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Energy Performance of a High-Rise Residential Building Using Fibre-Reinforced Structural Lightweight Aggregate Concrete

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Abstract: The increasing need for eco-friendly green building and creative passive design technology in response to climatic change and global warming issues will continue. However, the need to preserve and sustain the natural environment is also crucial. A building envelope plays a pivotal role in areas where the greatest heat and energy loss often occur. Investment for the passive design aspect of building envelopes is essential to address CO_2 emission. This research aims to explore the suitability of using integral-monolithic structural insulation fibre-reinforced lightweight aggregate concrete (LWAC) without additional insulation as a building envelope material in a high-rise residential building in the different climatic zones of the world. Polypropylene and steel fibres in different dosages were used in a structural grade expanded clay lightweight aggregate concrete. Physical and thermal properties of fibre reinforced structural LWAC, normal weight concrete (NWC) and bricks were measured in the lab. The Autodesk@Revit-GBS simulation program was implemented to simulate the energy consumption of a 29-storey residential building with shear wall structural system using the proposed fibre-reinforced LWAC materials. Results showed that energy savings between 3.2% and 14.8% were incurred in buildings using the fibre-reinforced LWAC across various climatic regions as compared with traditional NWC and sand-cement brick and clay brick walls. In conclusion, fibre-reinforced LWAC in hot-humid tropical and temperate Mediterranean climates meet the certified Green Building Index (GBI) requirements of less than 150 $kW{\cdot}h{\cdot}m^{-2}$. However, in extreme climatic conditions of sub-arctic and hot semi-arid desert climates, a thicker wall or additional insulation is required to meet the certified green building requirements. Hence, the energy-saving measure is influenced largely by the use of fibre-reinforced LWAC as a building envelope material rather than because of building orientation.

Keywords: lightweight aggregate concrete; lightweight expanded clay aggregate; steel fibre; polypropylene fibre; hybrid fibre; thermal conductivity; thermal mass; building energy simulation; energy performance; energy cost-saving

1. Introduction

Three-quarters of the total energy consumption in the building sector is residential, where great potential to improve energy efficiency exists [1]. The buildings consume about 40% of the overall energy demand worldwide and are responsible for carbon emissions [2]. In the US, the energy consumption for the residential sector surpasses the commercial sector, as reported in 2017 by the US Department of Energy [3], with both accounting to 38.9% of the total energy consumption. Among all sectors, the residential sector plays a pivotal role in global energy demand. The percentage of total residential consumption in different regions of the world fluctuates from an average of 20% in developed countries to more than 35% in developing countries [4]. Residential energy demand is prominent because of its present size and potential growth [5]. In developed countries, the energy consumption for the residential and commercial sectors has increased steadily, reaching between 20% and 40%, respectively, and has exceeded other major sectors, namely the industrial and transportation sectors [6].

In cities with developed economies, space heating is provided through oil- or gas-fired boiler plants and space cooling relies mainly on electricity [7]. As cooling loads increase due to global warming, a shift towards electrical power will also occur. A building envelope refers to the external portions or skin of a building where heat or thermal energy is transferred and governs the interior comfort level and energy usage of the building space as defined by the Malaysian Standard MS 2680:2014 [8]. Building envelope components as mentioned by Mirrahimi et al. [9] are the most important feature that can maximize energy efficiency and reduce energy consumption for a building because the envelope is where the largest heat loss or gain occurs.

A study published by the US Department of Energy [2] showed that 73% of the total heat/gain loss is contributed by the building envelope. In the United States, the building sector accounted for about 41% of primary energy consumption in 2010, 44% more than the transportation sector and 36% more than the industrial sector. Space heating, space cooling and lighting were the dominant end uses in 2010, accounting for close to 70% of site energy consumption. In the past decades, efforts have been made to reduce CO_2 emissions through energy conversation and efficient measures. The finite availability of fossil fuels and the highly transient nature of renewable energy sources have enhanced significant energy efficiency and conservation in various sectors. The top four energy consumption in residential and commercial buildings are space heating, space cooling, water heating and lighting, all of which accounted for approximately 70% of site consumption. Other end uses such as appliances and ventilation make up the remaining 30% [10].

Lightweight aggregate concrete (LWAC) has good thermal properties. However, its mechanical properties are generally diminished with an increase in thermal efficiency. Mitigating this problem with the use of mono and hybrid fibres in LWAC is crucial if LWAC is used successfully as an integral structural insulation concrete in the building industry. Real et al. [11] found that structural LWAC contributes positively to increasing energy efficiency by improving the thermal comfort in European countries regardless of the diverse outdoor conditions. Heating energy needs is 15% lower for LWAC as compared with normal weight concrete (NWC), while cooling energy needs do not experience significant variations in the type of concrete in Europe. Hence, designing a building envelope using LWAC would make a significant contribution to energy savings.

The brittleness behaviour of structural LWAC is a weakness of this type of concrete. Fibre is added to the concrete mix to overcome this drawback. A review on literature indicated the lack of studies on the thermal performance of fibre-reinforced LWAC and limited data on the thermal properties of these types of concrete are available. Therefore, further studies are needed to evaluate the effects of using different types of concrete on the energy consumption of buildings in various climatic regions of the world [12].

This research aims to explore the suitability of an integral–monolithic structural insulation fibre-reinforced LWAC without additional insulation to be used as a building envelope material that meets the structural code requirements and energy-certified high-rise residential buildings in different climatic zones of the world.

2. Literature Review and Background Studies

2.1. Fibre-Reinforced LWAC as a Structural Insulation Building Envelope Material

Asadi et al. [12] concluded that using lightweight concrete in a building envelope is an important approach in reducing the amount of heat transfer and energy consumption because of the low thermal conductivity of lightweight concrete compared to NWC. Real et al. [11] discovered that heating energy needs are 15% lower for LWAC as compared with NWC in Europe. Thus, designing a building envelope that uses LWAC could have a significant contribution to energy savings. The thermo-physical properties of a building envelope play a critical role in the thermal comfort and energy performance of buildings [13].

Ma and Wang [14] reported that the specific heat capacity for NWC is 790–960 $J{\cdot}kg^{-1}{\cdot}K^{-1}$, while for structural LWAC ranges from 920–1000 $J{\cdot}kg^{-1}{\cdot}K^{-1}$. LWAC has higher thermal mass capacity than NWC. Real et al. [15] studied LWAC without fibre and had thermal conductivity ranging from 0.94–1.21 $W{\cdot}m^{-1}{\cdot}K^{-1}$, a specific heat range from 932–1000 $J{\cdot}kg^{-1}{\cdot}K^{-1}$ and a thermal diffusivity range of 0.62–0.73 $mm^2{\cdot}s^{-1}$. Nagy et al. [16] concluded that increasing the steel (ST) fibre does not increase necessarily the thermal conductivity because of an increase in porosity. However, limited studies on thermal and mechanical properties of LWAC with fibres have been conducted to allow for conclusive results.

Gül et al. [17] studied the thermo-mechanical properties of steel and PP fibre-reinforced lightweight expanded clay aggregate (LECA)-LWAC. The addition of ST fibre will increase its mechanical strength and worsen the thermal conductivity while the polypropylene (PP) fibre has opposite effects. Grabois et al. [18] determined that steel fibre at high dosage will decrease its mechanical strength and increase the thermal conductivity k-value.

2.2. Energy Saving Measures of the Building Envelope

The performance and efficiency of different passive techniques have been investigated by many researchers, such as [13,19–21]. Their findings concluded that the thermophysical properties of a building envelope are the most crucial factor affecting energy conservation and indoor thermal comfort. The effects of six passive design strategies, namely insulation, thermal mass, glazing type, window size, colour of the external wall and external shading devices, on the annual cooling energy and peak cooling load on a high-rise apartment building in Hong Kong were investigated by Cheung et al. [19] using the Transient System Simulation Tool (TRNSYS) energy simulation software. The results showed a saving of 31.4% in cooling energy annually and 36.8% in the peak cooling load. Sadineni et al. [20] published a technical review paper on several building components that can be used in a building envelope in terms of their efficiency and energy-saving performance. The reduction in U-value over the years emphasizes the significance of the thermal performance of roofs and walls in the effort to increase the overall thermal performance of buildings. A study found that residential buildings facing a North-South orientation in Malaysia was the most optimum for energy savings because the wall elements do not have any wall insulation [22].

Energy-saving measures of a building envelope in a hot-humid climate were studied by Mirrahimi et al. [9], who reported that optimisation of the orientation reduces energy consumption by 10%, thermally insulated walls reduce annual cooling energy by 20%, high thermal mass is often not as comfortable as low mass insulated roofs, double glazing glass reduces cooling energy by 19% as compared to single clear glass, and external shading of 0.6 m provides a cooling load saving of 5.85–7.06%. Bano and Sehgal [23] have analysed energy performance of six conventional office buildings located at Lucknow, India. Their analysis revealed that a building located in this city should have North-South orientation. They found that among these buildings, a building with North-South orientation had the lowest energy consumption despite having a high window-to-wall ratio and being fully air-conditioned.

An extensive review of factors affecting the heat storage of concrete as a thermal mass to reduce the energy consumptions in the building has been reported by Shafigh et al. [24]. The low value of thermal conductivity is desirable because of the associated ability to provide thermal insulation [25]. An evaluation of the thermal performance of the walls using heat flux time lag and heat flux decrement factor was conducted by Jin et al. [26]. These parameters have a direct effect on the thermal performances of walls and considerably influence the energy consumption and thermal comfort of a room. In general, higher time lag and lower decrement factor are preferable because of their good thermal performance in tropical regions to minimize energy consumption.

Yunsheng and Chung [27] found that the high value of a specific heat is desirable to stabilise fluctuating room temperature and provide thermal lag. The low value of thermal conductivity is desirable to provide thermal insulation. Fathipour and Hadidi [28] concluded that the thickness and type of material have a significant effect on the time lag and decrement factor of a building wall envelope. Roberz et al. [29] determined that a building with high thermal mass affects the dynamic thermal characteristics by the shifting and reduction of peak load, that is, its time lag and decrement factor.

