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Life cycle sustainability assessment of fly ash concrete structures

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ABSTRACT

Concrete is one of the most widespread construction materials in the world, but its production is responsible for significant amounts of energy consumption, and even greater greenhouse gas emissions. However, the substitution of Portland cement with fly ash (FA) reduces both the energy consumption and the greenhouse gas emissions generated during the production of clinker. Currently, most studies of FA concrete focus on mechanical properties, sustainability assessments (environment, society and economy) of FA during its life cycle have not been reported. This paper presents a life cycle sustainability assessment (LCSA) that brings together environmental, economic and social impacts using a proposed three-dimensional coordinate diagram to combine the different units into a single sustainable value. The assessment method is applied to different substitutions of FA in concrete to ascertain the optimum substitution percentage across these three factors. Monte Carlo simulation is then used to evaluate the durability of concrete structures with different FA addition in order to calculate their service life. A case study is conducted of a bridge structure with different FA substitutions; this demonstrates that the addition of FA would improve the sustainability of concrete significantly in the short term. However, when the durability and service life of the structure are taken into account, without maintenance, the use of FA concrete may not improve the environment performance due a potentially shortened service life, but it can reduce the social burden and save costs significantly over the long term.

1. Introduction

Cement and concrete products are well accepted as man-made construction materials [1] and cement products are considered to be the second most-consumed substance on earth after water [2]. Currently, the global production of concrete amounts to 2 t per capita per annum [3] and it is predicted that by the end of 2050, this figure will increase to 18 billion tons [4]. Portland cement, the primary constituent of concrete, is produced and used in large quantities. It is observed that China has been the biggest cement producer in the world since 1985 [5] and produced 2.35 billion tons cement in 2015, accounting for around 50% of global cement production at that year [6].

The concrete industry consumes a significant amount of materials, resources, energy and even capital, leading to significant social costs and environmental burdens, especially CO_2 emissions [7]. It is estimated that the energy consumption of 1 t cement is 3.1–5 GJ [8],and generates approximately 0.73–0.99 t CO_2 emissions [9]. China is both the largest producer of cement and the biggest emitter of CO_2 emissions in the world [5]. The cement industry accounts for approximately 10% of current anthropogenic carbon dioxide emissions [10] and 12–15% of the total industrial energy [7].

It is recognized that the construction industry is responsible for considerable environmental impacts, thus it is important that alternatives to reduce these impacts are explored. For the cement sector, this includes cleaner production, recycling and lower impact cements [11]. Fly ash is recognized as an effective Portland cement substitution within concrete mixes. Many previous studies have pointed out that the addition of fly ash in the concrete can reduce the total CO_2 emissions [12] and energy consumption [13], on the premise that the basic performance of concrete is satisfied. Moreover, fly ash is the world's fifth largest raw material resource [14] and there is a successful track record of producing concretes mixed with FA for over 50 years [15]. Currently, the production of FA in China is significant, it is estimated that FA produced by the thermal power plants was as high as 700 million tons in 2014, making China become the largest producer of FA in the world [16,17]. Many countries around the world have made efforts to strengthen the research of replacing cement with FA [18,19].

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However, little work has carried out a full sustainability assessment of FA concrete structures.

The primary goal is to develop a quantified life cycle sustainability assessment (LCSA) model of FA concrete which not only considers social, environmental and economic aspects but also technical aspect such as the durability and reliability of a structure. The secondary goal is to verify the validness of the presented model by applying it to a case study. And then the sustainability impacts of traditional Portland cement with different FA replacements are assessed and compared. This method will enable the identification of the best socially, environmentally and economically sustainable alternative, demonstrating the optimum FA substitution.

2. Literature review

The corresponding literature can be divided into two areas: the development of sustainability assessment methods and their applications, and the study of fly ash concrete.

2.1. Development of sustainability assessment methods and their application

Currently, there is a considerable amount of relevant research relating to the study of life cycle sustainability assessment, they can be divided into two aspects: some literature which focuses on the whole life cycle assessment, and some literature that concentrates on the comprehensive sustainability assessment.

2.1.1. Literature focusing on the whole life cycle assessment

In 2009, based on the basic theory and technical framework of LCA, Zamagni et al. at Leiden University presented a guideline of life cycle sustainability assessment (LCSA) for general product. In their study, LCSA consists of LCA [20], LCC [21] and SLCA [22] which is short for life cycle sustainability assessment, life cycle (environment) assessment, life cycle cost and social life cycle assessment, respectively [23]. Research by Valdivia [24], Heijungs et al. [25] and Zamagni [26] also explored the area of LCSA based on the concept that the whole life cycle sustainability assessment should include social, environmental and economic aspects. But the problem is that even though studies put forward the concept of LCSA, they didn't mention the specific process of how to integrate the above three aspects together and there is almost no application of this method on concrete products at current.

