Internal Curing for Concrete Bridge Decks: Integrating a Social Cost Analysis in Evaluating the Long-Term Benefit

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ABSTRACT

Internal curing is used to describe a new approach to proportioning concrete mixtures where a portion of the fine aggregate in concrete is replaced with prewetted lightweight fine aggregate. Internally cured concrete (IC) has the potential to extend the bridge deck service life substantially due to a reduction in cracking and chloride ingress. While internally cured concrete has been used in practice, the IC usage is limited due to a slight increase in the initial cost and need for understanding batching operations and performing quality control. While some cost benefits studies have been performed, the potential life-cycle benefits of IC may be significantly underestimated, because the social costs (network traffic disruptions) have not been integrated in previous studies. This study evaluates the total life-cycle benefits of using high performance IC (HPC-IC) bridge decks compared to normal concrete (NC) bridge decks in a transportation network. Three bridges, located on an interstate highway, an arterial road, and an urban connector in the Minneapolis and St. Paul metropolitan area, are selected to examine the total life-cycle costs of bridge decks made of NC, high performance concrete, and HPC-IC. The results suggest that the use of HPC-IC can potentially reduce the total life-cycle costs by 50% compared to NC, and the scale of social costs reduction depends on the traffic volume carried by the bridges. The study provides insights that can be used to assist relevant decision-makers to use the internal curing process in bridge deck management activities so that limited resources can be more effectively allocated based on the potential benefits.
INTRODUCTION

The most recent report (1) on bridges in the National Highway System (NHS) of the United States (U.S.) shows that more than 20% of them were classified as either structurally deficient (potentially reduced load-carrying capacity due to deteriorated conditions of significant bridge elements) or functionally obsolete (bridge design fails to meet the current standards) in Year 2010. In addition, a large number of concrete highway bridges in the northern states of the U.S. exhibit serious corrosion-induced deterioration as a result of the deicing salts usage in winter (2, 3). Without proper maintenance, this deterioration may impede traffic flow, increase the bridge deck’s total life-cycle costs, and even cause the collapses of highway bridges (4). These issues increase the need for the public and private sectors to improve the bridge deck repair or renewal process by leveraging the development of construction management methods (5), effective inspection and monitoring of bridge deck performance (2), and alternative bridge deck materials (6, 7), etc.

Internal curing has recently been used as a new concrete technology that has the potential to dramatically extend the service life of the concrete infrastructure elements like bridge decks. Internal curing describes a process where water-filled inclusions are placed in concrete to refill the void space created due to chemical shrinkage during the early stages of hydration in cementitious systems (6). This process can reduce the early-age shrinkage cracking, thereby providing a significant reduction in the rate of penetration of chlorides in concrete (8). Also, internal curing increases hydration, further reducing the ingress of chloride ions. Internal curing with lightweight aggregate has been applied to bridge decks construction in at least four states (Indiana, New York, Utah, and on the Illinois Tollway) of the U.S. (9). A recent study (7) shows that the simulated service life of commercially produced internally cured, high performance concretes has the potential to triple the estimated 18 years of service life for a normal concrete bridge deck in Indiana. Extensive studies have been done in the field of internally cured bridge decks to identify the parameters needed for service life prediction (8) and implement internal curing processes in the field (6). One recent study (10) also shows that drinking water treatment waste can be used as an effective internal curing agent to improve cement hydration, compressive strength, and mitigate autogenous shrinkage. However, a key issue is that very little systematic research has been conducted to examine the benefits of internally cured concrete bridge decks at the network level to quantify its potential impacts in the context of reduced traffic disruptions resulting from bridge deck construction/replacement, inspections and maintenance, repair and rehabilitation activities (all of these activities are labeled as bridge management activities) and the varying traffic flow congestion levels across different time scales.

