INTEGRATED PROBABILISTIC LIFE CYCLE ASSESSMENT AND DURABILITY DESIGN FOR SUSTAINABLE SHCC INFRASTRUCTURE

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Abstract

Strain hardening cementitious composites (SHCC) have demonstrated durability superior to that of conventional reinforced concrete due to their unique cracking behavior which influences transport, as well as corrosion propagation and damage development. In addition to more durable infrastructure, SHCCs can result in more sustainable infrastructure when accounting for life cycle performance. Focusing on numerical modeling of SHCC deterioration, this paper presents an approach to operationalize SHCC design and maintenance for improved sustainability. This framework consists of two types of models: (i) material degradation models and (ii) life cycle assessment models.

Numerical modeling of deterioration is used to estimate the time to each repair. These deterioration models are coupled with environmental impact models of a given repair, rehabilitation, or strengthening activity based on a process-based LCA of individual repair activities. All models are formulated stochastically so that the time to repair and total sustainability impact are described by a probability density function. Results facilitate decision-making by infrastructure stakeholders when designing to meet sustainability targets.

1. INTRODUCTION

Numerous researchers have investigated the durability of strain hardening cementitious composites (SHCCs) including studies on long term mechanical behavior [1], freeze thaw exposure [2], tropical climate exposure [3], chloride immersion [1], deicing salt exposure [4], alkali-silica reaction [5], fatigue [6], creep under sustained load [7], wheel load abrasion [1], restrained drying shrinkage [8], and corrosion [9,10]. In each investigation, SHCCs demonstrate improved performance when compared to conventional reinforced concrete under similar conditions. However, widespread industry application of SHCC remains low.
To support a clearer view of the life cycle value proposition and a wider adoption of advanced cementitious and concrete materials, such as SHCCs, a more rational, probabilistic formulation of their life cycle performance and value proposition is needed. Beginning with the Duracrete initiative [11], and later within the 2006 fib Model Code [12], probabilistic design for durability of concrete structures has been actively researched and introduced to practice. In the context of design for sustainability, this paper presents an application of durability design that leverages the higher performance of advanced materials to meet infrastructure sustainability efforts recently proposed by the 2010 fib Model Code [13] and present a more compelling sustainability value proposition for the use of SHCC materials.

2. SUSTAINABLE INFRASTRUCTURE DESIGN FRAMEWORK

This framework focuses on the sustainable repair and rehabilitation of infrastructure. It comprises the measurement of the cumulative impact of a repair and rehabilitation timeline up to the time of functional obsolescence. This is shown in Fig. 1a.

As seen in the vertical segments of the cumulative impact in Figure 1a, the time at which any repair is made \( t_i \) is probabilistically characterized based on reaching a life safety limit state corresponding to a reduction in materials quality or structural performance beyond which is unacceptable to the owner or in violation of the design code. The probabilistic time between repairs \( t_{i+1} - t_i \) is based on the chosen repair strategy, the quality of the repair work, the variable nature of exposure and load conditions, limit state, etc.

The cumulative impact of the repair timeline is defined as the sum of each repair impact, \( i_0(t_i) \), due to the \( i^{th} \) repair event as measured using ISO 14040 series LCA methods [14]. Metrics of environmental impact are based on accepted environmental impact assessment midpoint indicators within the United States’ TRACI [15] or the Netherlands’ ReCiPe [16] protocols. In addition to the probabilistic determination of the time of future repairs, the impact associated with repairs is probabilistic in nature as shown in Figure 1a.

![Figure 1](image)

Figure 1: (a) Construction of a probabilistic envelope of cumulative impact of infrastructure from initial construction \( t_0 \) to functional obsolescence \( t_{i_0} \); and (b) Comparison of probabilistic envelopes for status quo and SHCC sustainable infrastructure designs. Failure probability of not meeting sustainability targets \( P_i \) is shown as a function of time.

Combining the probabilistic models for the life cycle repair timeline \( t_{i_0} \) and the amount of impact \( i_{i_0} \), a probabilistic envelope can be constructed for the entire infrastructure service...
life from the time of initial construction \((t_0)\) up to functional obsolescence \((t_{fo})\). Based on the boundaries of this larger envelope (shown in Figure 1a using dashes), an aggregated probabilistic assessment for cumulative impact at any time, \(t\), can be constructed.