Ramponi et al. [30] reported that the effective use of thermal mass plays a critical role in many design concepts for energy-conscious sustainable buildings and found that night-time ventilation strategies (i.e., night purge) have a major effect on the effectiveness of thermal mass in buildings. High thermal mass will lead to high radiant temperatures in winter and a reduced risk of indoor overheating in summer [31].

Chiraratananon and Hien [32] concluded that low thermal mass is more effective in passive cooling and economical in hot-humid tropical climates. Roberz et al. [29] reported that concluding on the effectiveness of high or low effective thermal mass in energy savings is not possible, especially in the case of cool and moderate climate zones. Al-Sanea and Zedan [33] found that selection is always case-specific and depends on many interrelated factors, such as weather conditions, occupancy patterns, internal heat gains, heating, ventilation, and air conditioning (HVAC) type, building orientation, fenestration and shading system. Hoes et al. [34] reported on the virtual impossibility of selecting an appropriate thermal mass that performs the optimal warm-up behaviour, overheating risk and overall energy saving simultaneously.

2.3. Energy Simulation Programs in Buildings

Building energy simulation software plays an integral role in the choice of the best energy efficiency measures for a given geographic location [20].

Building energy simulation programs (BESP) are an important tool for analysing and predicting the thermal performance and energy consumption of buildings to meet the building energy efficiency design and green building energy ratings.

An overview report by Crawley et al. [35] provided the features and contrasting capabilities of twenty major BESP, offering users key performance indicators such as energy use and demand, temperature, humidity and costs. Energy modelling has been used increasingly to strategize the specific design decisions that affect energy consumption of buildings.

Among the widely used open-source freeware BESP are eQuest, Energy Plus and cloud computing under BIM Autodesk@Revit-GBS. These freeware have their roots in the DOE-2 model. eQuest is an easy-to-use building energy use analysis tool but its input data are not graphically user-friendly and its unit is still based on imperial. EnergyPlus is a modular, structured code based on the features and capabilities of Building Loads Analysis and System Thermodynamics (BLAST) and DOE-2. The simulation module, which has a variable time step, calculates heating and cooling loads and plant and electrical system response [35].

Autodesk integrated its energy application tools (Revit, Vasari, GBS-DOE2) seamlessly in the BIM environment into one called Insight 360, where energy modelling is carried out in Revit and the energy simulation energy analysis under GBS—DOE-2 [36].

Andjelkovic et al. [37] reported on the effects of thermal mass on energy use and found that thermal comfort requires suitable energy simulation software with the following features:

(1) 3D-building geometry input to define surface areas and orientations to evaluate thermal mass behaviour.
(2) The ability to calculate surface, radiant and air temperatures, humidity, wind and buoyancy air movement, thermal storage, inter-zone conduction, convection and radiation.
(3) Hourly space heating and cooling load and energy balance calculations conducted with hourly weather data.

Autodesk@GBS was chosen because of its ease in generating 3D building geometry inputs for its building elements and conceptual mass in Revit, which can be converted into 3D energy modelling for the energy simulation compared with other energy simulation programs.

Autodesk@GBS offers easy interoperability with BIM tools and other software. It offers great interoperability with Autodesk Revit, ArchiCad, Ecotect, eQuest, and EnergyPlus [38]. Autodesk@GBS has the highest score as compared to Integrated Environmental Solutions Virtual Environment (IESVE) and Ecotect in terms of interoperability, usability and speed [39]. Autodesk@GBS is used to quantify the predicted energy savings against actual baseline energy loads of an envelope retrofit on a university dormitory. The validation study showed GBS prediction on electricity is 96%, at par with eQUEST (98%) and better than IESVE (72%) [40]. Autodesk@GBS has been used in scientific research since 2013 and validated with the actual energy use.

2.4. Research Contributions

The main research contribution of this paper is its production of an integral monolithic structural-insulation, fibre-reinforced LWAC without additional insulation as a building envelope material for energy certified buildings.

From the literature review conducted in Section 2, limited studies on the energy consumption and cost savings of fibre-reinforced LECA-LWAC as an integral structural-insulation building envelope material have been carried out. To address this gap, the present paper aims to provide simulation results considering the two main objectives listed below:

(1) Determine the energy use intensity (EUI) and energy cost savings of mono and hybrid fibre-reinforced LECA-LWAC as an integral structural insulation material as compared to NWC as a building envelope for energy-certified high-rise residential buildings.
(2) Investigate the robustness of the proposed fibre-reinforced LECA-LWAC on energy performance in adverse climatic zones and building orientation.

3. Research Method

The summary of the research method can be found in the energy simulation research framework for the fibre-reinforced LECA-LWAC, as described in Figure 1.

The experimental data of the physical and mechanical tests of fibre-reinforced LWAC were carried out following relevant European (EN) and American Society for Testing and Materials (ASTM) standards while the thermal test was based on the ASTM C518 [41] standard for thermal conductivity and ASTM C1784 [42] for volumetric specific heat measurement using the Fox 50 Heat Flow Meter (HFM) equipment.

A 29-storey residential high-rise apartment was used as a case study for energy modelling in AutoCAD@Revit and passed over to AutoCAD@GBS to run the energy analysis. The EUI and its energy savings for various fibre-reinforced LWAC as an integral monolithic structural insulated building envelope without additional insulation were determined and compared with NWC.

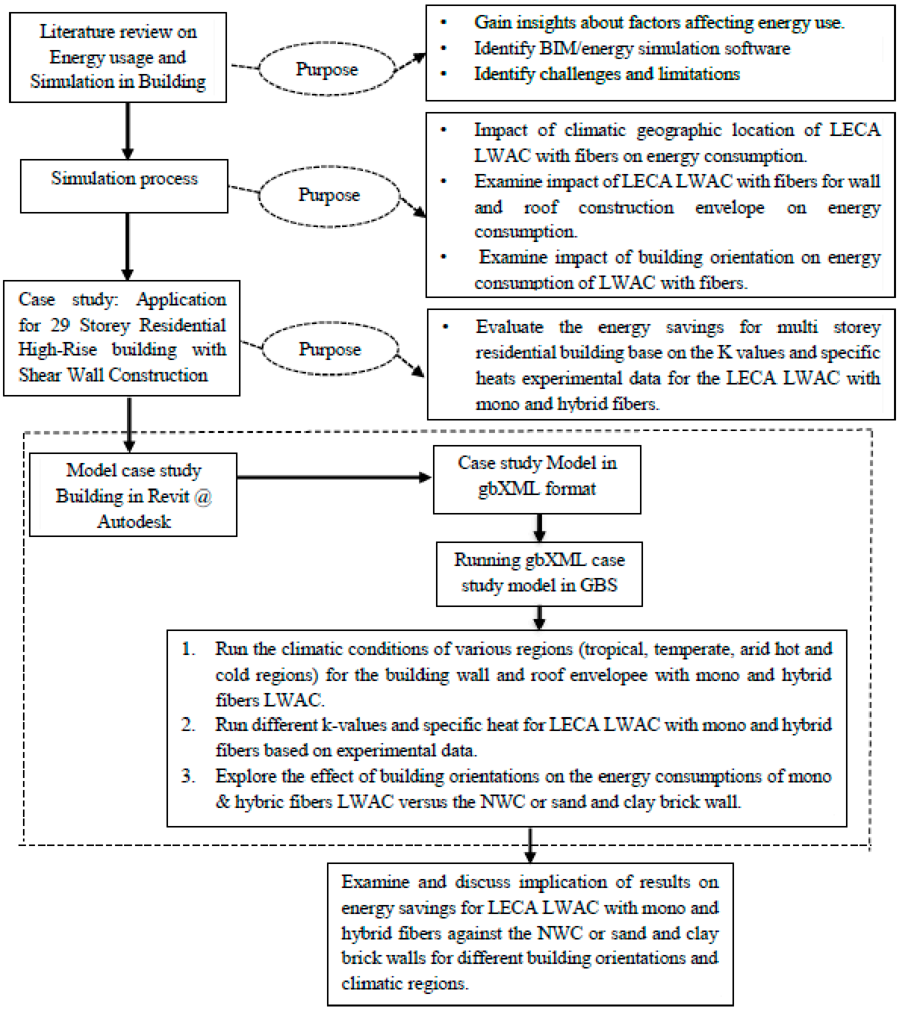

Figure 1. Summary of the energy simulation research framework for fibre-reinforced LECA-LWAC.

3.1. Energy Simulation for LWAC-Reinforced Fibres in a High-Rise Residential Building

A 29-storey residential high-rise apartment was used as a case study for the energy simulation. The LWAC reinforced with mono and hybrid fibres was compared with NWC or traditional sand-cement or clay brick wall as its envelope. The energy simulation was conducted to investigate the energy performance of the proposed material under hot-arid, cold, Mediterranean and hot-humid climates with 0°, 45° and 90° building orientations.

The simulation was executed in a cloud-based BIM environment using the Autodesk applications tools Revit for energy modelling and GBS for energy simulation. The four main criteria listed below were the main reasons for the use of the GBS BIM-based building energy modelling (BEM).

(1) The National Building Specification (NBS) has surveyed and placed Revit as the top two based on usage and preference in the construction industry of the UK since 2012 [43].
(2) GBS can analyse all energy efficiency measures with various orientations, types of wall and roof construction, window shade and glazing types, lighting efficiency, occupancy schedule, and different infiltration values simultaneously without having to modify the original geometric model.
(3) The interoperability of gbXML format becomes the de facto schema for writing BIM models because it can incorporate thermal descriptive data [44,45]. The use of gbXML for energy simulation tools without having to recreate the building geometry in the BEM will save time significantly [46].

(4) Revit can communicate seamlessly with GBS through gbXML without any loss of data [47].