In the literature, there exist models for evaluating the life-cycle cost/benefit of concrete bridge decks. Figure 1 presents a life-cycle cost model adopted from Kendall et al. (11). The total life-cycle cost of concrete bridge decks often has two main components, including agency costs and social costs that are further divided into user costs and environmental costs. Agency costs represent the expenditures incurred by the facility owner or operator in charge of the bridge management activities throughout the life-cycle of that bridge deck, minus residual value of that bridge deck at the end of the life-cycle. These costs are usually converted to present value in the total life-cycle cost analysis (8, 12). In practice, social discount rate is often used for agency costs and social costs calculation, as the potential benefits of public projects may not be reflected in today’s market (13). The majority of the studies consider either only the agency costs when they compare different bridge management scheduling or materials, or do not consider user costs differences under varying traffic flow volume. Kendall et al. (11) found that the total agency
costs account for only 3% of the total life-cycle costs of concrete bridge decks, while the largest portion of the total life-cycle costs of concrete bridge decks (over 90%) comes from the user costs. However, Kendall et al. (11) did not consider alternative construction plans, traffic disruption at the network level and service life optimization of bridge decks.

FIGURE 1 Life-cycle cost model (11).

User costs are often considered as the monetized value of vehicle operating costs, travel time costs, and safety costs. During the bridge management period, the traffic disruption caused by the capacity reduction of the concrete bridge deck leads to an increase in the total system travel time, total system vehicle miles traveled and the probability of traffic crashes related to the bridge management of the work zones. The increase of total travel time can lead to operating cost increases (e.g. increased gasoline consumption caused by taking detour to avoid the work zone) and travel time cost increases. To quantify the user impact due to travel time increase during the bridge management period, the problem is usually formulated in the context of the traffic assignment problem (TAP), by comparing the differences in the system total travel time and the system vehicle miles traveled between the pre-bridge management period and the under bridge management period. One basic assumption about the traffic assignment model is the user equilibrium flow pattern, which implies that “the journey times on all used routes are equal and less than those which would be experienced by a single vehicle on any unused route” (14). The potential long-term demand changes are often not captured in existing studies. For the safety costs during the bridge management period, extensive studies (for example, (15)) have been performed that indicate that the cause of crashes in the work zone relate to the traffic control plan used, implementation of the traffic control plan, individual driver characteristics, etc. The unit crash costs are often valued based on the Police-Reported Injury Severity System (KABCO scale) coding scheme (16).
The environmental costs of concrete bridge decks in the total life-cycle costs often include air pollution costs, noise costs, water pollution and runoff costs, and community disruption. The air pollution costs are often reflected in the total emissions increase caused by the increased travel time due to traffic disruption during the bridge management periods (9). However, noise costs, water pollution and runoff costs are often hard to quantify and vary significantly case-by-case (13). The U.S. Environmental Protection Agency (EPA) developed vehicle emission and construction equipment emission models that are usually adopted in the total life-cycle costs estimation (11).

A large body of work on the simulation method and Life-Cycle Cost Model (LCCA) that are often applied in the domain of various civil engineering structure and facilities has been conducted in the last two decades, and many studies have focused on evaluating different bridge management options of bridge decks (17, 18). These studies utilized the agency and social costs with probabilistic analysis to estimate the life-cycle costs of different alternatives. Monte Carlo Simulation was used to generate simulated activity timing. The major difference of these studies is the evaluation approach applied in cost estimation. However, most of these studies only consider the performance of individual bridge decks without evaluating the systematic impacts to the transportation network due to the bridge management needed during their life cycle.

In summary, although the life-cycle benefits of internal curing for high performance concrete bridge decks have been quantified from the agency/bridge owner perspective, the literature does not factor the social benefits in a network associated with the reduction of the bridge management activities throughout the service life that can be achieved by the use of the internal curing process. Without addressing the reduced traffic disruption by the use of internally cured concrete bridge decks, the potential life-cycle benefits of the internal curing process can be significantly underestimated. In this study, a quantitative evaluation of the total life-cycle costs of normal bridge decks made with and without internally cured high performance concrete is conducted at the network-level for different pre-construction traffic volumes.

The remainder of this paper is organized as follows. The next section describes the details of individual models that have been integrated in the total life-cycle cost estimation, including a bridge deck service life model, a regional travel demand model and a life-cycle cost model. It also discusses the estimation of agency costs and social costs. The section thereafter uses a case study in the Minneapolis-St. Paul area to analyze the total life-cycle benefits of internally cured bridge decks compared to normal bridge decks located in interstate highways, arterial roads and urban collector roads. Finally, some concluding comments are presented in the last section.

