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Review

Thermal Behavior and Energy Efficiency of Modified Concretes in the Tropical Climate: A Systemic Review

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Abstract: Concrete remains the most utilised construction material for building envelopes, which regulate the indoor temperature to achieve human thermal comfort. Often, the energy consumption for building performance appraisal is related to the thermal behaviour of building materials as heating, ventilation, and air conditioning systems all variously contribute to human comfort. Following the development of concrete technology, many types of concrete have been invented to serve several purposes in the construction industry. To clearly understand the concrete type tailored for the specifics of a construction project, the local climate, concrete mechanical properties, and concrete thermal behaviours should be primarily identified to achieve energy efficiency, which also suits the sustainability of global materials. This paper, therefore, reviews the modified concrete thermal behaviours in the tropical climate for more systematic city planning in order to achieve better energy efficiency. Urban heat islands in the tropics and contributing factors, as well as heat transfer mechanisms, are first highlighted. The requirements of concrete thermal behaviour for building envelopes are then discussed through specific heat capacity, thermal conductivity, thermal diffusivity, time lag, and decrement factor in the context of applications and energy consumption in the tropical regions. With a case study, it is found that concrete thermal behaviours directly affect the energy consumption attributed mainly to the use of cooling systems in the tropics. The study can be a reference to mitigating the urban heat island phenomenon in the planning of urban development.

Keywords: thermal behaviour; tropic; energy efficiency; concrete

1. Introduction

Population centralisation and increment customarily take place in urban and metropolitan areas in which impermeable construction materials surfaces, notably concrete, are gradually replacing natural green vegetation zones due to various financial opportunities and accelerated infrastructure development. Despite numerous evident revolutions in building technologies, concrete remains the primary material employed in a diversity of construction events. Hence, building and structural engineers expectedly need to acquire more knowledge on concrete than other building and construction materials. Concretes possess comparatively high specific heat that may contribute to extra energy consumption during the building performance stage. Their low albedo surfaces often result in secondary heat to buildings, and thereby promote the urban heat island (UHI) phenomenon [1]. To better appreciate the effects, a 7 °C of variation was discovered between high-density residential areas and adjacent rural areas [2] due to UHI.

Since ancient times, building envelopes act as a sheltering establishment to regulate the indoor temperature and achieve human thermal comfort. Accordingly, building science has been greatly progressed and continuously advances with various innovative materials to form building envelopes. In terms of architecture, a building envelope can be categorised into physical form and orientation, opaque system, transparent system, and shading. Energy consumption is most relevant to the heat gain from opaque systems [3–6]. Heating and cooling systems are among the main contributors to energy consumption as the building envelope plays an essential role in issues of energy efficiency [7]. Existing studies have shown that some 30% of the power consumption within buildings in tropical climates is spent to cool down the heat from roofs and walls [8,9]. In Europe, 27% of the annual energy consumption was contributed to by residential dwellings alone in 2009 [10].

The thermal bridging of concrete tends to let the heat from outside transfer indoors through the conductivity of building materials [3]. There are many efforts introduced to regulate indoor temperature from outdoor thermal fluctuation, for instance, with lightweight concretes [3,11,12], insulation panels [13], etc. Even so, the unnecessary gross energy consumption for mitigating human thermal discomfort within the building compound, especially in tropic climates, remains unavoidably high, thus resulting in massive energy consumption through cooling systems. Therefore, understanding the thermal behaviours of concrete materials is imperative to assist in better planning and improving the energy expenditure performance of buildings in these regions. Concerning the energy consumption aspect, this paper reviews the concrete thermal behaviours to achieve energy efficiency in building performance with the final aim of reducing the carbon footprint. For the benefits of tropical climates, the concrete thermal behaviours are summarised and discussed in the context of applications relevant to these regions. As concrete strength and thermal insulating properties are the concerned factors in minimizing the energy consumption in the later building performance stage, the discussions are made on these parameters in preliminary study.

2. Tropical Climate and Issues

2.1. Tropical Climate General Description

As one of the climate groups in the Köppen classification, a tropical climate, which is located below 25 latitudes of southern and northern hemispheres, has been defined as having a mean temperature of ≥19 °C during the coldest month. The territories associated with the weather group are those around the Equator, consisting of parts of Australia, Pacific Ocean islands, southern Asia, Central America, parts of South America, and Central Africa. Following the rain intensity of the driest month as exhibited in Table 1, this climate can be further subdivided into the tropical rainforest, tropical monsoon, and savanna climates. Therefore, this weather group is characterised as a two-season climate zone, with distinctively wet and dry seasons throughout the year.

Table 1. Tropical climate.

	Tropical Rainforest [14]	**Tropical Monsoon [15]**	**Savanna [16]**
Location	North and south latitudinal ranges of 5–10 degrees from the equator	Between the latitude of 10 degrees north and the Tropic of Cancer	Between 10° and 20° north–south latitude
Average temperature	21–30 °C	27.1 °C ± 3.6 °C	20–30 °C
Total precipitation	2540 mm	3409.2 mm	700–1000 mm

2.2. Urban Heat Island (UHI)

UHI is a phenomenon describing an isolated urban area associated with higher temperatures due to dense human population compared to its neighbouring suburban areas [17]. As a by-product of rapid development and civilisation, the trend of which is continually expanding worldwide, the UHI phenomenon may pose a new environmental threat towards the buildup of global warming. Urban areas with predominantly constructed materials over natural landscapes, aquatic terrains, and vegetation topographies are likely to attain a higher temperature than the surrounding outskirts. A UHI is likely to form in metropolitan areas that are characterised by a high percentage of water resistance, low vegetation, and non-reflective surfaces. In the UHI regions, the temperature is significantly higher during the nighttime, with no wind to dissipate the heat released from building materials back to the atmosphere.

Some consequences from UHI, such as an increase in monthly rainfall, prolonged growing seasons, and the deterioration of air and water qualities, negatively impact human health and daily activities, as well as the surrounding ecosystems.

