(ΔT)*** *is Temperature difference (Tout-Tin) (K)*

2.3 Simulation model

To simulate the thermal environment, ENVI-met software was employed due to its demonstrated accuracy in prior research for modeling the microclimatic environment. The software is recognized for its capability to simulate three-dimensional air temperature, relative humidity, wind speed, and atmospheric pressure with high spatial resolution [19]. Additionally, ENVI-met is noted for its precision in calculating direct, diffuse, and reflected solar radiation, as well as building surface temperatures, all of which are critical parameters that directly influence both indoor energy consumption and outdoor thermal comfort [20].

The three urban block typologies were modeled at a high spatial resolution of 1×1×1 m to ensure geometric and environmental accuracy. To reflect the actual meteorological conditions of the study site, an. epw weather file for Borg El Arab, Alexandria was used as the environmental forcing data. The indoor setpoint temperature was set to 23 °C, aligning with the thermal comfort zone identified through psychrometric analysis of the region's typical climatic conditions.

The thermal properties of the two construction materials (typical concrete and recycled construction waste) were sourced from previous experimental and laboratory studies and applied as simulation inputs [21]. The simulation was conducted on August 21st, representing a typical summer day with an average air temperature of 30 °C and relative humidity of 71%. To ensure thermal equilibrium and robust output data, the simulation was run for a total duration of 30 hours, allowing the model to stabilize before extracting analytical results.

2.4 Model validation

This study incorporates experimental data collected over a 24-hour summer period to validate the corresponding ENVI-met simulation results. The setup involved monitoring air temperature and relative humidity at three distinct locations, which were accurately mirrored within the ENVI-met model to enhance validation accuracy.

All sensors were installed at a height of 2 meters above ground level, positioned on paved surfaces, and were properly shielded from direct solar radiation to prevent overheating and ensure representative ambient readings. Data collection was conducted on a weekend to minimize anthropogenic heat contributions, ensuring that the recorded values reflect only the environmental and material-specific thermal dynamics, without interference from human activity.

To evaluate the model's performance, measured on-site data were compared with outputs from ENVI-met receptor points. The results show that the simulation effectively captured the diurnal temperature trends, demonstrating strong alignment with observed values. the Root Mean Square Error was calculated according to the following formula:

$$RMSE = \sqrt{(1/n) \times \Sigma_i^n (S_i - O_i)^2} \qquad (Eq.\ 3)$$

Where:

(n) *is Number of data points,* ***(Si)*** *is Simulated value at time* ***(Oi)*** *is Observed (measured) value at same time*

As illustrated in Figure 4, the simulation demonstrated a strong correlation with the measured data, with R^2 values of 0.98, 0.99, and 0.94 for monitoring points P1, P2, and P3, respectively. The detailed validation results are provided in Table 2. The maximum deviation observed between simulated and measured temperatures was 1.5 °C, while the Root Mean Square Error (RMSE) ranged from 1.3 to 2.4 °C. These values indicate a strong agreement and reliable performance of the ENVI-met model in capturing the actual thermal conditions of the study area.

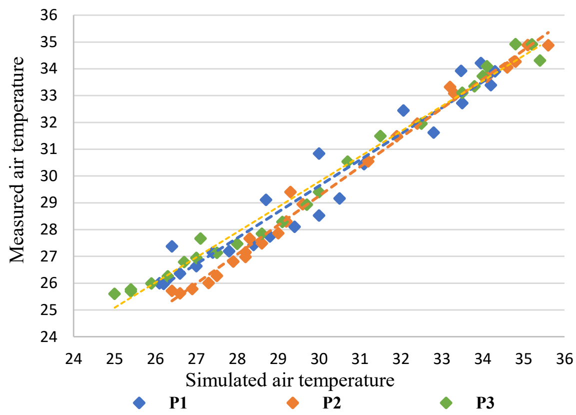

Fig. 4. Correlation between observed vs simulated air temperature in three recorded points.