MODEL DESCRIPTION
This study applies the framework proposed in Kendall et al. (11) to evaluate the life-cycle performance of the internally cured concrete bridge decks. The main components in the framework include a bridge deck service life model, a regional travel demand model with the consideration of the impacts from the bridge management activities of the bridge decks, and a life-cycle cost model.

Bridge Deck Service Life Model
To better assess the life-cycle performance of internally cured concrete bridge decks, a bridge deck service life model is needed to capture the agency costs due to the construction, maintenance and replacement activities throughout the analysis period.
The bridge deck service life model developed by Cusson et al. (8) was adapted and expanded upon in this study. In their study, three concrete deck options were considered, including: (i) normal concrete (NC), with a water-cement (w/c) ratio of 0.4 and no supplementary cementing materials (SCM); (ii) high performance concrete (HPC), assuming early-age cracking due to autogenous shrinkage, with w/c of 0.35, including 25% SCM as partial cement replacement by mass; and (iii) high performance concrete with internal curing (HPC-IC) with the same w/c and SCM as HPC. They developed a reliability-based model to predict the service life of the three concrete deck options, considering the variability of six key parameters (surface chlorides, diffusion, concrete cover depth, chloride threshold, corrosion rate and bar spacing) expressed in terms of their mean values and coefficients of variation, to optimize the maintenance schedules for these three concrete deck options. Figure 2a shows the probability of spalling over time for the three deck options. The schedules of bridge management activities were also adapted from Cusson et al. (8). In it, the major patch repairs were scheduled when approximately 10% and 25% of the deck surface would be spalled, and replacement was deemed necessary when approximately 50% of the deck surface would be spalled for the three deck options, based on the 2002 AASHTO guidelines (19) used in the U.S. and some Canadian provinces. As shown in Figure 2a, the 10%, 25%, and 50% probabilities of spalling for NC concrete deck option are reached after 9, 14, and 22 years. These threshold probabilities are reached after 15, 25, and 40 years for HPC, and 24, 39, and 63 years for HPC-IC. It was assumed that a similar bridge deck with a similar initial construction cost would be rebuilt for replacement activities for each concrete deck option. To simplify computation, in our study, the major patch repairs are scheduled after 10 and 15 years for NC concrete deck option (Figure 2b), 15 and 25 years for HPC (Figure 2c), and 25 and 40 years for HPC-IC (Figure 2d). The replacement is scheduled after 20, 40, and 60 years for NC, HPC, and HPC-IC, respectively, and no maintenance activity is scheduled during replacement activities.

Apart from major patch repairs and replacement activities, three types of maintenance activities are also considered, including protection, non-destructive evaluation, and routine inspection. Based on the Bridge Inspection Manual (20), routine inspections should be conducted at least every two years for most bridges. Routine inspections are scheduled at 2-year intervals for all three bridge deck options in this study. Protection and non-destructive evaluation are scheduled to identify and correct drying shrinkage, freeze-thaw damage, and other problems. In this study, for the NC deck, it is assumed that protection and non-destructive evaluation are scheduled at 5-year intervals. As shown in previous studies (7, 8, 9), HPC and HPC-IC are expected to perform better than NC. Hence, in this study, protection and non-destructive evaluation are scheduled at 10-year intervals for both HPC and HPC-IC. Notice that routine inspection and non-destructive evaluation would not impact the traffic, thereby these two maintenance activities would not create additional social costs. However, protection activities (e.g. correct drying shrinkage), major patch repairs (e.g. surface preparation) and replacement would cause traffic disturbances and increase social costs. Figures 2b-2d illustrate the maintenance and replacement schedules adopted in this study for NC, HPC and HPC-IC, respectively.
FIGURE 2a Time-dependent probability of concrete cover spalling (8).

FIGURE 2b Optimized maintenance schedules for NC deck alternative (8).

