Design and Construction of Conventional Bridge Decks That Are Resistant to Spalling

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An analysis was made to determine the length of time until spalling (induced by reinforcing steel corrosion) occurs and the relative cost for different conventional concrete bridge deck designs. Research results of others provided the data from which the time to corrosion was estimated. Three factors were considered: (a) frequency and rate of deicing salt application, (b) water-cement ratio of concrete, and (c) depth of concrete cover over reinforcing. The latter two were variables in deck design and construction. Decks with two combinations of water-cement ratio and clear cover each for two bridges were designed. From these, cost differences for labor and materials were determined. It was concluded that in Kansas conventional decks can be protected from spalling for a 50-year period. Also, life can be tripled for only a 2 percent cost increase by switching from decks with a 5-cm (2-in) cover and a water-cement ratio of 0.44 to decks with a 7.5-cm (3-in) cover and a water-cement ratio of 0.35.

Spalling of reinforced concrete bridge deck slabs is a serious and costly problem in Kansas, as it is in many other states. Much research on this problem has been and is being done. The type of spalling discussed in this paper is caused by corrosion of the reinforcing steel. Conventional bridge decks are those in which the only protection of the reinforcing steel from corrosion is provided by portland cement concrete. Further, conventional bridge decks are constructed in one course from a plastic concrete (5 to 10-cm or 2 to 4-in slump) that is placed, consolidated, finished, and cured by the usual methods.

RESEARCH RESULTS OF OTHERS

Although an ideal solution to the problem has not yet been defined, researchers have provided sufficient data for rational analysis of conventional bridge decks.

For conventional bridge decks, numerous researchers have shown that the length of time until corrosion, or spalling, is primarily a function of

1. The frequency and rate of deicing salt applications, combined with the amount of time the deck is wet (the less time the better),
2. The water-cement ratio of the concrete (the lower the better), and
3. The depth of concrete cover over the reinforcing steel (the more the better).

It is assumed for the purpose of this discussion that the latter two items are variables but that the first item is fixed.

Quantitative evaluation of alternatives showed that better conventional bridge decks can and should be built. The two parameters that need to be quantified are (a) life of the bridge decks before serious spalling occurs and (b) cost (differential).

Numerous researchers have found that lowering the water-cement ratio or increasing depth of cover over the steel or doing both increases the life of bridge decks at a given frequency and rate of deicing salt applications. Therefore, three alternates were studied in which the water-cement ratio (w/c) and depth of cover were varied:

Alternate	w/c	Depth of Cover (cm)
A	0.35	7.6
B	0.44	5
C	0.49	2.5

Alternate C is typical of decks constructed from 1960 to 1965. The data that are most easily used to determine the years of life of alternates A and B are those of Beaton and Stratfull (1), Spellman and Stratfull (3, 4), and Clear and Hay (2). (Because their data were developed in U.S. customary units, SI units are not given for the variables in their equations or their figures.)

Analysis Based on Data of Beaton, Spellman, and Stratfull

Beaton and Stratfull (1) give the following equation:

$$R_t = \frac{10^{0.0442C}\,C^{0.717}\,S_i^{1.22}\,1011}{K^{0.42}\,W_m^{1.17}} \tag{1}$$

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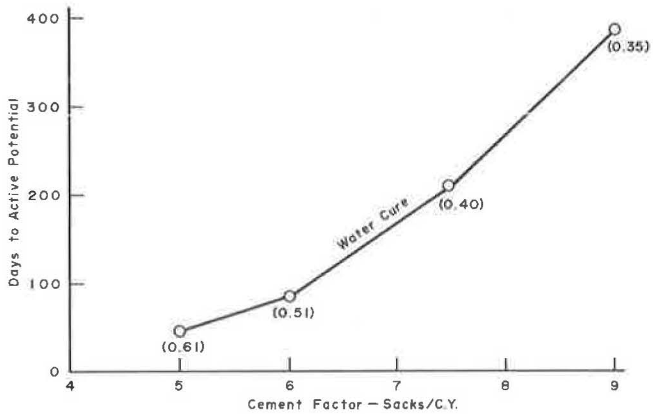
where

R_t = estimated years to deterioration,
C = sacks of cement per cubic yard of concrete,
S_i = inches of concrete cover over reinforcing steel,
K = chloride concentration in parts per million in environment, and
W_m = total water contained in concrete mix as percentage of concrete volume (including that contained by aggregate).

Spellman and Stratfull (3) give the following equation:

$$D = (5.164C^{3.12})/W^{3.06} \tag{2}$$

Figure 1. Effect of cement factor on time to active potential.



where

D = average days to active potential,
C = sacks of cement per cubic yard of concrete, and
W = mixing water as percentage of concrete volume (not including that contained by aggregate).

(Depth of steel cover and chloride concentration were not variables in this research.)