Table 2. Validation of simulation model using three different points.

Point	RMSE	MSE	R2 (Obs. vs Sim.)
P1	1.3	0.23	0.98
P2	2.1	0.61	0.99
P3	2.4	0.52	0.94

2.5 Thermal performance metrics

By employing a physics-based approach that combines numerical calculations with Computational Fluid Dynamics (CFD) simulations, this study offers a comprehensive assessment of how different construction materials influence both outdoor thermal comfort and indoor energy demand. The analysis is conducted across various urban block archetypes, using established thermal performance metrics to evaluate environmental and energy impacts.

2.5.1 Outdoor thermal comfort calculations

Outdoor thermal comfort has been extensively examined in previous research, highlighting the critical influence of urban and building configurations on achieving thermal comfort in urban environments [22]. To evaluate and benchmark outdoor thermal comfort, several indices have been employed, including the Physiologically Equivalent Temperature (PET), the ASHRAE Standard Effective Temperature (SET*), and the Universal Thermal Climate Index (UTCI) [23].

While these indices differ in their calculation assumptions and model complexity, they generally account for a comprehensive set of parameters encompassing both human physiological factors and urban microclimatic conditions. These parameters typically include metabolic rate, clothing insulation, air temperature, radiant temperature, air velocity, and humidity all of which collectively influence the human thermal experience in outdoor urban areas [24].

Among various thermal comfort indices, the Universal Thermal Climate Index (UTCI) stands out as a significant and widely validated metric, endorsed by previous research for providing a reliable and comprehensive indication of human thermal comfort [25]. The UTCI reflects the equivalent air temperature under standardized reference conditions that would produce the same physiological response (core and skin temperature balance) as the actual environmental conditions [26].

The UTCI is calculated based on a complex model incorporating air temperature, wind speed, mean radiant temperature (MRT), and relative humidity. The index is defined by the following formula:

$$UTCI = T_a + a_0 + a_1 v + a_2 T_{mrt} + a_3 e + a_4 v^2 + a_5 T_{mrt}^2 + \dots \quad (Eq.\ 4)$$

Where:
(T_a) *is Air temperature (°C),* ***(T_{mrt})*** *is Mean radiant temperature (°C),* ***(v)*** *is Wind speed (m/s),* ***(e)*** *is Water vapor pressure (hPa)*

2.5.2 Indoor energy calculations

Indoor energy calculations considered the thermal transmittance (U-value) of the typical wall structure using the two tested materials. The analysis accounted for the wall surface temperature, the indoor setpoint temperature (obtained from ENI-met simulation), and the percentage of glass façade, multiplied by the solar heat gain coefficient (SHGC), which was set to 0.49, representing a single-layer 5 mm blue glass window (see Eq. 3 and 4).

$$Q\_cooling = U \times A \times |T\_out - T\_in| \quad (Eq.\ 5)$$

$$Q\_solar = SHGC \times A\_glass \times I \quad (Eq.\ 6)$$

Where:
(Q_cooling) *is the cooling load in Watts (W),* ***(U)*** *is the thermal transmittance or U-value of the facade (W/m²·K),* ***(A)*** *is the surface area of the facade (m²) *,* ***(T_out - T_in)*** *is the absolute temperature difference between outside and inside.*

(Q_solar) *Solar heat gain (Watts),* ***(SHGC)*** *is dimensionless Solar Heat Gain Coefficient,* ***(A_glass)*** *Glazed area of the facade (m²),* ***(I)*** *Incident solar radiation (W/m²).*
**Each surface (NORTH, EAST, SOUTH, WEST, ROOF) is evaluated individually, and their contributions are summed to determine the total cooling requirement for the building.*