3.2. Energy Modelling in BIM@Autodesk Revit

The case study was simulated using a 29-storey high-rise residential building project located in Putrajaya, Malaysia. The architectural AutoCAD drawings of this building were obtained from the relevant authority. The typical floor plan from the ground floor to the 29th floor is given in Figure 2. Each floor consists of 11 units with a total of 319 units per block. The structures system used a shear wall construction for all its wall framing. Autodesk@Revit architectural modelling was used throughout the 3D modelling process with its full-featured building information modelling platform. Using this platform, 'Building Elements', including the walls, roofs, windows and floors, were created in 3D models. The conceptual massing capabilities feature of Autodesk@Revit uses basic shapes to model building forms and orientations at the early stage of the design process. At its modelling end, the Autodesk Revit model can be saved as a 3D energy analytical model that can be executed in Autodesk GBS energy simulation in the BIM cloud computing environment.

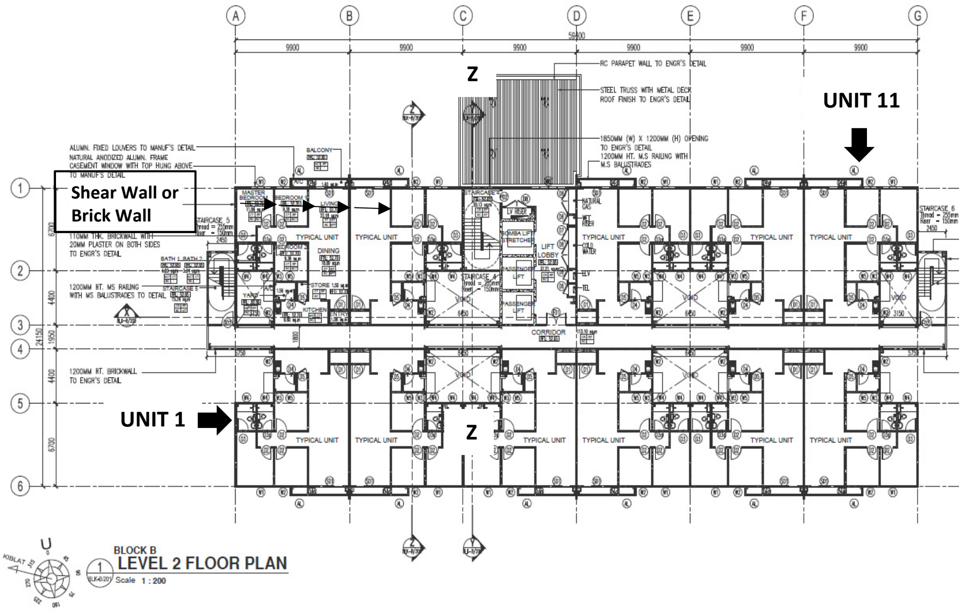

Figure 2. Typical floor layout plan.

The main elements assigned in the remodelling process of the building are as follows:

(1) Floor: 150-mm-thick LECA fibre-reinforced LWAC or NWC floor.
(2) Wall: 150-mm-thick fibre-reinforced LECA-LWAC for shear wall compared with NWC, 100-mm-thick clay brick and sand-cement brick walls 12.5 mm cement mortar on both sides.
(3) Doors: single panel (850 × 2000 mm) for rooms, single flush (762 × 2032 mm), double sliding (1700 × 2000 mm) for balcony and double flush (1700 × 2000 mm) for the storeroom.
(4) Windows: Several types of wall windows were used in this building, including casement with trim (610 × 1220 mm and 410 ×1220 mm) and top hung (300 × 300 mm) for void space in the building.
(5) Roof: Fibre-reinforced LECA-LWAC flat roof slab together with LWAC shear wall or 150-mm-thick NWC flat roof together with NWC shear wall or brick wall.

3.3. Construction Materials for Shear Wall, Floor and Roof in Autodesk@Revit

Roof, shear walls, floor, columns and beams are all referred to as the structural system. Autodesk@Revit material data for the floor and wall need to be customised based on experimental data. The material physical and thermal database is modified in the library based on the experimental values for fibre-reinforced LECA-LWAC of different fibre configurations. These values are then compared with that of NWC for floor and wall construction. The type of chosen wall, floor and roof material is cast situ with NWC as the baseline. The chosen wall, floor and roof materials were then compared against the LECA-LWAC with mono steel (ST) or polypropylene (PP) fibres and hybrid ST-PP fibres. Traditional clay and sand bricks were also used as a non-structural system for the walls and compared with the hybrid LECA-LWAC with fibres in terms of energy-saving comparison. The following factors are listed below for different configurations of LECA FRLWAC as a passive system of a building envelope:

(1) Thermo-physical properties of fibre-reinforced LECA-LWAC compared with the traditional NWC, sand-cement bricks and clay bricks building materials
(2) Four cities with diverse climates, namely Putrajaya (Malaysia), Makkah (Saudi Arabia), Istanbul (Turkey) and Lillhardal (Sweden)
(3) Building orientation—Base model (0°), 45° and 90°
(4) No window shades and double glazing were used to evaluate the worst-case design scenario.

All other parameters, such as the fenestration properties, HVAC system using split unit type and building occupancy schedule were kept constant for ease of evaluation. The occupancy schedule chosen for the energy simulation for the residential building is shown in Figure 3.

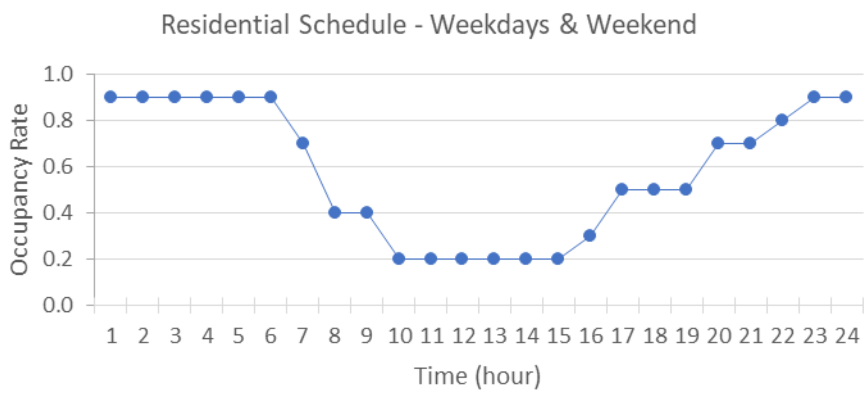

Figure 3. Occupancy schedule.

Table 1 provides the important parameters used for a multi-family residential building type to perform energy analysis, specifically the heating and cooling loads analysis in Autodesk@GBS. These values are based on ASHRAE 90.1–2019 [48] and ASHRAE 90.2–2019 [49] standards.

Table 1. Energy analysis parameters for multi-family occupant type.

Parameter	Value
Occupancy Schedule	Residential
People Sensible Heat Gain (W·person^{-1})	73.3
People Latent Heat Gain (W·person^{-1})	58.6
Lighting Load Density (W·m^{-2})	6.5
Equipment Load Density (W·m^{-2}))	5.4
Infiltration Flow (ACH) [1]	0.4
Outside Air (Ventilation Air) Flow per person (L·s^{-1})	Null
Outside Air (Ventilation Air) Flow per area (m^3·h^{-1}·m^{-2})	1.3
Unoccupied Cooling Set Point (°C)	29.4

Note 1: Infiltration rate is constantly at 0.4 air changes per hour (ACH).

3.4. Physical and Thermal Properties of the Materials

The physical and thermal properties of the fibre-reinforced LECA-LWAC and traditional construction materials are based on the extensive experimental program. Table 2 summarizes the physical and thermal properties of the materials used for the energy simulation. All physical and thermal properties of fibre-reinforced LECA-LWAC are measured against the relevant European (EN) and ASTM standards.

Table 2. Physical and thermal properties of the fibre-reinforced LECA-LWAC, normal weight concrete (NWC) and bricks and mortar based on experimental data.

Materials Type	Thickness, t (mm)	Density, ρ kg·m^{-3}	Thermal Conductivity, k W·m^{-1}·K^{-1}	Specific Heat C_p J·kg^{-1}·K^{-1}	Thermal Diffusivity, α mm^2·s^{-1}	U-Value W·m^{-2}·K^{-1}
Mono ST Fibre Category						
ST0	150	1831	1.144	893	0.706	3.321
ST0.25	150	1847	1.194	865	0.738	3.383
ST0.50	150	1865	1.307	932	0.750	3.511
ST0.75	150	1909	1.337	919	0.786	3.544
ST1.00	150	1934	1.375	914	0.800	3.583
ST1.50	150	1951	1.407	908	0.830	3.615
Mono PP Fibre Category						
PP0.1	150	1776	1.111	906	0.698	3.279
PP0.2	150	1759	1.090	896	0.698	3.251
PP0.3	150	1688	0.989	930	0.659	3.110
Hybrid ST+ PP0.2 Fibre Category						
ST0.5 + PP0.2	150	1815	1.273	942	0.778	3.476
ST0.75 + PP0.2	150	1854	1.280	943	0.744	3.484
ST1.0 + PP0.2	150	1916	1.285	989	0.744	3.489
Hybrid HST0.75+ PP Fibre Category						
HST0.75 + PP0.1	150	1869	1.269	938	0.743	3.471
HST0.75 + PP0.2	150	1857	1.251	916	0.755	3.451
HST0.75 + PP0.3	150	1870	1.251	921	0.709	3.451
Traditional Construction Materials						
NWC	150	2314	2.250	924	1.019	4.228
Sand-Cement +CM	125	1929	1.200	872	0.764	3.797
Clay + CM	125	1715	0.646	754	0.488	2.987
Mortar (CM)	12.5	2125	2.465	941	1.232	-

The default window properties in the analytic energy model are given in Table 3.

The model was represented by a 29-storey residential building with a window to wall ratio of 18.8% at all orientations. An HVAC type of the split air conditioning unit was implemented. The exterior layer of the building envelope had a solar absorptance of 0.6.

Table 3. Window Analytic Properties.