As a sustainability limit state, this framework adopts the concept of environmental sustainability through the reduction of environmental impact midpoint indicators such as global warming potential (CO₂ equivalents), acidification potential (H⁺ mol equivalents), and similar indicators as specified by ISO 14040. [14] Targets for achieving “sustainable development” are drawn from policy such as those proposed by the Intergovernmental Panel on Climate Change (IPCC) for reductions in global greenhouse gas emissions. [17]

With reductions in environmental impact in mind, an SHCC repair timeline can be designed to improve upon a status quo concrete repair timeline. The comparison of the two scenarios (a status quo concrete repair timeline and an SHCC alternative) is shown in Figure 1b. Based on this, the level of impact reduction using an alternative repair can be estimated at any future time and associated with a level of confidence. The probability of failing to meet a sustainability goal by using a new SHCC design is the overlap of these envelopes. This failure probability, \(P_f(t)\), over time is shown in Fig. 1b.

3. DEMONSTRATION CASE STUDY

A hypothetical case study of surface repairs performed on a Norwegian bridge is selected. The exposure loads are based on the OFU-Gimsoystraumen Bridge Project [19]. The two hypothetical repairs selected for demonstration in the framework suggested here were (1) a 40.0mm deep concrete cover replacement with water hydrodemolition and a cast-in-place concrete repair and (2) a 40.0mm deep SHCC repair with water hydrodemolition and a cast-in-place SHCC cover replacement. It should be noted that an SHCC repair was never considered for the actual OFU-Gimsoystraumen bridge repair but serves only as a comparison for illustration in this study. Traffic was approximately 3000 vehicles per day. However, no traffic was interrupted during the repairs due to their location outside of traffic lanes. Therefore, impacts from congestion-related traffic emissions do not occur in the case but can play an important part of the modeling when included.

3.1 Repair Life Cycle Inventory and Impact Assessment

To determine the life cycle impacts of repairs, a life cycle inventory and impact assessment of the materials and processes used to complete the two repairs was constructed in compliance with ISO 14040 standards. The main data sources were Kompen et al. [18] for repair data, primary data from contractors, construction product marketing materials, personal safety and hygiene sheets (MSDS), and commercial life cycle inventory datasets.

For each cover replacement activity, the commercial products used, equipment needed, and transportation associated with bringing the materials to the site were catalogued. Probabilistic variation of these inputs and their impacts was characterized. The overall environmental impact of the repair was calculated by summing the impacts from each construction stage. For example, the hydrodemolition impact is computed as the sum of impacts associated with water use, water for washdown purposes, waste disposal of the removed concrete, and impacts from operation of hydrodemolition equipment. The hydrodemolition equipment includes an air compressor (250 cfm capacity), a hydrodemolition machine, and a front-end loader. Probabilistic productivity rates and equipment schedules
were determined from RS Means Construction Cost Data [20], industry literature, and contractor interviews.

Monte Carlo analysis was carried out to determine the magnitude and shape of the uncertainty profiles for 10 environmental impact midpoint indicators for each repair activity. Fig. 2 shows the global warming potential probability density function per square meter of repair work performed (kg CO$_2$-eq/m$^2$). Similar charts were developed for each Ecoinindicator 99 environmental impact midpoint indicator [16].

As seen in Fig. 2a the 40.0mm cast concrete cover replacement has an average global warming potential impact per square meter of repair of 76.9CO$_2$-eq/m$^2$ with a standard deviation of 12.0 CO$_2$-eq/m$^2$. As seen in Fig. 2b, the 40.0mm cast SHCC has an average global warming potential impact per square meter of repair of 90.6 CO$_2$-eq/m$^2$ with a standard deviation of 13.9 CO$_2$-eq/m$^2$. The SHCC has a higher expected value due to the higher cement content per cubic meter. However, the coefficient of variation is lower for SHCC since there is less variability in potential mix designs associated with these materials.

