A METHODOLOGY FOR EVALUATING THE COST-EFFECTIVENESS OF CRCP DESIGN FEATURES

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Abstract

Continuously reinforced concrete pavement (CRCP) evolved out of a desire to minimize joint-related distresses and improve long-term smoothness of the pavement by eliminating transverse contraction joints. In CRCP, longitudinal reinforcing steel is continuous throughout the pavement length to hold cracks tight. A methodology for evaluating the cost-effectiveness of key CRCP design features and optimizing CRCP design was developed and presented. In this methodology, performance and cost data are combined to evaluate the cost-effectiveness of pavement design features and to determine the optimum combination of these features which has lowest life cycle cost (LCC). The developed methodology was used to examine the cost-effectiveness of five of the more influential CRCP design features PCC slab thickness, longitudinal steel reinforcement content, base type and thickness, shoulder type and thickness, and PCC slab width. A detailed life-cycle cost analysis (LCCA) of 13 current CRCP designs utilizing different combinations of these five design features was conducted using best estimates of the relative costs and performance effects of each of these design features. The cost data were obtained from State and contractors surveys, as well as published cost data and bid tabs. The performance data were obtained from State and contractors surveys, as well as empirical and mechanistic-empirical pavement performance prediction models.

Introduction

Continuously reinforced concrete pavement (CRCP) evolved out of a desire to minimize joint-related distresses and improve long-term smoothness of the pavement by eliminating transverse contraction joints. In CRCP, longitudinal reinforcing steel is continuous throughout the pavement length to hold cracks tight. This type of pavement has been constructed on a regular basis since the 1940's in the U.S. and, today, it is used extensively by some State highway agencies (e.g., Texas, Illinois) and frequently by several other states (e.g., Virginia, Oregon, Oklahoma, and South Dakota) [CRSI 2001]. CRCP has also been constructed in other countries, such as Belgium, Spain, France, Holland, Italy, Japan, and Australia. In more recent years, CRCP has been constructed

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on heavily trafficked highways for longer design lives, which required designing for equivalent single axle loads (ESAL's) ranging from 50 to 500 million.

The cost and performance of CRCP is influenced by several design features (e.g., steel content, slab thickness) that can be controlled by CRCP designers. For example, thicker slabs have an increased capacity to resist critical bending stresses and to provide adequate load transfer across cracks. As a result, the development of punchouts (the primary form of distress in CRCP) is reduced and pavement service life is increased. However, the thicker the slab is, the higher the initial cost is. A methodology is needed to assist pavement engineers determine the optimum CRCP design that achieves the target performance at the minimum cost.

The main objective of this study is to develop a methodology for determining the cost-effectiveness of key CRCP design features and optimizing CRCP design. The developed methodology examines the cost-effectiveness of five of the more influential CRCP design features based on their effect on the total life cycle cost (LCC) of the pavement. These design features are PCC slab thickness, longitudinal steel reinforcement content, base type and thickness, shoulder type and thickness, and PCC slab width. A detailed life-cycle cost analysis (LCCA) of 13 current CRCP designs utilizing different combinations of these five design features was conducted using best estimates of the relative costs and performance effects of each of these design features.

CRCP Design Optimization Methodology

This CRCP design optimization methodology was built upon a previously-published methodology for evaluating the benefits and costs of jointed plain concrete pavement (JPCP) design features [Gharaibeh and Darter 2001]. The JPCP methodology was based entirely on numerical models for predicting pavement performance and generic published cost data. In both methodologies, performance and cost data are combined to determine the cost-effectiveness of pavement design features and to determine the optimum combination of these features (the pavement design with the lowest LCC). This sequel methodology for CRCP, however, has the following improvements:

- Both numerical models (empirical and mechanistic-empirical) and experts' opinions (from State highway agencies, as well as paving contractors) are used for predicting pavement service life.
- Cost data were obtained from surveys of States and contractors, as well as actual bid tabs.

Changing a concrete pavement design feature often affects both costs and performance. This methodology determines which features add more service life benefit than cost for specific site conditions. The design optimization methodology consists of the following steps.

1. Select key design features that can be modified and have been shown to influence CRCP cost and performance.
2. Establish a reference design for comparison purposes (relative initial construction cost for reference design ($RICC_{ref}$) = 100 percent).