Parameter	Value
Window type—Casement Window	1/8-inch Pilkington Single Glazing
Panel Dimensions (H × W)	1220 mm × 610 mm
Front Window-Wall Ratio	18.8%
Corridor Window-Wall Ratio	11.7%
Visual Light Transmittance	0.9000
Solar Heat Gain Coefficient	0.7800
U-Value (W·m^{-2}·K^{-1})	3.6886
R-Value (m^2·K·W^{-1})	0.2711

3.5. Running the Autodesk@Green Building Studio

Revit provides conceptual forms and detailed architectural models to support energy analysis. The tools follow the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) conventions on automated thermal zoning for conceptual masses. Green Building Studio uses the DOE-2.2 simulation engine and creates input files for eQuest, EnergyPlus and an open XML schema. After selecting the desired energy settings and creating a 3D energy model in Revit, building data were submitted to a cloud web-based GBS simulation for energy analysis. Whole building energy analysis tools across Autodesk@GBS simulation engine block diagrams and its application tools are illustrated in Figure 4 [50].

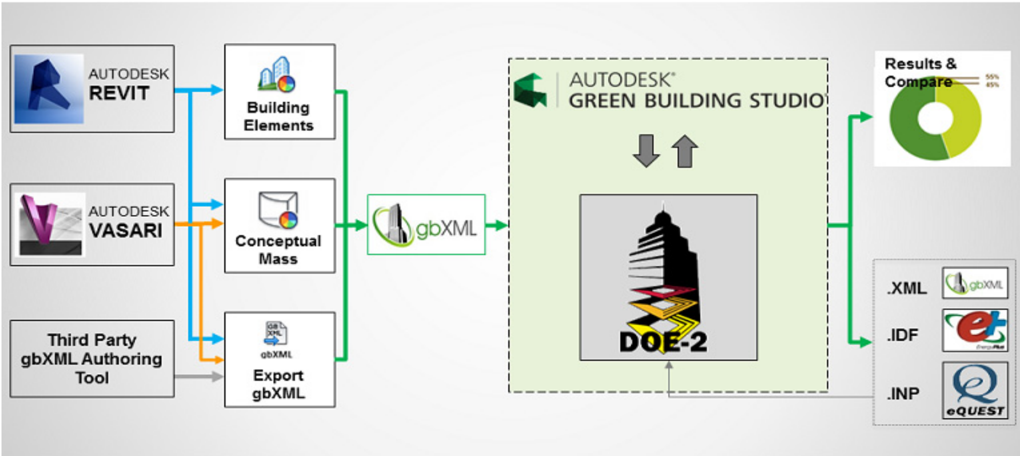

Figure 4. Autodesk@GBS Simulation Engine Block Diagrams use with Autodesk permission (Reproduced with permission from [50]. Autodesk, 2019).

3.6. Constructive Characteristics of Building Envelope Material

The constructive characteristics and design options of the building envelope used in the GBS energy simulation are shown in Table 4.

The energy performance of mono and hybrid fibre-reinforced LWAC was compared with traditional construction materials, including NWC, sand-cement brick and clay brick. Fibre-reinforced LWAC or NWC was used as a load-bearing shear wall system in a high-rise building. The fibre-reinforced floor and roof slab were constructed together with a fibre-reinforced LWAC shear wall. The NWC floor and roof slab were constructed together with an NWC shear wall. Sand-cement and clay bricks were used as non-load-bearing wall infill panel in the rigid-frame structural system with all the floor and roof slabs constructed from NWC.

A baseline design of NWC composed of NWC with 150 mm thick shear walls, floors and roof slab was first created. Sand-cement and clay brick walls of 125-mm thickness with 12.5 mm cement mortar with 150-mm-thick NWC floors and roof slab were also simulated. Next, the design configurations of mono fibre-reinforced and hybrid fibre-reinforced LECA-LWAC with 150-mm-thick walls, floors and roof slab were generated for comparison with NWC and the traditional sand-cement or clay brick wall to evaluate the energy performance.

All the thermo-mechanical properties of the mono ST, mono PP, ST-PP0.2 hybrid and HST0.75 + PP hybrid fibre-reinforced LECA-LWAC and traditional construction materials, such as NWC, sand-cement and clay bricks, were obtained from the experimental works. Each design option was created in the Material Window of the Revit energy analytical model and sent to the cloud-based Autodesk@GBS for energy analysis.

Table 4. Constructive characteristics and design options of the base model of a 29-storey residential building.

Simulation Option for Building Envelope Components—Construction Materials **Building footprint =40,102.4 m^2, Geometry = Rectangular, No of Floors = 29** **Orientation of baseline model = Front elevation facing north (0° orientation)**					
Envelope Material Option	Mono Fibre LECA-LWAC Configuration [1]	Hybrid Fibre LECA-LWAC Configuration [2]	NWC	Sand-cement brick wall	Clay brick wall
Wall Type	ST or PP LECA-LWAC	ST – PP LECA-LWAC	NWC	Sand-cement Brick	Clay Brick
Floor Type	ST or PP LECA-LWAC	ST + PP LECA-LWAC	NWC	NWC	NWC
Roof Type	ST or PP LECA-LWAC	ST + PP LECA-LWAC	NWC	NWC	NWC
Window Type	Aluminium frame glass window	Aluminium frame glass window	Aluminium frame glass window	Aluminium frame glass window	Aluminium frame glass window
Structural System	Shear Wall [3]	Shear Wall [3]	Shear Wall [3]	Rigid Frame [4]	Rigid Frame [4]

Notes: [1] Mono fibre configurations are ST0 to ST1.5, PP0.1 to PP0.3; [2] Hybrid fibre ST0.5/0.75/1.0 + PP0.2 and HST0.75 + PP0.1/0.2/0.3; [3] NWC and fibre-reinforced LWAC were used as a load bearing in a shear wall structural system of a high rise building; [4] Sand-cement and clay brick were used as a non-load bearing infill panel wall in the rigid-frame structural system of a high-rise building.

3.7. Climate and Weather Conditions for the Case Study

The energy consumption for the buildings using different fibre configurations of fibre-reinforced LECA-LWAC as compared to NWC or sand-cement or clay bricks based on the experimental data was used to evaluate the energy savings of four cities in different climatic regions based on the Köppen-Geiger climate classification [51] as follows:

(1) Tropical (Tropical Rainforest) Climate (Af)—Putrajaya, Malaysia
(2) Temperate (Hot Summer Mediterranean) Climate (Csa)—Istanbul, Turkey
(3) Continental (Sub-Arctic) Climate (Dfc)—Lillhardal, Sweden
(4) Dry (Hot Desert) Climate (BWh)—Makah Al Mukaramah, Saudi Arabia

The source of the climatic description was taken from ClimateData (2019) [52]. The climate in Putrajaya, Malaysia (2.99167 N, 101.6833 E) is tropical hot, humid and wet. The average temperature is 28 °C with an average rainfall of 2307 mm. The driest month is June and the wettest is November. May is the warmest with 33 °C and the coldest is February at around 23 °C. Wind speed average is 6 km/h. The average humidity is 80%. The sky is predominantly overcast and partly cloudy throughout the year.

Istanbul, Turkey (41.0500 N, 28.7667 E) has a warm and temperate Mediterranean climate with an average temperature of 14.1 °C and annual precipitation of 747 mm. The driest month is August and the wettest is December. The warmest month is August with 23.2 °C and the coldest at 5.7 °C is January. Wind speed average is 16 km/h. The average humidity is 72%. The sky is predominantly sunny and partly cloudy in summer and overcast and partly cloudy in winter.

Makkah, Saudi Arabia (61.85072 N, 14.07425 E) has a hot arid desert climate with virtually no rainfall all year long. The annual average rainfall is only 70 mm. The average annual temperature is 30.0 °C. The hottest month is June with a daily mean maximum temperature of 41 °C while the winter month mean minimum temperature of about 16 °C occurs in January. Average humidity low is about 43%. Wind speed average is 3 km/h. The sky is predominantly sunny throughout the year.

Lillhardal, Sweden (61.8167 N, 13.7167 E) has a sub-arctic climate with an average temperature of 2.4 °C. The temperatures are highest in July at around 20 °C and coldest in January with an average of −9 °C. Winter is long with seven consecutive months below freezing. The rainfall averages 645 mm. The least precipitation of 30 mm occurs in February and most rainfall occurs in August with an average of 80 mm. Wind speed average is 15 km/h. The average humidity is 68%. The sky is predominantly overcast and partly cloudy throughout the year.

3.8. Effect of Building Orientations

Figure 5 illustrates the building orientation for Case 1 Base Model—0° orientation and Case 2—90° orientation. Case 3 is with the building front facing Northeast (45° orientation).

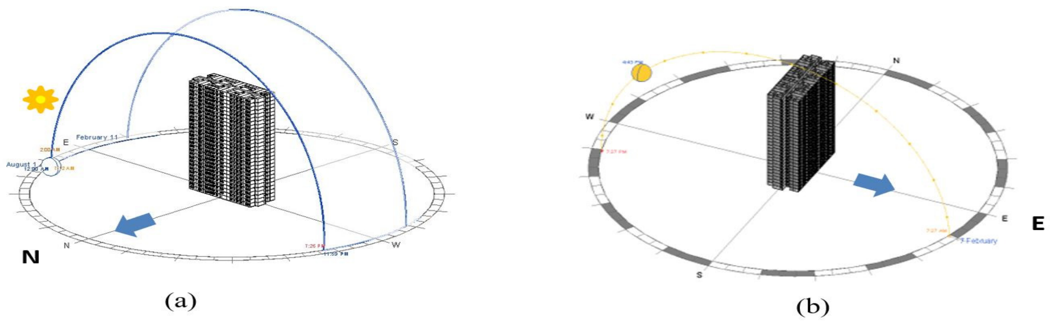

Figure 5. Building Orientation: (**a**) Case 1 Base Model—Building front facing North (0° Orientation); (**b**) Case 2 Building front facing East (90° Orientation).

