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A REVIEW ON THE BEHAVIOUR, PROPERTIES AND FAVOURABLE CHARACTERISTICS FOR THERMALLY INSULATED CONCRETE FOR TROPICAL CLIMATE

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Abstract

Tropical outdoor environment affects indoor temperature that consecutively interferes with human thermal comfort since most time is nowadays spent within buildings. A satisfactory indoor comfort can be achieved by providing a good building envelope. Therefore, the materials applied in constructing the building envelope should show characteristics of maintaining indoor temperature from the hot and humid outdoor environment utilizing heat transfer restriction through the thermal barrier implementation. In this regard, the thermal properties and performance of these materials are essential for building construction. Concrete, the main constituent in many building materials, has long been the key element in achieving human thermal comfort in the tropical climate. Nonetheless, there exists much room for improvement for conventional concrete in offering indoor thermal comfort, and thus leading to the need for innovative advances through the enhancement of thermal insulation properties by introducing novel additive materials. Therefore, this paper reviews the thermal insulation concrete including their thermal characteristics, classification, approach, added insulation material types, and usage in the context of tropical climates, concerning human thermal comfort. Key thermal properties needed for good thermal insulation performance have been discussed, from which beneficial behaviours relevant to thermal comfort are accordingly highlighted. Based on the reviewed materials and behaviours, recommendations for the most efficient method and characteristics to maintain indoor thermal comfort in tropical countries are consequently offered. Additionally, suggestions for future exploration are given where research gaps are identified. In summary, aerogel is the best thermal insulation material (lowest thermal conductivity, fire resistance and sustainable material) and incorporation of aerogel into concrete matrix able to produce thermal insulated concrete. In conclusion, thermally insulated concrete can reduce indoor temperature and therefore maintain indoor thermal comfort while capable of reducing electricity consumption for good thermal cycle sustainability.

Keywords: Thermal comfort, Thermal insulation material, Thermal performance, Thermal properties, Tropical climate.

1. Introduction

Indiscriminate urbanisations of rural areas all over the world impose significant alterations not only on their geographical and geometrical environments but cause also changes in their surrounding climates [1]. This is because urban structures change the surface energy budget, which introduces an additional thermal effect known as the anthropogenic heat. Anthropogenic heat is generated due to human activities and as the by-products of alternating cooling and heating of buildings, as well as from thermally-motivated events like manufacturing, transportation, and lighting [2, 3]. These activities directly increase the ambient temperature of urban areas through heat generation. The condition becomes more severe for cities with fewer plant populations to absorb carbon dioxide and release oxygen to the atmosphere, which leads to the creation of an urban heat island (UHI). UHI is a phenomenon when the temperatures of urban areas are higher than the surrounding rural areas [4]. As an immediate result, a higher outdoor temperature directly increases the indoor temperature, thus elevating also the indoor thermal discomfort level of tenants. To regulate such a globally common issue, thermal comfort has been introduced into the currently well recognised Sustainable Development Goals, which is the 2030 Agenda for Sustainable Development initiated by the United Nations. The aims are to promote and increase awareness, as well as to solve sustainability issues to conserve the environment.

Malaysia is one of the developing countries in the Southeast Asia region with a tropical climate that experiences the UHI phenomenon due to involvement in massive construction. Putrajaya [5] and Muar in Johor [6] are among the main cities suffering from UHI. Even elevated grounds like Cameron Highland in Pahang also experience UHI [7]. Under the calm and relatively clear night sky, the temperature difference between Kuala Lumpur, the capital of Malaysia, and surrounding rural areas can be up to 6-7°C due to UHI [8].

UHI phenomenon inflicts elevated temperatures in cities that cause outdoor thermal discomfort among the residents in urban areas [9]. In such conditions, people may fall ill while slowly suffering from heat stress, and in the worst-case scenario, are exposed to the possibility of heatstroke. Hence, most of the time, people tend to stay indoors due to hotter outdoor conditions. Despite the introduction of many technological advances, the use of natural or mechanical ventilation through fans is lowly efficient in maintaining thermal comfort [10]. To solve this problem, the air conditioning system remains a common solution. The scientific findings reported by [10-13] and show evidence that the peak electricity demand and energy price are in the rise due to the heat island phenomenon. Lundgren and Kjellstrom [12] stated that there is an increasing trend in the utilisation of air conditioning, especially in the South and Southeast Asia countries in recent years. It is well expected that the demand for air conditioning can be increased by 40 times in 2100 compared to 2000 [12].

In well-developed countries, the situation is not that much different either. Take Britain for example, the rural office building energy consumption for cooling is only 84% of urban consumption [13]. The simulation of the differences in the energy consumption of office buildings in several large cities affected by UHI in the United States of America [14] showed that the urban ambient temperature caused by the UHI effect was higher than the suburban temperature by 2°C on average and there was an observable increase of energy consumption by 17.3% for buildings cooling. Moreover, Oxizidis et al. [15] reported that the energy consumption for heating of buildings in the city centre of Lisbon was lower than that in the suburbs due to the UHI effect. Some existing literature also shows that 40% of energy demand accounted for building energy consumption is purposely used for cooling and heating [16-18].

The building envelope is defined as the physical separator between the conditioned and unconditioned environments of a building. There is a close relationship between the building envelope and indoor thermal comfort. Absorptivity of external surfaces, thermal capacity, and thermal conductivity of the building envelope all affect greatly the internal environment and consequently the energy consumption inside the building [17] to maintain thermal comfort. According to Gratia and De Herde [18], more than 50% of the embodied energy distribution in major elements in residential buildings comes from building envelopes, contributing approximately 50%-60% of their total heat gain [19]. To remedy this matter, Utama and Gheewala [20] found that building envelope materials can significantly affect the cooling load in high-rise buildings while contributing to their energy life cycle. This is because roofs and walls tend to absorb heat and discharge long wavelengths, the processes of which release the heat causing the UHI [21]. The texture and materials used for façades and roofs also affect the internal and external thermal ambiance [21].

Elevated outdoor temperature directly influences indoor temperature and hence bring about the indoor thermal discomfort. This then creates issues such as health problems and higher energy consumption to maintain the indoor thermal comfort level. For tropical countries that suffer from hot and humid weather every day, the demand for air conditioning is continually increasing from year to year. Due to limited technology and financial status, the main production of electricity in many regions still depends on fossil sources. This further increases the amount of greenhouse gases on Earth. Since the chief mechanism of thermal discomfort roots in the heat transferring event, an easier and practical way to maintain indoor thermal comfort level is to apply thermally-insulated materials to limit the movement of heat. In this regard, it is essential to understand the numerous characteristics of thermal barriers available in the market. Therefore, this paper offers a review of the thermal insulation behaviours of building materials for application to concrete, especially for the tropical climate in relation to human thermal comfort. The following sections begin with a discourse on the heat-related terminologies, issues, and the mechanisms of heat transfer across building envelopes in tropical countries. The review then continues with the thermal comfort and thermal insulation materials including the evaluation of their properties and relationship as the main subjects of discussion. A general outlook on these discussions concerning concrete as the building material intended for thermal insulation specifically in tropical countries is then provided. Concluding from the review, recommendations are given at the end of this paper for the most efficient method to maintain indoor thermal comfort in tropical countries.

2. Thermal Behaviour

2.1. Heat transfer mechanism

In principle, heat can be transferred due to the temperature difference between two or more regions. In terms of buildings, this corresponds to higher outdoor ambient temperature, which tends to affect indoor thermal comfort as heat is transferred from outside to inside or vice versa due to the change of temperature gradient from different regions. However, capturing or descriptively explaining the amount of heat transferred is rather a complicated task and it is customarily related to the heat transfer mechanism. The concept of heat flow is presented in Fig. 1. There are essentially three types of heat transfer mechanisms, namely conduction, convection, and radiation. In buildings, heat is transferred by means of radiation and convection via air, whereas conduction is carried out via a medium.

