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Environmental Benefits of Life Cycle Design of Concrete Bridges

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Keywords: life cycle performance, high performance concrete bridge, greenhouse gas emissions, life cycle cost.

ABSTRACT

This paper presents a life cycle-based approach for the design of concrete highway bridges that takes into account their physical, economic and environmental performances over their life cycles, with emphasis on the reduction of greenhouse gas emissions, construction waste production and life cycle cost. The analysis considers all the key stages in the life cycle, which include extraction of raw materials, construction, maintenance, repair, rehabilitation, replacement, and disposal. The proposed life cycle design approach is illustrated on the cases of two concrete highway bridge decks that are built in corrosive environments using high performance concrete containing industrial by-products and normal concrete. It is found that that use of high performance concrete leads to highway bridge decks with: (i) longer service lives (3 to 10 times longer than decks built with normal concrete; (ii) 65% reductions in CO_2 emissions associated with construction and rehabilitation compared to normal concrete decks; and (iii) 40% to 45% reductions in life cycle cost compared to normal concrete decks. This paper illustrates the multiple environmental benefits of using high performance concrete to build durable bridges with minimum maintenance that lead to a reduction in the consumption of raw materials and greenhouse gas emissions, and reclaiming industrial waste products and using them as effective construction materials.

Introduction

Highway bridges are critical links in Canada's transportation network that should be maintained to remain safe and functional during their service lives to enable personal mobility and transport of goods to support the economy and ensure high quality of life. Both owners and users of bridges expect their bridges to have a service life of 50 to 100 years, with only routine maintenance. But demands on most of Canada's bridges have been increasing annually because of growing traffic volumes, higher loads, and aggressive environments (e.g. deicing salts, frequent freeze-thaw cycles, etc.). These conditions, coupled with the inadequate funding allocated for maintenance, have led to the accelerated aging and extensive deterioration of these critical structures. The consequences of a bridge failure can vary from a minor disruption of traffic to catastrophic collapse with injuries and loss of life. Therefore, it is imperative that rigorous and reliable models and techniques be used to predict the performance and assess the corresponding risk of failure throughout the service life of the bridge.

The growing concerns of the public with climate change and the degradation of the environment due to pollution has led to the development of new approaches for the design of sustainable or "green" buildings and infrastructure systems to reduce the environmental footprint of the construction industry[1,2]. Concrete is the primary construction material in the world and its use is expected to double in the next thirty years. Cement is the main component of concrete and the world cement production was evaluated at 2 billion tons annually in 2004 and it is estimated that it would reach 7.5 billion tons annually by the year 2050 [3,4]. Concrete has enabled the construction of high strength, long life, and cost-effective buildings and infrastructure systems over the last decades. Furthermore, by enabling the construction of durable systems, concrete had a considerable positive impact on the environment by reducing the need for extensive and frequent rehabilitations, which in turn reduces the consumption of raw materials, water and energy. In addition, concrete provides heat storage capacity and chemical inertness. However, cement manufacturing is a very energy intensive process that leads to relatively considerable greenhouse gas (GHG) emissions, which in turn are the main factors responsible for climate change. In Canada, approximately 0.7 to 0.8 tons of CO_2 is produced for every ton of cement manufactured, depending on the plant efficiency. Since the cement content in a concrete mix accounts for only 7% to 15% (by weight), this translates into 0.11 to 0.29 tons of CO_2 per m^3 of concrete produced. In 2002, the GHG emissions from cement production were estimated at 9.8 million tons of CO_2-equivalent, which represented about 1.36% of the total GHGs emissions in Canada[5,6]. The *World Business Council for Sustainable Development* reported that cement production accounts for about 5% of the world CO_2 emissions, which are estimated at 9 billion tons per year[7,8]. For comparison purposes, the transport sector contributed an estimated 187 million tons of CO_2-equivalent, which accounts for 26% of the total GHGs emissions in Canada[6]. The CO_2-equivalent is defined as the quantity of a given GHG multiplied by its global warming potential. This is the standard unit for comparing the degree of harm that can be caused by emissions of different GHGs.

