LIFE-CYCLE COST ANALYSIS AND DESIGN OF HPC BRIDGES – WHY AND HOW?

Mostafa A. Hassanain, Ph.D., P.Eng.*
Edwards and Kelcey, Inc.
7401 Metro Boulevard, Suite 430, Minneapolis, Minnesota 55439, USA
Phone: 1-952-345-4111 Fax: 1-952-835-7376
E-mail: mh398@usa.net

ABSTRACT

It has been reported that almost 30% of all bridges in the United States are rated structurally deficient or functionally obsolete by the Federal Highway Administration. The situation is quite similar in many other developed countries. New construction materials such as high-performance concrete (HPC) could play a major role in the renewal of the deteriorated bridge infrastructure. Despite the potential benefits from the use of HPC with its increased strength and improved durability for precast, prestressed highway bridges, many designers and precasters are still reluctant to use it widely. This may be caused by the higher initial cost due to the increased material costs, and/or the high costs associated with the increased quality control required to produce HPC.

Proponents of the material often stress that longer life spans are possible with HPC designs. This may dramatically cut maintenance and replacement needs over the entire life of an HPC bridge. Opponents, however, argue that it is very difficult, if not impossible, to quantify the long-term benefits from the use of the initially expensive HPC. Their conviction is fuelled by the lack of a commonly accepted, comprehensive methodology for bridge life-cycle cost (LCC) analysis. This is defined as a process for evaluating the total economic worth of an HPC bridge by analyzing initial costs and discounted future costs, such as maintenance, rehabilitation, and reconstruction costs over the life span of the bridge.

Several existing regulatory requirements call for consideration of LCC analyses for civil infrastructure investments. However, the integration of these requirements in the analysis and design of civil infrastructure systems, especially bridges, has been very limited. The main objective of this paper is to promote LCC concepts in bridge engineering. This is accomplished through an explanation of the significance of incorporating LCC concepts in the analysis and design of HPC bridges, and through an overview of state-of-the-art LCC analysis methodologies. The paper is an effort towards convincing the sceptics that the use of HPC could lead to cost effective and durable bridges that will last well into the new millennium.

KEYWORDS: analysis; bridges; design; high-performance concrete; life-cycle cost; optimisation; prestressed girders; sustainable infrastructure.

---

* Author to whom correspondence to be addressed

1. INTRODUCTION

In March 2001, the American Society of Civil Engineers issued a report about the status of America's infrastructure [1]. The report indicated that almost 30% of the nation's bridges are rated structurally deficient or functionally obsolete by the Federal Highway Administration. The situation is quite similar in many other developed countries. In Canada, for example, the National Research Council's Institute for Research in Construction estimates that about 40% of all bridges operating in the country are older than 30 years, and most are in urgent need of replacement or rehabilitation.

New construction materials such as high-performance concrete (HPC) could play a major role in the renewal of the deteriorated bridge infrastructure. Several definitions of HPC exist that are mostly dependent upon the production capacities and practices at different locations. The American Concrete Institute broadly defines HPC as concrete that meets special performance and uniformity requirements that cannot always be achieved routinely by using conventional ingredients, normal mixing and placing procedures, and typical curing practices [2]. These requirements may involve enhancements of placement and compaction without segregation, long-term mechanical properties, early-age strength, toughness, volume stability, or service-life in severe environments.

Despite the widely known potential benefits from the use of HPC with its increased strength and improved durability for precast, prestressed highway bridges, many designers and precasters are still reluctant to use it widely. This may be caused by the higher initial cost of the material and/or the increased quality control requirements associated with its production. Several HPC bridges have been constructed in North America and around the world, many of them experimental/demonstration bridges, to showcase the advantages of the material.

Proponents of the material often stress that longer life spans are possible with HPC designs. This may dramatically cut maintenance and replacement needs over the entire life of an HPC bridge. Opponents, however, argue that it is very difficult, if not impossible, to quantify the long-term benefits from the use of the initially expensive HPC. Their conviction is fuelled by the lack of a commonly accepted, comprehensive methodology for bridge life-cycle cost (LCC) analysis. This is defined as a process for evaluating the total economic worth of an HPC bridge by analysing initial costs and discounted future costs, such as maintenance, rehabilitation, and reconstruction costs over the life span of the bridge.