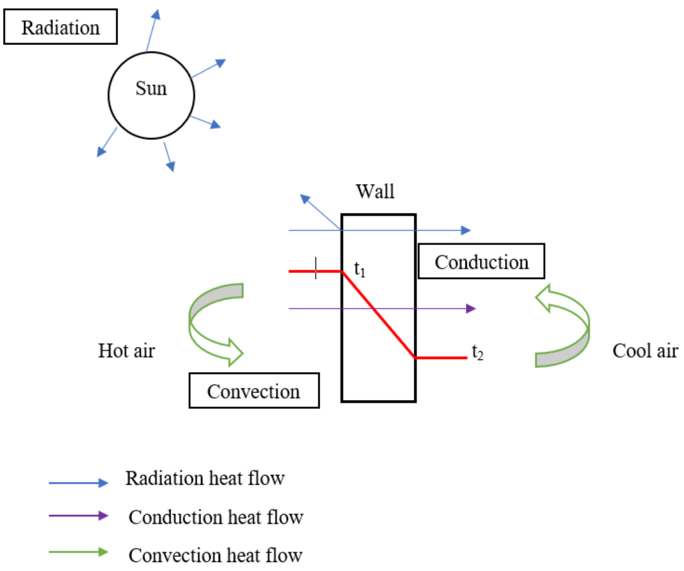

Fig. 1. Concept of heat flow.

Conduction of heat is the transfer of heat between adjacent molecules of solid, liquid, and gas and between different materials in close contact with each other without any bulk movement of those materials [22, 23]. Through conduction, heat is transferred in buildings via a temperature difference between the inside and outside regions, from which internal heating or cooling can be lost to the external environment, resulting in high operational costs, carbon emissions, and occupant discomfort. However, conduction can be reduced by insulating materials that have high thermal resistance through the reduction of heat transfer between the concerned areas.

Convection happens when there is a flow of heat by liquid or gas via loosely moving molecules from one place to another [23]. In other words, convection is resulted from the movement of air with different temperatures. Air movement in buildings can be divided into mechanical and natural ventilation. Mechanical ventilation refers to the enhanced movement of air by fans whereas natural ventilation depends on the openings (windows) on buildings for the same heat-dissipating mechanism. Natural air movement can be either wind-driven or buoyancy-driven. For example, hot air moves from the outside into the inside of buildings, which is much cooler in a tropical climate. Circular air force occurs as cooler air is much denser than hot air.

Thermal radiation is the process of heat released from materials due to its internal condition [24]. Bodies that are hotter than 0°K will emit thermal radiation. Despite that, the bodies also absorb thermal radiation emitted by their surroundings. Through the simulation of the heat transfer affecting a specific building envelope, Carlini et al. [25] confirmed that the introduction of an exterior insulation cover increases energy efficiency and thermal behaviour of the building. Surfaces in the built environment tend to absorb solar radiation and emit long-wave infrared radiation. For example, materials with high thermal mass, such as bricks, absorb heat during the daytime but release it during nighttime.

In summary, since all aforementioned heat flow concepts are relevant to thermal behaviours of buildings, to successfully maintain indoor thermal, it is necessary to limit heat transfer through these three mechanisms.

2.2. Thermal mass, thermal conductivity and thermal resistance

Thermal mass is defined as the ability of materials to absorb, store, and release heat. By definition, high thermal mass materials can store more heat than those with low capacity. High thermal mass materials, such as concrete, bricks, tiles, etc., can be referred to as high-density items as more heat is required to increase their temperatures. Meanwhile, an example of low thermal mass materials is timber. High thermal mass materials store heat during the daytime and release it at night. For countries with a cold climate, high thermal mass materials can maintain thermal comfort levels at night by releasing heat. Hence, lesser energy is required for heating purposes. However, in tropical countries, such function has low suitability. High thermal mass materials are not recommended for hot and humid tropical countries [26]. High thermal mass materials are not greatly attractive as construction materials since heat will be released at night, thus increases the indoor temperature and causes thermal discomfort. So, thermal mass is beneficial in areas where there is a big difference between day and night outdoor temperatures. Thermal mass for concrete, bricks, and autoclaved aerated concrete are 2060 $kJ/m^3{\cdot}J$, 1360 $kJ/m^3{\cdot}J$, and 550 $kJ/m^3{\cdot}J$, respectively [26]. Therefore, concrete and bricks possess high thermal mass compared to autoclaved aerated concrete, from which the thermal comfort level can be greatly influenced.

There are various ways to describe the characteristics of heat, the chief parameters of which are thermal conductivity and thermal resistivity. Thermal conductivity is the ability to conduct heat through a material. It is defined as the amount of heat (kcal, Btu, or J) that can be conducted in unit time through unit area of a unit thickness of the material. It is expressed as watt W/m°C or W/m·K. Thermal conductivity is also defined as the *k*-value, whereas thermal resistivity is the reciprocal of *k*-value (1/*k*). The larger the *k*-value, the smaller the thermal resistivity.

Moreover, the thermal performance of an element of a building can be represented by the thermal resistance (*R*-value) and thermal transmittance (*U*-value). *R*-value is the rate of heat transferred through a square meter multiplied by the difference in temperature on either side of the material. It is the reciprocal of the coefficient of thermal conductance, *l*, which is defined as the resistance of the material to heat. *l* is expressed as $W/m^2{\cdot}K$ depending on the material thickness. Based on its basic equation shown in Eq. (1), it is known that the thicker the material, the lower the thermal conductivity.

$$Thermal\ conductivity, k = \frac{Q \times d}{A \times \Delta t} \quad (1)$$

where Q is the amount of heat transferred (W), d = distance between 2 isothermal planes (m), A = area of the surface (m^2), and Δt = difference of temperature (K).

Therefore, the good performance of thermal insulation shall have a lower thermal conductivity value and a high value of thermal resistance. Other than that, the *U*-value, which is defined for the thermal transmittance, is a reference to quantify the thermal conductivity by means of the reciprocity of *R*-value, $1/R$. It is used to measure the effectiveness of elements of a building's fabric as insulators. In general, the thermal barriers with low thermal mass and thermal conductivity but high thermal resistance show great suitability to be applied in tropical countries.

2.3. Thermal comfort

Thermal comfort is the state of mind that expresses satisfaction with the thermal environment and is assessed by subjective evaluation [27]. It is also defined as no strong impulse to correct the environment by behaviour [28]. In general, the factors that contribute to thermal comfort are ambient temperature, radiant temperature, relative humidity, air velocity, metabolic rate, and clothing insulation [28], which can be assessed by the Predicted Mean Vote. Thermal comfort is influenced by both environment and the human body [29]. It can be discussed in terms of indoor and outdoor. Since the evaluation of thermal comfort is highly subjective, the perception of comfort or discomfort may vary. Therefore, there are many indices available to evaluate indoor thermal comfort, with Predicted Mean Vote proposed by Ole Fanger [30] as shown in Eq. (2) is the index that is widely used [31].

$$\text{Predicted Mean Vote} = (0.352e^{-0.042\times\frac{M}{A_{DU}}} + 0.032) \times \Big\{\frac{M}{A_{DU}} \times (1-\eta) - 0.35 \times \Big[43 - 0.061 \times \frac{M}{A_{DU}} \times (1-\eta) - \rho_\alpha\Big] - 0.42 \times \Big[\frac{M}{A_{DU}} \times (1-\eta) - 50\Big] - 0.023 \times \frac{M}{A_{DU}} \times (44 - \rho_\alpha) - 0.0014 \times \frac{M}{A_{DU}} \times (34 - T_\alpha) - 3.4 \times 10^{-8} \times f_{cl} \times [(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] - f_{cl} \times h_c \times (T_{cl} - T_\alpha)\Big\} \quad (2)$$

where M/ADU is the metabolic rate (W/m^2), η is mechanical efficiency, ρ_a is pressure of water vapour in ambient air (mmHg), = ϕ ×exp[16.6536 - 4030.183/ (T_a+235)], ϕ is the air humidity, T_a is air temperature (°C), f_{cl} is the ratio of the surface area of the clothed body to the surface area of the nude body, T_{cl} is the temperature of the clothing surface (°C), T_{mrt} is the mean radiant temperature (°C), h_c is the convection coefficient

h_c = {2.38(T_{cl}-T$_a$)$^{0.25}$, 2.38(T_{cl}-T_a) > 12.1√V {12.1√V, 2.38(T_{cl}-T_a) < 12.1√V, V = velocity of air

Equation (2) shows that thermal comfort is governed by environmental and personal factors. First, metabolic rate is the energy released by a human due to muscle activity and the value differs due to gender and activities conducted. Men tend to have higher metabolic rates than women and their body temperatures are higher than women. Physical exercises also produce more heat due to a higher metabolic rate than a relaxed condition. Accordingly, a higher metabolic rate contributes to lower tolerance towards thermal comfort as more heat is produced to maintain body temperature at around 37°C.