The growing concerns with climate change and the demands for the reduction of greenhouse gas emissions, energy efficiency and conservation of raw materials present considerable challenges to owners, engineers and all construction industries. To address these challenges, there is a need to develop effective approaches for life cycle design and management of highway bridges that will ensure their sustainability over a long planning horizon, in terms of improved physical performance, cost-effectiveness, and environmental compatibility. These optimized designs and management systems should provide the owners with the solutions that achieve an optimal balance between three relevant and competing criteria, namely: (i) engineering performance (e.g. safety, serviceability and durability); (ii) economic performance (minimum life cycle costs, minimum user costs); and (iii) environmental performance (minimum greenhouse gas emissions, reduced materials consumption, energy efficiency, etc.).

The largest environmental impact of the concrete industry comes from the cement manufacturing process that leads to relatively considerable greenhouse gas emissions, which in turn are the main factors responsible for climate change. However, the long life and low maintenance needs of high performance concrete bridges lead to considerable reductions in their environmental impacts. Furthermore, the use of industry by-products such as fly ash, slag and silica fume as cementing materials in concrete structures can lead to significant reductions in the amount of cement needed to make concrete, and hence reduces emissions of CO_2 and consumption of energy and raw materials, as well as reduced landfill/disposal burdens.

A comparative study of the physical, economic and environmental performances of two alternative designs of highway bridge decks built with normal concrete and high performance concrete is undertaken. This study will illustrate the importance of the design of durable bridge systems to reduce the burdens on the environment and to minimize the life cycle costs associated with the construction and maintenance of highway bridges.

Life cycle-based design of concrete bridges

The proposed approach for the life cycle-based design of concrete bridge systems takes into account their physical, economic and environmental performances over their life cycle, with emphasis on the reduction of greenhouse gas emissions, waste production and life cycle cost. The implementation of this approach requires prior knowledge of the service life of highway bridges for different design and maintenance alternatives in order to select an effective design and associated maintenance strategy that will minimize the environmental impact and cost over the life cycle of the bridge system. Therefore, a reliable prediction of the service life of a highway bridge system built in a given environment and subjected to different environmental and mechanical loads is a of utmost importance in order to obtain reliable estimates of its life cycle cost and environmental impact, which are the key decision support tools to an effective life cycle based-design, as illustrated in Figure 1. The development of approaches for life cycle design and life cycle management of concrete bridges requires a rigorous evaluation of its physical, economic, and environmental performances over its entire life cycle, i.e. from “cradle-to-grave”, or “cradle-to-gate” (if it is recycled).

In general, the life cycle of reinforced concrete bridges can be described as a five- stage process, as follows:

(i) Extraction, manufacture, transformation and transportation of raw materials to plants, including cement, aggregate, water, reinforcing and prestressing steels, as well as reclaimed industry by-products such as fly ash, granulated blast-furnace slag, and silica fume, which are used as supplementary cementing materials (SCMs).

(ii) Concrete production and component manufacturing, including the mixing of the above raw resources and the supplementary cementing materials to produce concrete with the required design properties, as well the production of precast concrete components (e.g. beams, slabs, etc.). This stage starts with the delivery of raw resources and SCMs at the plant gate and ends with the delivery of ready mixed concrete and/or manufactured products to the construction site.

(iii) Construction: This stage consists of placement of reinforcement and pouring concrete into the formworks to build the different cast-in-place sub-systems (e.g. abutments, piers, slabs, etc.) and erection and placement and assembly of precast components (e.g. prestressed concrete girders) to build all systems of the bridge. The costs, energy used and environmental impacts associated with transportation and use of on-site machines like cranes and mixers, temporary support and bracing, etc. should be considered in the life cycle analysis of HPC structures.