3. RESULTS AND DISCUSSION

3.1 Indoor energy efficiency

Comparing energy performance metrics between the two materials provides evidence advancing the use of waste concrete blocks over typical concrete blocks in terms of energy efficiency as shown in Fig.6. Across all façade orientations, North, South, East, and West—the total 24-hour energy load was significantly reduced when waste concrete was employed. For example, the South façade demonstrated a reduction from 39,739 Wh with typical blocks to 21,144 Wh with waste blocks, resulting in a 46.79% decrease. Comparable reductions were observed in other orientations: the North dropped from 37,906 Wh to 20,068 Wh (47.07% savings), the East from 38,616 Wh to 20,444 Wh (47.06%), and the West from 38,676 Wh to 20,531 Wh (46.92%). These improvements stem from the enhanced thermal insulation of waste concrete, characterized by a lower U-value of 0.9 W/m²·K compared to 1.7 W/m²·K for typical blocks. This lower

U-value effectively minimizes thermal transmission through the building envelope, especially during periods when outdoor temperatures exceed the indoor setpoint of 23°C. The result is a reduction in heat flux, leading to improved thermal comfort and decreased energy demand for cooling systems. The consistent ~47% savings across all facades underscore the substantial benefits of incorporating waste concrete blocks into modern building design—not only for their environmental merit through material reuse but also for their measurable impact on reducing cooling energy consumption and long-term operational costs.

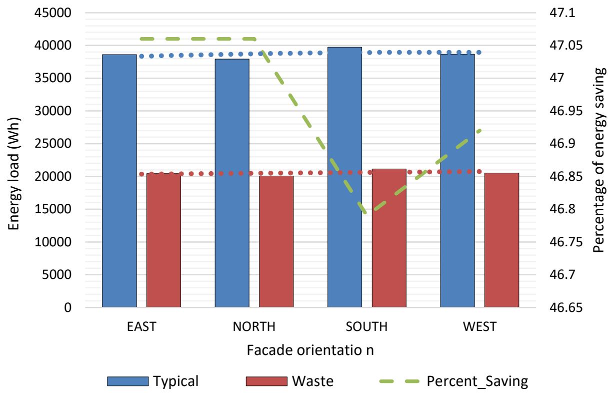

Fig. 5. Reduced energy load by facade and construction material.

In addition to the significant energy savings observed across individual façade orientations, Figure 7 highlights the absolute difference in calculated energy loads at the block scale, further emphasizing the broader impact of material choice. Notably, the use of waste concrete blocks led to substantial reductions in minimum energy loads across all three tested urban block configurations. For instance, in dot pattern pavilion block, the minimum energy load decreased from 1,569 W (typical) to 376 W (waste). In the slab block, it dropped from 960 W to 230 W, and in the closed court block, it declined from 320 W to just 96 W. These reductions occurred with varying percentages across different buildings, reflecting their relative positions within the block and their exposure to environmental conditions. This variability highlights the critical role of urban block form, including building arrangement, orientation, and surrounding structures—in modulating thermal performance. In essence, the synergy between material selection and urban morphology plays a pivotal role in maximizing energy efficiency, underscoring the need to integrate both factors in sustainable architectural and urban design strategies.

3.2 Outdoor thermal comfort effect

The thermal characteristics of the developed material allowed for effective manipulation of the heat budget and distribution across both outdoor and indoor environments. Functioning as a passive energy system, near to vertical green facades, the material offers additional advantages, eliminating the need for irrigation and contributing to the circular economy by incorporating waste-derived components, thereby reducing overall material waste