2.2.1. Factors Contributing to UHI

Asphalt, bricks, and concrete with low albedo effects are the materials most associated with urban and metropolitan areas, which are credited to the presence of a vast amount of infrastructure and the ability to exert significant temperature variation compared with suburban areas [18]. These materials exhibit darker artificial surfaces (as opposed to those of nature) that tend to absorb more heat during the daytime. As there are significant differences in thermal bulk properties (heat capacity and thermal conductivity) and surface radiative properties (albedo and emissivity) between building materials and natural surfaces, a UHI can be formed under these circumstances. Moreover, the lack of vegetation areas due to replacement by buildings and paved-over surfaces, such as parking lots and roads, results in lesser evapotranspiration activity, a natural cooling process performed by green plants.

Furthermore, different building layouts can produce different thermal properties [19]. In urban areas, in which urban canyon effects are created as the result of the existence of high-rise buildings with multiple reflective surfaces, more heat is absorbed that encourages the formation of UHI. Therefore, city geometry also plays a major role in promoting the development of UHI. In addition, the poor use of thermal mass in a building can contribute to UHI by absorbing a lot of heat during the daytime and radiating it out at night, exacerbating energy consumption, energy costs, and comfort liability. The heat generated from the mechanical air conditioning systems to the surrounding environments may cause a rise in the ambient temperature, also known as waste heat. The massive use of air conditioning systems in urban areas generates relatively high waste heat compared to rural areas.

2.2.2. UHI in Tropical Climate

Table 2 summarises the UHI effects in the tropics. From UHI models, it was found that regional temperature could rise by up to 2.26 °C in a two decade time frame in Central Asia [20]. Several studies have also been actively conducted to evaluate the UHI in Malaysia, by means of numerical investigation [21–23], satellite imagery and remote sensing [24–26], surface energy balance modelling [27,28], weather station monitoring [29–33], etc. Although there is no significant borderline for urban and rural areas in Singapore, a maximum of a 4.01 °C temperature difference was found [34]. The UHI studies in South Asia also have been included in Table 3 of previous published data [35].

Table 2. Summary of UHI effects in tropics.

Ref.	Country	Area	Year of Assessment	Method	Temperature Difference, °C
[34]	Singapore	Singapore	July–September, 2002	Temperature traverse	AT–4.01
[36]	Malaysia	Putrajaya	1999–2009	Satellite	ST–6.75
[37]	Malaysia	Putrajaya	2012	Numerical simulation	AT–3.10
[38]	Malaysia	Klang	2000 & 2010	Satellite	ST–21.50 & ST–22.70
[39]	Malaysia	Kuala Lumpur	2008–2009	Satellite & GIS	ST–14.50
[33]	Malaysia	Kuala Lumpur	2004	Temperature traverse & weather stations	AT–5.50
[40]	Brazil	Presidente Prudente	2016	Weather station	AT–2.40 (mean), 4.10 (monthly), 6.40 (hourly)
[41]	US	Puerto Rico	2008–2018	Weather station	2.06–3.04

AT = ambient temperature, ST = surface temperature.

2.3. Heat Propagation Mechanisms

Heat propagates from one medium to another when there exists a temperature difference between them. Fundamentally, there are three types of heat transfer mechanisms, namely, conduction, convection, and radiation. Heat is transferred by conduction through a medium, and via air by means of convection and radiation. Without a global movement of the matter, heat can be conducted between molecules or close contact materials. Heat conduction is referred to as the internal thermal energy transfer produced by microscopic particles collisions and the movement of electrons within a body [42]. In a solid body, heat propagates through two mechanisms: the transmission of thermal energy or the vibration of atoms [43]. To reduce heat transfer by conduction, high thermal resistance materials are the most useful. In terms of heat convection, the transferring mechanism is exerted by the fluid mass motion. Heat convection happens when there is a difference in surface temperature from surrounding fluid [42]. Unlike conduction and convection, heat transmission by radiation can be formed by all physical substances via their electromagnetic energy emission due to rotational and vibrational movements of molecules and atoms. A substance can emit thermal radiation at temperatures hotter than 0 °K.

2.4. Building Envelope for Indoor Thermal Comfort

A building envelope is essential for the restriction of heat gain from the outside environment in achieving human thermal comfort. About 30% of power consumption is due to the heat gain from opaque systems (walls and roofs) in tropical climates [8,9]. Thermal insulation, radiation barriers, and air barrier systems are currently the chief building envelope methods in controlling heat transfer. On one hand, heat can potentially transfer by convection where air gaps are wider than 5 mm in construction materials [44], thereby increasing the building's operation costs and energy consumption. On the other hand, heat radiation is predominantly due to the exposure of the roof to sunlight. It has been demonstrated by [45] that 50% of a building's heat load comes from its roof. Studies have shown that reductions of 6% to 7.7% of heat transfer rate [46], 17% of energy load [47], and 70% heat flux [48] can be achieved with radiant barriers. The application of retroreflective coating materials can also reduce heat gain from solar radiation [49]. Hence, minimising the solar absorption is the main objective in the consideration of the building envelope through the employment of high reflectivity (high albedo) and insulating materials.

Therefore, the building envelopes made with concrete materials serves as a thermal barrier to maintain indoor human thermal comfort. If the building envelope is not functioning as a barrier, more energy is needed for HVAC systems in regulating the indoor ambient temperature. It is essential to explore more concrete thermal behaviour in order to minimize energy consumption in achieving human thermal comfort.

3. Concrete Thermal Behaviour

Concretes exhibit low time lag and high thermal conductivity, and therefore are commonly linked to the increasing trend of energy consumption in the tropics [50]. As already stated, a 30% rise in the energy consumption of residential houses as as result of the UHI phenomenon was discovered in a recent survey [51]. As heat propagates through concrete walls, the manner of the heat amplitude drop is referred to as the decrement factor, while the time delay is known as time lag. These parameters relate to the thermal comfort evaluation of the building envelope and in turn concern the energy consumption response of building materials [52]. A low resistance to temperature change is the thermal behaviour preferred in cold regions, while high thermal inertia is the desired condition in tropics [53]. Thus, thermal comfort can be attained with building materials of high time lag and a low decrement factor [54]. Other parameters, such as specific heat, diffusivity, and conductivity, are also imperative. These engineering terminologies are the next subjects of discussion in the assessment of concrete thermal behaviour.