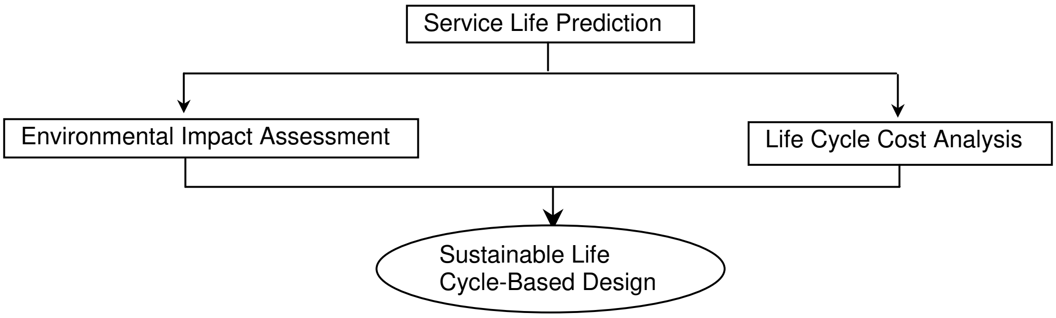

Figure 1: Decision Support Tools for Life Cycle-Based Design of Highway Bridges

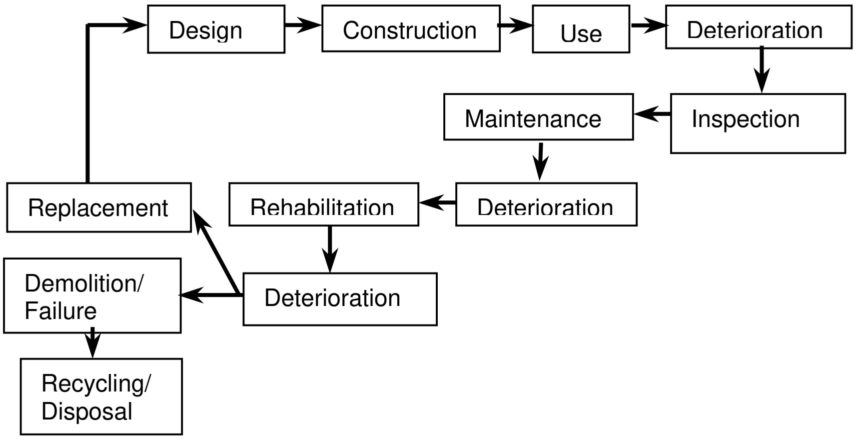

Figure 2: Multiple stages of life cycle design and management of highway bridges

(iv) Use, deterioration, and maintenance: This is the longest stage in the life cycle of highway bridges. The appropriate timing of the maintenance, rehabilitation and replacement activities is very important to the minimization of the life cycle environmental impact and cost of the bridge. At this stage, in addition to environmental impacts similar to those associated with phases (i), (ii) and (iii) identified above, there are additional impacts due to traffic disruption, such as increased fuel consumption and pollution. The forecasting and optimization of the times for maintenance and rehabilitation depends to a great extent on the availability of reliable service life prediction models. The development of such models is a complex task, as it requires an understanding of the performance of the bridge subject to mechanical loads and environmental effects, including the prediction of deterioration, loss of serviceability, and reduction of safety. It is critical to ensure that the risk of failure is kept at an acceptable level, otherwise the service life or life cycle of the bridge will be shorter than planned[9,10].

(v) Demolition, disposal and renewal: The disposal stage includes demolition, preparation for recycling or re-use and disposal as waste in landfills. This defines the end of a bridge or component life cycle although it is not the end for individual components or materials or products, which may be recycled or re-used. The reasons for demolition can include safety concerns, structural collapse, functional obsolescence, need for replacement, etc.

Environmental and Economic Benefits of High Performance Concrete Bridges

High performance concrete is used to define a concrete that enables the construction of structures with long service lives and high strength. High performance concrete (HPC) with low permeability and high strength can be obtained by using: (i) high quantities of cement (or low water-to-cement ratios); or (ii) by adding reclaimed industry byproducts such as fly ash (byproduct of coal combustion for electric power generation), granulated blast-furnace slag (byproduct of steel manufacturing), and silica fume (byproduct of semi-conductor manufacturing) as supplementary cementing materials (SCMs). In this paper, HPC refers to concrete containing SCMs that improve the physical performance of concrete structures and reduce the quantity of cement needed for concrete production. The environmental and economic benefits of using HPC containing SCMs can be summarized as follows:

(i) Reduction of raw materials due to extended service life: HPC enables to build bridges with service lives that can be much longer than those of normal concrete. As a result, HPC bridges will require fewer maintenance and rehabilitation activities to upgrade their conditions, which in turn will lead to considerable reduction in consumption or materials, water, energy, etc. The service life of concrete bridge decks built in corrosive environments can be evaluated using the diffusion theory for predicting the penetration of chlorides (from deicing salts) into the concrete deck[4,9,10].