FIGURE 2c Optimized maintenance schedules for HPC deck alternative (8).
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FIGURE 2d Optimized maintenance schedules for HPC-IC deck alternative (8).

Regional Travel Demand Model
To quantify the user costs due to the construction and maintenance processes, a regional travel demand model is used. In the traditional regional travel demand model, a four-step transportation planning model consisting of trip generation, distribution, modal split and traffic assignment, is often used (5). The traffic assignment step is the most commonly applied one to study the user impact of construction alternatives. On an urban network, a work zone may not only cause delays on the street where the work zone is located, but also result in shifting additional traffic to the adjacent routes due to travelers’ adaptive rerouting, which leads to traffic congestion in areas surrounding the work zone. This highlights the need to include the social impacts of bridge deck management activities at the network level.

In this study, the impacts of construction/maintenance on users were formulated as a traffic assignment problem. Drivers who travel through a work zone before the bridge management activities are assumed to adjust their routes such that a new user equilibrium (UE) flow pattern is achieved during this period. User costs induced by the bridge management activities, including increased operating costs, delays, and safety costs, are evaluated based on the new UE flow pattern.

A traffic assignment algorithm (21) is used to solve the traffic assignment problem under the assumption of UE. This algorithm is an origin-based (22) algorithm and operates using the network simplex method.

Life-cycle Cost Model
A life-cycle cost analysis was conducted to evaluate the economic performance of competing design, maintenance and traffic control alternatives. This is usually achieved by calculating the present value (PV) of each alternative’s life-cycle costs over the same evaluation period and can be formulated as (11),

\[
PV = C_0 + \sum_{t=1}^{T} \frac{C_t}{(1 + r)^t} - \frac{R_v}{(1 + r)^T}
\]

where \(C_0\) is the initial construction cost; \(C_t\) is the \(t^{th}\) expenditure at a given time \(t\) (years) after construction; \(T\) is the analysis period; \(r\) is the discount rate; and \(R_v\) is the residual value of the project at the end of the analysis period.

Given the optimized maintenance schedules for each alternative shown in Figure 2, the analysis period in this study was considered as 60 years and the initial year of construction is
Year 2014. The discount rate $r$ used in this study is 1.9%, which is based on the 30-year real
discount rate recommended by the United States Office of Management and Budget (23).

**Estimation of Agency and Social Costs**
To conduct total life-cycle cost analysis, it is important to estimate the costs under various types
of the bridge management activities. The unit construction costs and costs of maintenance
activities depend on many factors (e.g. type and quantity of cement). In this study, these costs
were estimated based on Cusson et al. (8) and were converted to Year 2014 dollars using a
consumer price index (24).

In this study, social costs consist of three types of costs including travel time costs, safety
costs, and vehicle operating costs. Pollution damage costs were not included in this study, as
previous studies (e.g. 11) found the environmental costs for bridge deck construction only
account for a relatively small portion of the total life-cycle costs. To avoid the work zone, users
need to detour and travel longer distances which can induce higher fuel consumption. Therefore,
operating costs are proportional to the vehicle miles traveled (VMT). Travel time increase caused
by traffic disruption was measured as the difference between undisrupted system travel time and
system travel time during the construction and maintenance periods. Increased vehicle operating
costs were estimated based on the additional VMT during the construction and maintenance
periods. Safety costs include the increase in traffic crashes caused by taking detours and the
increasing crash rate in the bridge management work zone. In the bridge management work
zones, workers and users may have a higher risk of fatality and injury compared to the same road
when no work zone is in place (9).

**CASE STUDY**
To quantify the potential life-cycle benefits of internally cured concrete bridge decks, a case
study in the Minneapolis and St. Paul metropolitan area is introduced in this study. As the user
costs are the main proportion of the total life-cycle costs, the performance of internally cured
concrete decks is linked to the corresponded impacted traffic. In this study, we seek to evaluate
the potential benefits of internally cured concrete over normal concrete under different levels of
travel demand by selecting three types of bridges carrying different levels of demands. The three
bridge types are interstate highway, major arterial, and urban collector; the locations of these
three bridges are identified in Figure 3, including the I-35E Bridge over Roselawn Ave East
(Figure 3a), the Arcade Street Bridge over Phalen Boulevard (Figure 3b), and the Edgerton Street
Bridge over Phalen Boulevard (Figure 3c), respectively. The three bridges are located in the
Minneapolis and St. Paul metropolitan area (Figure 3d).