3. Alter the reference design to establish a matrix of combinations of the key design features that constitute different, yet realistic designs.
4. Obtain the relative initial cost for the design combinations. (In this study, these data were obtained from State highway agencies [SHA's] and contractors surveys and actual bid tabs.)
5. Predict CRCP service life for the design combinations. (In this study, service life data were estimated from experts' opinions and numerical performance prediction models.)
6. Compute the relative total life cycle cost (RLCC) for each of the design combinations as a percentage of total LCC of the reference design. RLCC for the modified design (*i*) is expressed in percent of NPW of the reference design as follows. (RLCC is used if the CRCP designer chooses to consider both initial and future rehabilitation costs.)

$$RLCC_i = \frac{LCC_i}{LCC_{ref}} * 100$$

Application of the Design Evaluation Methodology

The following sections of this paper describe the application of the developed methodology to an assumed CRCP project that has an initial traffic loading level of 750,000 equivalent 80-kN single-axle loads (ESALs) and an annual ESAL growth rate of 3 percent.

CRCP Key Design Features

Most of the existing CRCP in the U.S. has been designed using the 1986/1993 AASHTO Design Guide or modified versions of it. It is anticipated that in the future, CRCP will be designed using the new mechanistic-empirical (M-E) design procedure developed under NCHRP project 1-37A (2002 Design Guide). The following design features are critical for both the performance and cost of CRCP.

- PCC slab thickness
- PCC slab width
- Longitudinal steel reinforcement content
- Base type and thickness
- Shoulder type and thickness

Each design feature affects CRCP performance in different ways and amounts depending on site conditions (traffic, climate, and subgrade, etc.). These effects are well-documented in previous studies (Dhamrait and Taylor 1979, Gharaibeh et al. 1999, Selezneva et al. 2001, Tayabji et al. 1995, Zollinger et al. 1998). In addition, performance of a pavement system depends on the interaction between these features. CRCP designers can use other CRCP design features (e.g., subdrainage systems and

PCC material characteristics) in this methodology if these features found to have major effects on CRCP performance and cost.

Design Combinations and Reference Design

Table 1 shows the matrix of possible CRCP design combinations, based on these design features. Although there are 270 design combinations, only a fraction of these combinations are considered to be realistic and somewhat representative of SHAs' current design practices. Thirteen such design combinations are the focus of the investigation into the cost-effectiveness of CRCP design features. These 13 representative designs are designated 1 through 13 in Table 1.

The reference design used in this study consists of 254-mm thick by 3.66-m wide CRCP slab, with 0.65 percent longitudinal steel reinforcement, resting on a 102-mm asphalt-treated base [ATB] and adjoined by a full-depth AC shoulder. The reference design is simply a bench mark for measuring the relative cost and performance of the studied designs.

Cost Data

To best estimate the costs of constructing the 13 representative designs given in Table 1, the relative cost data obtained through SHA and paving contractor surveys were supplemented with bid tabulation unit prices from recently let highway paving contracts.

Of 22 questionnaires sent to SHA's and PCC paving contractors, 6 sets of responses were returned. Table 2 summarizes the statistics of the relative cost estimates provided in these responses. Besides the obvious effects of increasing or decreasing slab thickness or steel content, it can be seen that using a 152-mm dense-aggregate base instead of a 102-mm ATB or reducing the asphalt concrete (AC) shoulder thickness, results in a markedly lower cost of construction. In contrast, use of a 152-mm cement-treated base, full-depth tied PCC shoulders, or a widened slab, generally results in a higher initial cost.

Table 1. Matrix of CRCP design combinations evaluated for cost-effectiveness.

Base Type	Shoulder Type	Lane Width m	200-mm CRCP			230-mm CRCP			250-mm CRCP			280-mm CRCP			300-mm CRCP		
			0.6% Steel	0.65 % Steel	0.7% Steel	0.6% Steel	0.65 % Steel	0.7% Steel	0.6% Steel	0.65% Steel	0.7% Steel	0.6% Steel	0.65 % Steel	0.7% Steel	0.6% Steel	0.65 % Steel	0.7% Steel
150-mm Dense Aggregate Base	130-mm AC	3.7						4									
		4.3															
	Full-Depth AC	3.7								*							
		4.3								6							
	Full-Depth Tied PCC	3.7									8						
		4.3															
100-mm Asphalt-Treated Base	130-mm AC	3.7								*							
		4.3															
	Full-Depth AC	3.7		*					*	5* (ref.)	*					*	13
		4.3								*							
	Full-Depth Tied PCC	3.7				2				*	7			10			
		4.3															
150-mm Cement-Treated Base (w/ asphalt breaker)	130-mm AC	3.7															
		4.3															
	Full-Depth AC	3.7								0	9						
		4.3	1											11			
	Full-Depth Tied PCC	3.7					3									12	
		4.3															

* Design feature variation presented in SHA and PCC Paving Contractor surveys for estimating relative cost and performance.

Table 2. Relative cost statistics from CRCP cost survey.