![Figure 2: Global warming potential of material production and construction per square meter of (a) 40.0mm cast concrete cover replacement; and (b) 40.0mm SHCC cover replacement](image)

### 3.2 Service Life Model

The fib 2006 Model Code for Concrete Durability Design was chosen for probabilistic modeling of the concrete repair service life. [12] For this case study, “loss of cover integrity” was chosen as the limit state for each repair. Cracking due to chloride-induced corrosion of steel reinforcement was the limit of failure for concrete while the exhaustion of tensile strain capacity due to chloride-induced corrosion of steel reinforcement defined “loss of integrity” for SHCC. For concrete, this comprised a two-stage process of chloride transport and cracking. The transport limit state in concrete is shown in Eqn. 1 [12].

$$C_{cr} = C(x = d, t)$$  \hspace{1cm} (1)

where, $C_{crit}$ is the critical chloride concentration for depassivation in weight % of cement –Beta[0.6, 0.15, 0.2, 2.0]; $C(x=d,t)$ is chloride concentration at the depth of the reinforcement at time, $t$ in weight % of cement. This time dependent concentration of chlorides at a given depth is computed using Eqn. 2 [12].
\[ C(x = d, t) = C_0 + (C_{\text{cor}} - C_0) \left( 1 - \text{erf} \left( \frac{d - \Delta x}{2a \sqrt{b \left( \frac{1}{T_{\text{ref}}} - \frac{1}{t} \right) / \rho_{\text{rust}} \ell}} \right) \right) \]

where, \( C_0 \) is initial chloride content of concrete in weight % of cement [0.0]; \( C_{\text{cor}} \) is chloride content at a depth \( \Delta x \) in weight % of cement \( \sim \text{N}[6.0, 0.5] \); \( d \) is concrete cover in millimeters \( \sim \text{N}[40, 10] \); \( \Delta x \) is depth of concrete convection zone in millimeters [0.0]; \( b_2 \) is a regression variable in Kelvin \( \sim \text{N}[4800, 700] \); \( T_{\text{ref}} \) is standard test temperature in Kelvin \( [293.0] \); \( T_{\text{ref}} \) is temperature of the structural element or ambient air temperature in Kelvin \( \sim \text{N}[279.7, 10.93] \); \( D_{\text{BMC}, a} \) is chloride migration coefficient in m²/s \( \sim \text{N}[6.9 \times 10^{-12}, 1.38 \times 10^{-12}] \); \( k_b \) is a transfer parameter [1.0]; \( t_0 \) is a reference point in time in years [0.767]; \( t \) is time in years; \( a \) is an aging exponent \( -\text{Beta} [0.6, 0.15, 0.0, 1.0] \); \( \text{erf} \) is the error function.

Time to cracking of conventional concrete following depassivation is modeled as uniform corrosion using the mechanics-based model of Liu and Weyers shown in Eqn. 3. [21]

\[ T_{cr} = \frac{\rho_{\text{rust}} \bar{\sigma} \left( a \frac{d_f f}{E_{\sigma}} \left( \frac{a^2 + b^2}{b^2 - a^2} + \nu_{r} \right) + d_f R_{0} + \frac{W_{\text{ste}}}{\rho_{\text{ste}}} \right)^{2}}{0.208 \rho_{\text{rust}} \ell_{\text{corrosive}}} \]

where \( T_{cr} \) is time to cracking after depassivation in years; \( \rho_{\text{rust}} \) is density of corrosion products [3600 kg/m³]; \( f'_{c} \) is tensile strength of concrete in MPa \( \sim \text{N}[3.6, 0.72] \); \( E_{\sigma} \) is effective elastic modulus of concrete in MPa [20 GPa]; \( a = 0.5(D_o + 2d_o) \); \( b = x + a \); \( \nu_{r} \) is Poisson’s ratio for concrete [0.18]; \( d_o \) is the thickness of a rebar surface porous band in mm [0.025]; \( D_o \) is initial diameter of reinforcement in mm \( \sim \text{N}[12, 0.24] \); \( W_{\text{ste}} \) is mass of corroded steel in mg/mm; \( \rho_{\text{ste}} \) is steel density [7850 kg/m³]; \( \alpha \) is molecular weight of steel divided by molecular weight of corrosion products [0.57]; \( \ell_{\text{corrosive}} \) is corrosion current density in µA/cm² \( \sim \text{N}[55.1, 16.5] \).