3.1. Thermal Conductivity

Several factors affect the concrete thermal conductivity [55]. For instance, the type of aggregate [56,57], the properties of cementitious materials [58–66], moisture content [67,68], design buildup [69–74], temperature [75,76], concrete density [12,77–80], etc. The measurement of concrete thermal conduction is divided into steady-state and transient methods [81]. A constant heat transfer is referred to as a steady-state condition, a description that is relevant to homogenous materials. The required measurement is time-consuming while more accurate results can be commonly obtained. Meanwhile, time and temperature dependencies inherent in the transient method are more suitable for heterogeneous materials with moisture content variation [82]. A previous study quantified that hot wire (transient approach) was the most popular method to determine the thermal conductivity of concrete [81]. For a general perspective of currently available efforts in literature, Table 3 summarises different concretes with their thermal conductivities (k-values), obtained using theoretical model, steady-state, and transient approaches.

3.1.1. Theoretical Model

The cubic model is one of the prediction models of concrete thermal conductivity, which accounts for the individual conductivity of cement paste, aggregate, and aggregate volume, as mathematically displayed in Equation (1). It is noted that the model may suffer from discrepancies due to the effects of minerals of different types even though the contained aggregates have the same density, thus needing extra care in the prediction event. For practice, ACI [91] suggests some practical values for thermal conductivity of both normal and lightweight aggregate concretes, which can be readily applied without the experimental data, such as in the following equation:

$$k_c = k_p \left[\frac{V_a^{2/3}}{V_a^{2/3} - V_a + \left(\frac{V_a}{\left(\frac{k_a V_a^{2/3}}{k_p} \right) + 1 - V_a^{2/3}} \right)} \right] \tag{1}$$

where V_a is the aggregate volume, k_p is the thermal conductivity of cement paste, k_a is the thermal conductivity of aggregate, and k_c is the thermal conductivity of concrete.

Table 3. Concrete thermal conductivity (*k*-value).

Ref.	Mix Description	Measurement	Density, kg/m^3	*k*-Value, W/m °C	Referred Guideline
[82]	Self-Compacting Concrete with Perlite	Steady-state hot plate	2227 2253 2279 2292	$2.094_{30–40}$–$0.715_{70–80}$ $2.179_{30–40}$–$0.761_{70–80}$ $2.355_{30–40}$–$0.761_{70–80}$ $2.430_{30–40}$–$0.793_{70–80}$	ASTM C177
[83]	Oil palm shell foamed concrete with fly ash and silica fume	Steady-state hot plate	1156 1192 1354 1409 1506 1594	0.40 0.41 0.50 0.54 0.55 0.57	BS EN12664
[84]	Oil palm shell foamed geopolymer concrete with POFA and fly ash	Steady-state hot plate	1300–1800	0.47–0.58	BS EN12664
[85]	Polystyrene foamed concrete	Steady-state hot plate	150 200 250 400	0.0848 0.0864 0.0927 0.1566	Not specified
[86]	Lightweight aggregate and glass bead	Transient hot wire	1800	1.1–1.4	ASTM D5334
[87]	Lightweight aggregate concrete with diatomite and pumice	Transient hot wire	1500 900	0.44 0.13	ASTM C1113
[88]	Modified waste expanded polystyrene lightweight aggregate concrete	Transient hot wire	876–1956	0.6–1.99	ASTM C1113
[89]	Expanded perlite lightweight aggregate concrete with silica fume and fly ash	Transient hot wire	509 493 485 511 498 483	0.1720 0.1552 0.1558 0.1676 0.1643 0.1472	ASTM C1113
[90]	Autoclaved aerated concrete	Transient plane source	415 520 630	0.1–0.2	Not specified

Equation (2) expresses the relationship between thermal conductivity (k_c) and density (d) of the concretes. It should be noted that the k_c values of concretes that have same densities, but are made of different aggregates, can deviate from the calculated values derived from Equation (2). For instance, the k_c values obtained for normal weight and lightweight concretes might be underestimated because the different types of aggregates contained in the concretes have their own specific thermal properties.

$$k_c = 0.072e^{0.00125d}(\text{S.I. units}) \tag{2}$$

Practically, concretes contain moisture. Equation (3) is therefore used to provide a more accurate k_c value by taking the densities of concrete in moist and oven-dry conditions into account:

$$k_c(corrected) = k_c\left[1 + \frac{(6d_m - d_o)}{d_o}\right] \tag{3}$$

where k_c is the thermal conductivity of the concrete, and d_m and d_o are the densities of the concrete in moist and oven-dry conditions, respectively.

3.1.2. Steady-State Approach

The steady-state boxed method [92] operates by determining the energy transferred from one hot end to the cold end based on the second law of thermodynamics. The k-value can be calculated through the air temperature difference of both sides [68,93]. Meanwhile, a guarded hot plate measures the thermal conductivity with the mean temperature difference between two surfaces [94]. The temperature range can be set within the plates as studied by [82,83]. The steady-state approach is usually used for thermal conductivity measurement of homogenous materials in which the temperature is time -independent. Accurate results can be obtained but it is time consuming. Equation (4) is the Fourier Law of heat conduction for thermal conductivity measurement:

$$q = -k\nabla T \tag{4}$$

where q is the heat flux, k is the thermal conductivity, and ∇T is the gradient of temperature.

3.1.3. Transient Method

On the other hand, the transient method is preferred to measure the thermal conductivity of moist concrete that is made of heterogeneous materials. Hot wire and plane source are the most common methods employed under the transient approach category. The temperature is measured at a specific distance from the hot wire [95]. In various studies on lightweight aggregate concretes, thermal conductivities have been determined using such a setting [88,96,97]. Moreover, the plane source method measures the thermal conductivity of power input and time variation for the transient plane and line sources. Studies relevant to this method for the measurement of thermal conductivity are [90,98].