Design Feature Variation	Description	Mean Estimated Relative Cost, %	Standard Deviation, %	Range, %	No. of Respon ses
Reference	254-mm CRCP, 0.65% steel, 102-mm ATB, FDAC shoulder, 3.66-m lane	100.00			
A	203-mm CRCP	84.80	3.70	80 - 90	5
B	305-mm CRCP	111.50	4.93	104 - 118	6
C	0.6% Steel	99.00	0.00	99 - 99	5
D	0.7% Steel	101.60	0.55	101 - 102	5
E	152-mm DAB	92.80	5.40	84 - 98	5
F	152-mm CTB (w/ asphalt interlayer)	104.75	7.27	98 - 115	4
G	127-mm AC shoulder	95.17	2.79	90 - 98	6
H	Full-depth tied PCC shoulder	107.33	4.27	102 - 113	6
I	4.27-m lane	104.33	3.27	101 - 110	6

To supplement the relative cost estimates provided by SHA's and contractors alike, SHA's were also asked to provide any available unit cost data associated with CRCP construction. Though some data were furnished by two agencies, searches of on-line bid tabulation files unearthed more complete cost data from five of the six States surveyed. For a couple States, however, the available data consisted of the average pay item bid prices for all contracts let within the last 12 months. To the extent possible, pay item bid price data obtained from these files centered around sizeable CRCP paving contracts let within the last 3 years for Interstate and other primary highways.

To ensure that the unit costs derived from actual bid tabulation data produced relative costs consistent with State and contractor estimates, the overall pavement structure costs for the 10 design feature variations were computed. Table 3 lists the resulting structure costs (generated from the bid tab unit costs) and the corresponding relative costs, as compared to the reference design. It also shows the mean relative costs computed from the survey responses.

As can be seen, there is generally good consistency between the relative costs computed from bid tab data and the mean relative costs computed based on survey responses. Most are within 2 percentage points of each other. Only the 127-mm AC shoulder and the 4.27-m widened lane showed appreciable differences between the bid tab data and survey responses.

Table 3. Comparison of relative pavement costs generated from bid tab data and survey responses.

Design Feature	Design Feature Variation	Total Initial Cost, $million (from bid tabs)	Relative Cost, % (from bid tabs) [(a)]	Mean Relative Cost, % (from survey)	Difference[(b)]
Slab Thickness	A (203-mm CRCP)	1.525	85.96	84.80	1.16
	Reference (254-mm CRCP)	1.774	--	--	--
	B (305-mm CRCP)	1.996	112.53	111.50	1.03
Longitudinal Steel Amount	C (0.6%)	1.756	99.02	99.00	0.02
	Reference (0.65%)	1.774	--	--	--
	D (0.7%)	1.809	101.97	101.60	0.37
Base Type/ Thickness	E (152-mm DAB)	1.638	92.80	93.00	-0.20
	Reference (102-mm ATB)	1.774	--	--	--
	F (152-mm CTB)	1.827	103.02	104.75	-1.73
Shoulder Type/ Thickness	G (127-mm AC)	1.745	98.39	95.17	3.22
	Reference (full-depth AC)	1.774	--	--	--
	H (full-depth, tied PCC)	1.885	106.26	107.33	-1.07
Slab Width	I (4.27 m)	1.792	101.01	104.33	-3.32
	Reference (3.66 m)	1.774	--	--	--

[a] Relative Cost = Total Initial Cost of Design Alternative ■ Total Initial Cost of Reference Design
[b] Difference = Relative Cost Computed from Bid Tab Data ■ Mean Relative Cost Computed from Survey Responses

CRCP Performance Data

The other component of the cost-effectiveness evaluation is the service life of the original CRCP. Service life is defined as the time (or number of ESALs) it takes for a new pavement to deteriorate to a condition that warrants major structural improvement in the form of an overlay, extensive restoration work, or reconstruction. Typically, a pavement needing structural improvement possesses a rough ride and has become too expensive to maintain.

To best estimate the service lives of the 13 representative designs given in Table 1, the performance estimates obtained through the SHA survey were supplemented with predictions from two numerical models.

State Highway Agency Surveys

Of the six questionnaire surveys sent to SHAs, three sets of responses were received. The respondents included two States located in a wet-nonfreeze climate and one in a wet-freeze climate. Table 4 lists the performance estimates provided by each responding State, based on a specified traffic loading forecast (750,000 ESALs/year initially, annual ESAL growth rate of 3 percent) representative of a moderately heavy, 4-lane Interstate highway. As can be seen, there is significant variation in the responses, particularly between States with different climates.

Table 4. CRCP service life estimates from State surveys.