The results indicate that the specific heat of waste-based concrete blocks is 1930 J/kg·K, reflecting their ability to absorb significant heat energy with minimal temperature increase. In contrast, typical concrete blocks have a specific heat of approximately 840 J/kg·K, which is about 56.48% lower than that of the waste-based blocks. To evaluate the outdoor thermal comfort implications of using this material, the closed court urban block archetype was selected as a representative test environment. When comparing outdoor thermal comfort, the waste-based block consistently exhibits lower UTCI values than the typical block during the hottest hours, indicating improved thermal performance. However, between 06:00 and 19:00, particularly during peak solar hours from 09:00 to 16:00—both block types show minimal differences in UTCI, suggesting that intense solar radiation dominates and diminishes the effect of material-specific thermal properties during this period. At night, the typical block retains more heat, resulting in higher UTCI values compared to the waste block—an indication of greater thermal mass or slower heat dissipation. On average, the UTCI difference between the two blocks was recorded at 0.5 K. To contextualize these results, they were benchmarked against studies on vertical greening systems, which demonstrate cooling effects ranging from 0.2 K to 6 K [27, 28]. This comparison highlights the promise of waste-based concrete as a sustainable and low-maintenance alternative, offering meaningful thermal comfort improvement without the cost, water use, or upkeep required by green wall systems.

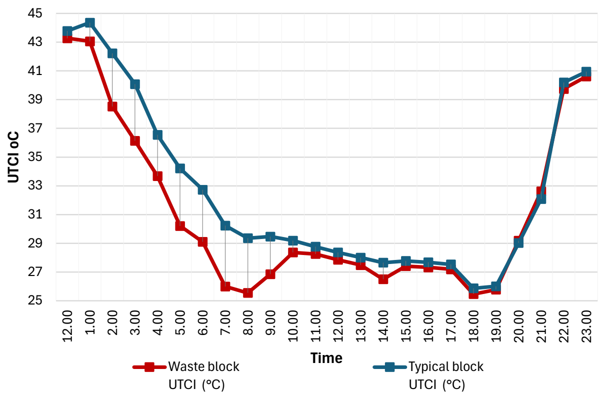

Fig. 6. Comparing UTCI over 24 hours period using waste vs typical concrete blocks.

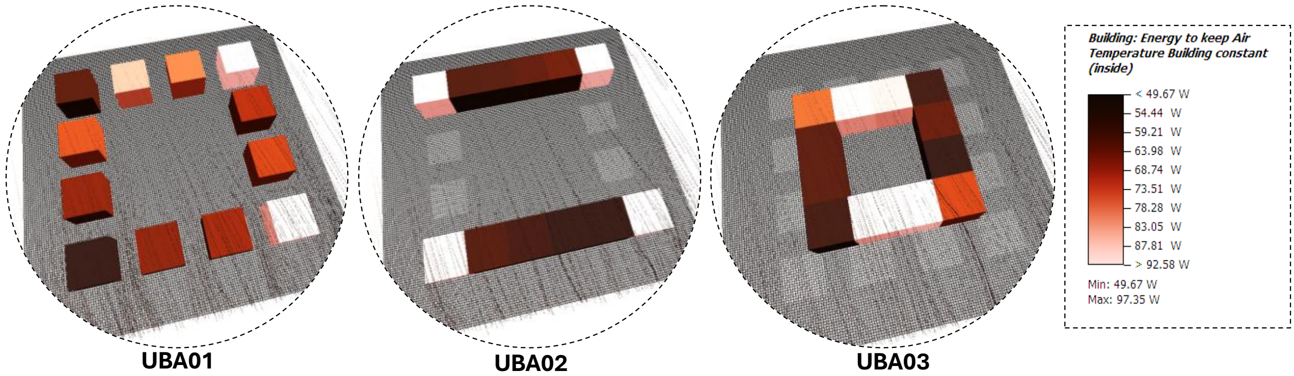

Fig. 7. Absolute differences in energy loads for three urban block archetypes.