4. Results and Discussion

4.1. Energy Use Intensity (EUI) Performance of Fibre-Reinforced LECA-LWAC

The EUI and energy savings at 0°, 45° and 90° building orientation in four cities of diverse climatic zones are shown in Table 5. The table shows a comparison of the energy performance of the integral structural-insulation fibre-reinforced LECA-LWAC (without insulation) against traditional construction materials, including NWC, sand-cement and clay bricks.

Mohareb et al. [53] analysed the data provided by the New Buildings Institute and determined that the average certified annual EUI for residential buildings was 220 kW·h·m^{-2} in the USA.

A Malaysia Green Building Index (GBI)-certified green office building in Kuala Lumpur was designed at an annual EUI of less than 150 kW·h·m^{-2} [54].

Li, et al. [55] investigated Leadership in Energy and Environmental Design (LEED)-certified residential high-rise building average annual EUI values in the USA for different climatic zones and they were as follows:

(1) Warm and Hot (ASHRAE 1–3) = 140 kW·h·m^{-2}
(2) Mixed (ASHRAE 4) = 159 kW·h·m^{-2}
(3) Cool (ASHRAE 5) = 150 kW·h·m^{-2}
(4) Cold (ASHRAE 6–7) = 173 kW·h·m^{-2}

The EUI requirement for Putrajaya was based on the Malaysia GBI-certified building and the rest of the cities were based on the climatic zone suggested above. The worst-case scenario of the EUI at 90° orientation was used to evaluate against the approved EUI values of the certified GBI and LEED buildings.

Putrajaya annual EUI values at 90° orientation for fibre-reinforced LWAC ranging from 147.0–149.6 kW·h·m^{-2} qualify for the GBI requirement of less than 150 kW·h·m^{-2} while traditional materials failed to qualify. The best performance EUI was HST0.75 + PP0.1 hybrid (147.0 kW·h·m^{-2}) and HST0.75 + PP0.3 hybrid (147.0 kW·h·m^{-2}).

Istanbul annual EUI values at 90° orientation for fibre-reinforced LWAC ranging from 146.7–149.8 kW·h·m^{-2} qualify for the LEED requirement in a cool climatic zone of less than 150 kW·h·m^{-2} while the traditional materials failed to qualify. The best performance EUI was HST0.75 + PP0.3 hybrid (146.7 kW·h·m^{-2}) and PP0.3 (146.7 kW·h·m^{-2}).

Makkah annual EUI values at 90° orientation for fibre-reinforced LWAC ranging from 159.2–165.0 kW·h·m^{-2} failed to qualify for the LEED requirement in a hot climatic zone of less than 140 kW·h·m^{-2}. The best performance EUI was HST0.75 + PP0.3 hybrid (159.2 kW·h·m^{-2}) and HST0.75 + PP0.1 (159.2 v). Based on the IEA (2017) energy data, the EUI estimate for residential buildings of Saudi Arabia was 195.8 kW·h·m^{-2} [56] and the Eastern Province with Zone 1 climate was similar to Makkah for apartments that have a EUI of 196.5 kW·h·m^{-2} [57]. EUI performance of the fibre-reinforced LWAC was much lower than the above EUI estimates.

Lillhardal annual EUI values at 90° orientation for fibre-reinforced LWAC ranging from 201.0–212.7 kW·h·m^{-2} failed to qualify for the LEED requirement in a cold climatic zone of less than 173 kW·h·m^{-2}. The best performance EUI was PP0.3 (201.0 kW·h·m^{-2}) followed closely by the HST0.75 + PP0.3 hybrid (203.7 kW·h·m^{-2}).

The EUI values of Putrajaya and Istanbul for monolithic structural-insulation fibre-reinforced LWAC (without additional insulation) qualified for the certified building EUI requirement of less than 150 kW·h·m^{-2} for GBI and LEED.

Extreme climatic conditions of sub-arctic (Lillhardal, Sweden) and semi-arid desert climates (Makkah, Saudi Arabia) require additional insulation material with double glazing windows to meet the EUI of an LEED-certified building.

In terms of best EUI performance for fibre, HST0.75 + PP hybrid was the best, followed closely by PP except for Lillhardal PP0.3 which performed better than HST0.75 + PP. ST1.0 and recorded the highest EUI among the fibre-reinforced LECA-LWAC because of its high thermal properties.

The effect of the fibre category on the EUI from the lowest to the highest order was HST0.75 + PP < PP < ST + PP0.2 < ST. HST0.75 + PP and was the most effective energy efficiency fibre type except for Lillhardal PP0.3. Lillhardal had the highest EUI, followed by Istanbul, Makkah and Putrajaya. EUI was the highest at a 90° orientation followed by a 45° and at 0° orientation.

The EUI of the traditional materials was the highest as compared with the categories of fibre-reinforced LECA-LWAC in all climatic regions.

Fibre-reinforced LWAC exhibited positive contributions in increasing energy efficiency by reducing energy consumption regardless of the diverse outdoor climatic conditions.

Table 5. Energy use intensity (EUI) performance and savings compared to NWC at different orientations, continued.

Location	**Putrajaya (Tropical Rainforest at 28 °C)**					**Makkah (Hot Arid Desert at 30 °C)**				
EUI at Building Orientation kW·h·m^{-2}	**EUI at 0° Orientation—Base Model kW·h·m^{-2}**	**EUI at 45° Orientation kW·h·m^{-2}**	**EUI at 90° Orientation kW·h·m^{-2}**	**EUI at 0–90% Savings Due to Orientation**	**EUI at 90% Savings against NWC**	**EUI at 0° Orientation—Base Model kW·h·m^{-2}**	**EUI at 45° Orientation kW·h·m^{-2}**	**EUI at 90° Orientation kW·h·m^{-2}**	**0–90% Savings Due to Orientation**	**EUI at 90% Savings against NWC**
NWC	148.1	149.5	151.7	2.43	-	163.7	167.9	169.1	3.36	-
Control	145.0	146.3	148.4	2.33	2.18	155.3	159.5	160.7	3.46	4.96
ST0.25	145.5	146.8	149.0	2.40	1.77	156.1	160.3	161.5	3.48	4.47
ST0.5	145.7	146.9	149.1	2.34	1.72	156.6	160.8	162.0	3.43	4.22
ST0.75	145.8	147.0	149.2	2.35	1.63	158.9	163.1	164.3	3.40	2.81
ST1.0	146.0	147.2	149.4	2.36	1.52	159.3	163.5	164.7	3.39	2.62
ST1.5	146.1	147.4	149.6	2.37	1.39	159.6	163.8	165.0	3.39	2.45
PP0.1	144.9	146.2	148.3	2.34	2.27	157.1	161.3	162.5	3.44	3.88
PP0.2	144.9	146.1	148.3	*2.35*	2.27	155.0	159.2	160.4	3.48	5.15
PP0.3	144.1	145.3	147.4	2.29	2.87	155.7	159.9	161.1	3.45	4.75
ST0.5 + PP0.2	145.6	146.8	149.0	*2.36*	1.75	156.4	160.6	161.8	3.44	4.31
ST0.75 + PP0.2	145.5	146.8	148.9	2.33	1.85	156.3	160.5	161.7	3.43	4.40
ST1.0 + PP0.2	145.1	146.2	148.3	2.22	2.29	155.7	159.8	161.0	3.39	4.81
HST0.75 + PP0.1	143.9	145.0	147.0	2.15	3.19	153.9	158.0	159.2	3.46	5.85
HST0.75 + PP0.2	144.0	145.1	147.1	*2.18*	3.11	153.9	158.1	159.3	3.48	5.79
HST0.75 + PP0.3	143.9	145.0	147.0	2.16	3.18	153.9	158.0	159.2	3.47	5.86
Clay Brick	148.6	150.2	152.2	2.45	−0.34	176.9	181.1	182.5	3.19	−7.96
Sand-cement Brick	151.6	153.6	155.7	2.69	−2.60	182.3	186.8	188.1	3.20	−11.24
Location	**Istanbul (Hot Summer Mediterranean at 15 °C)**					**Lillhärdal (Sub-Arctic Climate at 3.5 °C)**				
EUI at Building Orientation kW·h·m^{-2}	**EUI at 0° Orientation—Base Model kW·h·m^{-2}**	**EUI at 45° Orientation kW·h·m^{-2}**	**EUI at 90° Orientation kW·h·m^{-2}**	**EUI at 0–90% Savings Due to Orientation**	**EUI at 90% Savings against NWC**	**EUI at 0° Orientation—Base Model kW·h·m^{-2}**	**EUI at 45° Orientation kW·h·m^{-2}**	**EUI at 90° Orientation kW·h·m^{-2}**	**0–90% Savings Due to Orientation**	**EUI at 90% Savings against NWC**
NWC	151.2	152.6	153.2	1.30	-	226.1	226.5	226.7	0.37	-
Control	146.2	147.6	148.0	1.25	3.52	205.2	205.7	205.7	0.24	10.21
ST0.25	146.7	148.2	148.6	1.31	3.11	207.1	207.6	207.6	0.21	9.24
ST0.5	147.2	148.7	149.1	1.28	2.78	209.7	210.2	210.2	0.24	7.86
ST0.75	147.4	148.8	149.3	1.31	2.63	210.5	211.0	211.0	0.25	7.48
ST1.0	147.6	149.0	149.5	1.30	2.48	211.4	211.9	211.9	0.25	7.01
ST1.5	147.9	149.3	149.8	1.32	2.32	212.7	212.1	212.7	0.25	6.61
PP0.1	146.0	147.5	147.8	1.24	3.68	204.5	205.0	205.0	0.22	10.62
PP0.2	145.9	147.4	147.7	1.25	3.74	203.9	204.5	204.4	0.21	10.93
PP0.3	145.0	146.4	146.7	1.20	4.43	200.6	201.0	201.0	0.22	12.79
ST0.5 + PP0.2	147.0	148.5	148.9	1.28	2.89	209.0	209.5	209.5	0.23	8.25
ST0.75 + PP0.2	147.0	148.5	148.9	1.26	2.94	209.1	209.6	209.6	0.24	8.20
ST1.0 + PP0.2	146.7	148.0	148.4	1.16	3.24	208.7	209.1	209.2	0.29	8.39
HST0.75 + PP0.1	144.8	146.1	146.8	1.35	4.41	203.8	204.0	204.1	0.16	11.10
HST0.75 + PP0.2	144.8	146.1	146.8	1.37	4.40	203.5	203.8	203.8	0.15	11.27
HST0.75 + PP0.3	144.7	146.0	146.7	1.36	4.45	203.4	203.6	203.7	0.16	11.32
Clay Brick	149.8	150.4	151.2	0.92	1.32	210.5	211.3	210.9	0.00	7.53
Sand-cement Brick	154.1	154.9	155.9	1.15	−1.69	230.3	230.3	230.7	0.35	−1.72

4.2. Building Energy End Use Analysis

Building energy end use analysis was carried out based on the energy consumption breakdown of end use for Putrajaya, Makkah, Istanbul and Lilhardall.