Other research also focuses on whole life cycle assessment, but this often only incorporates one or two aspects from the environment, economy and social angles. For example, Setunge et al. [27,28] has published a series of articles to evaluate life cycle cost and environment impact of residential building. Monsalud et al. [29] analyzed the sustainability of an airport during the process of design, master planning, operations, and maintenance from the aspect of greenhouse gas emissions. Russell-Smith and Lepech [30] presented sustainable target values (STV) which integrated life cycle assessment and construction management to assess the ecologic carrying capacity of buildings from cradle-to-gate, including design, production, and construction stages. Pang et al. [31] presented a life cycle environmental impact assessment model of a bridge with different maintenance schemes at the end-of-life stage. Dong [32] developed a Social-impact Model of Construction (SMoC) using SLCA model to assess social life cycle impact assessment of building construction project in Hong Kong.

2.1.2. Literature focusing on comprehensive sustainability

Here, the comprehensive sustainability refers to not only assess the traditional aspect of sustainability, namely, the environment aspect, but also to find some method to combine different aspects (environmental, social and economic) together. For example, Spanish Structural Concrete Code (EHE-08) [33] presented an Integrated Value Model for Sustainable Assessment (MIVES) model to assess the sustainability of concrete structure in 2008. In their study, the MIVES is based on value analysis and involving a methodology that transforms different types of variables into one single unit via "requirement tree" [34]. According to the code, a series of research was carried out by different researchers, such as Pons and de la Fuente [35], del Caño et al. [36], San-José et al. [37,38], they analyzed the sustainability of concrete columns, concrete structures, industrial buildings, respectively.

Another method to evaluate sustainability is using optimization or multi-criteria decision-making (MCDM) or a similar method to find the best design alternative. For example, Yeo and Gabbai [39] and Yeo and Potra [40] presented optimization approaches with the view to allow decision makers to balance environment (embodied energy and carbon emissions) and economic objectives of concrete structures. Chiang et al. [41] developed an optimization model to identify the optimal portfolio of materials that would minimize three sustainability objectives including carbon emissions, cost, and labor deployment for sustainable building maintenance. Yadollahi [42] applied the multi-criteria analysis to assess the sustainability of one bridge in Malaysia with the analytical hierarchy process (AHP) [43]. In Kim et al. study [44], they developed a 'low-carbon-emission concrete (LCEC) mix design system' applying evolution algorithm (EA) as a design tool to minimize CO_2 emissions of concrete mix design, their goal is to evaluate CO_2 emission quantities, economic value, and strength concrete reduction performance.

The common short-comings of these particular models are that even though they put forward the methods to integrate different sustainable aspects together, these methods don't capture the whole life cycle.

2.2. Study of fly ash concrete

As to the study of FA concrete, most of the current research focuses on its mechanical properties [45,46]. Although there have been some studies which explore environmental [47–49] and economic aspects [50,51], but there is little understanding of the impact on social sustainability. Sun [52] in his master thesis presented an SLCA model to evaluate the social life cycle impact of FA concrete, but currently there is no comprehensive sustainability assessment that brings together environmental, economic and social aspects of FA concrete, especially during the whole life period.

It can be seen from the above analysis that there are a number of deficiencies in the current studies for the study of life cycle sustainability assessment and its application on FA concrete. (1) There is a limited number of studies on comprehensive life cycle sustainability at moment, although LCSA guideline has been put forward, since it does not give the specific process of how to integrate different sustainability aspects together, no application of this method onto concrete products has been reported. (2) Even though some proposed the so-called "life cycle sustainable assessment" model, most of the literature only focuses on one or two aspects of sustainability, often on environment element or environment element combined with economy element, thus they are not "truly" comprehensive life cycle sustainability. (3) There is some literature that attempts to build a comprehensive sustainability assessment including social, environmental and economic aspects, but they often only focus on one stage of the life cycle, such as the stage of construction, maintenance or demolition. (4) As to the life cycle sustainability assessment of fly ash concrete, especially considering social aspect and technical performance (reliability and durability), there is no published research yet. It is thus especially important to establish a comprehensive LCSA model which not only considers the environmental, economic and social impacts but also considers the reliability and durability performance of corresponding structures and apply it to FA concrete.