Construction and Building Materials 167 (2018) 414–425

Contents lists available at ScienceDirect

Construction and Building Materials

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

Performance assessment and design of ultra-high performance concrete (UHPC) structures incorporating life-cycle cost and environmental impacts

You Dong

Department of Civil and Environmental Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

HIGHLIGHTS

- An approach to aid the design of UHPC bridge is proposed.
- Life-cycle cost and environmental impacts are assessed.
- Reliability and durability of novel bridges using UHPC are evaluated.
- UHPC bridges can reduce CO_2 emissions significantly in a life-cycle.
- Application of UHPC is with significant benefit of sustainable perspective.

ARTICLE INFO

Article history:
Received 19 September 2017
Received in revised form 18 January 2018
Accepted 7 February 2018

Keywords:
UHPC
Life-cycle cost
Structural reliability and durability
Environmental impacts
CO_2 emissions
Equivalent annual cost

ABSTRACT

Ultra-high performance concrete (UHPC) as a novel concrete material is associated with very high strength and low permeability to aggressive environment. There have been many studies focusing on the development of UHPC materials. More studies are needed to implement the knowledge obtained from material level into the structural design and construction level. This paper emphasizes on the structural modeling and performance assessment of bridge girders made of UHPC considering the major improvements in terms of structural performance, durability, environmental impacts, and cost-effectiveness in a long-time interval. Additionally, the effect of the concrete strength increase on the life-cycle environmental impact and cost is assessed on a structural scale. An illustrative example is established to demonstrate the use of UHPC within precast-prestressed girder bridge. It is found that the use of UHPC can result in a significant reduction of concrete volume and CO_2 emissions compared with conventional bridge with the same span length. Additionally, the life-cycle cost and equivalent annual cost associated with these two bridges are compared. This study aims to aid the development and adaptation of novel materials within civil engineering to make optimal use of the favorable material properties.

1. Introduction

Nowadays, the engineering community, along with the society, is realizing the importance of sustainability-oriented infrastructure systems. Concrete, as a widely used construction material, represents a significant worldwide environmental impacts and cement product is responsible for 7% of the total CO_2 emissions worldwide. Thus, incorporating the sustainability concept into the structural design procedure is of great importance and still remains as a challenging task to the engineers. Sustainable construction and design approaches are critically needed. The concrete industry has devoted effects to reduce the greenhouse gas emissions. For instance, the alternative fuels and substitutions of clinker material by mineral additions were adopted to reduce CO_2 emissions [18,39]. Another possible solution to help achieve higher infrastructure sustainability is the development and application of high-performance materials, such as ultra-high performance concrete (UHPC) to reduce the concrete volume used for the infrastructures. However, current construction practice, and design codes and standards fail to permit the full application of the emerging materials. The challenges for the wide use of these materials are generally due to the lack of quantitative tools to evaluate the structural performance, sustainability, and environmental impacts in a long-term range. The relevant research on the application of UHPC within bridges in a life-cycle context is conducted in this paper.

E-mail address: you.dong@polyu.edu.hk

https://doi.org/10.1016/j.conbuildmat.2018.02.037

UHPC, as a new generation of fiber reinforced cementitious material, is composed of cement, fine silica sand, superplasticizer, water, and steel fibers, etc. The development of UHPC represents a significant innovation in the concrete industry and can overcome some shortcomings of normal concrete in terms of strength and permeability to chlorides. Generally, UHPC is associated with extremely high mechanical and durability properties and has the potential to tackle challenges with respect to the load capacity, durability, sustainability, and environmental impacts of concrete structures. For instance, the reinforced concrete structures are easily cracked under service loads, which can cause the ingress of water and chlorides and lead to corrosion of steel reinforcement. Furthermore, the corrosion of steel rebar can lead to spalling of concrete cover and even collapse of structures. UHPC has the potential to address these issues. Thus, the construction of new structures using UHPC can improve the performance and extend the service life, providing a green solution for the development of the next generation of civil infrastructures.

The recent studies on the UHPC on basis of material science aim to produce the materials with high mechanical and durability properties. The application of UHPC in structural design and construction areas has lagged behind the progress on the material level. The knowledge obtained at the UHPC material level should be transferred into the structural engineering and design process. This paper aims to link the behavior of the material to the corresponding structural performance level. UHPC has been adopted for some structures. For instance, a number of bridges have been designed using UHPC in Europe, United States, and China. The first UHPC simply supported bridge with two spans was designed in France and opened to traffic in 2002. Later, a pedestrian bridge in Seoul, Korea, that spans 120 m was constructed. In 2006, the first UHPC bridge in US was built in Wapello County, Iowa. Subsequently, the *pi* girders using UHPC were used in Jakway Park Bridge in Iowa. The first UHPC footbridge, Beichen delta bridge, was constructed in Changsha, China, in 2016. As most of the current structural design codes are related to the concrete with the maximum compression strength of 80–85 MPa, which is much lower than the strength of UHPC, the comprehensive design and assessment guidance of UHPC structures is urgently needed in practice. Though there exist some design guidelines for UHPC structures, such as French Interim Recommendation [6] and guidance developed by the Japan Society of Civil Engineering [20], they are not well developed and future modifications are needed. In order to aid the full implement of UHPC within civil infrastructures, the reliability-informed evaluation procedures should be well established and is assessed in this paper.