(ii) Reduction of greenhouse gas emissions due to lower cement consumption: As mentioned earlier, the production of one ton of cement results in approximately a reduction of 0.8 ton of CO_2. The reduction of quantities of materials needed (concrete and reinforcing steel) for the construction or rehabilitation of HPC structures will result in a reduction of CO_2 emissions and consumption of water, and non-renewable energy and reduction of waste production.

(iii) Reduction of landfilled construction materials waste by enabling the construction of durable bridges that can last more than 70 years with minimum maintenance, thus reducing the quantities of concrete waste after demolition for rehabilitation and replacement. In addition, waste products such as fly ash, slag, silica fume from the coal, steel and semi-conductor industries, respectively that should otherwise end up in landfills are reclaimed and used as effective concrete construction materials.

(iv) Reduction of life cycle costs due to reduction of maintenance activities.

Illustrative Example

The proposed life cycle design approach is illustrated for the case of a highway bridge deck built in a corrosive environment as a result of the use of deicing salts during winter. This deck is part of a two-lane bridge with a width of 12.35 m and a span length of 35 m. The deck has a thickness of 200 mm and is reinforced with an isotropic reinforcement made of conventional "carbon" steel with a percentage ratio of 0.3% for both the top and bottom mats. The life cycle environmental and economic performances of two different designs of reinforced concrete bridge decks using normal concrete and high performance concrete (HPC) are evaluated within their life cycles. A simplified life cycle environmental analysis of the bridge deck is considered by focusing on two main impacts: (i) emissions of CO_2; and (ii) waste production (or landfill use). In this example, the service life of a concrete bridge deck is defined as the time it takes for the initiation of the corrosion of the reinforcing steel. Using appropriate values for the diffusion coefficients of chlorides into the concrete deck, the average values of the service lives are found equal to 15 years and 45 years for normal concrete deck and HPC deck, respectively[4,10]. The environmental impact analysis and life cycle cost analysis are undertaken assuming a life cycle of 30 years and a discount rate of 3% .

Within the assumed life cycle of 30 years, a major rehabilitation was needed for the normal concrete deck and only routine maintenance and inspection were needed for the HPC deck. Two types of costs are associated with the maintenance and rehabilitation of highway bridge decks: (i) agency or owners' costs, which include the costs of construction, inspection, routine maintenance, repair, rehabilitation, replacement, demolition, and disposal; and (ii) costs to the users of the bridge associated with the maintenance of bridge decks that include the traffic delay costs, accident costs and vehicle operating costs, which can be summarized as follows:

(i) The present values of the life cycle costs for the bridge owner are \$987/m^2 for the normal concrete decks and \$524/m^2 to \$584/m^2 for the HPC decks. Therefore, the life cycle cost of the HPC design alternative is about 40% to 45% lower than the life cycle cost of the normal concrete deck alternative.

(ii) The present values of the bridge user costs are \$53/m^2 and \$16/m^2 for the normal concrete and HPC decks, respectively. The reduction by 70% of the user cost for the HPC deck is mainly the result of the difference in frequency and schedule of patch repairs and the need for replacement of the normal concrete deck within the considered life cycle.