During non-construction/non-maintenance periods, the I-35E Bridge over Roselawn Ave
East has three lanes in each direction with one-way average annual daily traffic flow (AADT) of
132,000 vehicles in Year 2010 (25). Its estimated structure length is 100 meters long with 275
meters of approach on each side, and depth is 0.3 meters. The length and depth of the bridge are
estimated using Google Maps. The I-35E Bridge over Roselawn Ave East was included in the I-35
corridor project to replace bridges currently on the Trunk Highway Bridge Improvement
program Chapter 15 (26) and provide line-of-sight improvements for the interchanges and I-35E.
The estimated replacement project lasted for four months and one out of three lanes in each
direction was closed at the same time.

The Arcade Street Bridge over Phalen Boulevard is a major arterial road with 2 lanes in
each direction. It had AADT of 14,800 in Year 2009, with a structure 100 meters long and 115
meters of approach on each side, and 0.3 meters in depth. The Edgerton Street Bridge over Phalen Boulevard is an urban collector road with AADT of 4,800 vehicles. It is 80 meters long with 40 meters approach on each side, and 0.3 meters in depth with one lane in each direction.
Unit construction costs, costs of maintenance activities, and social costs used in this study are summarized in Table 1. The initial construction costs of different concrete materials are adopted from Cusson et al. (8). They estimated the construction costs of three concrete types (same types are used in this study) by combining the costs of reinforcing steel and the in-place cost of concrete. The in-place cost of concrete includes formwork installation, detailing of reinforcing steel, placing and surface finishing of concrete, and form stripping. Since the in-place cost of concrete depends on the type and quality of cement, aggregates, supplementary cementing materials and admixtures used in the concrete mix, and their availability, the initial construction costs can vary in different regions of the U.S. In this study, the unit cost of HPC was estimated 33% higher than NC due to the increased quantity of cement in the mix, while the unit cost of HPC-IC was set to be 4% higher than HPC because of the purchasing and transporting of the lightweight aggregate sand. It is important to note that such cost increase can be offset by using less cement in the concrete mix. The reason is that HPC-IC has a more effective cement hydration due to the internal curing process, and similar concrete strength can be achieved even with less cement in the concrete mix (27). Since the study was done by Cusson et al. (8) in 2011, these values are converted to year 2014 U.S. dollars using a consumer price index (24). Also, these costs are similar to those experienced by the Indiana Department of Transportation (28). For each bridge, the initial construction cost is equal to the unit construction cost multiplied by its structural length and depth.

**TABLE 1** Costs Estimation in 2014 U.S. Dollar

<table>
<thead>
<tr>
<th>Activity type</th>
<th>Cost in 2014 U.S. dollar</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Initial construction costs (agency costs)</em></td>
<td></td>
</tr>
<tr>
<td>Unit cost of NC ($/m³)</td>
<td>490.95</td>
</tr>
<tr>
<td>Unit cost of HPC ($/m³)</td>
<td>654.61</td>
</tr>
<tr>
<td>Unit costs of HPC-IC ($/m³)</td>
<td>680.79</td>
</tr>
<tr>
<td><em>Costs of maintenance related activities (agency costs)</em></td>
<td></td>
</tr>
<tr>
<td>Routine inspection ($/m²)</td>
<td>2.18</td>
</tr>
<tr>
<td>Non-destructive evaluation ($/m²)</td>
<td>21.82</td>
</tr>
<tr>
<td>Protection ($/m²)</td>
<td>21.82</td>
</tr>
<tr>
<td>Patch repair ($/m²)</td>
<td>218.20</td>
</tr>
<tr>
<td>Replacement (disposal and reconstruction) ($/m²)</td>
<td>381.85 + unit costs of reconstruction</td>
</tr>
<tr>
<td><em>Social costs at the time of bridge management activities</em></td>
<td></td>
</tr>
<tr>
<td>Auto vehicle operating cost ($/mile)</td>
<td>0.35</td>
</tr>
<tr>
<td>Occupant value of time ($/hour)</td>
<td>15.20</td>
</tr>
<tr>
<td>Average number of occupants per vehicle</td>
<td>1.07</td>
</tr>
<tr>
<td>Safety costs in work zone ($/VMT)</td>
<td>0.17</td>
</tr>
<tr>
<td>Safety costs for taking detour ($/VMT)</td>
<td>0.07</td>
</tr>
</tbody>
</table>