In recent years, an important expansion of the LCC concept has been made in terms of taking into account user costs, in addition to costs accruing to bridge owners. User costs represent the societal costs that are imposed when the serviceability of a bridge is reduced or eliminated, most notably during routine maintenance operations. Examples of user costs include those associated with travel delay, vehicle operation, and accidents. Several studies have shown that user costs comprise a very sizeable component of total LCC estimates [3].

Several existing regulatory requirements call for consideration of LCC concepts for civil infrastructure investments in the USA. For example, the Intermodal Surface Transportation Efficiency Act of 1991, and the National Highway System Designation Act of 1995 mandate that life-cycle costs, rather than initial costs alone, be considered in the design and engineering of bridges, tunnels, and pavements in state and metropolitan-level transportation planning. However, the integration of these requirements in the analysis and design of civil infrastructure systems, especially bridges, has been very limited.

This paper presents a brief review of the potential benefits from the use of HPC for highway bridges. The main objective of the paper, however, is to promote LCC concepts in bridge engineering. This is accomplished through an explanation of the significance of incorporating LCC concepts in the analysis and design of new HPC bridges, and through an overview of state-of-the-art LCC analysis methodologies. The discussion is directed towards precast, pretensioned I-girder bridges, also known as slab-on-girder bridges. These were chosen because they represent the most common type of prestressed concrete bridges constructed in North America over the past 50 years. However, most of the concepts and methodologies are general enough, and could be applied to other bridge types. The paper is an effort towards convincing the sceptics that the use of HPC could lead to cost effective and durable bridges that will last well into the new millennium.

2. BENEFITS OF HPC FOR HIGHWAY BRIDGES

2.1. Cost effectiveness

The main reason for considering the use of HPC, especially for precast, prestressed concrete bridge I-girders, is the possible reduction in overall costs leading consequently to less expensive bridges. This would help stretch out the services transportation authorities can provide with the funds available. The cost savings with HPC may come from several areas. Although the basic concrete cost per cubic metre is obviously increased, primarily due to increased mix constituent and quality control costs, this may be partially or fully offset by the reduced quantities of concrete required in the form of fewer girders for a given span length as a result of the proportionate increase in girder capacity. One area of cost which may not change very much is the cost of prestressing strands. Typically, the total number of strands required for any bridge design decreases only slightly as the concrete strength increases. As the number of required girders decreases, the number of strands per girder increases, usually resulting in little net change in strand requirements. Consequently, the cost of prestressing strands may remain relatively unchanged.

The most significant cost savings in using HPC may come from the reduction in non-material costs associated with the production of girders. These include the labour to produce the girders, the precaster's overhead allocated to each girder, transportation costs, and erection costs. The amount of non-material costs associated with a HPC girder is the same as that for a normal-strength concrete girder; the cost savings come from the reduction in the number of girders [4]. Some earlier studies [5-7] have revealed that, for a given span, it is most economical to use as few girder lines as possible, i.e., to place girders at the largest practical transverse spacing, although the fact that this could be achieved through the use of HPC was not directly acknowledged in them.

Alternatively, for a given transverse girder spacing, the use of HPC may result in significant increases in girder span lengths [4,8,9]. When span lengths increase, the number of piers and foundations can be reduced for multi-span bridges, reducing in turn the cost of the substructure. If the bridge is crossing an existing roadway, a reduction in the number of piers and foundations would also ease traffic disruptions to the roadway underneath during construction of the bridge.

Some of the long spans achievable through the use of HPC may exceed the practical limit for highway transportation. For such cases, girder transportation requires detailed planning and cooperation from federal and state authorities. Because handling and transportation constraints may impose a limit on maximum span lengths, economies gained through the use of HPC may also be limited if one considers only increased span lengths. However, HPC may result in significant economies by allowing shallower girder sections to span longer lengths. The potential large savings come from the reduction in the expense of bridge piers, abutments and approaches. The cost of these components will usually exceed the cost savings associated with the efficiency of deeper girders. If the elevation of a bridge can be reduced, the total cost of the bridge will decline. Therefore, the utilization of HPC would lead to potentially large savings [10].