Moreover, the surrounding air temperature is another variable that contributes to thermal comfort. Higher ambient temperature tends to cause thermal discomfort among humans. Furthermore, radiant temperature, which is the heat radiated from a warm object, is also one of the variables in determining thermal comfort. A person will feel cool when the wall of the building is cold even though the air temperature of the building is hotter than the wall and vice versa [32].

Additionally, air velocity also affects the thermal comfort level. When the temperature inside a building is hot, the situation when coupled with a stagnant air can be worsened by a further increase in the thermal discomfort of the residents. Likewise, when there is air movement and the air is cool, residents' comfort is increased as well. Humidity is also a factor affecting thermal comfort. When the surrounding temperature is higher, the body will start to sweat as a mechanism to prevent overheating. However, high humidity with hot air temperature prevents the evaporation of sweat from the skin, thus causing thermal discomfort. Lastly, clothing insulation also plays a role in influencing thermal comfort. Some clothing materials such as cotton tend to absorb sweat and allow filtration of air through the material, whereas spandex causes some relative discomfort.

According to Kabrein et al. [33], the outdoor condition has a great influence on the indoor climate. The influence of the outdoor environment towards the indoor climate is attributed to the heat transfer mechanisms that encourage the heat flow through the building envelope to increase the indoor temperature as walls and ceiling will absorb and release heat. Hence, the design and materials of walls greatly affect the building's thermal properties. Nowadays, non-residential building façades are often highly glazed with a large area of glass for aesthetic appearance and prestige. Solar radiation and window performance heavily affect the thermal comfort of occupants in buildings glazed perimeter zones [34]. Solar radiation passes through the glass façade to the internal part of the building, which in turn causes thermal discomfort to the occupants, especially in a tropical climate where the heat is trapped inside the building.

The glass façade allows the direct transfer (minimum blockage) of solar radiation from outside, hence, negatively affects the indoor thermal comfort. Therefore, there is a relationship between façade and indoor thermal comfort. Also, buildings such as terracotta ventilated façade finished cement mortar, buildings with brick plastering by mortar, curtain walls with single glazing, and double skin steel façades have different effects towards indoor temperature. According to Khadraoui et al. [35], terracotta ventilated façades finished cement mortar and buildings with brick plastering by mortar have low and stable indoor thermal comfort. Curtain walls with single glazing and double skin steel façades show the tendency in increasing indoor temperature after certain exposure to sunlight, since the heat is released by the materials. It is, therefore, apparent that walls have a direct relationship with indoor thermal comfort.

In short, heat is one of the factors contributing to thermal discomfort. To address the problem, the prevention of heat transfer through its three main mechanisms is necessary by determining the thermal performance using Predicted Mean Vote.

2.4. Building envelope in thermal control

Shelters or buildings are constructed to achieve a constant temperature from the outside environment. From ancient caves living to current building systems, the application of building science has been improved by the use of well-developed materials to form the building envelope. Building envelopes consist of several components architecturally, namely physical form and orientation, opaque system, transparent system, and shading. Relating to indoor thermal performance and energy consumption, a building envelope is essential in limiting the heat gain from the outside environment. Chua and Chou [36] and Zingre et al. [37] found that about 30% of power consumption is due to the heat gain from opaque systems, namely walls and roofs in the tropical climate.

One of the principles of enclosure design is through heat flow control, which is related to wall or roof performance. In building envelope consideration, the control strategy of heat transfer includes thermal insulation, radiation barriers, and air barrier system. These systems consist of several materials to control the unwanted movement of air into and out of the building enclosure. Operating cost and energy consumption can be reduced as air leakage and air convection are being minimised. Airtight insulating materials will not allow the formation of convective heat transfer, but the transfer can occur in air gaps located in materials wider than 5 mm [38].

Radiation, which is largely attributed to the roof, is the main cause of heat transfer in non-commercial buildings [39]. The roof is the main component of a building subjected to a full-time exposure of sunlight compared to walls as the exposure of sunlight to the wall depends on the orientation of the building. Heat is transferred through radiation from the roof and subsequently heat conduction to allow transfer to the whole building. Alyasari et al. [40] found that 50% of the heat load in the buildings come from the roof, which increased indoor temperatures above comfort levels during summer. Radiant barriers can reduce the heat transfer rate in attics compared to attics without radiant barriers by 6%-7.7% [41]. The experiment conducted by Asadi and Hassan [42] showed that the radiation barrier reduced the energy load by 17% depending on the climatic conditions. A radiation barrier has been exhibited to minimise 70% of heat flux to the inside of the residential area during the day of higher solar radiation [43]. The radiant barriers are thin sheets made from highly reflective material, such as aluminium, which are applied on one or both sides of the sheets. To increase durability, aluminium is applied together with plastic films or carton. The lower the emissivity of a material, the better the radiant barrier performance. This is because more heat is reflected away than being absorbed. Thus, the application of radiant barriers is a promising material to maintain indoor thermal comfort.

One of the current architectural trends is using glass as the façade as it can be easily installed and has a relatively low cost. However, the use of glass as the façade for buildings for aesthetical and natural lighting purposes consumes more energy than the traditional façade [44]. This is because the transparent properties of glass allow the solar heat to directly penetrate buildings such that more energy is needed to maintain thermal comfort. Therefore, a material with high reflectivity or high albedo is introduced as a remedy to minimise the absorption of solar radiation, thus reduces its restitution in long-wavelength at night. Traditional façades are defined and referred to buildings with brick plastering by mortar. Widely used building materials such as bricks and concrete have high thermal mass and high thermal conductivity. Heat tends to be absorbed in the morning and released by night. Moreover, from the study of Zhang et al. [45], it is concluded that the application of retro-reflective coating materials can reduce the need for cooling in the daytime significantly since there is a decrease in the heat gain from solar radiation. Simulation of heat transfer affecting a specific building envelope and future improvements by adding exterior insulation by Carlini et al. [25] confirmed that an insulation cover increases the energy efficiency and thermal behaviour of the building. Materials with high reflectivity (high albedo) and insulated building façade (material) can minimise the absorption of solar radiation, thus reduce release of long wavelength at night.

In summary, thermal control of a building is discussed in three methods (thermal insulation, radiation barriers, and air barrier system) that are employed as effective ways to control the heat flow of a building. However, among the systems, only the thermal insulation system is further discussed in the following section.

2.5. Thermal insulation system

A thermal insulation system functions to conserve energy while insulating buildings from heat and cold, thus preventing thermal discomfort among the tenants. It can be achieved by the implementation of thermal insulation materials to prevent heat flow mainly through heat conduction. A thermal insulation system can be applied to the external, internal, or core of the building. External thermal insulation refers to the application of thermal insulation materials on the outer wall exposed to the outer environment. Meanwhile, internal thermal insulation refers to the application of thermal insulation materials on the wall for the internal environment. Besides, core thermal insulation is the application of thermal insulation materials in the wall cavity either by complete or partial filling. External and internal thermal insulation systems are better compared to core thermal insulation because it applies to both new and existing buildings. The main key to the success of a thermal insulation system is the thermal insulation materials.

Numerous insulation materials available in the market have been applied to building systems, namely reflective materials, insulating boards, blanket insulation, slab insulation, block insulation, lightweight materials, loose-fill insulation, and bat insulating materials. Moreover, roof shading, good building orientation, and proper ceiling height contribute also to effectively cool down the building heat. Having described the insulation system, existing insulation and material types including their required characteristics employed for the system restricting specifically to concretes are next reviewed.

3. Type of Thermally-insulated Concrete

Thermal insulation materials play an important role in the good functioning of a thermal insulation system. There are several parameters of building envelope components for consideration in building science, including building dimensions, materials, insulation system, window-to-wall ratio, building orientation, as well as glazing types and layers. By ratio, walls and roofs are exposed to heat more frequently than other building envelope components. Da Silva and Ssekulima [46] demonstrated that the design and materials of the entire wall have a direct influence on the energy properties. Traditionally, a thermal insulation system is applied with an insulating layer to improve energy efficiency and human comfort in the indoor environment.