An examination of mean radiant temperature (MRT) for the closed court urban block at 14:00 revealed a temperature difference of 1.5 K between the two materials (see Fig. 8), with the waste-based concrete resulting in lower MRT. This reduction directly contributes to enhanced outdoor thermal comfort. Although the urban blocks maintain identical built-up area, floor area ratio, and average height, they exhibit distinct thermal outcomes due to variations in sky view factor (SVF) and height-to-width (H/W) ratios. These morphological characteristics significantly influence how construction materials interact with the urban microclimate. A detailed analysis confirms that the effectiveness of construction materials on outdoor thermal comfort is strongly dependent on block configuration, underscoring the close relationship between urban form and thermal performance. As shown in Fig. 5(a), the court block demonstrates notable spatial variation: internal courtyard areas with SVF values below 0.7 exhibit greater sensitivity to material differences, while outer zones with higher sky exposure show minimal thermal variation between materials. This illustrates how urban geometry, sky openness, and spatial adjacency modulate the impact of materials on thermal comfort, making urban morphology a critical factor in passive climate-responsive design strategies.

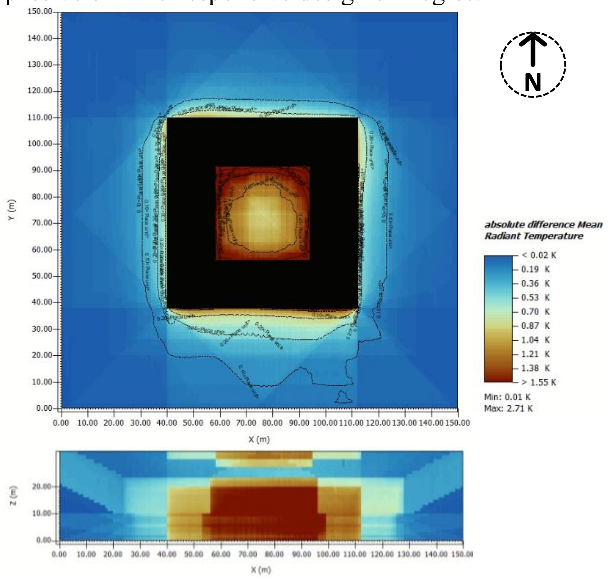

Fig. 8. Absolute differences in MRT in pavilion dot pattern block archetype.

4. CONCLUSION

This research demonstrates the substantial advantages of utilizing waste concrete blocks over conventional concrete blocks with respect to both energy efficiency and outdoor thermal comfort. These findings demonstrate the potential of waste-based materials to significantly improve thermal comfort and energy efficiency by moderating heat fluctuations and regulating heat transfer. The comparative assessment of typical and waste-based concrete blocks across thermal comfort and energy efficiency dimensions reveals the clear superiority of waste concrete as a sustainable construction material. With a specific heat of 1930 J/kg·K, which is 56.48% higher than that of conventional blocks, the waste-based concrete demonstrates enhanced heat storage capacity and slower temperature rise—qualities that translate into tangible improvements in both outdoor and indoor thermal environments. In urban simulations, particularly within a closed court block configuration, the waste concrete led to consistently lower UTCI values during peak thermal stress periods, reducing heat retention and improving nighttime comfort by an average of 0.5 K.In terms of energy performance, the benefits are equally pronounced. Energy load analysis across all façade orientations—North, South, East, and West—shows a remarkable reduction of approximately 47% in cooling energy demand when using waste-based blocks, primarily attributed to their lower U-value of 0.9 W/m²·K, compared to 1.7 W/m²·K for typical blocks. These savings were reinforced at the urban block scale, where waste concrete blocks significantly lowered minimum energy loads in all tested configurations. For instance, in the dot pattern pavilion, energy load dropped from 1,569 W to 376 W; in the slab block, from 960 W to 230 W; and in the closed court block, from 320 W to 96 W. These variations underscore the critical role of urban morphology—including block form, building arrangement, and exposure—in modulating the effectiveness of material-based interventions. Furthermore, the material's passive thermal regulation characteristics are comparable to those of vertical green façades, yet without the associated requirements for irrigation or maintenance. This positions waste-based concrete as a highly effective, circular-economy-aligned solution, offering both environmental and performance advantages. Its integration into architectural and urban design not only supports energy-efficient development but also reinforces broader goals of sustainable urbanism by reducing material waste, improving microclimates, and lowering long-term operational costs.

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