In some recent actual bridge projects, it was found that the initial costs of HPC bridges can be sometimes higher than those of equivalent designs with normal-strength concrete [11]. This may be attributed to the fact that most precasters and contractors are still unfamiliar with HPC. Therefore, they assume higher risk levels and subsequently submit higher bids. Another possibility is that HPC requires additional mix development and testing under increased quality control requirements, which increases the initial costs. If these costs are distributed over a small volume of concrete, such as the case in most experimental/demonstration bridge projects, this could inflate the cost of HPC. It is anticipated that initial costs associated with the use of HPC will diminish significantly with increased familiarity with the material, and increased frequency of applications since mix trial, testing and developmental premiums would be spread more proportionally.

2.2. Structural benefits

There are many structural benefits from using HPC for precast, prestressed concrete highway bridges. One advantage of HPC is its greater compressive strength, which can be evaluated in relation to unit cost, unit weight, and unit volume. HPC, with its greater compressive strength per unit cost, is the least expensive means of carrying compressive force. In addition, the material's greater compressive strength per unit weight and unit volume allows lighter and more slender bridge members and piers to be used, leading consequently to improved horizontal clearance underneath the structure [12].

Other benefits of HPC include increased modulus of elasticity and increased tensile strength. Increased modulus of elasticity gives smaller elastic shortening losses at the transfer of prestress in pretensioned girders. In addition, increased stiffness is advantageous when deflections or stability govern the design of the bridge. Increased tensile strength is advantageous in service load design of prestressed concrete because it increases the permissible stress range under service conditions [12].

Mitchell *et al.* [13] studied the influence of HPC on the transfer length and development length of pretensioning strands. They found that an increase in the concrete compressive strength results in a reduction of the transfer and development lengths. These improved bond characteristics permit the use of larger pretensioning strands which are required to effectively utilize HPC in precast bridge girders.

In general, HPC can decrease the effects of volume changes, such as creep and shrinkage. Based on an extensive review of the information available in the literature, Dilger and Wang [14] presented a detailed discussion on creep and shrinkage of HPC. They indicated that total creep of HPC is significantly lower than that of normal-strength concrete. In some cases, the ultimate creep coefficient of HPC can be as low as 50% or even 30% of the value observed for normal-strength concrete. Additionally, total shrinkage of HPC is also lower than, or similar to, that of normal-strength concrete. Reduced creep and shrinkage of HPC reduces, in turn, the long-term prestress losses.

2.3. Durability aspects

Primarily due to its low permeability, HPC exhibits excellent durability to various physical and chemical agents that are responsible for concrete deterioration [15]. Using HPC can be a very effective way of protecting bridges against corrosion of the reinforcement, alkali-aggregate reaction, sulphate attack, freezing and thawing, and abrasion. This is possible because of the low porosity, and more uniform and homogeneous microstructure of HPC compared to that of normal-strength concrete. Although the initial costs of HPC bridges may be sometimes higher than those of equivalent designs with normal-strength concrete, the increased durability of the former translates into longer service lives and fewer repairs, leading consequently to a reduction in the life-cycle costs.

3. WHY LCC ANALYSIS AND DESIGN?

In 1992, Veshosky and Beidleman [16] published a one-page article entitled “Life-Cycle Cost Analysis Doesn’t Work for Bridges,” in which they expressed concerns regarding the practicality of applying LCC analysis to bridges. They cited the lack of reliable, consistent cost data that is collected on a systematic basis for a variety of bridges, the changes in design criteria and techniques, the variability in construction materials and methods, and other factors contributing to costs. They argued that the use of LCC criteria in the evaluation of bridge construction alternatives could introduce as much uncertainty as it is intended to solve!

Despite these concerns, LCC analysis can still provide a significant and powerful approach if it is regarded not in light of an “exact science,” but rather “as a method that allows maintenance costs to be studied in parametric fashion so that they can be given a truer weighting in the design process and not forgotten entirely” [17]. Conceptually, the approach can be used in the process of design selection for new bridges, and in the optimal operation and maintenance of existing ones. More importantly, the exercise of LCC estimation provides valuable economic insight into the various cost components and identifies the specific information required to make such an estimation [3].