Thermal conductivity is calculated using Equation (5) below:

$$k_c = \gamma D(\tau_i)/\Delta E(t) \tag{5}$$

where k_c is the thermal conductivity of the concrete, γ is the constant of the different resistances in the Wheatstone bridge, $D(\tau_i)$ is the theoretical expression of time-dependent increase, and ΔE is the variation in potential across the Transient Plane Source sensor.

Other than heat transfer, the thermal inertia of building materials also affects the indoor temperature. Thermal inertia characterises the reluctance of temperature change, and the abilities of heat absorption and storage in a building. In tropical regions, where thermal comfort is affected by the hot and humid climate, a comfortable interior temperature could be achieved by using concrete walls with high thermal inertia [99]. The heat diffusivity, capacity, time lag, and decrement factor of building materials are all often measured to determine the thermal inertia. The relationship of thermal inertia with material density, specific heat, and thermal conductivity is expressed in Equation (6):

$$I = \sqrt{\rho c k} \tag{6}$$

where I is the thermal inertia, while ρ, c, and k are the density, specific heat, and thermal conductivity of the material, respectively.

For a well-thermal-insulated concrete, low-rate thermal diffusivity and heat capacity are important. Table 4 lists the thermal inertia obtained for some selected construction materials.

Table 4. Thermal inertia of selected construction materials [100].

Material	Density kg/m^3	Specific Heat, kJ/kg.K	Thermal Mass, kJ/m^3.K	Time Lag	
				Hour	Thickness, mm
Water	1000	4.186	4186	-	-
Concrete	2240	0.920	2060	6.9	250
AAC	500	1.100	550	7.0	200
Brick	1700	0.920	1360	5.0	125
Sand stone	2000	0.900	1800	-	-
Compressed FC sheet	1700	0.900	1530	-	-
Earth wall (Adobe)	1550	0.837	1300	9.2	250
Rammed earth	2000	0.837	1673	10.3	250
Compressed earth blocks	2080	0.837	1740	10.5	250

Thermal diffusivity is the heat transmission rate within a material, which is mathematically defined by the k-value divided by specific heat capacity and density for the same unit of pressure. The specific heat capacity is the amount of heat required to raise the unit temperature for a given mass. Concrete, with low thermal diffusivity but high specific heat capacity as compared to other construction materials, is preferable as a building material.

The time lag and the decrement factor relate closely in defining the indoor thermal comfort in a building. The time of the peak of outdoor heat to appear indoors, is referred to as time lag, while the temperature decrease from the peak temperature is known as its decrement factor. These values can be obtained from the calibrated hot box and in situ field tests where temperature changes are measured. For instance, 6.9 h of time lag was reported for a piece of 250 mm thick concrete [100]. The effectiveness of the decrement factor can be achieved with the increment in insulation thickness, which is a direct indicator of cost. For tropic climate applications, it can be generally ascertained that concretes remain, by comparison to other construction materials, in the category of having good performance in terms of the aforementioned thermal properties, although the most optimal material design can be always be examined and enhanced.

3.2. Other Thermal Behaviours

Concrete expands slightly when the temperature rises and contracts when the temperature falls. This expansion is known as thermal expansion, which is usually influenced by the types of aggregate, cement, and water content and the age of the concrete [101,102]. The coefficient of the thermal expansion of concrete is about 10 millionths per degree Celsius (10×10^{-6} °C), indicating that a 1 m long piece of concrete subjected to a temperature increase of 1 °C will expand by 10×10^{-6} m, or 0.010 mm. Problems occur when the heat in the massive concrete structures cannot be dissipated. Temperature changes that cause a thermal differential can potentially induce thermal stress in the concrete and eventually lead to cracking over time. Control joints are an effective way to control cracking by providing space for the expansion and shrinkage of the concrete. Concrete with high melting points are likely to have lower thermal expansions.

4. Energy Consumption

Table 5. Study on energy performance in numerous areas.

Ref.	Location	Concrete Property/Building Model	Energy Consumption	Remark
			Reduction of 18% HVAC energy in	

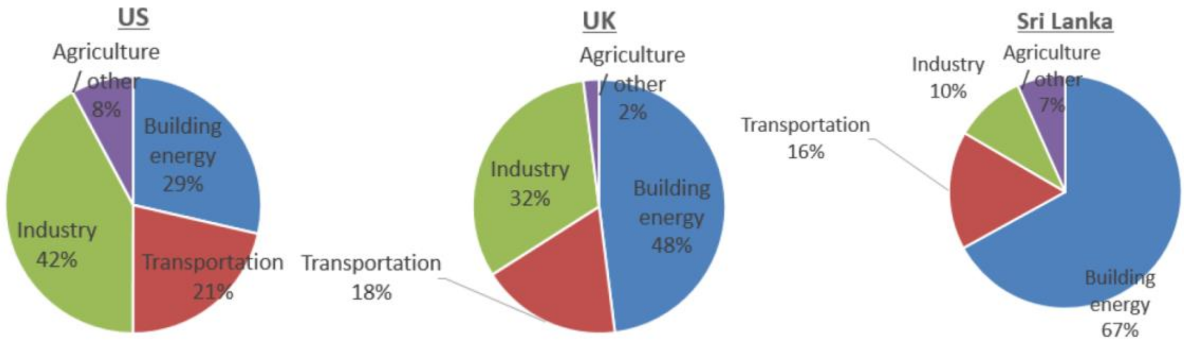

Figure 1. Energy utilisation in the US, UK, and Sri Lanka [2].

In general, the energy utilised for maintaining building performance is especially higher in the tropics to achieve human thermal comfort. There are also some solutions embedded with negative impacts, such as the improper height of building and width of road, lack of green areas, inappropriate building geometry, etc. To reduce the energy consumption, some procedures are recommended, namely, natural ventilation, appropriate building materials, and increased green areas.