Design Feature Variation	Description	Estimated Service Life, years		
		State 1 (Wet-Nonfreeze)	State 2 (Wet-Nonfreeze)	State 3 (Wet-Freeze)
Reference	254-mm CRCP, 0.65% steel, 102-mm ATB, FDAC shoulder, 3.66-m lane	28	35	20
A	203-mm CRCP	24	30	5
B	305-mm CRCP	30	40	50+
C	0.6% Steel	25	30	17
D	0.7% Steel	30	40	26
E	152-mm DAB	22	30	10
F	152-mm CTB (w/ asphalt interlayer)	30	28	9
G	127-mm AC Shoulder	28	30	20
H	Full-Depth, Tied PCC Shoulder	33	40	20
I	4.27-m lane	30	40	--[a]

[a] No estimate provided

Performance Model Predictions

CRCP service life estimates from State surveys were supplemented by predictions from two numerical models. The first model is empirical and was developed based on field data from 786 CRCP sections throughout Illinois (Gharaibeh et al. 1999). The second model is mechanistic-empirical (M-E) and was developed was developed under NCHRP 1-37A (2002 Design Guide) (Selezneva et al. 2001).
The Illinois model relates the number of failures per mile to three specific design parameters, traffic, a construction factor, and a materials durability factor (Gharaibeh et al. 1999).

The M-E model predicts punchouts based on accumulated fatigue damage associated with the formation of a longitudinal crack between two closely spaced transverse cracks. The longitudinal crack initiates at the top of the slab and propagates downward through the CRCP slab after the transverse cracks have lost load transfer efficiency (LTE). The prediction period is divided into monthly time increments beginning with the traffic opening month. Material properties, subgrade properties, axle loading, and climatic effects are predicted for each increment. Within each increment a critical stress or deflection is calculated, as well as the damage incurred in that increment. The incremental damage is accumulated month by month and is converted to punchouts per mile using calibration models that relate the calculated damage to observed punchouts.

Using the M-E and Illinois models and the traffic level established for the study (750,000 ESALs/year initially, annual ESAL growth rate of 3 percent), the predicted service lives of the 10 design feature variations presented in the CRCP cost/performance survey and the 13 representative designs were computed. A value of 5 punchout failures/mi was used as the threshold for determining the expected life, and it was assumed that all designs employed chairs for placing reinforcement and had no D-cracking.

In using the 2002 Design Guide CRCP performance model, two different predictions of service life were developed: one corresponding to a pavement in a wet-freeze climate (e.g., Chicago, Illinois) and the other to a pavement in a wet-nonfreeze climate (e.g., Dallas, Texas). Predictions from the Illinois model represent the wet-freeze climate that Illinois experiences.

Table 5 shows the resulting model predictions for each design feature variation. As can be seen, the predictions from the models are fairly comparable, with most being within a few years of each other. In comparison with the SHA service life estimates, the model-predicted values are mostly considerably higher, suggesting that the respondents' estimates are more conservative. It should be pointed out that some of the predictions listed for feature variations F, G, and H are the same as the predicted values for the reference design. This is because AC shoulder thickness is not a factor in the M-E model and shoulder type and lane width are not factors in the Illinois model.

Best Estimates of CRCP Service Life

To develop best estimates of service life for the 13 representative designs, two steps were taken. First, the SHA estimates provided in Table 4 for the 10 design feature variations were extrapolated to produce service life estimates for the 13 representative designs. This was done by multiplying the service life of the reference design by the individual service life ratios associated with each changed design feature. For instance, for design 7, the 28-year life estimated by State 1 was multiplied by the service life ratio associated with increased percent steel (30/28 = 1.07) and the service life ratio associated with the shoulder structure change (33/28 = 1.18). Thus, the State 1 extrapolated life for design 7 was computed as 28*1.07*1.18 = 35.3 years.

The second step involved averaging the three extrapolated State service life values and the three model-predicted service lives to reach a reasonable final estimate of life. In the case of design 7, for example, a best estimate of 39.4 years was computed by averaging the following:

- State 1 (wet-nonfreeze) extrapolation = 35.3 years.
- State 2 (wet-nonfreeze) extrapolation = 45.7 years.
- State 3 (wet-freeze) extrapolation = 26.0 years.
- M-E Model (wet-nonfreeze) model prediction = 47 years.
- M-E Model (wet-freeze) model prediction = 44 years.
- Illinois (wet-freeze) model prediction = 39 years.

Table 5. Performance model service life predictions for 10 design feature variations.