As mentioned earlier, several existing regulatory requirements call for consideration of LCC concepts for transportation infrastructure investments. Endorsement of LCC analysis by the US Congress is a reflection of the reality that much of the nation’s highway system, especially bridges, is in poor condition, and that sufficient funds are not available to maintain, repair, and/or replace deficient facilities. To a large extent, this poor condition reflects the results of designs based exclusively on the lowest initial cost without consideration of, or adequate provision for, the potential maintenance, repair, and/or replacement costs. Use of LCC analysis provides a means of structure selection on the basis of the least long-term cost to society [18].

In order to achieve a sustainable level of development for bridges in the new millennium, it is apparent that funding for bridge maintenance and repair will have to be increased significantly. Recognizing the funding constraints that exist due to the other deficient components of the transportation infrastructure, it is clear that the return on the available funding needs to be maximized. This can only be accomplished by increasing the minimum useful service-life to at least 100 to 120 years, and by selecting bridges on the basis of LCC analyses [18]. HPC, which exhibits excellent durability, as discussed earlier, appears to be the logical material of choice for new bridges to ensure the achievement of a 100- to 120-year service-life.

4. HOW TO INCORPORATE LCC CONCEPTS IN BRIDGE ENGINEERING?

4.1. General

The two primary obstacles for applying LCC concepts to highway bridges have been the lack of access to reliable cost and service-life data, and the lack of a commonly accepted methodology [19]. In what follows, an overview of the efforts to remove these obstacles is presented. Although the field of bridge LCC analysis and design is relatively recent, the number of publications is so large that it is prohibitive to review all relevant literature due to space limitations. Thus, this brief overview is by no means considered to be exhaustive. Rather, it is believed that several important developments will be captured.

4.2. Cost data

In order to compare alternative infrastructure investment choices with the objective of minimizing life-cycle costs, it is necessary to be able to quantify the total cost associated with the several stages of the structure life. The design problem then becomes an optimisation problem of a set of variables (e.g., the amounts of reinforcement, the concrete compressive strength, and the parameters related to inspection, maintenance, and repair) based on the expected costs subject to a set of deterministic (e.g., code requirements) and probabilistic (i.e., reliability) constraints. Several cost functions exist in the literature [3,20-24]. In this paper, the global cost function developed by de Brito and Branco [21,22] is presented as an example.

The cost function, C, includes the structural costs, C_{ST}, and the functional costs and benefits, C_{FU}, during the structure life cycle:

$$C = C_{ST} + C_{FU} \tag{1}$$

The structural costs include the initial costs of design and construction, C_0, inspection costs, C_I, current maintenance costs, C_M, repair costs, C_R, and structural failure costs, C_{FSF}:

$$C_{ST} = C_o + C_I + C_M + C_R + C_{FSF} \tag{2}$$

These costs are mainly associated with the civil engineering works. For new bridges, most of the structural costs can be approximately predicted based on current cost indices, historical data from similar bridges, and/or expert opinions. Sobanjo [25] argued that historical data could have inherent statistical randomness, and that expert opinions could introduce some subjectivity into the final estimates. He suggested that statistical data randomness can be adequately handled in a decision analysis through the use of probability theory, and that subjectivity in estimates can be accounted for using the concepts of fuzzy sets theory. He presented a set of conceptual algorithms and equations to illustrate how those uncertainties can be handled in bridge LCC analysis.

An item in Eq. [2] that requires special consideration is the structural failure costs, C_{FSF}. These include all costs resulting from a structural collapse of the bridge. Although collapse does not occur under normal circumstances, these costs can still be considered in an economic analysis as insurance costs. The structural failure costs can be obtained from the probability of failure, P_f, and the cost of the actual collapse, C_{FF}, as follows:

$$C_{FSF} = P_f \, C_{FF} \tag{3}$$

Attention is now drawn back to Eq. [1]. The functional failure costs, C_{FFF}, (referred to earlier in this paper by the more common term “user costs”) are those associated with reductions in the operation conditions of a bridge, such as speed limitation and live load reduction. The benefits, B, correspond to negative functional failure costs because they are associated with an improvement of the service level in the structure. The functional costs and benefits can be expressed as follows:

$$C_{FU} = C_{FFF} - B \qquad [4]$$

The functional failure costs include the following components: (1) the costs due to delayed traffic, caused by the slowing down of the traffic crossing the bridge, especially during rush hours; (2) the costs due to light traffic detoured in terms of volume, caused by the traffic being detoured from one bridge to others nearby because of the saturation of the bridge in terms of traffic flow; and (3) the costs due to heavy traffic detoured in terms of load, caused by a certain margin of exceptionally heavy traffic having to be detoured from one bridge to others nearby because of its insufficient structural capacity.