To aid the development of novel materials within civil engineering, it should ensure that the structures using novel material (e.g., UHPC) should have the least impact on our environment and help to minimize construction and especially maintenance costs in a long term [25]. The production of UHPC is usually associated with high CO_2 emissions and could have an adverse consequence on the environment. Then, life-cycle assessment (LCA) should be incorporated within the evaluation process. LCA is a comprehensive and standardized approach for quantifying life-cycle cost, resource consumption, and environmental impacts of an asset, product, among others. There exist some studies focusing on the UHPC structural performance assessment. Steinberg [34] examined three analytical approaches to evaluate the ultimate flexural strength of UHPC girders; Almansour and Lounis [5] presented an initial design and construction approach for the UHPC girder; Van den Heede and De Belie [37] investigated the structural performance and environmental impact of traditional and novel concrete materials; Gunes et al. [17] presented a two-phase model to investigate the behavior of UHPC and was implemented within a preliminary design case. However, all these studies were focused on the initial structural performance assessment without considering the life-cycle performance and environmental impacts (e.g., CO_2 emissions). In this paper, the long-term benefit of using UHPC within structures is assessed considering a decrease in the amount of concrete used, decrease in maintenance and repair costs, and a longer projected lifespan. In detail, the presented approach considers the interaction between materials and structure, and link them with the life-cycle model to assess the design of infrastructures using novel materials.

In this paper, the life-cycle cost and environmental impact associated with UHPC and normal concrete bridges are assessed considering not only production, design, and construction phases, but also the operation, maintenance, failure, as well as demolition phases. The benefit associated with UHPC structures in terms of structural efficiency, durability, and cost-effective in a life-cycle context is investigated and compared with normal concrete structures. The aim of this paper is to provide evidence that allows the owner and the constructor to make decisions regarding the selection of novel materials for the civil infrastructures that are associated with minimum environmental impact while on the other hand with maximum performance and durability. The rest of this paper is structured as follows: an overview of UHPC material properties, structural reliability, and durability assessment is presented in Section 2. Section 3 discusses the need and methodology for the life-cycle assessment and equivalent annual cost, and environmental impacts assessment (e.g., CO_2 emissions) of UHPC structures. The description of a case study of bridges using normal concrete and UHPC is outlined in Section 4. Finally, Section 5 provides the discussion and conclusions of this study.

2. UHPC material and structural reliability assessment

2.1. Mechanical properties and durability of UHPC

UHPC is a class of novel cementitious composite materials that is associated with superior mechanical and durability properties than those of normal concrete [35]. UHPC consists mostly of the same constituents as the normal concrete, such as cement, silica fume, water, and quartz sand. However, it also contains finely ground quartz, steel fibers, and superplasticizer. Thus, UHPC tends to be a very low water-to-cementitious ratio composite material with discontinuous fiber reinforcement and little or no coarse aggregate. Due to the low water-to-cementitious ratio, high performance plasticizers are needed to guarantee the workability of fresh UHPC. Due to the existence of the steel fibers, UHPC is associated with a high tensile strength and ductility, allowing the concrete to resist stresses after initial crack [32]. Additionally, the dense nature of the UHPC matrix decreases the porosity of concrete, thus its durability is much better than the normal and high-performance concrete (HPC).

Generally, the mechanical properties of UHPC include compressive strength greater than 150 MPa and sustained post-cracking tensile strength greater than 5 MPa [16]. The tensile strength of UHPC depends on two main factors: the volume of fibers in cross section and fiber orientation. Additionally, due to its dense particle packing and steel fiber, the UHPC exhibits high flexural strength properties. Under given mixture design and curing regime, flexural strength values can be up to 48 MPa [27]. Typically, the relationship of stress-strain of UHPC under compression is a linear elastic portion up to 80 – 90% of the maximum stress value [15]. The stress-strain curve of UHPC obtained from French design recommendations [6] is shown in Fig. 1(a) for illustrative purpose. Given more detailed information from the comprehensive lab tests, the model can be updated and easily incorporated.