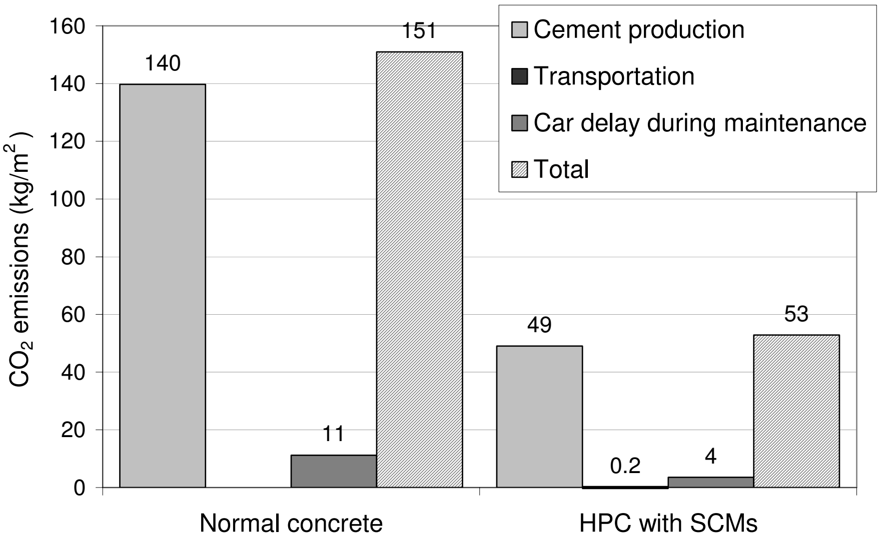

Figure 3: CO_2 emissions within life cycles of concrete bridge decks

The emissions of CO_2 are estimated for the two bridge deck alternatives and are shown in Figure 3. These estimates include the major components that illustrate the difference between the two alternatives, namely: (i) cement production; (ii) additional transportation needed for the SCMs; and (iii) CO_2 emitted by cars delayed by the maintenance, repair, and replacement activities. The CO_2 released by the production of reinforcing steel is not accounted but would typically be the same for both deck alternatives. In this example, it is found that the CO_2 emissions for the normal concrete deck alternative are almost three times higher than those of the HPC deck alternative. This difference is mainly due to the shorter service life of the normal concrete deck (the deck is completely replaced after 15 years), which also leads to an increase in traffic disruption. A comparison of the waste produced (or landfill use) for the two deck alternatives is shown in Figure 4, which includes the volume of waste material produced during the replacement of asphalt overlay, patch repair, and replacement.

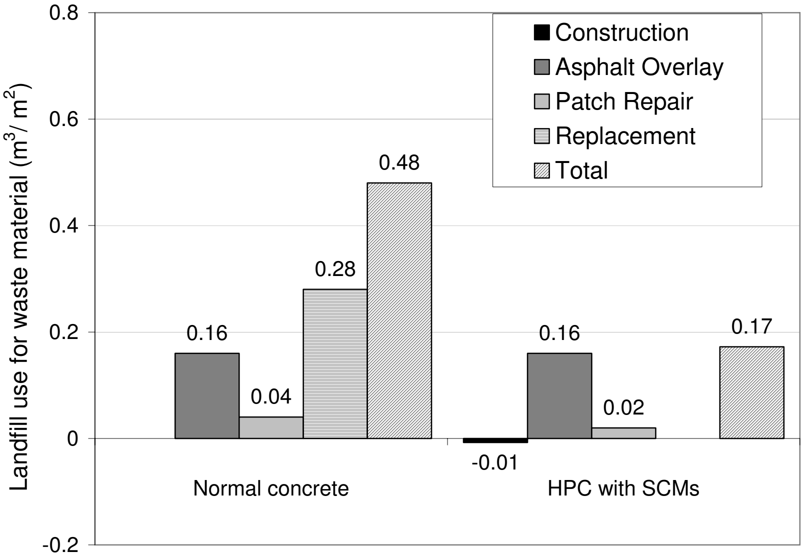

Figure 4: Volume of construction waste materials from HPC and normal concrete bridge decks

Summary and Conclusions

In this paper, it was shown that the implementation of life cycle-based design and maintenance management approaches would lead to the construction of high performance bridges with reduced environmental footprints. It was shown that industrial byproducts (such as fly ash, slag, and silica fume) could be reclaimed and used in high performance concrete as effective complementary construction materials. The use of HPC materials results in bridge decks with extended service lives, reduced life cycle costs and better environmental profiles when compared to conventional normal concrete bridge decks. From the example above, the following conclusions can be drawn:

- In terms of durability, the HPC deck alternative incorporating SCMs has a service life that can vary from 3 to 10 times the service life of normal concrete deck.
- In terms of environmental impact, it is estimated that the HPC deck alternative yields a reduction of 66% in the CO_2 emissions compared to the normal concrete deck.
- In terms of life cycle costs, the HPC deck alternative incorporating SCMs is found to be more economic than the normal concrete deck for both agency costs and user costs.

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