4.2.1. Putrajaya

The breakdown of end-use energy consumption of the base model was compared between NWC and HST0.75 + PP0.1. The highest energy consumption was in July, while the lowest was in February. Figure 6 illustrates the percentage breakdown of energy consumption by the end-use base model. In Malaysia, ventilation (26%) and space cooling (24%) constituted about 50% of the energy consumption, followed by the miscellaneous equipment (21%), lighting (15%), hot water (13%) and external use (1%). Cooling loads represented 24% of the total energy consumption use. Mahlia and Chan [58] also reported that 21% of electricity was used as a cooling load in the residential sector of Malaysia.

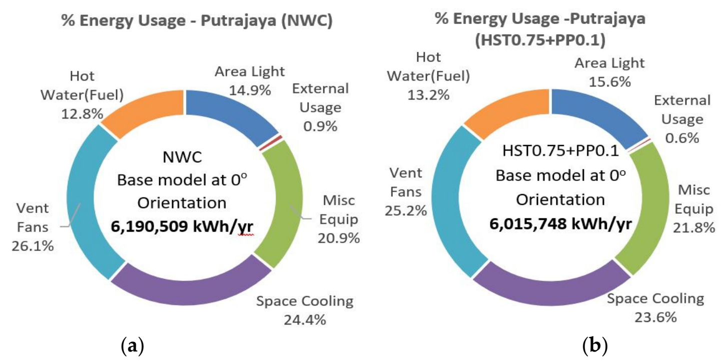

Figure 6. Percentage breakdown of annual energy consumption end-use comparison for Putrajaya: (**a**) NWC; (**b**) HST0.75 + PP0.1.

Cooling energy and ventilation needs were both higher by 6.2% for NWC as compared with HST0.75 + PP0.1. The other energy needs showed no significant variations.

4.2.2. Makkah

The breakdown of end-use energy consumption of the base model was compared between NWC and HST0.75 + PP0.3. Figure 7 illustrates the percentage breakdown of energy consumption by end-use of the base model (0° orientation) of NWC and HST0.75 + PP0.3 for Makkah.

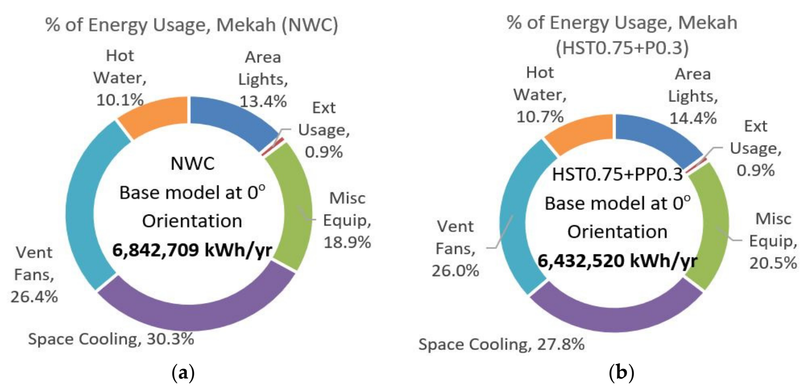

Figure 7. Percentage breakdown of annual energy consumption end-use comparison for Makkah: (**a**) NWC; (**b**) HST0.75 + PP0.3.

Ventilation (26%) and space cooling (29%) constituted about 55% of the energy consumption followed by miscellaneous equipment (20%), lighting (14%), hot water (10%) and external use (1%). Cooling loads represented 29% of the total energy consumption use.

4.2.3. Istanbul

The breakdown of end-use energy consumption of the base model was compared between NWC and HST0.75 + PP0.3. The highest energy consumption was in January, which is the coldest month of the year, while the lowest was in September.

Figure 8 illustrates the percentage breakdown of energy consumption by the end-use of the base model in Istanbul. Space heat (6%) and space cooling (9%) constituted about 15% of energy consumption. The highest consumption category was ventilation (24%) followed by miscellaneous equipment (20%), hot water (20%), lighting (15%), space heating (6%), heat-pump supply (4%) and external use (1%). Most of the energy consumption in the end use (about 44%) was related to ventilation (24%) and hot water (20%). In Istanbul, space heating and space cooling needs were 43.2% and 21.4% higher, respectively, for NWC in comparison with HST0.75 + PP0.3, while other energy end use needs had no significant variations. The HST0.75 + PP0.3 thermal envelope material exhibited lower space heating and cooling energy needs in contrast to NWC.

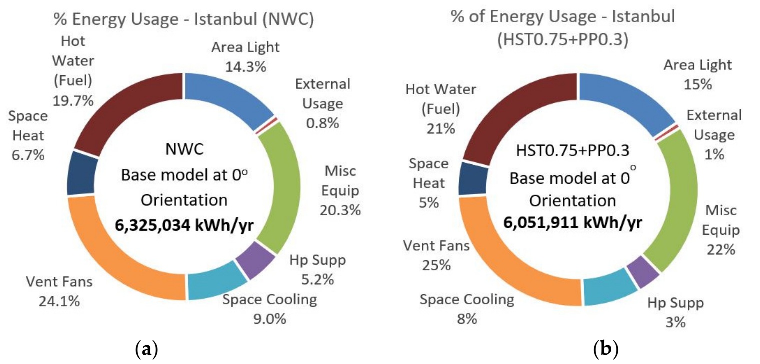

Figure 8. Percentage breakdown of annual energy consumption end-use comparison for Istanbul: (**a**) NWC; (**b**) HST0.75 + PP0.3.

4.2.4. Lillhardal

A comparison of the breakdown of end-use energy consumption of the base model between NWC and PP0.3 was conducted. The highest energy consumption was in March where it was one of the coldest months of the year, while the lowest was in September which had the lowest heating and cooling loads. Figure 9 illustrates the percentage breakdown of the energy consumption by end use for NWC as compared to PP0.3.

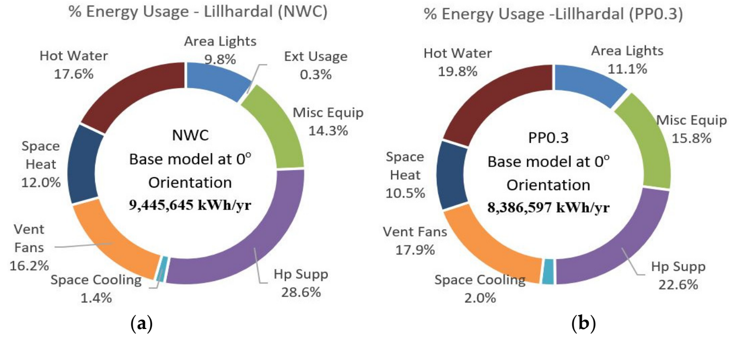

Figure 9. Comparison of percentage breakdown of annual energy consumption end-use comparison for Lillhardal: (**a**) NWC; (**b**) PP0.3.

Space heating (12%) and heat-pump supply (26%) comprised about 38% of energy consumption followed by hot water (18%), ventilation (17%), miscellaneous equipment (15%), lighting (10%) and space cooling (2%). A greater part of the energy consumption in end use (about 38%) was related to heating needs. Space heat was reduced noticeably with the implementation of PP0.3. Space heating and heat-pump supply needs were 29.4 % and 43.2% higher, respectively, for NWC as compared with PP0.3, while other energy needs showed no significant variations.

4.3. Energy Saving of Fibre-Reinforced LECA-LWAC Compared with NWC

Figure 10 breaks down the percentage of energy savings of fibre-reinforced LECA-LWAC as compared with NWC when the building front is facing east (90° orientation) for Putrajaya, Istanbul and Lillhardal. In Putrajaya, HST0.75 + PP0.1 had the highest energy saving with 3.19%, followed by PP0.3 which had the best overall energy saving of 2.87% with respect to NWC and all other fibre configurations. In the ST category, ST0.25 had the highest energy saving of 1.77% compared with NWC. In the ST + PP0.2 hybrid category, ST1.0 + PP0.2 had the highest energy saving of 2.29% as compared with NWC. The order of energy-saving materials based on the category from high to low in Putrajaya was HST0.75 + PP hybrid > mono PP > ST + PP0.2 hybrid > mono ST > NWC > Brick.

In Makkah, for the building with front elevation facing east (90° orientation), HST0.75 + PP0.3 (5.86%) had the best overall energy followed closely by HST0.75 + PP0.1 (5.85%). In the ST category, ST0.25 had the highest energy saving at 4.47%. In the ST + PP0.2 hybrid category, ST1.0 + PP0.2 had the highest energy saving at 4.81%. The order of energy-saving materials based on the category from high to low in Makkah was HST0.75 + PP0.1 > PP0.3 > ST1.0 + PP0.2 > ST0.25.

In Istanbul, HST0.75 + PP0.3 (4.45%) followed closely by PP0.3 (4.43%) had the best overall energy savings compared with NWC and all other fibre configurations. In the ST category, ST0.25 had the highest energy saving of 3.11% compared with NWC. In the ST + PP0.2 hybrid category, ST1.0 + PP0.2 had the highest energy saving of 3.24% in contrast to NWC. The order of energy-saving material based on the category from high to low in Istanbul was HST0.75 + PP0.1 hybrid > mono PP0.3 > ST1.0 + PP0.2 hybrid > mono ST0.25 > NWC > Brick.