Each of these components can be divided in costs in terms of time wasted by drivers, fuel costs, vehicle maintenance costs, and traffic accident costs. For an economic analysis, these costs have to be computed using several data, such as daily and yearly traffic surveys, service design level of the road, future traffic estimates, existing alternatives to each bridge, the bridge’s traffic and structural capacity, and energy and vehicle maintenance average costs [21].

4.3. Service-life data

An important step in a LCC analysis is to determine the desired analysis period (i.e., the design service-life, or as it is sometimes called, the planning time-horizon). This period should be sufficiently long to reflect long-term differences associated with feasible design alternatives. For new HPC bridges, a minimum of 100 years should be considered. In addition to determining the desired service-life, the terminal serviceability level needs to be defined. Terminal serviceability (also referred to as end-of-functional-service-life) is the maximum level of degradation that will be permitted prior to major repair of the structure. To a large degree, terminal serviceability will depend on the functional requirements (e.g., structural capacity, aesthetics, smooth ride, etc.) of the bridge [26].

At the design phase, studies of physical deterioration have to be conducted to guarantee that the defined service-life will be met. These studies should be taken into account in the bridge durability design, and the resulting requirements included in the project’s construction specifications. The service-life shall be expected to be achieved in most of the bridge components, mainly in the structural ones, with minor repair costs [21].

The estimation of the service-life based on physical deterioration is a complex problem. It includes the definition of the reference limit states associated with the end of the service-life, the environment characterization, the study of the degradation phenomena of the materials and structural components, and the definition of mathematical models for evaluation of the degradation path. In concrete bridges, the most important degradation mechanisms are corrosion of reinforcement, and carbonation of concrete [21].

Currently, there are no specific code recommendations in terms of easily measurable concrete properties (e.g., minimum cement content, maximum water/cementitious materials ratio, minimum strength) and reinforcement cover that would guide designers to achieving the expected durability for structures with service-lives of 100 and more years. In such cases, the study of the service-life must be performed in terms of physical deterioration models [e.g., 26-28], based on local environmental conditions, experience, and the limit states adopted for design. With these models, an estimation of the degradation process could be obtained for specific concrete properties and reinforcement cover. Normally, several alternatives may be used in the choice of concrete properties and bars cover, and a cost-efficiency analysis performed to reach a decision [21].

For important bridges, and because current mathematical models do not yet yield sufficiently accurate results, a monitoring system should be planned for the design phase. Monitoring during construction and service-life (associated with periodic inspections) will provide the main parameters that control the degradation mechanisms, and will allow the confirmation or adjustment of the deterioration rates assumed in the design [21]. Currently, condition assessment of bridges is an ongoing task for state departments of transportation. Several bridge management systems (such as PONTIS and BRIDGIT) have been developed during the past decade to assist in the enormous task of acquiring and interpreting inspection data from the nation's bridges [29]. The sharing of information among states should lead to a large database of service-life data.

4.4. LCC analysis methodologies

As mentioned earlier, the lack of a commonly accepted methodology for LCC analysis is a primary obstacle to applying LCC concepts to bridges. Several methods for the implementation of LCC analysis have been presented in the literature. In what follows, a brief review of some of the recent methods is presented.