The value of travel time for automobile occupants in St. Paul is $15.20/hour and the auto vehicle operating cost is $0.35/mile in 2014 dollars. These costs were adopted from Mikovits and Tempesta (5) and have been converted to 2014 dollars using a consumer price index (24). The average number of occupants per vehicle was based on the average value of St. Paul in Year
The estimated safety costs are $0.17/VMT inside the construction work zone and $0.07/VMT when detour is taken. These costs were estimated based on St. Paul 2013 Crash Factors and converted to monetary values using average comprehensive cost by injury severity from the U.S. National Safety Council.

The transportation network used to analyze the traffic disruption in the case study area is the Minneapolis and St. Paul metropolitan area network. It contains 22,476 links and 8,618 nodes, of which 1201 are traffic analysis zones (TAZs) that generate and attract trips. A trip table, derived from the 2005 Longitudinal Employer-Household Dynamics (LEHD) database (can be accessed via http://www.vrdc.cornell.edu/onthemap/data), was adopted as the origin-destination demand data.

Based on the annual VMT of the Minneapolis and St. Paul metropolitan area between Year 2008 and Year 2013, a static travel demand was assumed. For each alternative, the traffic assignment algorithm referred to in the previous section was used to evaluate the differences in system travel time and vehicle miles traveled.

As stated in the previous sections, protection, patch repair and replacement are the three key activities that would impact the traffic in the work zone. Table 2 summarizes the durations of partial closure (PC) and full closure (FC) for protection, patch repair and replacement processes. For the partial closure case, the duration of replacement time for the I-35E Bridge over Roselawn Ave East was estimated using the construction plan for the I-35 corridor project and the estimation by Cusson et al. (9). The replacement durations of the Arcade Street Bridge over Phalen Boulevard and the Edgerton Street Bridge over Phalen Boulevard were estimated accordingly. It was assumed that the durations of the bridge management activities were the same for different materials. For the I-35E Bridge over Roselawn Ave East, the partial closure alternative involves closing one of the three lanes in each direction during the bridge management activities. The partial closure alternative for the Arcade Street Bridge over Phalen Boulevard implies closing one of the two lanes in each direction, while for the Edgerton Street Bridge over Phalen Boulevard, it involves shutting down traffic in one direction.

User safety costs in work zones are equal to zero during the bridge management activities for the full closure alternative, because the traffic is equal to zero in the work zone for this alternative. Only automobile travel is included in this study, and additional studies are needed to understand the impacts of internal curing of bridge decks on freight carriers and truck drivers (31). In both PC and FC alternatives, the length of the work zone includes the length of the bridge and the length of the approaches on both sides. This is because the work zone has to be longer in order to provide potential detour options to users before they reach the work zone.

In this study, six different construction and material alternatives are considered, including internally cured high performance concrete under partial closure alternative (HPC-IC-PC), high performance concrete under partial closure alternative (HPC-PC), normal concrete under partial closure alternative (NC-PC), internally cured high performance concrete under full closure alternative (HPC-IC-FC), high performance concrete under full closure alternative (HPC-FC), and normal concrete under full closure alternative (NC-FC).
TABLE 2 Maintenance and Replacement Durations for Partial and Full Closure Alternatives

