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Concrete as a thermal mass material for building applications - A review

Payam Shafigh[a,b,*], Iman Asadi[a,b], Norhayati Binti Mahyuddin[a,b,*]

[a] Department of Building Surveying, Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia
[b] Center for Building, Construction & Tropical Architecture (BuCTA), Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia

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ABSTRACT

Identifying new energy saving methods in the building sector is essential due to limited natural energy sources and the rising population. Thermal mass materials have the ability to absorb and store heat before releasing it later on when necessary. They act as heat sinks during the daytime and as heat sources during the nighttime. Thermal performance is evaluated according to the specific heat capacity and specific latent heat. Applying thermal mass materials such as concrete is deemed a suitable strategy to reduce the energy consumption of buildings. Concrete with low thermal conductivity and high specific heat capacity is desirable in building construction. The aim of this study is to review factors affecting the heat storage capacity of concrete. In addition, common measurement methods of cement-based materials' thermal conductivity, thermal diffusivity and specific heat capacity are reviewed. Various studies reveal that temperature, humidity, aggregate type, cementitious material type as well as phase change material (PCM) used influence the thermal properties of concrete. The advantages and limitations of PCM-concrete are also summarized in this study.

1. Introduction

Energy conservation is essential on account of population growth and limited natural energy sources. The global energy consumption (EC) increased by about 92% since 1971–2014. The total end-user EC is related to the transportation, industrial, residential, commercial and other sectors with contributions of 30%, 29%, 27%, 9% and 5%, respectively [1]. One-third of the total EC and 30% of greenhouse gas emissions are attributed to buildings in most countries [2,3]. The estimated EC growth for buildings worldwide is illustrated in Fig. 1.

Building EC is categorized into embodied energy (EE) and operational energy (OE). EE includes resource extraction and transportation, the manufacturing of components and the energy required to demolish constructions and transport the substances to landfill sites. OE involves the energy required for lighting, heating, cooling and ventilation to provide a comfortable indoor environment for occupants [4,5].

Most people spend around 90% of their lives indoors [6]. Consequently, energy conservation and thermal comfort are debatable issues regarding buildings. The energy required for cooling and heating buildings as well as thermal comfort are greatly dependent on the thermo-physical properties of the building construction materials employed [7].

Thermal mass is defined as a material's ability to absorb, store and release heat. Thermal mass materials, such as water, earth, bricks, wood, rocks, steel and concrete act as heat sinks in warm periods and as heat sources during cool periods (Fig. 2). High thermal mass materials maintain indoor temperatures within desirable ranges without extreme EC [8]. Density, thermal conductivity (K), thermal diffusivity (α) and specific heat capacity (C) are some of the factors influencing thermal mass behavior [9]. Employing adequate thermal mass materials can reduce the EC in buildings by at least 7–22% [10–12]. The thermal performance of materials is evaluated according to their specific heat capacity (KJ/Kg °K) or heat capacity per unit volume (KJ/m^3 °K). However, heat capacity per unit area (KJ/m^2 °K) is preferred in building applications and can be calculated with Eq. (1) [13].

$$C_{ar} = C_{vol} \times X \tag{1}$$

Where C_{ar} is the heat capacity per unit area (KJ/m^2 °K), C_{vol} is the heat capacity per unit volume (KJ/m^3 °K) and X is the mass thickness.

Thermal energy storage is based on sensible and/or latent thermal energy storage methods [14]. With the sensible method, heat is released or stored by lowering or raising the thermal mass material's temperature. Whereas with the latent method, heat is released or stored as a material's phase change [15]. The amounts of sensible and latent heat can be calculated with Eqs. (2) and (3), respectively [16].

$$Q_s = \int_{T_1}^{T_2} m_s.\ c.\ dt = m.\ c.(T_2 - T_1) \tag{2}$$

Where Q_s is the sensible heat storage (KJ), T_1 is the initial temperature (°C), T_2 is the final temperature (°C), m_s is the mass of the heat storing

* Corresponding authors at. Department of Building Surveying, Faculty of Built Environment, University of Malaya, 50603 Kuala Lumpur, Malaysia
E-mail addresses: pshafigh@um.edu.my, pshafigh@gmail.com (P. Shafigh), asadi8564@gmail.com, asadi@siswa.um.edu.my (I. Asadi), hayati@um.edu.my (N.B. Mahyuddin).