LCC analysis is generally based on the concept of discounted cash-flow analysis. Normally, all the costs incurred and the benefits gained by the owner and users throughout the entire life of a bridge are estimated and converted into a single equivalent cost value (such as the present worth, annual worth, or future worth) for the purpose of comparison of various structural alternatives [25]. Bridge management systems typically employ the present worth, defined by Eq. [5] below, as the equivalent cost, where PW is the present worth equivalent, F is the future cost, r is the discount rate, and t is the timing of the future expenditure from the time of construction (in years).

$$\mathrm{PW} = \mathrm{F}(1+\mathrm{r})^{-\mathrm{t}} \qquad [5]$$

Mohammadi *et al.* [30] combined the present worth value, PW, with a new parameter they called the value index, VI, that can be used to help quantify the bridge decision-making process. Specifically, VI describes three major elements of a bridge LCC analysis: (1) bridge or bridge-element condition rating; (2) the cost associated with various bridge expenditures; and (3) bridge service-life expectancy. A condition rating range from 1 to 9 (with 1 representing the worst condition) can be used. Ideally, VI can be formulated in terms of the three independent parameters described above. The VI, as a function of time, can then be used as the objective function in an iterative optimisation scheme in which various constraints on the three parameters as well as on time can be imposed. Using this approach, the option with the greatest VI and the least PW is taken to be the most desirable one. The advantage of using both VI and PW instead of PW alone during LCC analysis is that VI also includes the optimum time schedule for the selected bridge expenditures as well as the cost in the analysis.

Recently, there has been more interest in including bridge lifetime reliability in the process of optimising investments based on life-cycle costing. It has been reported that deterministic condition assessment of bridges can be overconservative, leading to an overestimation of the need for bridge repair [23]. Also, due to the large uncertainties related to live loads and to the deterioration of concrete bridges, an assessment based on probabilistic (i.e., reliability) modelling of the significant parameters seems to be warranted.

Frangopol *et al.* [23] presented a LCC analysis methodology that integrates maintenance, repair, and replacement decisions in bridge management based on reliability, optimisation, and life-cycle costing. Using this methodology, maintenance, repair, and replacement actions can be based on an acceptable level of risk (i.e., failure), which can be quantified using structural reliability methods. Optimum maintenance, repair, and replacement strategies can be identified which provide safety and serviceability at minimum expected life-cycle cost. As an example, the authors indicated that for a given environment, the dimensions of bridge elements could be modified to increase the time between repairs and to reduce the total number of repairs over the life-span of the bridge. The dimensions of the bridge elements are identified using optimisation techniques, and a reliability-based optimum maintenance strategy is identified which minimizes the total LCC. It was mentioned briefly that this approach can be used to compare several feasible bridge designs for a variety of materials (e.g., HPC) based on the total expected LCC criterion.

Neff [26] presented a methodology for incorporating reliability concepts in predicting the LCC of concrete bridges subject to corrosion of the reinforcement. The methodology is applicable to all corrosion protection systems. An example of LCC analysis for selecting a corrosion protection system for a reinforced concrete bridge deck was presented. Five different protection strategies were evaluated and compared against a base case of no corrosion protection. These strategies included: epoxy coating one or both mats of reinforcement, stainless steel rebar, galvanized steel rebar, and a combination of HPC and epoxy-coated rebar. The alternatives were compared using an analysis period of 75 years. It was found that the combination of HPC and epoxy-coated rebar was the most economical corrosion protection alternative over the life-cycle of the bridge.

5. CONCLUSION

New construction materials such as HPC could play a significant role in the renewal of North America’s deteriorated bridge infrastructure. Despite its known potential advantages, it is unlikely that HPC will gain wide acceptance in the precast, prestressed concrete industry without a clear long-term economic incentive. In addition, the lack of funds available to repair and/or replace deficient bridges necessitates that the return on future transportation investments has to be maximized through smart decision-making processes that take into consideration the potential maintenance, repair, and replacement costs, and not just the lowest initial cost. Properly used, LCC analysis is a powerful tool that can facilitate better decision-making, and thereby managing risk and optimising investments. Much work has been done during the past decade to overcome the obstacles for applying LCC to highway bridges. However, very few researchers have tried to quantify the long-term benefits from the use of HPC for bridges based on the total expected LCC criterion. Those who tried, have found that this material is the most economical alternative for protecting concrete bridges from the most devastating deterioration mechanisms. More research is still needed to confirm the findings of those studies, and to show that the use of HPC could lead to cost effective and durable bridges that will last well into the new millennium.