<table>
<thead>
<tr>
<th></th>
<th>Protection</th>
<th>Patch Repair</th>
<th>Protection &amp; Patch Repair</th>
<th>Replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>The I-35E Bridge over Roselawn Ave East</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial closure (days)</td>
<td>30</td>
<td>45</td>
<td>60</td>
<td>240</td>
</tr>
<tr>
<td>Full closure (days)</td>
<td>20</td>
<td>30</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>The Arcade Street over Phalen Boulevard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial closure (days)</td>
<td>15</td>
<td>25</td>
<td>30</td>
<td>120</td>
</tr>
<tr>
<td>Full closure (days)</td>
<td>10</td>
<td>15</td>
<td>25</td>
<td>75</td>
</tr>
<tr>
<td>The Edgerton Street Bridge over Phalen Boulevard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Partial closure (days)</td>
<td>8</td>
<td>14</td>
<td>15</td>
<td>60</td>
</tr>
<tr>
<td>Full closure (days)</td>
<td>5</td>
<td>8</td>
<td>12</td>
<td>40</td>
</tr>
</tbody>
</table>

RESULTS

Figure 4 shows the present value (PV) cumulative expenditures for the total life-cycle costs over the 60-year analysis period for the three concrete deck alternatives for three bridge locations with partial (PC) or full closure (FC) bridge management strategies. It illustrates that the HPC-IC bridge decks have overall low total life-cycle costs compared to HPC and NC bridges decks over the 60-year analysis period in all cases. For the I-35E Bridge (interstate bridge) over Roselawn Ave East, the total life-cycle costs of bridge decks using HPC-IC-PC are 49% lower than those of NC-PC and 23% lower than those of HPC-PC. The initial investment required for using HPC-IC-PC in bridge decks can be offset in only 5 years when compared to that required for the HPC-PC. However, the corresponding time for the Arcade Street Bridge (arterial bridge) over Phalen Boulevard and the Edgerton Street Bridge (urban connector bridge) over Phalen Boulevard is much longer, 15 years and 10 years, respectively. It indicates that the potential benefits of applying internally cured concrete bridge decks to locations with high traffic volume may be larger than for locations with relatively low traffic volume. The main reason is that the levels of traffic disruption caused by bridge management activities are different for these three bridges.

In addition, the FC alternative is more costly than the PC one in all three cases. In all cases, the total life-cycle costs of the FC alternative are at least twice as expensive as those of the PC life-cycle costs. This highlights the importance of traffic control and management in the total life-cycle analysis, since the significant increase in user costs can offset the agency cost savings for the FC alternative.

To further analyze the potential benefits of HPC-IC bridge decks, the total life-cycle costs of each alternative were divided into six types of costs. Figure 5 shows the construction/replacement costs, inspection/non-destructive evaluation/protection costs, patch repair costs, operation costs, value of time costs, and safety costs. An important observation is that construction/replacement costs represent only a small portion (less than 10%) of the total costs in all three concrete deck alternatives for the three bridge locations with PC or FC bridge management strategies.
FIGURE 4a Present value (PV) cumulative expenditures for the I-35E Bridge over Roselawn Ave East.

FIGURE 4b Present value (PV) cumulative expenditures for the Arcade Street Bridge over Phalen Boulevard.
FIGURE 4c Present value (PV) cumulative expenditures for the Edgerton Street Bridge over Phalen Boulevard.

FIGURE 5a Break down of present value (PV) for different costs in the I-35E Bridge over Roselawn Ave East.
FIGURE 5b Break down of present value (PV) for different costs in the Arcade Street Bridge over Phalen Boulevard.

FIGURE 5c Break down of present value (PV) for different costs in the Edgerton Street Bridge over Phalen Boulevard.

For I-35E Bridge over Roselawn Ave East, the largest portion of total life-cycle costs is safety costs (40.2%) if NC is used under the partial closure alternative (NC-PC). By applying the HPC-IC bridge decks under partial closure alternative (HPC-IC-PC), the safety costs were significantly reduced (nearly 50%) compared to NC-PC and represented the largest individual cost reduction. The use of HPC-IC-PC can significantly reduce the frequency of maintenance activities, thereby reducing the user costs increase caused by traffic disruption. Apart from the social cost reduction, the agency costs for using HPC-IC-PC in I-35E Bridge over Roselawn Ave
East also dropped by 64.9% compared to NC-PC. Under the full closure alternative of using HPC-IC (HPC-IC-FC), the total life-cycle costs were two times higher than those for the PC alternative (HPC-IC-PC). The potential low agency cost of using HPC-IC-FC was offset by the high social costs from the significant traffic disruption in the FC alternative.