4.1. Sustainability in Concrete Construction

In the concrete industry, there are several solutions to reduce the carbon footprint, such as phase-change materials [108–110], lightweight concrete [11,12,55,111–113], or cement-free concrete [59,65]. Some of these reduce the carbon footprint through minimising the use of cement since its production contributes much carbon to the environment, while some solutions provide more long-term effects on building performance or services. Lightweight concrete is one of the alternatives to reduce energy consumption in the building service stage, while phase-change materials may store or release energy according to the surrounding temperature.

As buildings may have a serviceability period of 50 years, where the cumulative saved energy may become greater, lightweight concrete and phase-change materials in concrete are therefore the focus in the current research trend towards sustainability. One of the challenges of lightweight concrete is the reduction in strength as the voids in the concrete matrices increased. A balance is needed in order to satisfy both design specifications of structural strength and thermal insulating properties.

4.2. Prediction Models for Residential Energy Consumption

Electricity is the main source of residential energy consumption. However, these data are captured through automatic meter reading or advanced metering infrastructure and are not available to the public. To circumvent this, the only prediction models for energy consumption are developed as observed in the current research trend, even though several case studies may be available upon permission of authorities. Prediction methods for energy consumption are customarily derived from physics-based (engineering), data-driven inverse modelling (artificial intelligence), or a combination of both approaches [114]. Table 6 shows the available prediction models adopted for residential energy consumption, namely regression analysis, artificial neural networks, the Gaussian model, etc. It is worth noting, however, that all these models do not represent the full capacity or a well-accepted consensus on current or future predictions of energy consumption. This is due to several governing factors, e.g., different consumption patterns for different families, different electrical appliances, different perceptions towards human comfort, etc. Therefore, the existing models are still under development and are far from maturity.

4.3. Concrete Properties in Energy Consumption

Concrete can be divided into structural and non-structural uses. Concrete for structural use has a higher density as it can provide load-bearing characteristics in building envelopes. Despite their densities, concretes may contribute variously to thermal behaviours. Regarding density, the energy consumption of a concrete building can be further discussed. From Table 7, although low thermal properties can be achieved with lower densities, they may not achieve structural requirements in building construction. Depending on the requirements, as long as the designed usage is clear, both types can be applied for building construction.

Placing high expectations on the load-bearing requirement, designers often ignore concrete thermal properties even though they are essential in the consideration of energy consumption at a later serviceability stage. In this regard, thermal conductivity is a contributing factor to the energy consumption of the building performance. The heat from the sun is radiated into the building envelope, mostly onto walls and roofs, and raises the external surface temperature, which relates to the specific heat of concrete.

Furthermore, heat conduction will take place when there is a temperature gradient, from a hotter surface towards the inner wall. Thus, this potentially increases the indoor ambient temperature and cooling loads may be applied to achieve human thermal comfort, yielding a rise in the overall energy consumption level.

For tropical climate, thermal conductivity is correlated to concrete's compressive strength and density, as described by Equations (7) and (8) [115]. To achieve 17 MPa of structural use for foamed concrete, 1.8 W/mK of thermal conductivity and 200 kg/m^3 density are obtained from Equations (7) and (8), respectively. It is thus far unproven that 17 MPa can be achieved with 200 kg/m^3 concrete density. Therefore, optimisation in various aspects of concrete produc tion is needed to fit into the climate requirement.

$$\text{Thermal conductivity} = 0.9558 \ln f_c - 0.8871 \tag{7}$$

$$\text{Thermal conductivity} = 0.0311 \mathrm{e}^{0.019\gamma} \tag{8}$$

where f_c and γ are the compressive strength and density of concrete, respectively.

5. Concrete in Tropical Climate

In the tropics, hot and humid are the primary characteristics of the local weather conditions. In the same region, the average temperature ranges from 20 °C to 30 °C throughout the year. In order to reduce the heating and cooling loads for a building, concrete with minimum heat transfer may be applied to maintain indoor thermal comfort. Specifically, concretes with low specific heat and conductivity are highly preferable in this weather. In terms of thermal behaviour at ambient temperature, a high time lag and a low decrement factor [99] are the other two desired performance characteristics. A high time lag and a low decrement factor illustrate that the heat is transferred slowly from outside to insider within a long time frame with low heat dispersion.

Additionally, the construction material thickness and the insulation system have been studied for the consideration of energy consumption [120]. The increase of the material thickness may effectively prevent the heat being transferred from the outside at the expense of an increment in material cost. A standardised single brick thickness (112.5 mm, in Malaysia) wall is usually applied in tropical countries, such that the effectiveness of heat transfer restriction can be optimised by using concrete with low density.

Lightweight concrete is an alternative in achieving both mechanical and functional properties when relating to thermal performance [11,12,55,113]. From non-structural (brick, 5 MPa) to structural uses (17 MPa), the concrete densities can range between 1000 to 1800 or 2000 kg/m^3 for foamed concrete [11,134] or lightweight aggregate concrete. These lightweight concretes have relatively low thermal conductivity. Table 8 presents the cooling load for structural and non-structural concrete, with an 8 °C temperature difference of a 1 m^2 wall surface. Depending on the concrete's application, there is a varying range of concrete density and strength that can be applied within the construction industry. The cooling load is calculated according to Equation (9):

$$\text{Cooling load} = \text{US}\ (T_o - T_i) \tag{9}$$

where US is the transmission area and $(T_o - T_i)$ is the temperature difference between outside and inside the building (8 °C taken from the previous study, [55]).

In the tropics, the hot weather increases the energy consumption of HVAC systems in order to achieve human thermal comfort. The pores, or concrete density, governs the heat transfer of the building envelope. Concerning the heat barrier of concrete, lightweight concrete serves as an alternative in the tropics to reduce energy consumption. The strength and pores of concrete are two contrasting properties and a balance should be achieved to move towards sustainability.

Table 6. Residential energy consumption prediction.