The purpose of thermal insulation material is to reduce the heat flow by limiting heat conduction, convection, radiation, or all three while performing several functions. First, the material reduces heat loss or gain by conserving energy. Second, the surface temperature is controlled to provide personnel protection and comfort. Third, the material increases the process of vapour flow and water condensation. Fourth, the material enhances the operating efficiency of heating/ventilating/cooling, plumbing, steam, process, and power systems found in commercial and industrial installations.

There are various types of thermal insulation materials available for implementation. Naturally, porosity is the criterion that can enhance thermal insulation properties. The material can either be naturally or synthetically produced. Many scholars have noticed that porosity can reduce heat transfer [47, 48]. This is because heat will pass through from the surface of the material to the bulk and then leaves the material. With high internal porosity, the material contains a large volume of air. Air is a much better insulator than any solid material as it has the lowest thermal conductivity [49]. Accordingly, less heat is conducted across the air to the outside of the material. Concretes such as autoclaved aerated concrete, lightweight concrete, and aerated concrete do not only have low density but also low thermal conductivity properties [49]. A study by Real et al. [50] confirmed that in European countries, the application of structural lightweight aggregate concrete in buildings could reduce 15% of the heating energy compared to normal weight concrete. Asadi et al. [39] stated that autoclaved aerated concrete, lightweight foam concrete, and aerated concrete are all used as thermal insulation materials based on the principle that porosity is present in all these materials. Further, it was reported by Asadi et al. [39] that by increasing the concrete porosity by 1%, the thermal conductivity can be reduced by about 0.6%.

Other than using the material that originally has low thermal conductivity properties such as porosity, the incorporation of materials with low thermal conductivity inside another material without thermal reduction properties is an approach to reduce thermal transfer. It depends on the thermal conductivity of the material added. Porosity encloses air inside the material and air is known to have the lowest thermal conductivity [51], thus reduces the heat transfer across the material. In general, thermal barrier materials can be categorised into fibrous insulation, cellular insulation, and granular insulation [52]. Common fibrous insulation materials are mineral wool and cellulose, whereas cellular insulation can be represented by expanded polystyrene (EPS), extruded polystyrene (XPS), cork, and polyurethane. Expanded perlite is a common granular insulation material nowadays. Meanwhile, the latest insulation material is aerogel. All aforementioned materials are discussed in detail in the following sections.

3.1. Fibrous insulation

Fibrous insulation contains generally small-diameter fibres that finely divide the air space. The fibres within the material capture air by preventing heat transmission through convection. It can restrain heat conduction between molecules of gases by reducing collisions between the particles. Even though this kind of insulation is flexible, it can become rigid by using additives to form specific shapes.

Mineral wool is the general term for rock mineral wool and glass mineral wool. These materials are prepared by melting quartz sand, basalt, dolomite, and glass at high temperatures [53]. Glass mineral wool can be in the shapes of flexible rolls, rigid slab, and preformed pipe section [52]. The wool is suitable for steam pipelines, hot water lines, and aircraft industries [54]. Besides, the non-flammable properties make the wool very suitable to be used in high-temperature applications [55]. Rock mineral wool is applicable for insulation and fire protection of plants, equipment, and structures in commercial and industrial sectors [52]. In the investigation of the thermal performance of glass wool after 25 years in masonry cavity walls, Tittarelli et al. [56] verified that about a 12% increase could be observed in the average thermal conductivity due to the decreased hydrophobicity of the glass wool. Menon and Naranje [57] showed that rockwool used as the insulator in the concrete block was able to reduce the temperature. Cabeza et al. [58] observed that with the implementation of mineral wool as the insulation material, monthly energy consumption of approximately 5.8 kW·h could be reduced. It is also a non-combustible material [52]. However, mineral wool is very vulnerable to moisture as the material absorbed approximately 4%-8% water of their weight and the thermal conductivity increased more than four times, thus making it difficult to determine the proper performance as an insulator in a high humidity area [59] although its thermal conductivity is 0.03-0.04 W/m·K [60]. Thus, mineral wool is not suitable to be applied in tropical countries with high humidity. Figures 2 and 3 displays images of rock wool and mineral wool respectively.

Cellulose is made from recycled newsprint and treated to resist mould, fire, and insects. It is one of the eco-friendliest insulators. Due to compactness, oxygen is not present inside cellulose. Therefore, the material is highly promising as a fire retardant. Cellulose-based fibre thermal insulation materials are better than other types of materials from the sustainability point of view [61]. Nevertheless, cellulose tends to absorb moisture, which in turn reduces the thermal conductivity. Moreover, some people tend to be allergic to the dust from newspapers. The thermal conductivity of cellulose is 0.04-0.05 W/m·K [60]. Figure 4 shows image of cellulose.

Fig. 2. Rock wool [62].

Fig. 3. Mineral wool [63].

Fig. 4. Cellulose [64].

3.2. Cellular insulation

These materials are formed from small individual cells either through interconnecting or sealed from each other to form a cellular structure. Cellular insulation can be open cell (cells are interconnecting) or closed cell (cells are sealed from each other). A high amount of spaces or porosity in the materials is good in reducing heat transmission.

Expanded polystyrene, EPS (Fig. 5), is made from expanded polystyrene, which is a rigid cellular plastic containing an expansion agent [65]. The material has performed well in packaging and building insulation. It is useful for shipping temperature-sensitive substances due to its properties, such as insulation, shock absorption, durability, no-biodegradability, and low cost. EPS was initially mainly used for insulation foam of closed cavity walls, roofs, and floor insulation [66]. The material is now used in the construction of roads, bridges, floatation, railway lines, buildings, and drainage. EPS is also commonly used for wall panels and slabs with steel meshes as reinforcement [67]. Singh [68] concluded that the use of EPS insulated cavity walls achieved about 31.9% less heat transfer compared to conventional solid brick walls. Li et al. [69] showed that when using external solid brick walls composed of 50-mm thick EPS boards on their outside surfaces, the hourly heat transfer was reduced to about 67.5%, thus provided a good thermal comfort condition for the indoor environment. However, it is a non-biodegradable material, and its panels must be protected against the harmful effects of humidity as the moisture content greatly influences thermal conductivity. EPS properties such as brittle and lightweight make the material hard for most mixed recycling systems to handle [70]. Not only does EPS causes environmental problems at the end of its life, but the production of virgin EPS is also an energy-intensive process, with a slew of associated negative environmental impacts. Many studies reported that EPS is commonly one of the top items of debris recovered from shorelines and beaches worldwide [71-73]. Polystyrene microspheres (components of EPS) are one of the only microplastics available from scientific companies. They have been related to bringing negative impacts to humans. Their thermal conductivity is 0.03-0.04 W/m·K [60].

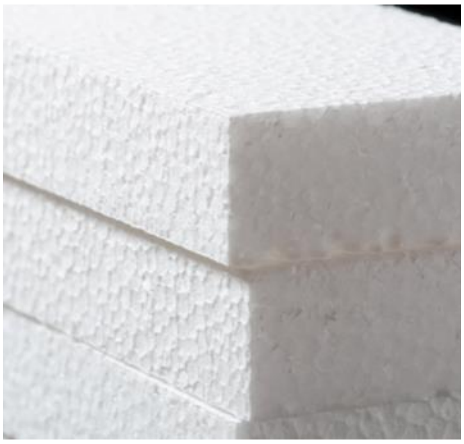

Fig. 5. EPS [74].

Through the depressurised foaming process, the foam forms a perfect regular closed-cell structure with high mechanical properties, outstanding creep resistance, and no dust. Extruded polystyrene, XPS, has the properties of dust-free, non-corrosive, very good resistance to water vapour condensation, but poor fire resistance [75]. The difference between EPS and XPS is that the beads of XPS are thermally fused and exhibit an interstitial space, in which water vapour can condense and affect the performance of thermal insulation. Cabeza et al. [58] observed that with the implementation of XPS as the insulation material, about 6 kW·h of monthly energy consumption can be reduced. According to Vo et al. [76], more than 200 million m^2 of XPS is used in Europe and is expected to further increase in demand due to its long-term performance and durability. However, XPS is a non-biodegradable material, making it non-environmentally friendly. Its thermal conductivity is 0.03-0.04 W/m·K [60].