In Lillhardal, PP0.3 provided the best overall energy saving of 12.79% followed closely by HST0.75 + PP0.3 with 11.32% as compared with NWC and all other fibres. In the ST category, ST0.25 had the highest energy saving of 9.24% as compared with NWC. In the ST + PP0.2 hybrid category, ST1.0 + PP0.2 displayed the highest energy savings of 8.39% with respect to NWC. The order of energy-saving material based on the category from high to low was mono PP > HST0.75 + PP hybrid > ST + PP0.2 hybrid > mono ST > NWC > Brick.

In the cold sub-arctic climate of Lillhardal, the mono PP0.3 fibre performed better in terms of energy savings, whereas, in the hot-humid climate of Putrajaya and warm Mediterranean climate of Istanbul, the HST0.75 + PP was the best in terms of energy savings. The effect on energy savings of the use of fibre-reinforced LECA-LWAC was more significant in the sub-arctic region of Lillhardal with a substantial saving of 12.79%, followed by a temperate Mediterranean climate of Istanbul with a moderate saving of 4.45%. The tropical hot and humid climate of Putrajaya, Malaysia had the least savings with a margin of 3.19%. The use of fibre-reinforced LWAC had the most energy-saving benefit in areas with cold sub-arctic climate as Lillhardal.

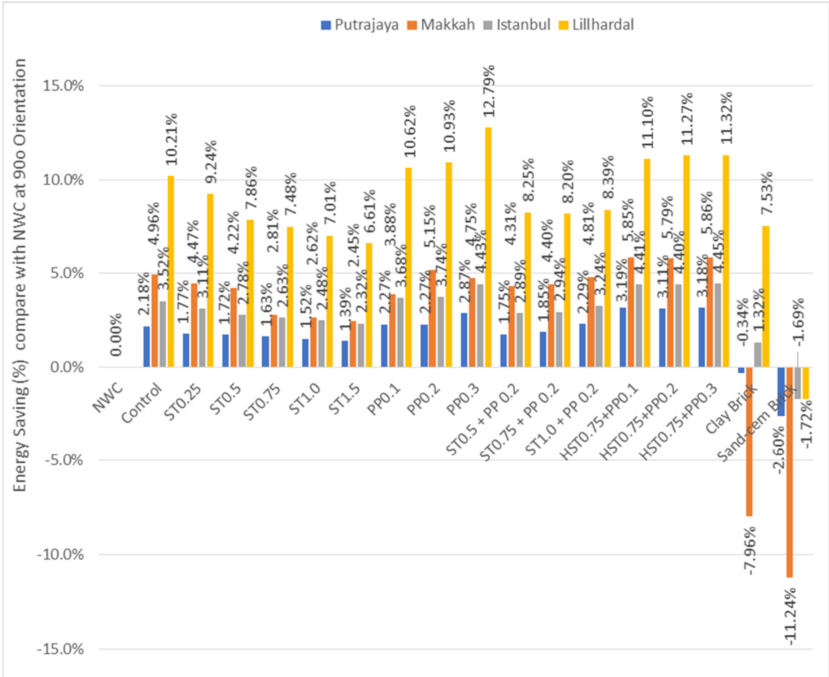

Figure 10. Percentage of energy saving using fibre-reinforced LECA-LWAC as compared with NWC.

4.4. Effect of Building Orientation on Energy Saving

Figure 11 illustrates the effect of building orientation on energy saving of fibre-reinforced LECA-LWAC, NWC, clay and sand-cement bricks.

In Putrajaya, changing the building orientation from 90° to 0° (base model) for NWC reduced energy consumption by 2.43% (EUI reduction of 3.6 kW·h·m^{-2}). HST0.75 + PP0.1 hybrid fibre achieved a higher energy reduction of 3.19% (EUI reduction of 3.1 kW·h·m^{-2}). V. Shabunko et al. investigated two-storey residential houses in Brunei using clay brick wall with insulation and found that it could reduce the annual EUI by 2.3 kW·h·m^{-2} [59].

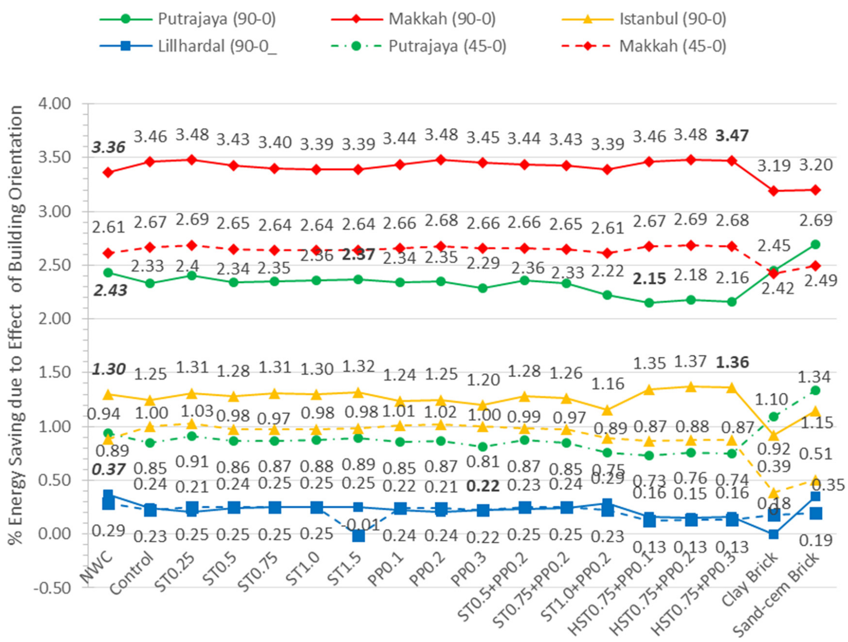

Figure 11. Energy-savings because of building orientations to the base model.

In Makkah, changing the building orientation from 90° to 0° (base model) for NWC reduced energy consumption by 3.36% (EUI reduction of 5.4 kW·h·m^{-2}). HST0.75 + PP0.3 hybrid fibre achieved a higher energy reduction of 3.47% (EUI reduction of 5.3 kW·h·m^{-2}).

In Istanbul, changing the building orientation from 90° to 0° (base model) for NWC reduced energy consumption by 1.30% (EUI reduction of 2.0 kW·h·m^{-2}). HST0.75 + PP0.3 hybrid fibre achieved a higher energy reduction of 1.36% (EUI reduction of 2.0 kW·h·m^{-2}).

In Lillhardal, changing the building orientation from 90° to 0° (base model) for NWC reduced energy consumption by 0.37% (EUI reduction of 0.6 kW·h·m^{-2}). PP0.3 hybrid fibre achieved a higher energy reduction of 0.22% (EUI reduction of 0.4 kW·h·m^{-2}).

In a cold sub-arctic climate like Lillhardal, building orientation does not play a significant role in energy saving. The energy savings amounted to only 0.22% as compared with the energy savings of up to 12.8% for changing the building envelope from NWC to fibre-reinforced LWAC.

The effect of building orientation on energy saving was insignificant for Istanbul and Lillhardal and marginally significant for Putrajaya and Makkah. The building orientation has less of an effect on energy savings than optimising the building envelope material.

4.5. Economic Aspects of Energy Saving

The cost of electricity and fuel is computed based on the Tenaga Nasional Berhad (TNB) electricity tariff [60] for a private dwelling as shown in Table 6 and by the Gas Malaysia 2020 fuel tariff rate of RM23.72/MMBtu or 8.094 sen (US 1.955 cent) per kW·h for residential buildings [61]. The TNB's domestic tariff is highly subsidized by the Malaysian government at around 50% for the first 300 kW·h per month of usage. The actual amount of cost savings would be much higher without the subsidy.

The electricity tariff in Makkah is SAR0.18 (4.80 US cents) per kW·h for the first 6000 kW·h (SEC, 2019) [62] and the natural gas fuel rate is at SAR2.81 (USD0.75) per MBtu or SAR0.009588 (USD0.00255) kW^{-1}·h^{-1} for residential buildings [63]. The electricity tariff in Istanbul is 12.67 euro cents (US14.19 cents) per kW·h [64] with a natural gas fuel rate of 2.16 euro cents (US2.42 cents) per kW·h for residential buildings [65]. The electricity tariff in Lillhardal is 20.15 euro cents (US22.57 cents) per kW·h [66] with a natural gas fuel rate of 11.25 euro cents (US12.60 cents) per kW·h for residential buildings [67].

Table 6. TNB Domestic Electricity Tariff Rates [60].

Tariff Category	Unit	Current Rate
Tariff A—Domestic Tariff		
For the first 200 kW·h (1–200 kW·h) per month	sen (US cent)·kW^{-1}·h^{-1}	21.8 sen (US 5.27 cent)
For the next 100 kW·h (201–300 kW·h) per month	sen (US cent) kW^{-1}·h^{-1}	33.4 sen (US 8.07 cent)
For the next 300 kW·h (301–600 kW·h) per month	sen (US cent) kW^{-1}·h^{-1}	51.6 sen (US 12.47 cent)
For the next 300 kW·h (601–900 kW·h) per month	sen (US cent)·kW^{-1}·h^{-1}	54.6 sen (US 13.19 cent)
For the next kW·h (901 kW·h onwards) per month	sen (US cent) kW^{-1}·h^{-1}	57.1 sen (US 13.79 cent)
The minimum monthly charge is RM3.00 (USD0.725)		

Average exchange rate RM1.00 = US 24.157 cent for the year 2019.

Table 7 illustrates the energy cost per month for each unit and the relative cost savings between fibre-reinforced LWAC and NWC with its associated orientation using the respective country's utility rates. The increase in energy cost per month per unit in NWC is higher at USD5.41, USD2.84, USD3.04 and USD2.05 for Putrajaya, Makkah, Istanbul and Lillhardal, respectively, when the building is at a 0° to 90° orientation.