Ref.	Investigated Method/Parameter	Building Performance/Prediction Model	Remark
[116]	Sensor measurements collected every 15 min	Linear Regression; Feed Forward Neural Network (FFNN); Support Vector Regression (SVR); Least Squares Support Vector Machines (LS-SVM); Hierarchical Mixture of Experts (HME) with Linear Regression Experts; HME with FFNN Experts; and Fuzzy C-Means with FFNN.	Least squares support vector machine is the best for future electrical consumption prediction
[117]	Building global heat loss coefficient (G), the south equivalent surface (SES), and the difference between the indoor set point temperature and the sol-air temperature	Multiple regression prediction model	Three inputs and one output, simplicity, large applicability, good match with the simulations and the energy certification calculations plus the inclusion of human behaviour correction
[118]	Day-ahead electricity load forecasting	Seasonal Autoregressive Integrated Moving Average	Ability to capture a variety of input factors that influence load behaviour and to enable a dynamic trade-off between them, as well as between different model parameter values
[119]	Total energy and total electricity consumptions	Artificial Neural Network (ANN) model, Grey models, Regression model, Polynomial Model, and Polynomial regression model	ANN is the most acceptable forecasting method
[120]	Different material thicknesses and insulation properties	Extreme Learning Machine (ELM) and Artificial Neural Network (ANN)	ELM algorithm can achieve the smallest training error and also normalise the weights
[121]	Hourly prediction of building electricity consumption	Improved Particle Swarm Optimisation algorithm (iPSO) and Genetic Algorithm Artificial Neural Networks (ANNs), iPSO-ANN, and GA-ANN	iPSO-ANN model has a shorter modelling time
[122]	HVAC hot water energy consumptions	Change-point regression model, Gaussian process regression model (GPM), Gaussian Mixture Regression Model (GMM), and Artificial Neural Network model (ANN)	GMR model shows slightly better statistical performance; insufficient data training of ANN results in an inaccurate prediction
[123]	Temperature-dependent change point model selection	Change point model	Able to select the most appropriate temperature-dependent change point model for all 48 cases tested
[124]	Daily residential energy use	Change-point models for residential energy use	Evaluated the differences in energy slope when compared with energy audit data; increasing the thickness of the duct insulation
[125]	Heating and cooling loads of residential buildings	Geometric Semantic Genetic Programming (GSGP)	Integrating a local searcher and linear scaling in GSGP can speed up the convergence of the search process

Table 6. *Cont.*

Ref.	Investigated Method/Parameter	Building Performance/Prediction Model	Remark
[126]	Whole-building energy	Three-parameter change-point regression model	36.9% global CV (RMSE) of the initial simulation was improved to 8.8% after a calibrated simulation
[127]	Optimal ON/OFF status for home appliances	Lightning Search Algorithm (LSA)-based Artificial Neural Network (ANN)	Reduce the peak-hour energy consumption
[128]	Feasible Time-of-Use (ToU) tariffs	Gaussian Mixture Model	Grouping half-hour interval flat-rate tariffs within a day into clusters to determine ToU tariffs
[129]	Electricity consumption with three consumption profiles	Constrained Gaussian Mixture Model	Consumer behaviour evolves over time depending on the contextual variables
[130]	Weather, time of day, and previous consumption	Support Vector Regression (SVR)	Impact of temporal and spatial granularity

Table 7. Concrete properties from previous research.

Ref.	Type of Concrete	Density, kg/m^3	Compressive Strength, MPa	Thermal Conductivity, W/mK	Specific Heat Capacity, kJ/kgK	Thermal Diffusivity, $\times 10^{-6}$ m^2/s	Remark
[131]	Foamed concrete						
	FA0-F30	1346.25	1.62	0.086			
	FA10-F30	1403.661	2.76	0.088			
	FA20-F30	1489.345	2.93	0.089			
	FA30-F30	1524.345	3.505	0.09	-	-	FA = Fly ash, F = foam
	FA0-F40	855.57	0.26	0.0842			
	FA10-F40	908.3	0.36	0.0853			
	FA20-F40	980.98	0.53	0.0863			
	FA30-F40	1010.74	0.62	0.0875			

Table 7. *Cont.*

Ref.	Type of Concrete	Density, kg/m^3	Compressive Strength, MPa	Thermal Conductivity, W/mK	Specific Heat Capacity, kJ/kgK	Thermal Diffusivity, $\times 10^{-6}$ m^2/s	Remark
[115]	Different grades of normal weight concrete with different proportions, water/cement ratios, and superplasticiser contents	2205 to 2498	15.8 to 62.1	1.6	1.04	0.69	
				2.2	1.1	0.87	
				2.5	1	1.06	
				2.7	0.95	1.19	
				2.4	1.04	1	
				2.9	1.01	1.18	
				2.3	0.99	1.02	
				1.8	1.16	0.7	
				2.3	1.03	0.93	
				2.7	0.94	1.2	
				2.4	1.11	0.94	
				2.5	1.04	1.01	
				3.2	0.95	1.34	
				2.9	0.92	1.29	
[132]	Formcrete Cement:sand = 2:1 Water/cement = 0.5	650		0.23	-	-	
		700		0.24			
		800		0.26			
		900		0.28			
		1000		0.31			
		1100		0.34			
		1200		0.39			
[133]	Concrete with expanded glass granules (GG)				-	-	GG300 = expanded glass granules 300 g GG400-S100 = expanded glass granules 300 g + sand 100 g
	GG300	685	5.8	0.163			
	GG400	561	4.1	0.141			
	GG500	558	4	0.14			
	GG400-S100	523	3.2	0.138			
	GG400-S200	645	3.8	0.161			
	GG400-S300	699	4.5	0.177			

Table 8. Cooling load of several wall materials without covers.

Mix Design	U-Value, W/m^{2}K	Cooling Load, W/m^2	Remarks
Structural lightweight concrete with expanded clay and oil palm shells [55,135]	6.62–7.18	55.5–60.16	New proposed equation: $U_c = 0.904 \times \sigma_c^{0.7}$ U_c = transmittance value and σ_c = concrete compressive strength, applicable to concrete strength $\geq$ 17 MPa
Normal structural concrete	21.96	175.68	
Clay brick	7.69	61.52	100 mm thickness
Concrete block	11.11	88.88	100 mm thickness
Non-structural foamed concrete [83]	3.92–5.29	31.36–42.32	102 mm thickness

5.1. Preliminary Study

It is necessary to quantify the energy consumption or energy saved when applying different types of concretes using a cooling load calculation or simulation. Before quantifying the energy consumption, the hypothesis of thermal resistance for lightweight concrete is better than normal concrete. In this preliminary study, the surface temperatures (the internal and external surfaces) of the casted wall sample and the conventional wall sample are recorded for further comparison. Figure 2 shows the experimental setup of the preliminary study.