6. REFERENCES

[1] American Society of Civil Engineers (2001) (www.asce.org/reportcard/)
[2] Russell, H.G. Concrete International 19 (8) (1997) 62-63.
[3] Chang, S.E. and Shinozuka, M. Journal of Infrastructure Systems (ASCE) 2 (3) (1996) 118-126.
[4] Hassanain, M.A. and Loov, R.E. PCI Journal 44 (2) (1999) 40-55.
[5] Scott, N.L. Highway Research Record 34 (1963) 117-129.
[6] Jacques, F.J. PCI Journal 16 (2) (1971) 24-42.
[7] Rabbat, B.G. and Russell, H.G. PCI Journal 27 (4) (1982) 88-104.
[8] Castrodale, R.W., Kreger, M.E. and Burns, N.H. Report No. FHWA/TX-88+381-4F, Center for Transportation Research, The University of Texas at Austin, Austin, Texas, USA (1988).
[9] Zia, P., Schemmel, J.J. and Tallman, T.E. Report No. FHWA/NC/89-006, Center for Transportation Engineering Studies, North Carolina State University, Raleigh, North Carolina, USA (1989).
[10] Russell, B.W. PCI Journal 39 (4) (1994) 76-89.
[11] Juliano, M.L. and Waszczuk, C.M. Proceedings of the PCI/FHWA International Symposium on High Performance Concrete, New Orleans, Louisiana, USA (1997) 475-487.
[12] Jobse, H.J. and Moustafa, S.E. PCI Journal 29 (3) (1984) 44-73.
[13] Mitchell, D., Cook, W.D., Khan, A.A. and Tham, T. PCI Journal 38 (3) (1993) 52-66.
[14] Dilger, W.H. and Wang, C. Adam Neville Symposium on Concrete Technology, Las Vegas, Nevada, USA (1995) 59-84.
[15] Gjørv, O.E. High Performance Concrete: Properties and Applications, McGraw-Hill, Inc., New York, New York, USA (1994) 139-160.
[16] Veshosky, D. and Beidleman, C.R. Civil Engineering (ASCE) 62 (7) (1992) 6.
[17] Leeming, M.B. Bridge Management 2, Thomas Telford, London, UK (1993) 574-583.
[18] Freyermuth, C.L. Concrete International 23 (2) (2001) 89-95.
[19] Hawk, H. Proceedings of the Fifth International Conference on Short and Medium Span Bridges, Calgary, Alberta, Canada, Vol. 3 (1998) 1307-1314.
[20] Koskisto, O.J. and Ellingwood, B.R. Journal of Structural Engineering (ASCE) 123 (3) (1997) 298-304.
[21] de Brito, J. and Branco, F.A. Practice Periodical on Structural Design and Construction (ASCE) 3 (2) (1997) 68-75.
[22] de Brito, J. and Branco, F.A. Canadian J. of Civil Engineering 25 (2) (1998) 261-270.
[23] Frangopol, D.M., Enright, M.P. and Estes, A.C. Presentations from the 8th International Bridge Management Conference, Denver, Colorado, USA, Vol. II (1999) 13 pp.
[24] Thoft-Christensen, P. Advanced Technology in Structural Engineering, Proceedings of Structures Congress 2000 (ASCE) Philadelphia, Pennsylvania, USA (2000) 8 pp.
[25] Sobanjo, J.O. Presentations from the 8th International Bridge Management Conference, Denver, Colorado, USA, Vol. I (1999) 14 pp.
[26] Neff, T.L. Presentations from the 8th International Bridge Management Conference, Denver, Colorado, USA, Vol. I (1999) 16 pp.
[27] Troive, S. and Sundquist, H. Proceedings of the Fifth International Conference on Short and Medium Span Bridges, Calgary, Alberta, Canada, Vol. 2 (1998) 1101-1113.
[28] Hjelmstad, K.D., Lange, D.A., Parsons, I.D. and Lawrence, F.V. Journal of Infrastructure Systems (ASCE) 4 (3) (1998) 126-133.
[29] Khan, M.S. Concrete International 22 (8) (2000) 53-56.
[30] Mohammadi, J., Guralnick, S.A. and Yan, L. Journal of Transportation Engineering (ASCE) 121 (5) (1995) 417-424.