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Nomenclature

A	Area (m^2)
C	Specific heat capacity (KJ/Kg °C)
E	Energy power
K	Thermal conductivity (W/m °K)
m	Mass of sample (Kg)
Q	Heat flow (W)
q	Heat flux (W/m^2)
r	Degree of hydration
T	Temperature (° C)
X	Thickness of mass (m)
α	Thermal diffusivity
∇T	Temperature gradient (°K/m)
∂T	Temperature difference (°K)
∂x	Distance (m)
ρ	Density (Kg/m^3)

Subscripts and superscripts

0	Hardened concrete
1	Initial condition
2	Final condition
ar	Area
eq	Equilibrium
I	Reference material
l	Latent
s	Sensible
vol	Volume

Acronyms

EC	Energy consumption
EE	Embodied energy
OE	Operational energy
FA	Fly ash
FRSCC	Fiber reinforced self-consolidating concrete
HVAC	Heating, ventilation and air conditioning
LFC	Lightweight-foamed concrete
LWA	Lightweight aggregate
NWC	Normal weight concrete
PCM	Phase change material
SCC	Self-consolidating concrete
SF	Silica fume
SLWAC	Structural lightweight aggregate concrete
TESCM	Thermal energy storage cement mortar
TPS	Transient plane source

material (Kg) and C is the specific heat (KJ/Kg °C).

$$Q_l = m_l. \quad L \tag{3}$$

Where Q_l is the latent heat storage (KJ), m_l is the mass of the phase change material (Kg) and L is the specific latent heat of the phase change material (KJ/Kg).

Concrete is a thermal mass material mainly composed of cement, water and aggregates. Concrete is used in building materials twice as much as all other building materials like plastic, wood and steel [17]. Improving the thermal behavior of concrete reduces the EC in buildings. The K-value, specific heat and thermal diffusivity denote thermo-physical properties of concrete.

This review presents the thermal properties of hardening and hardened concrete as well as various approaches of measuring the thermal properties of concrete. In addition, the factors affecting the heat capacity of concrete are discussed. Based on data reported in the literature, the sensible and latent heat storage of concrete for building applications is determined.

2. Thermal properties of concrete

The K-value of concrete represents its heat conduction capability [18,19] and can be calculated with Eq. (4) [20].

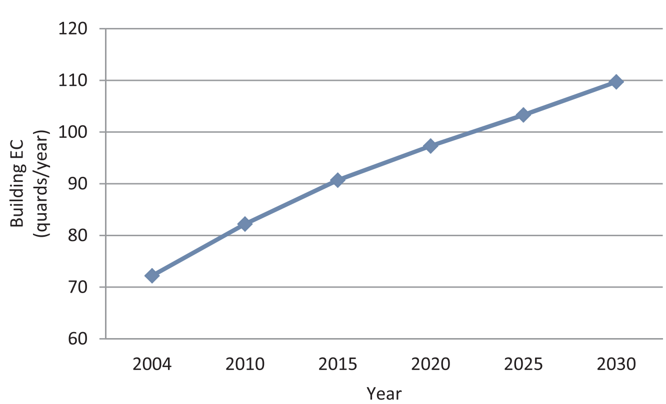

Fig. 1. Worldwide building energy consumption [1].

$$Q = -kA\frac{\partial T}{\partial x} \tag{4}$$

The heat capacity of a material is defined as ρC, where ρ is the density (Kg/m^3) and C is the specific heat (J/kg °K). Both heat capacity and specific heat represent a material's heat storage capability. Heat capacity indicates the heat storage capability per unit volume (J/m^3 °K), whereas specific heat expresses the heat storage capability of a material per unit mass (J/kg °K) [21]. Specific heat is described as the amount of energy required to raise a unit of mass by one degree of temperature. Based on whether this process occurs at a constant volume or constant pressure, specific heat is categorized into specific heat volume (C_v) and specific heat pressure (C_p). For incompressible substances like concrete, the amounts of C_p and C_v are similar and can be denoted by a single symbol, C (C_p = C_v = C) [21]. The specific heat of solid materials depends on temperature. Eq. (2) presents the relation between the heat energy and temperature change of materials.

Concrete with high specific heat is useful for boosting the temperature stability of buildings [22]. Concrete with a low K-value and high specific heat is desirable for building construction and insulation [23,24].

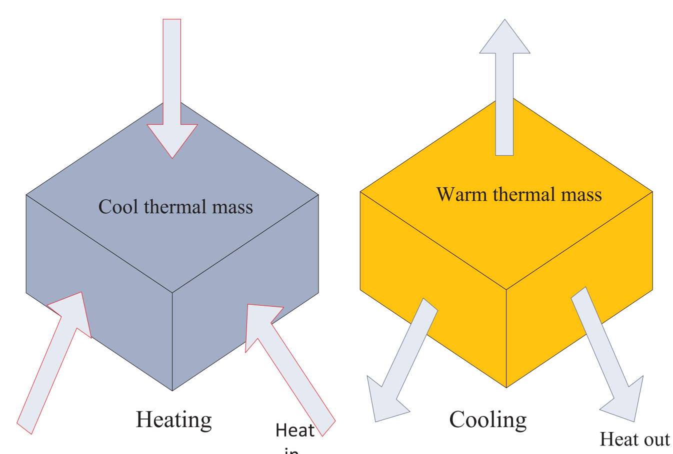

Fig. 2. Thermal behavior of thermal mass materials [13].