In Putrajaya, the building at a 90° orientation had the highest solar heat gain and HST0.75 + PP0.1 had the highest energy cost savings of 4.04% compared with NWC. The order of energy cost savings based on the best of each fibre category from high to low is HST0.75 + PP0.1 > PP0.3 > ST1.0 + PP0.2 > ST0.25.

Table 7. Energy cost (USD) per month/unit and its savings as compared to NWC associated with its orientation at different climatic regions, continued.

Location	**Putrajaya (Tropical Rainforest at 28 °C)**				**Makkah (Hot Desert 30 °C)**			
Building Orientation	**0° Orientation Base Model**	**45° Orientation**	**90° Orientation**	**At 90° Orientation**	**0° Orientation Base Model**	**45° Orientation**	**90° Orientation**	**At 90° Orientation**
Energy Consumption Cost (USD)·Unit^{-1}	**Front Elevation Facing North Cost·Unit^{-1}**	**Front Elevation Facing North-East Cost·Unit^{-1}**	**Front Elevation Facing East Cost·Unit^{-1}**	**% Saving against NWC**	**Front Elevation Facing North Cost·Unit^{-1}**	**Front Elevation Facing North-East Cost·Unit^{-1}**	**Front Elevation Facing East Cost·Unit^{-1}**	**% Saving against NWC**
NWC	169.52	171.61	174.93	-	77.58	79.82	80.42	-
ST0	164.96	166.82	170.06	2.79%	73.22	75.39	76.03	5.46%
ST0.25	165.70	167.70	170.96	2.27%	73.62	75.82	76.47	4.92%
ST0.5	165.93	167.83	171.07	2.21%	73.87	76.04	76.68	4.65%
ST0.75	166.10	168.01	171.26	2.10%	75.11	77.31	77.94	3.09%
ST1.0	166.34	168.27	171.52	1.95%	75.27	77.47	78.10	2.89%
ST1.5	166.58	168.54	171.80	1.79%	75.42	77.63	78.26	2.69%
PP0.1	164.76	166.63	169.86	2.90%	74.15	76.34	76.98	4.28%
PP0.2	164.72	166.62	169.86	2.90%	73.03	75.21	75.86	5.68%
PP0.3	163.59	165.36	168.56	3.64%	73.40	75.56	76.21	5.24%
ST0.5 + PP0.2	165.84	167.76	171.01	2.24%	73.79	75.97	76.61	4.74%
ST0.75 + PP0.2	165.68	167.53	170.77	2.38%	73.72	75.89	76.53	4.85%
ST1.0 + PP0.2	164.96	166.61	169.82	2.92%	73.40	75.53	76.16	5.30%
HST0.75 + PP0.1	163.22	164.80	167.87	4.04%	72.46	74.61	75.24	6.44%
HST0.75 + PP0.2	163.32	164.98	168.05	3.93%	72.49	74.66	75.29	6.38%
HST0.75 + PP0.3	163.22	164.83	167.90	4.02%	72.44	74.60	75.23	6.46%
Clay Brick	170.24	172.69	175.71	−0.45%	84.52	86.76	87.47	−8.76%
Sand-cement	174.87	177.92	174.93	−3.48%	87.33	89.71	80.42	−12.38%
Location	**Istanbul (Hot Summer Mediterranean at 15 °C)**				**Lillhärdal (Sub-Arctic Climate at 3.5 °C)**			
Building Orientation	**0° Orientation Base Model**	**45° Orientation**	**90° Orientation**	**At 90° Orientation**	**0° Orientation Base Model**	**45° Orientation**	**90° Orientation**	**At 90° Orientation**
Energy Consumption Cost (USD)·Unit^{-1}	**Front Elevation Facing North Cost·Unit^{-1}**	**Front Elevation Facing North-East Cost·Unit^{-1}**	**Front Elevation Facing East Cost·Unit^{-1}**	**% Saving against NWC**	**Front Elevation Facing North Cost·Unit^{-1}**	**Front Elevation Facing North-East Cost·Unit^{-1}**	**Front Elevation Facing East Cost·Unit^{-1}**	**% Saving against NWC**
NWC	195.46	197.54	198.50	-	513.68	515.28	515.73	-
ST0	187.59	189.86	190.42	4.07%	462.73	463.88	463.96	10.04%
ST0.25	188.37	190.70	191.34	3.61%	467.43	468.70	468.48	9.16%
ST0.5	189.15	191.38	192.07	3.24%	473.74	475.03	475.00	7.90%
ST0.75	189.43	191.65	192.41	3.07%	475.54	476.84	476.83	7.54%
ST1.0	189.77	192.01	192.75	2.90%	477.80	479.12	479.12	7.10%
ST1.5	190.10	192.35	193.12	2.71%	479.75	479.69	481.06	6.72%
PP0.1	187.26	189.54	190.07	4.25%	460.96	462.16	462.08	10.40%
PP0.2	187.11	189.41	189.94	4.31%	459.61	460.81	460.67	10.68%
PP0.3	185.72	187.98	188.42	5.08%	451.25	452.34	452.33	12.29%
ST0.5 + PP0.2	188.92	191.17	191.84	3.36%	471.94	473.23	473.14	8.26%
ST0.75 + PP0.2	188.84	191.06	191.71	3.42%	472.14	473.43	473.39	8.21%
ST1.0 + PP0.2	188.40	190.43	191.04	3.76%	470.99	472.15	472.47	8.39%
HST0.75 + PP0.1	185.43	187.37	188.47	5.06%	459.09	459.74	459.88	10.83%
HST0.75 + PP0.2	185.42	187.39	188.50	5.04%	458.35	459.01	459.11	10.98%
HST0.75 + PP0.3	185.34	187.30	188.39	5.09%	458.13	458.79	458.91	11.02%
Clay Brick	193.29	194.19	195.42	1.55%	476.59	477.52	476.59	7.59%
Sand-cement	199.84	201.05	202.58	−2.06%	523.54	524.64	525.51	−1.90%

In Makkah with the building at a 90° orientation, HST0.75 + PP0.3 had the highest energy cost savings at 6.46% compared with NWC. The order of energy cost savings from high to low is HST0.75 + PP0.3 > PP0.2 > ST1.0 + PP0.2 > ST0.25.

In Istanbul with the building at a 90° orientation, HST0.75 + PP0.3 had the highest energy cost savings at 5.09% compared with NWC. The order of energy cost savings from high to low is HST0.75 + PP0.3 > PP0.3 > ST1.0 + PP0.2 > ST0.25.

In Lillhardal with the building at 90° orientation, HST0.75 + PP0.3 had the highest energy cost savings at 12.29% compared with NWC. The order of energy cost savings from high to low is PP0.3 > HST0.75 + PP0.3 > ST0.25 > ST1.0 + PP0.2.

The effect of energy cost saving using PP0.3 fibre-reinforced LECA-LWAC is more significant in the sub-arctic region of Lillhardal. Makkah, which has a hot arid desert climate, and Istanbul, with a temperate Mediterranean climate, have moderate cost savings of 6.46% and 5.09%, respectively, using HST0.75 + PP0.3 fibre-reinforced LECA-LWAC. Putrajaya, with its tropical hot-humid climate, has the least cost savings of 4.04% using HST0.75 + PP0.1 fibre-reinforced LECA-LWAC.

5. Conclusions

This study used integral-monolithic structural insulation fibre-reinforced LWAC (without additional insulation) as building envelope material for high-rise residential buildings in tropical hot-humid and Mediterranean climates. The major drawback of structural LWAC is its brittleness behaviour and the use of fibres can mitigate this issue. Adding fibres to the LWAC mixture affects its thermal properties. In this study, the thermal properties of LECA-LWAC reinforced with different doses of steel (ST) and polypropylene (PP) fibres in mono and hybrid forms were measured and energy consumption in a high-rise residential building constructed with these types of LWAC was calculated using a simulation program. The energy consumption in the building was compared with NWC and conventional brick walls together with the building orientation in diverse climatic regions of the world. The following conclusions can be drawn from the results of the data analysis.

(1) HST0.75 + PP0.1 has the most efficient EUI performance and cost savings for Putrajaya at 3.19% and 4.04%, respectively, as compared with NWC.
(2) HST0.75 + PP0.3 has the most efficient EUI performance and cost savings for Makkah at 5.86% and 6.46%, respectively, as compared with NWC.
(3) HST0.75 + PP0.3 has the most efficient EUI performance and cost savings for Istanbul at 4.45% and 5.09%, respectively, as compared with NWC.
(4) PP0.3 has the most efficient EUI performance and cost savings for Lillhardal at 12.79% and 12.29%, respectively, as compared with NWC.
(5) The energy and cost savings of the fibre-reinforced envelope material is in the following order based from high to low: HST0.75 + PP hybrid > mono PP > ST + PP0.2 hybrid > mono ST > NWC > Brick for Putrajaya, Makkah and Istanbul, while Lillhardal is mono PP > HST0.75 + PP hybrid > ST + PP0.2 hybrid > mono ST > NWC > Brick.
(6) The use of the integral monolithic structural-insulation fibre-reinforced LWAC in tropical (Putrajaya, Malaysia) and Mediterranean (Istanbul, Turkey) climates meets the certified-EUI requirements of less than 150 $kW{\cdot}h{\cdot}m^{-2}{\cdot}year^{-1}$ without additional insulation or double-glazing window/shade.
(7) Extreme climatic conditions of sub-arctic (Lillhardal, Sweden) and semi-arid desert climates (Makkah, Saudi Arabia) require additional insulation material with double-glazing windows to meet the LEED-certified green building requirements.
(8) All traditional construction materials, such as NWC, sand-cement brick and clay brick, fail to qualify for the certified-EUI requirements.
(9) The energy-saving measure is driven largely by using fibre-reinforced LECA-LWAC as a building envelope material rather than building orientation.

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