The limit state for SHCC is defined by the material surrounding the corroding rebar reaching strain capacity. This straining is a result of the hoop expansion of oxidizing rebar. This is based on the mechanics-based model proposed by Lepech shown in Eqn. 4. [22]

\[ T = \frac{\rho_{\text{ste}} \bar{\sigma} \left( a \frac{d_f f}{E_{\sigma}} \left( \frac{a^2 + b^2}{b^2 - a^2} + \nu_{r} \right) + d_f R_{0} + \frac{W_{\text{ste}}}{\rho_{\text{ste}}} \right)^{2}}{0.208 \rho_{\text{rust}} \ell_{\text{corrosive}}} \]

where, \( T \) is time to exceed strain capacity in years; \( f'_{c} \) is tensile strength of SHCC in MPa \( \sim \text{N}[4.8, 0.32] \); \( E_{\sigma} \) is effective elastic modulus of SHCC in MPa [12 GPa]; \( \nu_{r} \) is the Poisson’s ratio for SHCC [0.18]; and \( \varepsilon_u \) is the ultimate strain capacity of SHCC \( \sim \text{N}[2.2, 0.17] \). Underlying distributions and parameters for all models are from [12, 23, 24, and 25].

Based on Equations 1 through 4, the time to end of service life for a cover replacement of conventional concrete or SHCC cover can be modeled as a lognormal distribution with means 7.4 and 15 years and standard deviations 3.8 and 4.7, respectively, as seen in Fig. 3.
3.3 Integration of Service Life and Life Cycle Assessment Models

The time of future cover replacements is modeled as a Markovian chain of independent, recurring, identical deterioration processes. The duration of any construction work is considered to be insignificant when compared to the duration of the depassivation process.

Combining the probabilistic life cycle inventory with this probabilistic model of service life, a probabilistic envelope of cumulative impact can be numerically constructed (shown conceptually in the dashed lines of Fig. 1a). This is shown in Fig. 4 for each of the scenarios. Within this case study the functional unit of analysis is one square meter of cover replacement, which deteriorates and then is repaired.

As seen from Figure 2, the mean impact per square of one cover replacement using SHCC was 18% higher than for conventional concrete. However, as seen in Figure 4, when accounting for the greater durability of the SHCC cover replacement, the cumulative impact...
over the life cycle is reduced. Over a 100-year life, the SHCC has a 41% lower GWP impact as compared to the concrete.

4. DISCUSSION

The probabilistic nature the of LCA and material deterioration models allows for consideration of many uncertain parameters including material properties, corrosion currents, environmental exposure, material supply chains, productivity variations, etc. when considering the life cycle benefits of SHCC. In addition to varying these parameters however, correct stochastic modeling of deterioration processes requires a thorough knowledge of fundamental transport, corrosion initiation, and corrosion propagation phenomena in both concrete and SHCC. While understood in many respects for concrete, significant research is needed to improve probabilistic models of transport, corrosion initiation, and corrosion propagation (uniform versus pitting) in finely cracked SHCCs. Modeling assumptions of perfect rebar-SHCC bond behavior, uniform transport and corrosion processes, and axisymmetric deformation of SHCC surrounding corroding rebar made in this study have only been validated in small scale, independent research studies. Likewise, variation in vehicle traffic models, emission models, material supply chain models, and worksite productivity models must be better characterized to strengthen confidence in LCA and, ultimately, the sustainability benefits of SHCC. Such efforts should form a part of the RILEM Technical Committee FDS work, charged with investigating the durability of SHCC materials.

5. CONCLUSION

Infrastructure, in particular transportation infrastructure, lies at the nexus of two major global sustainability challenges; large amounts of emissions from both vehicles and construction materials production. Therefore, opportunities exist to reduce environmental impacts associated with infrastructure construction and use. In line with recently proposed sustainability requirements in the fib 2010 Model Code, the framework presented in this paper integrates probabilistic life cycle assessment with probabilistic service life models to provide a foundation for more rational design, construction, and operation of SHCC infrastructure that looks to meet international environmental goals. While a great deal of research remains in the development and validation of these methods and tools for the SHCC community, the establishment of a comprehensive method and value proposition that aligns with accepted risk-based design principles is an initial step toward enabling infrastructure engineers an opportunity pursue a more sustainable built environment.

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REFERENCES