Design Feature Variation	Description	Predicted Service Life, years		
		M-E Model (Wet-Nonfreeze)	M-E (Wet-Freeze)	Illinois Model (Wet-Freeze)
Reference	254-mm CRCP, 0.65% steel, 102-mm ATB, FDAC shoulder, 3.66-m lane	33	33	33
A	203-mm CRCP [d]	5	3	12
B	305-mm CRCP	50+	50+	50+
C	0.6% Steel	27	29	30
D	0.7% Steel	36	39	39
E	152-mm DAB	19	19	21
F	152-mm CTB (w/ asphalt interlayer)	32	34	18
G	127-mm AC Shoulder	33 [a]	32 [a]	33 [a]
H	Full-Depth, Tied PCC Shoulder	39	43	33 [b]
I	4.27-m lane	47	50+	33 [c]

[a] Prediction is same as reference design, since model does not distinguish between FDAC and 127-mm AC shoulder.

[b] Prediction is same as reference design, since model does not distinguish between FDAC and Tied PCC shoulder.

[c] Prediction is same as reference design, since model does not distinguish between standard and widened lane.

[d] Filed data from Illinois indicate that the service life for this design variation is approximately 20 years. (Gharaibeh and Darter, 2003).

Table 6 lists for all 13 representative designs the extrapolated service lives derived from the SHA survey responses and the predicted lives computed from the M-E and Illinois performance models. It also contains the final estimates used in the LCCA, which are simply rounded averages of the extrapolated and predicted estimates. As expected, longer service life is predicted for the designs with thicker slabs, higher steel content, and an ATB. However, it should be noted that the Illinois model predictions for designs using CTB are probably low, since that model does not take into account the positive effect of including an asphalt bond-breaker between the base and the PCC slab and because Illinois CTB was not of sufficient quality to prevent erosion.

Life-Cycle Cost Analysis

LCCA is an economic technique that allows comparisons of investment alternatives having different cost streams over the analysis period. Though there are several ways of performing a LCCA, the most common and accepted method is the Net Present Worth (NPW) method. In NPW, all future costs (maintenance and rehabilitation) and salvage value projected for a particular design alternative over a specified analysis period are discounted to present-day using a discount factor that reflects the long-term market interest rate and inflation rate. The discounted costs are then summed with the initial cost of constructing the design to yield the NPW. When comparing multiple design alternatives, the alternative with the lowest NPW is considered to be the most cost-effective. The equation for computing NPW is as follows:

$$NPW = \text{Initial Cost} + \sum \text{Future Cost}_k * [1 / (1 + i_{dis})^{n}{}_{k}]$$

where: i_{dis} = Discount rate (interest rate i_{int} minus inflation rate i_{inf}).
n = Year of expenditure.
k = Individual cost item.

Table 6. Service life estimates for the 13 representative CRCP designs.

Representative Design	Extrapolated State Estimates of Service Life, years (State 1, State 2, State 3)	Models Service Life Predictions, years (M-E W-NF, M-E W-F, IL WF)	Average of Extrapolated and Predicted Life, years	Service Life Used in LCCA, years
1	24.6, 23.5, NA	17, 18, 5	17.6	18
2	26.8, 31.8, 13.8	20, 24, 18	22.4	22
3	32.2, 29.7, NA	29, 29, 10	26.0	26
4	21.5, 27.3, 10.6	14, 15, 15	17.2	17
5 (reference)	28.0, 35.0, 20.0	33, 33, 33	30.3	30
6	23.6, 34.3, NA	31, 29, 21	27.8	28
7	35.3, 45.7, 26.0	47, 44, 39	39.4	39
8	27.8, 39.2, 13.0	33, 30, 26	28.2	28
9	32.1, 32.0, 36.4	38, 36, 22	32.8	33
10	36.0, 49.0, 50.0	50, 50, 50	47.4	47
11	35.1, 39.2, NA	50, 50, 35	41.9	42
12	37.9, 36.6, 22.5	50, 50, 45	40.3	40
13	32.1, 45.7, 50.0	50, 50, 50	46.3	46

NA: Not available due to incomplete State estimate data.
W-NF = Wet-nonfreeze, WF = Wet-freeze

For computing the NPW of each representative CRCP design, a 50-year analysis period and a 4 percent discount rate were established. The 50-year analysis period covers the estimated service life of the longest lasting design alternative (Design M, 42 years). The discount rate of 4 percent is close to the mean discount rate experienced in the U.S. over the last few decades, and is commonly used by many SHAs.

Salvage value represents the economic worth at the end of the analysis period. It was computed using the prorated life method by multiplying the ratio of the remaining life to expected life of the pavement (original construction or rehabilitation) in-place at the end of analysis period by the most recent cost of that pavement.