Oakwood is generally used in cork, which can be obtained from a cork oak tree. This tree exists in Portugal and Northwest Africa. It needs a lot of sunlight and a highly unusual combination of low rainfall and slightly high humidity. Cork extraction is carried out when its growth is the highest during summer because the phellogen is in full meristematic activity, allowing easy separation of cork layers. The air makes up 90% of its volume and about 50% of the weight is enclosed in the cork micro-cells. The material is lighter than water and virtually unsinkable as the material is also impermeable to water. Besides, cork is chemically inert. Its structure is impervious to liquids, gases, and chemicals. Cork also maintains neutrality of taste and odour and does not absorb either. The presence of air inside the cork makes it a good thermal insulator. Cork is usually used in petrochemical-based insulation products. Despite that, cork can be found in aerospace applications due to its thermal properties, slow burn rate, and shock absorption capacity [77]. Its thermal conductivity is 0.04-0.05 W/m·K [60].

Polyurethane (PU) is a composite solid-gas material, in which the continuous phase is the PU polymer, and the gas phase is the discontinuous phase. PUs are an extremely flexible group of polymers that can be produced in a wide range of crosslink densities, stiffness, and densities [78]. These components are mixed to form a rigid, cellular foam matrix. They are produced by mixing an isocyanate, for example, methylene diphenyl diisocyanate with a polyol blend. Most of the PU foams are applied in the furniture industry, where 32% is used for the production of mattresses from flexible slab stock foams. Furthermore, they are applied for flexible PUs in automotive manufacturing, such as seat cushions, bumpers, and sound insulation. Meanwhile, rigid PU foams are used in thermal insulation of buildings and refrigerators, pipe insulation, thermal insulation in chemical, and food industries [78]. However, PU foams are not fire-resistant and likely to degrade upon exposure to elevated temperatures during the fire accident [79].

Moreover, PUs are derived from petroleum-origin raw materials [79]. Based on the findings of Václavík et al. [80], by using PU as the aggregate for mortars and lightweight concrete, moisture was able to be drained naturally away from the interior of buildings, less labour intensive, whereas rendering and plastering could be applied manually or mechanically. Besides, for refurbishment and additional thermal insulation, PU rendering can be applied directly to coarse-grained renders of Brizolit type. It increases the total resistance of buildings towards the thermal of the building, and simultaneously allows water vapour to freely move across through the walls. Gutiérrez-González et al. [81] investigated the effects of PU waste in a lightweight plaster material. They observed that the thermal conductivity was reduced by up to 66% relative to the material without PU foam waste. Lanjekar and Kadam [82] also found that 0.5% of PU foam in concrete was able to reduce thermal conductivity by 17.9% for 28 days of curing.

3.3. Granular insulation

Granular insulation comprises small nodules containing voids or hollow spaces. A foaming agent is used to connect all of the small nodules. Voids are the key to reduce heat transfer as air has the lowest thermal conductivity than solid materials.

Perlite is a type of rock produced during the eruption of volcanic rock consisting of amorphous silica (70%-76% wt. SiO_2) with low amounts of other metal oxides (aluminium oxide, potassium oxide, sodium oxide, iron oxide, calcium oxide, magnesium oxide). The presence of 2%-6% of chemically-bound water in its structure can be expanded up to 35 times its original volume when heated rapidly at high temperature in the range between 700 and 1260 °C [83] as the trapped water vapourises and pushes its way out of the grain [84] to form expanded perlite (EP). EP is a white, ultra-lightweight aggregate with a particle size up to 6 mm [85]. The material can provide excellent thermal insulation over an extremely wide temperature range from -273 up to over 1,000 °C [85]. Its surface can absorb a high amount of heat and has a very low bulk density, and hence ideal as a carrier or low-cost filler for many compound formulations. EP has good characteristics, such as chemical resistance, low water absorption, and good thermal insulation [86]. From the finding of Purandara et al. [85], using EP aggregates instead of sand can provide good thermal protection to concrete as the concrete still achieved more than 90% of its ambient strength when exposed to temperatures up to 600 °C. When 15% of EP in powder form was added to mortar, the thermal conductivity was reduced by 50% [87]. Pruteanu et al. [88] mentioned that EP in mortar reduces the thermal conductivity without any loss in compressive strength. The thermal conductivity of EP is 0.4-0.6 W/m·K [88].

3.4. Aerogel

Aerogel is a porous material comprising cross-linked nano-solid particles (usually 2-5 nm in particle diameter) [89] with nano-pores (normally 10-100 nm in average pore size diameter) [90]. Hence, aerogel has a high specific surface area (~500-1200 m^2/g), high porosity (~80%-99.9%), and low density (~3-350 kg/m^3) [91]. Due to its nanostructure, the heat transfer across solid conduction and gas conduction can be effectively prevented with low thermal conductivity (~0.01-0.02 W/m·K), which is lower than air (~0.025 W/m·K) [92]. Furthermore, aerogel is significant as a material for fireproof and soundproof materials with sound velocities down to 40-100 m/s [89, 90]. Aerogel is also visibly transparent with thermal insulation properties, which is very suitable to be applied for windows.

All of these properties make aerogel a promising material with good thermal insulation, sound resistance, and fire prevention. Recently, aerogels can be found available in the market as blankets, sandwich panels, glazing, and based coatings [90, 93]. Aerogel is applied for oil and gas pipeline insulation, cryo insulation, daylighting applications, construction materials, flexible blanket insulation, aerospace, apparel, and shipping containers [94]. However, aerogel is mainly used for thermal and acoustic insulation in buildings [94]. NASA has also used aerogel to collect space dust particles and for thermal insulation of space suits [95-97]. Although aerogel is a multifunctional material, there are some drawbacks. It has a high production cost, poor mechanical properties, and exhibits health threats [94]. Supercritical drying is one of the steps to produce aerogel, but it is very costly [98]. Due to the porosity present inside aerogel, the material is very fragile.

Aerogels can also bring discomfort to the eyes, skin, respiratory tract, and digestive systems due to its size. Based on the research by Schuss et al. [99], 4 cm of aerogel plaster on an existing 42-cm brick wall, including 2 cm of plaster, reduced the *U*-value from 1.25 to 0.46 $W/m^2 \cdot K$. When aerogel was applied in windows, the thermal conductivity reduced by 32% than windows without aerogel [100]. According to the study of Nuruddin et al. [101], the highest difference of outdoor and indoor temperatures was evident at 8.6°C at 1 p.m., which was achieved by aerogel insulation roof compared to stone wool and aluminium insulation. In short, aerogel is introduced as promising new thermal insulation material as it is able to insulate thermal.

4. Properties of Thermal-insulated Concrete

Numerous types of thermally insulated concrete have gained the attention of researchers and being introduced into the market such as lightweight concrete. Lightweight concrete block is one of the well-known thermally insulated concrete nowadays. It comprises EPS and vermiculite lightweight concretes. Besides that, composite concrete panel and vacuum insulated panel also consider as thermally-insulated concrete. Hence, in the following, properties of the thermally-insulated concretes are the concerned topic of discussion.

4.1. Appearance

In the study of Gao et al. [102], silica aerogel was incorporated in concrete in a volume percentage of 0% - 60%. It was concluded that silica aerogel was intact after the mixing and curing processes. Silica aerogel was also found to be separated from the surrounding concrete matrix by several microns [102]. Figure 6 shows the SEM image of silica aerogel concrete. A gap can be seen between the aerogel and concrete matrix in Fig. 6. The presence of air voids between the aerogel and concrete matrix could further enhance the thermal properties. It is because air has lower thermal conductivity than concrete. Furthermore, the presence of air voids tends to disturb the path flow of heat through the material and hence retards the heat flow. Aerogel itself is also known to have low thermal conductivity among thermal repellent materials in the market. This characteristic further minimises the heat flow through the concrete. This behaviour has also been observed in foam concrete, which has lower thermal conductivity than porous clay brick and conventional concrete. The existence of air voids in foam concrete prevents the movement of heat through the material [103]. Figure 7 represents the SEM image of foamed concrete of 500 kg/m^3 with the existence of air voids [104]. The heat flow path inside foam concrete can be observed as functionally retarded by the air voids.

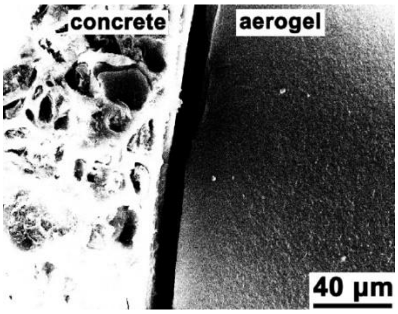

Fig. 6. SEM image of silica aerogel concrete [102].