Safety costs were the largest portion (29.7%) of the total life-cycle costs for the Arcade Street Bridge over Phalen Boulevard using NC under the PC alternative (NC-PC), similar to the case for the I-35E Bridge over Roselawn Ave East. The use of HPC-IC-PC can reduce the construction/replacement costs by more than 65% and the total agency costs by nearly 65% in the 60-year analysis period compared to NC-PC, similar to the case for the I-35E Bridge over Roselawn Ave East. However, the large savings in the life-cycle costs using HPC-IC-PC are due to the reduction in social costs. User safety costs for HPC-IC-PC were reduced by nearly 80% compared to those for NC-PC. It illustrates that the most important benefit of using internally cured concrete bridge decks is in terms of the reduction of social costs. For the FC alternative of the Arcade Street Bridge over Phalen Boulevard, the total life-cycle costs of HPC-IC-FC was nearly three times those of the PC alternative (HPC-IC-PC). To reduce the potential construction/replacement costs, relevant decision-makers can consider effective management programs to improve construction labor productivity and reduce on-site labor costs (32, 33).

For the Edgerton Street Bridge over Phalen Boulevard, travel time increase costs were found to be the largest cost (24.9%) component of the total life-cycle costs using NC under the PC alternative (NC-PC). The use of HPC-IC-PC can reduce over 65% of construction/replacement costs compared to NC-PC, and this reduction was the largest cost reduction of using HPC-IC-PC. However, the largest cost reduction percentage wise is the patch repair costs (nearly 70%). In addition, the FC alternative (HPC-IC-FC) of the Edgerton Street Bridge over Phalen Boulevard was found to be more expensive than that of the PC alternative (HPC-IC-PC).

The results of case study suggest that the percentage/amount of individual cost savings of using HPC-IC varies for different types of bridge decks as their traffic volumes are different.

CONCLUDING COMMENTS
Past studies to address the benefits of internal curing for bridge decks have several specific limitations, including the scope of transportation networks considered, construction alternatives included, and the life-cycle costs considered. The life-cycle costs include only the costs of materials and maintenance, without considering the impacts related to traffic, safety and pollution. In this study, the benefits of internally cured high performance bridge decks have been studied by quantifying the total life-cycle costs for three types of bridges (interstate highway, arterial, and urban connectors) in the Minneapolis-St. Paul area under partial and full closure alternatives. Three types of material used for these bridges were evaluated, including normal concrete (w/c=0.40), high performance concrete (HPC) with SCM and conventional curing (w/c=0.35), and high performance concrete with internal curing (HPC-IC) and use of SCM (w/c=0.35).

The results from the case study emphasize the importance of conducting total life-cycle analysis at a network level, as the increase in user costs caused by the bridge management activities represents a significant part of an infrastructure’s total life-cycle costs. The results of total life-cycle analysis reveal that HPC-IC can potentially reduce the total life-cycle costs of bridge decks by over 50% compared to bridge decks made of normal concrete and over 20% compared to bridge decks made of HPC. In addition, the social costs, which were not included in
previous studies related to understanding the benefits of internal curing for concrete bridge decks, are significantly reduced. This study also shows that the reduction in life-cycle costs can be attributed to fewer bridge management activities and fewer traffic disruptions caused by these activities. However, the largest cost reduction component in each alternative can be different for bridges on interstates highway and bridges on arterial/urban connectors depending on the traffic demand. In terms of the bridge management strategies, the partial closure alternative was found to be economically effective with lower social costs compared to the full closure alternative in all three bridge decks, and these reductions in costs can offset the relatively high agency costs under the partial closure alternative. The findings and insights from this study can be used to assist planners/agencies to efficiently assess and plan the bridge management activities of bridge deck and other related public infrastructure so that the potential benefits from the use of internally cured concrete can be maximized.

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