For this study, it has been assumed that proper materials and construction practices are used and thus no significant materials- or construction-related distresses will develop. To simplify the LCCA, the following maintenance and rehabilitation strategies were assigned:

- Longitudinal lane-lane joint resealing (100% of length) every 20 years until first rehabilitation.
- Limited (0.5% of surface area) full-depth PCC patching at 6 to 8 years prior to first rehabilitation.
- Rehabilitation #1—Resurfacing with 76-mm AC overlay at end of CRCP service life. Extensive (2.5% of surface area) full-depth CRCP repair prior to overlay.
- AC crack routing and sealing (hot-pour) at 3 years (762 linear meters) and 7 years (457 linear meters) following first rehabilitation.
- Rehabilitation #2—Resurfacing via 76-mm mill and AC replacement. Extensive (2.5% of surface area) full-depth CRCP repair prior to AC replacement.
- AC crack routing and sealing at 3 years (762 linear meters) and 7 years (457 linear meters) following second rehabilitation.
- Rehabilitation #3—Resurfacing via 76-mm mill and AC replacement. Extensive (2.5% of surface area) full-depth CRCP repair prior to replacement.
- AC crack routing and sealing at 3 years (762 linear meters) and 7 years (457 linear meters) following third rehabilitation.
- Rehabilitation #4—Reconstruction using the same CRCP structure as initially used.

The service life of a 76-mm AC overlay on CRCP was estimated to be 13 years on average. However, for the first resurfacing, this value was varied between 10 and 13 years to account for the CRCP on which the overlay would be placed (a thicker slab resulting in longer life) and the time at which it would be placed (the farther into the future, the shorter the life due to substantially higher traffic loadings). Also, the service lives of the second and third resurfacings, as compared to the first, were shortened by 1 and 2 years, respectfully, to account for the additional projected traffic loadings. Finally, for each resurfacing, the amounts of crack sealing for the first and second applications were fixed at 762 linear meters and 1524 linear meters, respectively.

With respect to the upkeep of the paved shoulders, the following strategies were established for the LCCA:

- 127-mm AC shoulders—Crack seal (1219 linear meters) 7 years after initial construction. Mill 38 mm of surface, replace with new AC, and reseal longitudinal shoulder joint at 12 years after initial construction. Mill 76 mm of surface, replace with new AC, and reseal longitudinal shoulder joint every 12 years thereafter until first rehabilitation. Match each mainline rehabilitation and seal cracks at 3 years (762 linear meters) and 7 years (457 linear meters) after each rehabilitation.
- Full-depth AC shoulders—Crack seal (914 linear meters) 7 years after initial construction. Apply surface treatment and reseal longitudinal shoulder joint at 12 years after initial construction. Mill 38 mm of surface, replace with new AC, and reseal longitudinal shoulder joint every 12 years thereafter until first rehabilitation. Match each mainline rehabilitation, except mill 38 mm instead of

76 mm for the second and third rehabilitations. Seal cracks at 3 years (762 linear meters) and 7 years (457 linear meters) after each rehabilitation.

- Tied PCC shoulders—Reseal transverse joints and longitudinal shoulder joint every 15 years until first rehabilitation. Match each mainline rehabilitation (including extensive [2.5% of surface area] full-depth JPC repairs prior to resurfacing), except mill 38 mm instead of 76 mm for the second and third rehabilitations. Seal cracks at 3 years (1219 linear meters) and 7 years (914 linear meters) after each rehabilitation.

The following unit costs were assumed for the various maintenance and rehabilitation treatments. These values are considered to be fairly representative of actual costs nationwide.

- Longitudinal and Transverse (in PCC Shoulder) Joint Resealing: $5.90/m.
- Full-Depth CRCP Repair: $239/m^2.
- Full-Depth JPC Shoulder Repair: $120/m^2.
- Crack Sealing in AC: $4.10/m.
- Cold Milling AC (76-mm depth): $2.69/m^2.
- Cold Milling AC (38-mm depth): $1.79/m^2.
- Surface Treatment: $0.96/m^2.

LCCA Results

Figure 1 shows the resulting set of costs for each of the 13 representative designs. These include the initial construction cost (light shading), the present-worth of all future costs including salvage value (dark shading), and the NPW (listed at the top of each column). As can be seen, the design with the lowest NPW is design 4, a 229-mm thick by 3.66-m wide CRCP with high steel (0.7 percent), supported by a dense aggregate base and a 127-mm AC shoulder.

Designs 6 and 8, both 254-mm CRCP with 0.65 to 0.7 percent steel and a dense aggregate base, are the next most cost-effective designs. These are followed closely by design 7 and reference design 5, which are also 254-mm CRCP with 0.65 to 0.7 percent steel and an asphalt-treated base. The least cost-effective designs were designs 12 and 13 (305-mm CRCP supported by treated bases), design 11 (279-mm CRCP with a cement-treated base), and design 1 (203-mm CRCP with a cement-treated base).