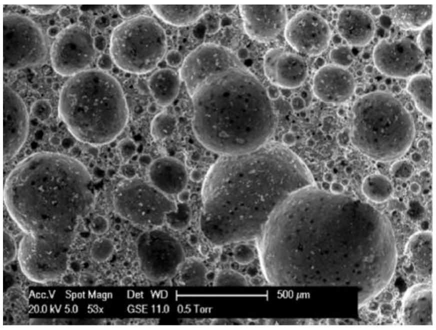

Fig. 7. SEM image of 500 kg/m^3 foamed concrete [104].

In most cases, thermally insulated concretes offer the ability to entrap air as the main thermal insulation mechanism. Entrapped air has low thermal conductivity than concrete. Hence, less heat is transmitted through it compared to concrete. The study of Awoyera et al. [105] also mentioned the relationship between air void and thermal conductivity. The lower the thermal conductivity, the more the air void presence. Moreover, findings by Fatina Md Sali and Deraman [106] revealed that high water cement ratio concrete result in low thermal conductivity. It was because of the present of air void after excess water in concrete matrix evaporated. Consequently, it can be identified that the presence of low thermal conductivity material or the presence of air voids inside thermally insulated concrete is the highlighted characteristic for good insulation performance.

4.2. Mechanical properties

Based on the literature review, it was found that the compression and flexural strengths of thermally insulated concrete tend to decrease when the inclusion of thermal repellent material is increased. This is because by replacing either cement or aggregate with thermal repellent material, the strength development in the concrete matrix is reduced. The main strength of concrete is attributed to the reaction between cement and water to produce a C-S-H bond. According to ASTM C1329 [107] mortar cement is categorised into type N, S, and M. Also, the minimum compressive strength at 28th day for type N, S, and M are 6.2 MPa, 14.5 MPa, and 20.0 MPa, respectively. An ideal thermally insulated concrete should be able to maintain the strength as required and at the same time provide insulation. Based on Table 1, compression strength, flexural strength, and modulus of elasticity of insulated concretes can be seen vary a great deal. However, insulated cement or boards are having a narrow range of compression strength, flexural strength, and modulus of elasticity.

Table 1. Mechanical properties of thermal insulated concretes.

Thermally insulated concrete	Compression strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (GPa)	Reference
Polypropylene concrete	3.4 - 30.4 (50% -10%)	1.4 - 6.4 (50% -10%)	1.6 - 4.3 (50%-10%)	[108]
Sheep wool panel cement	0.4 - 2.9 (5% - 2%)	0.2 - 1.0 (5% - 2%)	-	[109]
Silica aerogel concrete	8.3 - 61 (60% - 10%)	1.2 - 7.8 (60% - 10%)	-	[102]
Rice husk wallboard	1.4 - 13.4	60.9 - 4.2	-	[110]
Autoclaved aerated concrete	9.4 - 34.2	-	7.133×10^{-10} - 19.133×10^{-10}	[111]
Polypropylene fibre foam concrete	7.78 - 10.78 (2.73 kg - 1.82 kg)	-	-	[112]
Polyurethane concrete	16.71 - 21 (0.5% - 0.1%)	-	-	[82]
Perlite cement mortar	18.34 - 27.06 (15% - 5%)	-	-	[87]

In general, thermally insulated concretes are a promising group of building materials to provide thermal insulation without much compromising the strength required. Besides that, among the reviewed concretes, it is highlighted that silica aerogel demonstrates the ability to achieve higher strength.

4.3. Functional properties

Thermally insulated concretes can provide functional properties such as low thermal conductivity, good fire resistance, and good soundproof property. Table 2 summarises the functional properties of some existing thermal insulated concretes. Thermally insulated concretes show low thermal conductivity compared to brick (0.6 W/m·K) and concrete (0.9 W/m·K). The presence of low thermal conductivity material and air void inside concrete contribute to its low thermal conductivity. However, there remains a lack of research about other functional properties of thermally insulated concretes such as fire resistance and sound absorption properties.

Table 2. Functional properties of thermal insulated concretes.

Thermally insulated concrete	Thermal conductivity (W/m·K)	Thermal transmittance (W/ m^2·K)	Fire resistance	Sound absorption	Absorption (%)	Reference
Bamboo paper sludge/fly ash floating beads board	0.12 - 0.165	-	-	-	-	[113]
Sheep wool panel cement	0.1 - 0.28	-	-	-	-	[109]
Silica aerogel concrete	0.26	-	Good	-	-	[102]
Polypropylene fibre foam concrete	0.66 - 0.71	-	-	-	-	[112]
Autoclaved aerated concrete	0.1 - 0.7	-	-	Reasonable	-	[114]
Agglomerated cork layer brick wall	-	< 0.12	-	-	-	[115]
Polyurethane foam waste plaster	0.1039 - 0.2931	-	-	-	-	[81]
Polyurethane concrete	0.823 - 0.993	-	-	-	-	[82]
Perlite cement mortar	0.73 - 1.15	-	-	-	10.75 - 13.99	[87]

To summarise, thermally insulated concretes exhibit many prospective and widespread functional properties as listed. It is better than normal concrete since the latter is mainly considered for strength only. However, due to lacking in finding other functional properties of thermally insulated concretes, it is crucial to further explore these potential materials for performance optimisation.

4.4. Characteristics of thermally-insulated concrete

Often, thermal properties of construction material are related to the energy profile, where energy-efficient buildings can be obtained from the design. In this regard, ACI 122 [116] has been developed for energy efficiency for concrete and masonry building design. To address the energy efficiency, codes like IECC [117] require more details on the thermal properties of the materials for the envelope system, which correlate with the construction industry.

Concrete is a common construction material that is applied in the building envelope, which can have a multipurpose function, including sustaining applied action, adequate durability, thermal behaviour, fire resistance, etc. Other than satisfactory structural performance, lightweight concrete may serve as an alternative with enhancement in thermal characteristics as a wall system (having a predominant area in building envelope system). Therefore, the characteristics of thermally insulated concretes are next discussed with respect to their thermal conductivity and thermal inertia.

4.4.1. Thermal conductivity

The obviously useful characteristic of thermally insulated concretes is their low thermal conductivity as compared to other types of concrete or building materials, in the same context of high thermal resistivity. The thermal conductivity or resistance of concrete can be obtained by experimental investigation, theoretical cubic model, and practical values from the ACI recommendations, while the performance of the wall system is calculated with the steady-state method.

4.4.1.1. Theoretical cubic model

ASTM C177 [118] and C1363 [119] are the referred codes for the measurement of material thermal conductivity. When experimental data are not available, some prediction models can be used for design. However, they may not be sufficiently accurate for different types of aggregate with the same density. Generally, relevant to concrete density, the type of aggregate used can affect the concrete thermal conductivity [120].

The cubic model describes the thermal conductivity of a unit volume of concrete, by considering the contribution of thermal conductivity of each constituent (cement paste, aggregate, and aggregate volume) in the model. These values are encountered for heterogeneous materials in the concrete matrix and thermal bridge, as shown in Eq. (3). ACI [116] also suggests some practical design values of thermal conductivity for both normal and lightweight aggregate when experimental data is not available.

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

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

4.4.1.2. Steady-state thermal resistance of wall systems

Since thermal bridge may not exist in thermally insulated concretes and precast walls, the thermal resistance of the wall can be simplified to the consideration of each layer of the system, as only one heat path can be obtained. Their resistance is the reciprocal of its thermal conductivity. These resistance values could be obtained from laboratory measurements according to ASTM C177 [118].

In the study of Jeong et al. [121], thermal conductivity testing based on ASTM C177 [118] (guarded hot wire method) was lower by 9 - 36% compared to testing by a thermal conductivity meter. It might be due to the heating process that causes the evaporation of pore water in foam concrete, hence further increases vacant pores and decreases thermal conductivity [121]. Based on the study of Mydin [122], thermal conductivities of foam concretes with densities of 650 - 1200 kg/m^3 were 0.23 - 0.39 W/m·K. In the meantime, Othuman Mydin and Wang [123] stated thermal conductivities for foam concretes range from 650 - 1850 kg/m^3 were 0.226 - 0.486 W/m·K.

