Construction and Building Materials 128 (2016) 422–435

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Incorporating environmental evaluation and thermal properties of concrete mix designs

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HIGHLIGHTS

- Evaluated embodied CO_2-e and thermal conductivity for 90 concrete mix designs.
- Compiled embodied CO_2-e coefficient for each individual component in concrete.
- Wide ranges of embodied CO_2-e and thermal conductivity were found.
- Embodied CO_2-e was reduced through the use of supplementary cementitious materials.
- The embodied CO_2-e coefficient calculation method varies across inventory databases.

ARTICLE INFO

Article history:
Received 27 April 2016
Received in revised form 30 September 2016
Accepted 19 October 2016
Available online 1 November 2016

Keywords:
Concrete mix design
Embodied emission
Thermal conductivity
GHG
CO_2-e

ABSTRACT

One of the main challenges in sustainable design of buildings is to improve the energy efficiency of the building during its lifetime along with reducing the environmental impact of the design. Recent advances in concrete technology offer lower embodied emission through the application of supplementary cementitious materials and recycled aggregates. There are also improvements to thermal properties with the application of admixtures. However, the relationships between the environmental impact (Cradle to Gate) and thermal performance of concrete mix designs have not been researched adequately. The Green House Gas (GHG) emissions associated with each individual concrete component and its production need to be considered with greater refinement. This study correlates the impacts of selecting a concrete mix design in terms of CO_2-e with resulting thermal conductivity and density at the design stage of buildings. This paper examines 90 concrete mix designs from published literature to identify their embodied emissions and thermal conductivity in order to discuss the relationship between low embodied carbon dioxide equivalents (CO_2-e) emission alternatives and thermal conductivity. The embodied CO_2-e of a variety concrete mix designs were quantified by compiling embodied CO_2-e coefficient for each individual component in the concrete. The results show the variation in embodied CO_2-e and thermal conductivity of concrete mixes. The application of readily available supplementary cementitious material can reduce embodied CO_2-e (kg CO_2-e) by up to 16% in comparison with general practice. Furthermore, the thermal conductivity of concrete mix is influenced by changing the density of aggregates and the proportion of cementitious materials. In completing this work the results obtained from the study are compared with six different inventory databases: ICE (Hammond et al., 2011), Crawford (2011), Alcon (2003), eTool (2014), BPIC (2014) and AusLCI (2013). The comparison identifies some inconsistencies in calculation of embodied CO_2-e across the different databases. This is attributed to variation in embodied CO_2-e coefficients and lack of in-depth consideration of the detailed properties of each individual concrete mix design.

1. Introduction

Concrete is the most widely used construction material in the building industry and consumes the second highest amount of natural resources [7]. The main constituents of general purpose concrete are cement, water and aggregates. The most carbon

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http://dx.doi.org/10.1016/j.conbuildmat.2016.10.092
0950-0618/

intensive components in manufacturing concrete are cement and aggregates. A report released by the United States Geological Survey shows that global cement production increased by 100 million tonnes in one year to a total of 4.18 billion tonne in 2014 [8]. The American Portland Cement Association (PCA) has estimated this cement consumption trend will continue to increase into the future [9].

Concrete is a popular material because it has excellent mechanical and durability properties. It is adaptable, relatively fire resistant and generally available and affordable. Concrete has the ability to absorb and retain energy for a considerable period of time. This action reduces energy consumption by transferring heat in a natural daily cycle through the structural components (thermal mass) of the building. The mass components reduce the temperature fluctuations in building spaces and can therefore reduce the associated peak heating or cooling loads [10].

Through its high thermal mass, a concrete slab can often absorb heat during the day and release it back to the room at night. The relatively high specific heat of solid concrete makes it attractive as a passive thermal store. An appropriate design of concrete mix can offer this thermal performance benefits, leading to a reduction in heating and cooling energy consumption in buildings [11,12].

This situation raises a question about how best to design a concrete mix with respect to strength, thermal properties, environmental impact and CO_2-e intensity of concrete. The objective of this paper is to identify the environmental impact and thermal performance of different concrete mix designs by considering both the embodied CO_2-e and the impact on the thermal properties of concrete.