Figure 2 shows the relationship between expected service life and relative NPW. The columns represent the service life while the line represents the relative NPW, as compared to the reference design (design 5). In other words, the reference design is set at 100 percent, and the other designs are computed as a percentage of this design's NPW.

The relative NPW ranges from 96.6 percent (more cost-effective) to 111.3 percent (less cost-effective). Generally speaking, the most cost-effective designs are those with moderately long (24 to 35 years) service lives. However, the very low initial construction cost (229-mm slab, dense aggregate base, partial-depth shoulder) of design 4 helps outweigh its relatively short service life (17 years) to produce the lowest NPW. Also, the extremely long life (45 years) of design 13 helps outweigh its very high initial construction cost (305-mm slab, 0.7 percent steel, ATB) to produce a relatively low NPW.

Concerning individual design features, the 229- and 254-mm slabs (designs 4 through 9, respectively) were generally most cost appropriate, whereas thinner slabs resulted in higher future costs and thicker slabs resulted in higher initial costs. Among base types, the results suggest that the added expense of using cement-treated aggregate is probably not justifiable. With respect to percentage of steel, shoulder type, and slab width, indications about cost-effectiveness are far less certain. The only intimation that can be made is that higher amounts of steel are generally economically beneficial.

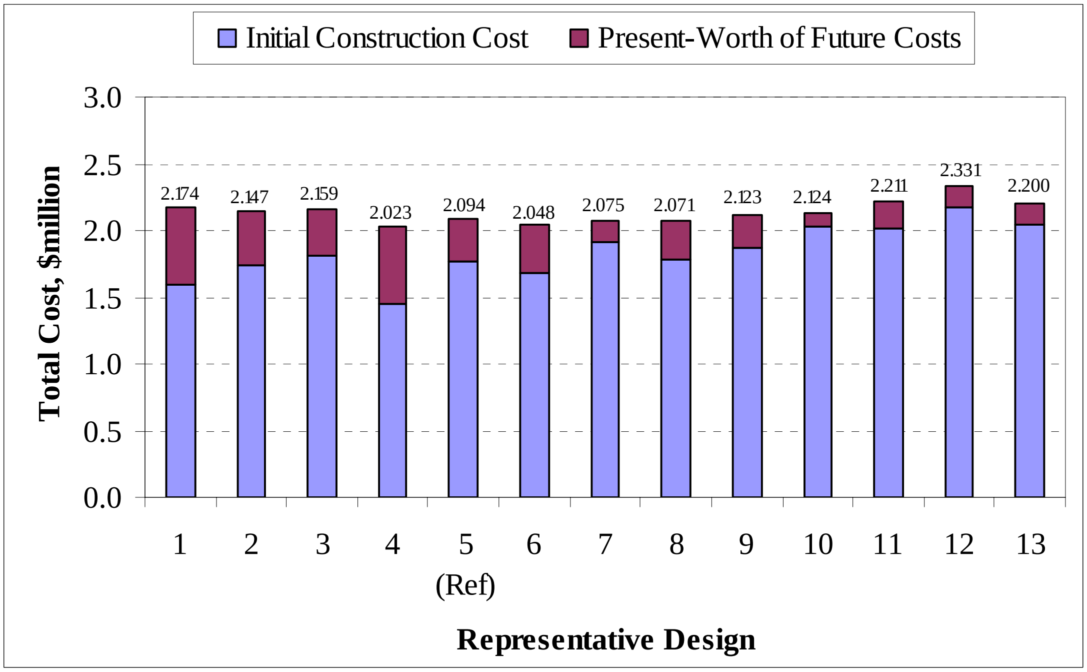

Figure 1. Summary of projected total life-cycle costs for 13 representative CRCP designs.