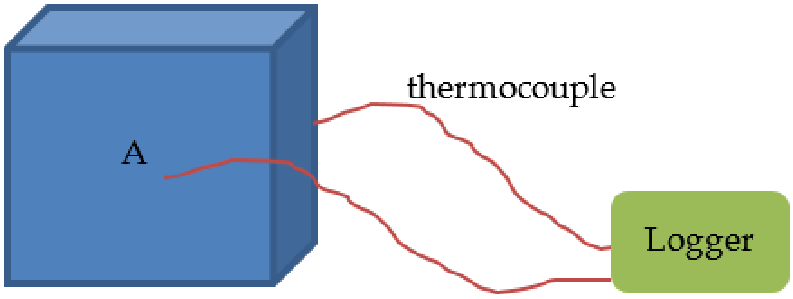

Figure 2. Experimental setup of the preliminary study.

The design mix of OPS & 50-QD of [55,135] has been adopted for preliminary data collection from tropical climate conditions and was compared to conventional concrete, as shown in Figure 2. The mix contained oil palm shells (OPS) as coarse aggregate and 50% quarry dust as a fine aggregate replacement. Scaled walls measuring 300 × 300 × 102 mm have been constructed. One surface of the wall was exposed to sunlight for 3 hours and another, opposite side was covered by polystyrene.

As shown in Figure 3, the surface temperatures of conventional concrete were found to not have a significant difference where variation was ranged in 1 °C or 2 °C, whereas, for lightweight concrete using OPS may have higher a variation at a particular time. The gradient of the graph for conventional concrete is steeper than the lightweight concrete. This can be related to the specific heat capacity since conventional concrete possesses higher specific heat capacity, which is a disadvantage during nighttime, as the heat will be released to the building's interior. There is a lack of information on lightweight concrete used in building envelopes as most of its applications have secondary uses in the construction of buildings. Therefore, further investigation on heat transfer should be conducted for lightweight concrete in tropical climate.

5.2. Case Study on a Residential House

The energy consumption for HVAC also related to the thermal properties of concrete, time lag, and decrement factors, and this case study is performed to examine the effects of lightweight concrete in cooling load calculation, assuming that the inner surface temperature is the indoor ambient temperature.

To exemplify the concrete thermal behaviour in a tropic climate, the surface temperature of an external wall of a residential house in Johor Bahru, Malaysia [136] has been used in the case study. The time lag and decrement factor, as well as mechanical properties of various concretes, have been obtained from a previous study [135], as summarised in Table 9. Some assumptions have been made to calculate the total amount of electricity used with different types of concrete, such that the material indoor surface temperature is the indoor ambient temperature. The surface temperature and ambient temperature were collected using thermocouple wire type-T with Graphtec Midi data logger and bad HOBO data logger, respectively. Otherwise, there are no other contributing factors for the concrete's thermal behavior.

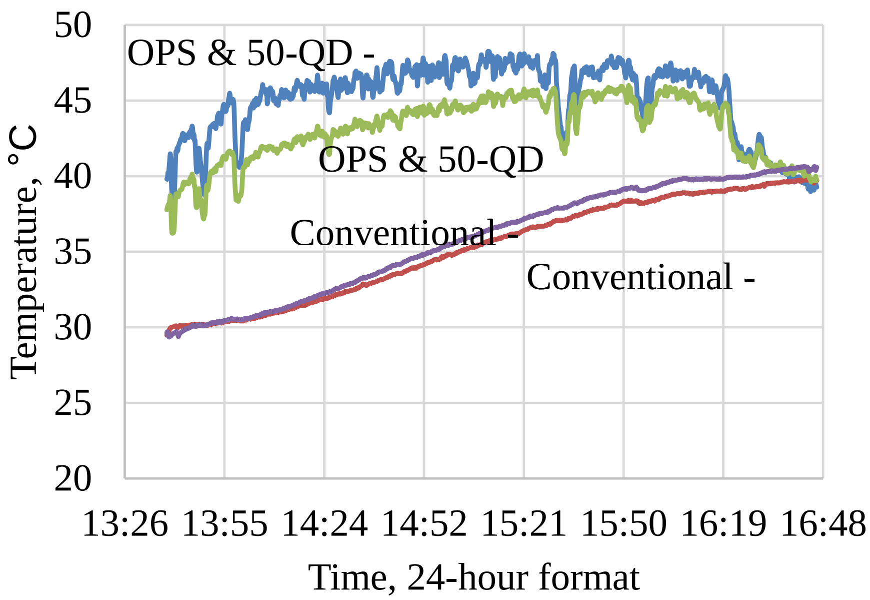

Figure 3. Comparison of surface temperatures for OPS & 50-QD and conventional concrete under three hours of natural sunlight exposure.

Table 9. Concrete thermal behavior [135].