4.4.2. Thermal inertia

The terms thermal inertia or thermal mass is defined as the heat absorption and storage of building material due to temperature changes [124]. Concrete reacts slowly with the heat transfer process, resulting in some losses and delays through the building envelope. Thermal inertia is related to diffusivity and heat capacity, which is often correlated with the parameters of time lag and decrement factor in thermal performance analysis. Thermally-insulated concretes typically have low rate thermal diffusivity and heat capacity.

4.4.2.1. Thermal diffusivity and specific heat capacity

Metallic materials have high thermal diffusivity properties whereas concretes possess low thermal diffusivity. Concrete also able to store a significantly large amount of heat during the heat transfer process. Therefore, concretes are good construction material as compared to steel or aluminium structures. Specific heat capacity is defined as the amount of heat necessary to raise the temperature of a given mass by one degree. Heat capacity is popularly applied in the energy codes where concrete demonstrates a higher specific heat among construction materials.

Thermally insulated concretes normally have pores within the concrete matrix, for the prevention of heat transfer and no storage of heat in the concrete mass. Therefore, these concretes exhibit low thermal diffusivity and low heat storage, which are greatly suitable for applications in hot weather countries. Concrete is said to have 880 J/kg·K and 0.75 mm^2/s [125]. In Table 3, thermally insulated concrete is noticed to have relatively lower thermal diffusivity and specific heat capacity. Hence, thermally insulated concrete can act as a barrier for heat transfer compared to conventional concrete. Nonetheless, it is noted that there remains a lack of research regarding the thermal diffusivity and heat capacity of thermally insulated concrete.

Table 3. Thermal diffusivity and heat capacity of thermal insulated concretes.

Reference	Insulated concrete type	Thermal diffusivity (mm^2/s)	Specific heat capacity (J/kg·K)
[126]	Ultra-lightweight concrete	0.2	870
[127]	Fly ash concrete	0.6	0.989

4.4.2.2. Time lag and decrement factor

Concrete can store a certain amount of heat from outdoor during the daytime and release back to indoor at night. This delay in heat transfer is called thermal lag or time lag while the pattern of the reduction in the heat is represented by the decrement factor. A calibrated hot box test is commonly used to measure the static and dynamic responses of a wall with outdoor and indoor temperature change. The obtained values can be further analysed to obtain its thermal lag and decrement factor, both of which are the thermal inertia parameters.

Therefore, for tropical countries that experience no diurnal temperature variation, a construction material that can provide low time lag shall be adopted. Whereas low decrement factor indicates the effectiveness of material to suppress temperature swing. In the study of Yuan [128], it was observed that there is a relationship between insulation thickness and decrement factor. With the increase of insulation thickness, the decrement factor can reach nearly zero. Hence, such an insulation material shows the possibility of maintaining indoor thermal comfort level. In terms of time lag, it was found that there was a change of time lag with the increase of insulation thickness. Certain thicknesses of insulation are able to provide nearly zero time lag. Based on the report of Baggs [129], 250 mm thick concrete exhibits 6.9 hours of time lag. It means that heat absorbed during the afternoon will be released to the indoor region during nighttime, hence, causing thermal discomfort to the inhabitants. With the presence of thermally insulated concrete, this phenomenon can be dismissed. In the research of Oktay et al. [125], brick showed a 0.1061 decrement factor and a time lag of 7.3 hours. This time lag is even higher than the concrete.

In conclusion, thermally insulated concretes provide low time lag and decrement factors, which are useful to maintain the indoor thermal comfort level in tropical countries.

5. Further Outlook and Discussion

In the following sub-section, will have further outlook and discuss about the thermal performance of concrete, thermal insulation in the tropical climate and importance of thermal insulation in tropical countries.

5.1. Thermal performance of concrete

Insulation can be categorised based on organic and inorganic materials [59]. Organic thermal insulators are EPS and XPS, whereas inorganic thermal insulators include mineral wool, cellulose, and cork. In general, organic insulation has excellent thermal performance, absorption, and workability. Therefore, more than 90% of the insulations are dominantly available in the market. However, in terms of fire resistance, styrofoam (XPS) and urethane have less than 5-second ignition time and it takes 50 second to spread toxic gases generated during combustion, such as formaldehyde, ethylene cyanide, hydrochloric acid gas, and cyanide gas, which are very dangerous to the human body [130].

For inorganic insulation, it has excellent fire resistance characteristics. Nevertheless, its moisture absorbability is very high and thus affects thermal performance [131]. To summarise, from the sustainability point of view, inorganic materials are more suitable to be chosen as thermal insulators. However, as the fire-resistant property is a concern, organic materials should be chosen over inorganic materials.

For heavy industrial buildings such as factories, organic thermal insulation materials are recommended to provide thermal reduction as the fire-resistant property is highly required. In the meantime, residential and non-residential buildings should apply inorganic thermal materials to provide thermal insulation that simultaneously protect the environment. When conventional thermal barrier materials are compared with the latest thermal barrier materials listed in Table 4, aerogel is the best thermal insulation material as it has the lowest thermal conductivity, as well as good fire resistance and sustainable.

In the study by Li et al. [132], EPS was used to fill sintered hollow bricks at ratios of 0%, 20%, 40%, 60%, 80%, and 100% to determine its thermal performance. Their results showed that the peak surface temperature of bricks was reduced from 0% to 100% of EPS compared to heated surface temperature. Therefore, EPS can successfully reduce the inner surface temperature of the walls. These results further prove the link between thermal insulation materials and thermal comfort. Even though the ambient temperature is kept under a comfortable level (27°C), the high radiant temperature tends to cause thermal discomfort (i.e., high Predicted Mean Vote index level) [32].

Generally, a better thermal insulator should be able to reduce thermal transfer with high thermal resistance, *R*-value, and low *U*-value. From Table 4, it can be noticed that normal construction materials such as concrete, timber, and brick have lower *R*-values and higher *U*-values compared to thermal insulation materials. This means that thermal insulation materials can reduce heat transmission across buildings. Due to the fact that, EPS and aerogel have the highest *R*-value and lowest *U*-value among all considered materials. Thus, these two materials are more efficient in terms of the reduction of thermal conductivity across buildings.

Apart from that, with the application of thermal insulation, it can be observed that the reduction in terms of CO_2, energy consumption, and cost are some benefits as listed in Table 5. It is witnessed that the usage of thermal insulation in building successfully reduces energy consumption and hence encourages cost-saving for energy. In terms of sustainability, the utilisation of thermal insulation establishes a reduction in carbon footprint or CO_2 emission. For example, concrete requires numerous production steps to reach the final product.

Quarrying of aggregate, transportation of aggregate/sand, production of cement, and production of concrete all require a large amount of energy especially in operating the machines and fuel consumption for transportation. At the same moment, carbon dioxide is produced from the burning of fuel and the operation of machines as well as reactions from concrete. The situation is worsened with the increased usage of air conditioning to maintain the indoor thermal comfort level. More energy is needed to operate the air conditioning that directly also increases the amount of carbon dioxide.

In Table 5, it is displayed that the application of thermal insulation material can create a sustainable environment. To sum up, thermal insulation should be correctly chosen based on the purpose of the building to have a better outcome in terms of sustainability and economy.

Table 4. Properties of thermal insulating building materials.

Material	Thermal Conductivity (W/m·K)	Fire Resistant	Sustainability	*R*-value (Thickness/ Thermal Conductivity)	*U*-value (1/*R*-Value)
Mineral Wool (Glass Wool, Rockwool)	0.03-0.04	Yes	Yes	4.00	0.25 [133]
EPS	0.03-0.04	No	No	6.67	-
XPS	0.03-0.04	No	No	-	-
Cellulose	0.04-0.05	No	Yes	-	-
Cork	0.04-0.05	Yes	Yes	-	-
PU	0.02-0.03	No	No	-	-
EP	0.057	Yes	Yes	-	-
Aerogel	0.01-0.02	Yes	Yes	0.30-6.67	0.15-3.3 [134]
Concrete	0.9 [135]	Yes	No	0.33	3.03 [136]
Timber	0.1-1.4 [135]	No	Yes	0.23-0.46 [136]	2.17-4.35
Brick	0.6 [136]	Yes	Yes	0.37-0.85 [136]	1.18-2.70

Table 5. Effects of thermal insulation.