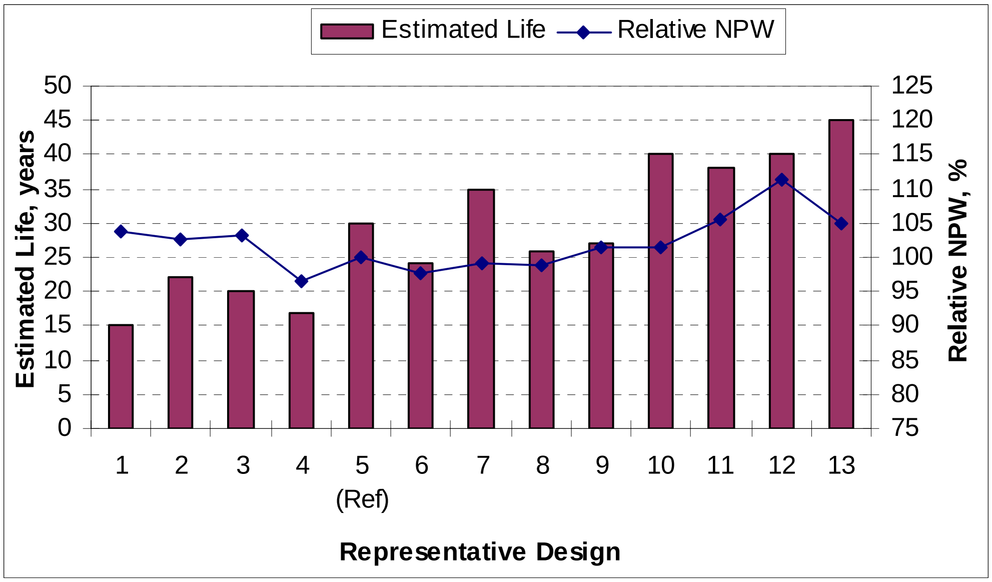

Figure 2. Expected service life & relative NPW of 13 representative CRCP designs.

Summary and Conclusions

A methodology for evaluating the cost-effectiveness of key CRCP design features and optimizing CRCP design was developed. In this methodology, performance and cost data are combined to evaluate the cost-effectiveness of pavement design features (i.e., determine design features that provide the largest increase in service life for the least initial cost) and total LCC (i.e., to determine the optimum combination of these features which has the lowest LCC).

The developed methodology was applied to examine the cost-effectiveness of five of the more influential CRCP design features. These design features are PCC slab thickness, longitudinal steel reinforcement content, base type and thickness, shoulder type and thickness, and PCC slab width. A detailed LCCA of 13 current CRCP designs utilizing different combinations of these five design features was conducted using best estimates of the relative costs and performance effects of each of these design features.

The cost data was obtained from State and contractors surveys as well as published actual cost data and bid tabs. The performance data were obtained from State and contractors surveys as well as numerical performance prediction models. These service life estimates were based on a traffic level of 750,000 ESALs/year initially and an annual ESAL growth rate of 3 percent, which results in a cumulative 84.6 million ESALs over the 50-year analysis period.

Based on the information collected and evaluated and the inputs established for the LCCA, the following conclusions are made with respect to key CRCP design features:

- **Slab thickness** is one of the first features that should be considered when looking to make a CRCP more cost-effective. A 25 mm increase in thickness from 203 to 229 mm or from 254 to 279 mm is likely to increase initial cost by 5 to 8 percent and increase service life by 5 to 10 years. For the LCCA conducted in this study, 229- and 254-mm slabs were generally among the most cost-effective. However, this level of traffic is generally moderate compared to traffic on many CRCP projects, so this finding would obviously vary with traffic level.
- **Longitudinal steel amount**, which is critical to establishing the desired transverse crack spacing of 0.9 to 1.5 m and crack width of 0.079 mm or less, should also be given prime consideration when optimizing CRCP design. While a minimum value of 0.6 percent is generally recommended, the results of the LCCA conducted in this study suggest that values of 0.65 and 0.7 percent can be more cost-effective. Increasing the amount of steel from 0.6 to 0.65 percent or from 0.65 to 0.7 percent yields a 1 to 2 percent increase in initial cost and a 3- to 5-year increase in life.
- **Base type** is also an important feature in the cost and performance of CRCP. Though unbound bases are more likely to experience erosion than bound bases, their lower initial cost may outweigh the additional future costs. A 102-mm asphalt-treated base was found to be more cost-effective than a 152-mm cement-treated base.
- **Shoulder type** has a considerable impact on the initial cost of CRCP, but less impact on performance. As compared to a full-depth AC shoulder, partial-depth

AC is 2 to 3 percent less expensive initially and has marginal impact on CRCP service life. However, a partial-depth AC shoulder will require greater amounts of maintenance and surface rehabilitation in the future, which could offset the lower initial cost. A full-depth JPC shoulder, on the other hand, increases initial cost by about 6 percent, but is likely to add at least two years of life to the CRCP structure. Based on the detailed LCCA conducted in this study, the cost benefits seem to favor the full-depth AC and full-depth JPC shoulder designs.

- **Slab width** does not appear to be as important as slab thickness and steel content in optimizing CRCP design. Nevertheless, it should not go without consideration. Though the estimated additional cost of constructing a widened slab for CRCP design is not substantially high (2 to 3 percent more than a standard slab width), the 2 to 3 years minimum additional life it is expected to provide, can make it a cost-effective option.

These findings are limited to the designs, costs, and performance used in the analysis. This paper is mainly intended to provide the pavement design engineer with a methodology to assist in obtaining the most cost-effective CRCP design possible.

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