Specimen	Density, kg/m^3	Compressive Strength, MPa	Decrement Factor (f)	Time Lag (ϕ), min.	Cooling Load, %
Conventional	2480	56.1	0.941	45	100
U-POFA	2360	55.3	0.913	45	100
G-POFA	2340	52.4	0.897	60	100
25-LECA & 75-OPS	1780	17.2	0.786	120	65
OPS & 50-QD	1880	19.3	0.834	105	29

The estimated inner wall surface temperatures are plotted for various concretes, as displayed in Figure 3. The reference line is introduced at 25 °C, as this is the average temperature for human thermal comfort [104]. Whenever the curves are higher than 25 °C, it is assumed that the cooling system is required. In other words, energy is required for the air-conditioning to regulate the drop in temperature. It can be seen that the concrete with 25% lightweight expanded clay (LECA) and 75% oil palm shell (OPS) with the lowest density of 1780 kg/m^3 demands relatively low energy for cooling loads. Other concrete walls necessitate more operational time of the cooling system. Although this estimation seems simple and may need further improvement and verification, the exercise illustrates qualitatively the effects of walls made from different concretes on the thermal flow behaviors. Next, the period time that the temperature was above the reference temperature has been measured and divided by the 48 hours of the designated total time frame. Table 9 shows the percentage of the resulting cooling load from which lightweight aggregate concrete with OPS showed a lower cooling load than the other concretes. The pores in the OPS and lightweight aggregates reduce the heat transfer within the concrete, proven by the decrement factor, leading to lower amounts of energy required for the indoor cooling system. The pores relate to the concrete density formation, and more pores means less density and lower heat transfer in concrete. With superior thermal resistance capability, the concrete strength is neglected, as both properties are not able to exist together. However, lightweight aggregate concrete with OPS possesses a lower density with a minimum structural requirement of 17 MPa according to the ACI specification and has better thermal performance. Hence, these two concrete mixes are highly recommended for future study in the consideration of optimal thermal behaviors coupled with mechanical considerations for tropical applications. Figure 4 shows the wall inner surface temperature estimation.

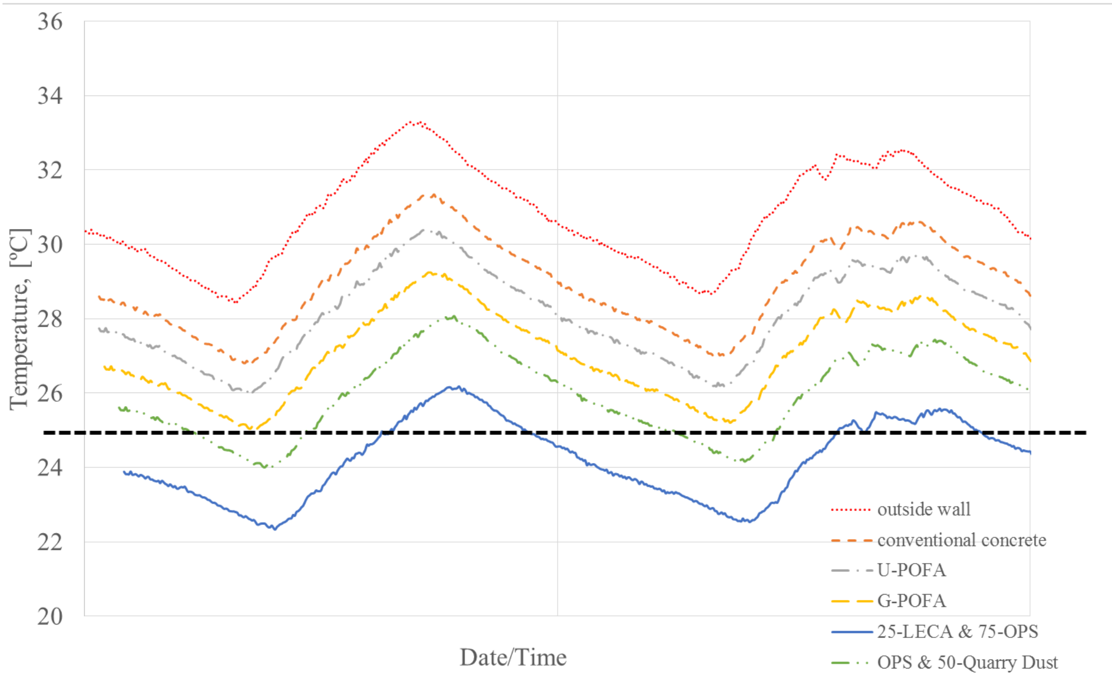

Figure 4. Wall inner surface temperature estimation.

5.3. Further Investigation and Application

In order to obtain more reliable thermal barriers in concrete building envelope design, quantifying the saved energy from various types of concrete can be an useful information in urban development planning. Energy consumption can be theoretically determined by simple cooling load calculation using Equation (9) [55]. Compressive strength is related to thermal conductivity as described in Equations (7) and (8). The correlation of the cooling load (concrete voids) and concrete strength can be proposed in future study.

For more accurate energy saving quantification, numerical investigation is one of the research trends that can be ventured for systematic urban planning. Other than concrete construction, thermal behaviour of dry construction and various types of building (such as commercial buildings) can also be studied for better energy consumption strategies in terms of a building’s performance stage. Development is a continuous activity that may cause environmental issues and systematic planning should be applied to minimize the negative effects.

6. Conclusions

This paper reviews concrete thermal behaviours in the context of a tropical climate. Based on this review study, several conclusions have been drawn as follows:

i. Temperature differences observed in UHIs of tropical countries have been highlighted.
ii. The building envelope is used to maintain the indoor temperature from outside temperature fluctuation and achieve human thermal comfort. Building materials are the sources of the heat regulation for the building envelope. Heat is transferred through conduction, convection, and radiation within the envelope before reaching indoors.
iii. Concrete thermal behaviours, such as thermal conductivity and thermal inertia, in terms of heat diffusivity, heat capacity, time lag, and the decrement factor can be determined and utilised for building materials to minimise heat transfer, and

thus reduce energy consumption since residential energy consumption contributes predominantly to the energy consumption of the overall country.

iv. Residential energy consumption remains the highest amongst all building energy expenditure performances in one tropical case study.

v. Current residential energy consumption models are still under the development and are far from maturity for real scenario application. Further study is warranted.

vi. Due to hot and humid weather conditions in the tropics, low specific heat and thermal conductivity are required to minimise the heat transfer through the building envelope. In other words, high time lag and a low decrement factor should be achieved for optimal energy efficiency in this weather condition.

vii. From a case study of a residential house located in Johor Bahru, Malaysia, a lower density concrete with a low decrement factor displays a superior thermal performance attributed to the lowest cooling load required to maintain the indoor temperature. Reducing the consumed energy paves the way towards the sustainability of human comfort in the tropical zone.

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