Reference	Insulation	Energy consumption reduction (kW·h)	CO_2 reduction	Cost reduction
[58]	Mineral wool	5.8	-	-
[58]	XPS	6.0	-	-
[137]	Polystyrene and rockwool	-	-	21$/m^2
[138]	Stropor	-	50%	-
[139]	Coal	-	-	14.09$/m^2
[140]	EPS, XPS, foamed PU, perlite and foamed polyvinyl chloride	-	-	39 $/m^2- 54.8 $/m^2
[141]	Rock wool, glass wool, and cellulose fibre	-	20%	-

5.2. Thermal insulation in the tropical climate

In general, thermal barriers are used for hot and cold climates. However, the purpose of the application is different. For a cold climate, thermal insulation intends to maintain the temperature at an acceptable range, which is higher than the outdoor cold temperature by preventing the infiltration of hot air from indoor to outdoor. The heating of indoor air is a normal practice to produce hot air to maintain the thermal comfort condition. Without thermal insulation, a lot of heating is required. Meanwhile, in hot climate areas such as tropical countries, thermal insulation is used to maintain the acceptable indoor temperature by preventing the infiltration of hot air from outside to inside. When there is no thermal barrier being applied, heat is transferred with less obstruction to the indoor. Thus, air conditioning is widely used to produce cold air for lowering the indoor temperature to thermal comfort temperature.

There are three heat control methods for buildings, namely thermal insulation, air barrier, and radiation barrier. During the daytime, the dominant heat transfer is by radiation through the roof [142]. This is because a larger area of the roof is exposed to the highest intensity of solar radiation. The heat is then transferred from the roof to the attic and the whole building by conduction and convection. Thus, it is more effective to use a radiation barrier or thermal insulation in attics, especially in tropical countries.

Tropical countries experience high humidity and temperature throughout the year. Therefore, exterior walls are exposed to sunlight at least for 8 h. Without any barrier of the exterior wall, heat will flow into buildings with fewer obstacles. Moreover, buildings can never be completely sealed with no gap at all in practice. Hence, due to openings, leakages of air can happen. Infiltration of hot air from outside to inside will affect the efficiency of air conditioners. In such a condition, more energy is required to maintain the temperature set. An air barrier system through the use of building wrap can minimise the opening of buildings and prevent infiltration of hot air to the inside of buildings, especially in tropical countries that are consistent with a hot and humid climate. Ideally, the applications of these three heat control methods are able to promote indoor thermal comfort efficiently and critically for tropical countries. Furthermore, Al-Homoud [143] observed that the application of thermal insulation in the area with hot and humid climate is more significant than an area with a hot dry climate. Thus, the use of thermal insulation in the construction industry should be highly recommended in tropical countries.

Nevertheless, the cost of building materials and the ease of installation are other parameters worthy of consideration. Readily available materials without further modification are preferred in eliminating the extra secondary manufacturing cost. If it is unavoidable, the simple yet low manufacturing cost is allowable. Thermal barriers with easy installation steps have popular use for building construction. Tedious installation procedures may be needed to achieve better thermal insulation systems. Parallel with this intention, for conventional concrete construction, it is suggested to incorporate insulation materials into the concrete matrix during the casting process, which can reduce the finishing period. Thermally insulated concretes are able to minimise the building's unused geometries where the thermal barriers may increase the gross floor area.

Based on the aforementioned discussion, it is advised to enforce the application of the thermal barrier to having an optimised usage of energy in the building.

5.3. Importance of thermal insulation in tropical countries

Due to reasons such as UHI and global warming, it is indisputable that our Earth is suffering from rising ambient temperature and climate change. It is evident that the world is getting hotter across the centuries. Higher outdoor temperature tends to induce the rising of indoor temperature. It is proven that high temperatures incite the sensation of thermal discomfort. Discomfort can then further decrease the productivity of workers. Desk jobs such as administration, education, hospitality, etc. require a full-time indoor working environment. If workers are feeling discomfort due to extremely hot conditions, it negatively affects productivity. Furthermore, high temperatures will badly affect the health of residents. Under such a circumstance, residents may suffer from heat stress. If untreated and continually exposed, heatstroke may happen. In the worst-case scenario, death could happen specially to elders or children. In terms of economy, the high expenditure of electricity owing to the great energy consumption is a definite event to operate air conditioner especially for tropical countries, which require air conditioning sometimes up to 24 hours per day. This further deteriorates the environmental quality since fossil resources such as coal operating power plants are in high demand causing the continuous release of greenhouse gases. It becomes an endless operational cycle that devastates the Earth. Thus, a perfectly functional thermal insulation is crucial to create a sustainable environment, especially for tropical countries.

6. Conclusion

This paper reviews the performance of thermally insulated concretes for applications in tropical countries. Of emphasis is the importance of various thermal behaviours of the insulation constituents filling the concrete and the end products while promoting sustainability among the scientific and overall communities specifically for the construction and building prospects. Several conclusions have been drawn as follows:

- Heat quality worsened by the UHI phenomenon is transferred from outside into buildings via several heat transfer mechanisms, namely conduction, convection, and radiation. High temperatures will create thermal discomfort and thus heat stress to the residents. To ensure uniformity in description and assessment, various parameters defining the thermal comfort quality, such as thermal mass, conductivity, and resistance have been discussed. Furthermore, thermal comfort has been defined with certain formula useful for quality evaluation.
- The thermal insulation materials are introduced, which can maintain the indoor thermal comfort level as many studies have exhibited their effectiveness to reduce heat across the materials. However, many thermal barriers are widely available in the market, thus causing difficulty in the selection-making process.
- This paper provides the direction in choosing the appropriate thermal insulation judging by the type of building. To this end, thermal behaviours, i.e., physical, mechanical, and functionality of numerous potential constituents for thermally insulated concretes including fibrous, cellular, and granular types as well as aerogel have been presented.
- In general, the thermal barriers with low thermal mass and thermal conductivity but high thermal resistance show great suitability to be applied in tropical countries. The chief performances for building applications are their relatively lower thermal diffusivity and specific heat capacity. Also, they provide low time lag and decrement factors, which are useful to maintain the indoor thermal comfort level in tropical countries.

- Generally, a better thermal insulator should be able to reduce thermal transfer with high thermal resistance, good fire resistance, show sustainability, and economical. Even though all thermal barriers are capable of providing insulation, there are some drawbacks in certain materials, either they are not sustainable or flammable. Among conventional thermal insulation materials, mineral wool has been identified as the best material as it has lower thermal conductivity, sustainable, and resistant to fire. Aerogel, which is relatively new thermal-insulated materials in building construction, have better thermal insulation properties.
- As the main recommendation, it is suggested from the current review to incorporate thermal-insulated materials into the concrete matrix for future construction and building purposes in shortening the finishing period and maximizing the building saleable area. These thermal insulated concretes are generally better than normal concrete since the latter is mainly considered for strength only. It is worthwhile to stress also that due to lacking in finding other functional properties of thermally insulated concretes, it is crucial to further explore these potential materials for other applications as well.

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Nomenclatures

A	Area of the surface, m^2
d	Distance between 2 isothermal planes, m
f_{cl}	Ratio of the surface area of the clothed body to the surface area of the nude body
h_c	Convection coefficient
K	Thermal conductivity
k_a	Thermal conductivity aggregate
k_c	Thermal conductivity of concrete
k_p	Thermal conductivity of cement paste
l	Thermal conductance
M/ADU	Metabolic rate, W/m^2
Q	Amount of heat transferred, Watt
R	Thermal resistance
T_a	Air temperature, °C
T_{cl}	Temperature of the clothing surface, °C
T_{mrt}	Mean radiant temperature, °C
U	Thermal transmittance
V	Velocity of air
V_a	Aggregate volume
η	Mechanical efficiency

Greek Symbols

Δt	Difference of temperature, K
ϕ	air humidity
η	Mechanical efficiency
ρ_a	Pressure of water vapour in ambient air, mmHg

Abbreviations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
EP	Expanded perlite
EPS	Expanded polystyrene
exp	Exponential
IECC	International Energy Conservation Code
NASA	National Aeronautics and Space Administration
PU	Polyurethane
SEM	Scanning electron microscopic
SiO_2	Silica dioxide
UHI	Urban heat island
WHO	World Health Organization
XPS	Extruded polystyrene

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