1.1. Thermal performance of concrete

Concrete is one of several building materials that possess high thermal properties. In cold seasons, high thermal mass building elements that contain concrete such as walls and floor slabs, absorb radiant heat from the sun during the day and release it gradually back into the system (space) during night when outside temperatures drop [13]. The distinct benefit of high thermal mass is to moderate changes in peak load of energy requirements due to fluctuations between inside and outside temperatures. High thermal mass causes a time lag between internal and external temperatures (Fig. 1). It also stores heat which dampens the fluctuation between peaks. This often results in improved thermal comfort and less energy demand for heating and cooling [13]. Beside thermal mass, thermal properties of concrete mix design such as conductivity have a considerable influence on passive heating design strategy. An optimum design of concrete mix could either reduce escape of passive heating before being absorbed or re-released a stored heat before the colder night [14].

Thermal conductivity of concrete mix designs is influenced by the thermal properties of the ingredients such as cement, aggregates and the existing moisture [15]. Thermal conductivity of concrete is dependent on the type of aggregates used in the concrete mixture. Some published construction properties databases associate thermal conductivity to concrete density, for example ACI122R [15] and CIBSE [16]. Therefore, it is possible to take into the account some thermal properties of concrete mixes at the initial stage of the structural design of buildings. This study quantifies the thermal conductivity for different concrete mix designs.

1.2. Environmental aspects of concrete

The basic constituents of concrete are binder (cementitious materials), coarse and fine aggregates (or inactive mineral filler) and water. The properties of these materials, their combination, the effects of various admixtures and how it is handled during construction determine the properties of the in-situ concrete.

The major source of greenhouse emissions during the production of concrete is the Portland cement. The cement sector was responsible for 2823 million metric tonnes (Mt) of embodied CO_2-e in 2010 [17]. This related to almost 9% of global CO_2-e emissions from burning of fossil fuels in 2010 [17]. Traditional methods to respond to this issue are the development of energy efficient cement production plants through improved technology, changes to energy sources used and the application of substitutes for clinker by using waste materials such as fly ash and ground granulated blast furnace slag [18–21].

The concrete industry is addressing some of the worries about environmental issues by supplementing or replacing the use of cement and other components that are associated with high embodied CO_2-e. Several researchers have studied the possibility of cement replacement in the concrete with recycled materials [22–24]. The use of alternative cementitious materials remains the main path to the reduction of embodied CO_2-e in the concrete industry [25]. Wimpenny [26] conducted a study in low CO_2-e alternatives to concrete by exploring strategies being adopted and developed in 12 countries around the world. The results have been classified into seven groups as shown in Table 1.

The most commonly used alternative cementitious materials are Ground Granulated Blast Furnace Slag (GGBFS) and coal

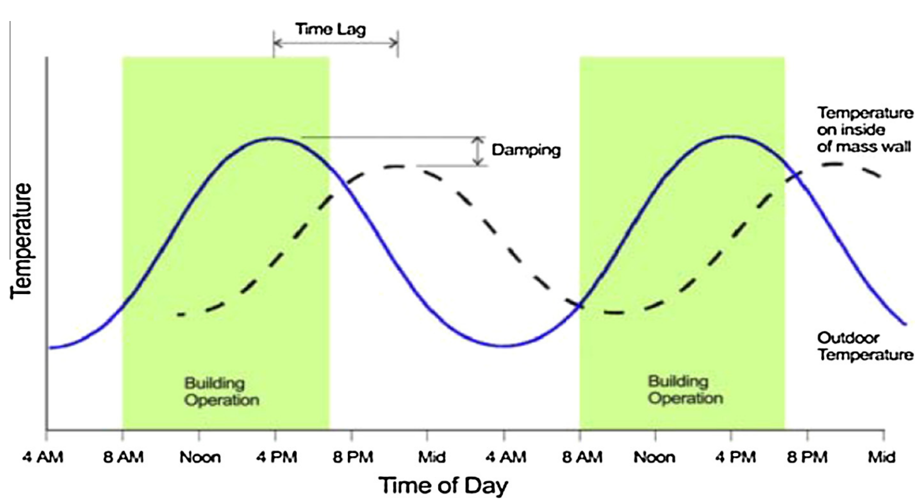

Fig. 1. Damping and lag effect of thermal mass [13].