Figure 1 is taken directly from Spellman and Stratfull (4) except that the water-cement ratio of the mixes has been added below the data points. The water-cement ratios were calculated from the mix proportion given in Table 1 of their paper (4).

One procedure used to estimate the life of Kansas bridge decks before serious spalling occurs is as follows.

1. Determine the values of S_i, C, W_m, and W:

Alternate	S_i	C	W_m	W
A	3	8.0	18.5	15.8
B	2	6.4	18.5	15.8
C	1	6.4	20.1	17.2

W_m values are based on the assumption of 890 kg/m³ (1500 lb/yd³) of coarse aggregate at 3 percent absorption.

2. Assume K to be constant.

3. Separate the effect of S_i from the effect of C and W_m in equation 1.

$$R_t \sim S_i^{1.22} \tag{3}$$

$$R_t \sim (1.107C\, C^{0.717}/W^{1.17}) \tag{4}$$

Figure 2. Spalling versus average chloride content.

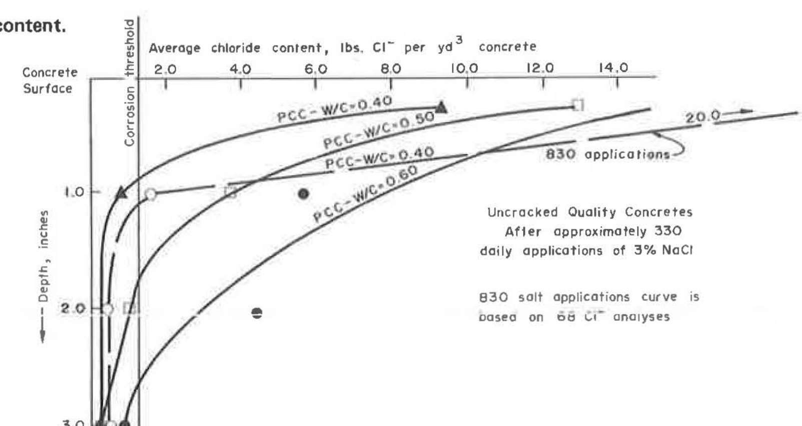


Figure 3. Spalling versus maximum chloride content.

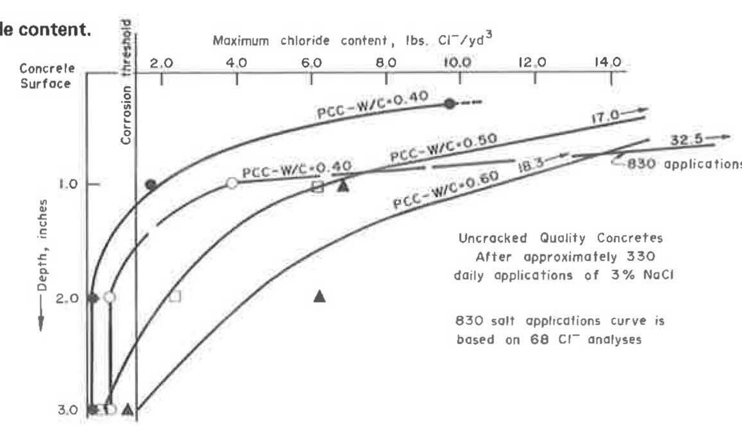


Table 1. Cost increase by item.

Bridge	Size (m^2)	Item	Difference in Quantity (kg)	Unit Cost ($/kg)	Increase ($)
1	608	Cement	41 355	0.03	1304
		Reinforcing	2 671	0.37	968
Total					2290
2	773	Cement	14 613	0.03	461
		Reinforcing	1 768	0.37	653
Total					1114

Note: 1 m^2 = 10.7 ft^2; 1 kg = 2.2 lb.

Table 2. Cost increase per unit area and percentage.

Bridge	Average Cost/m^2 ($)	Item	Cost/m^2 ($)	Percent
1	1.95	7.5 versus 5 cm of cover	0.0186	1.0
		w/c = 0.35 versus 0.44	0.0139	0.7
Total			0.0325	1.7
2	2.79	7.5 versus 5 cm of cover	0.0056	0.2
		w/c = 0.35 versus 0.44	0.0073	0.3
Total			0.0129	0.5
Average			0.0232[a]	1.1

Note: 1 m^2 = 10.7 ft^2; 1 cm = 0.39 in.

[a]$1.88/$m^2$.

4. Calculate the numerical values of the ratio of the length of time measures in equations 2, 3, and 4 and Figure 1 by using alternate C as the base.

5. Average the numerical ratio values produced by equations 2 and 4 and Figure 1 to yield a w/c effect value. Then multiply these values by the numerical ratio values obtained from equation 3 (the S_1 effect value). The resulting combined values are as follows:

Alternate	S_i Effect	w/c Effect	Combined	Life (years)
A	3.82	2.60	9.9	99
B	2.33	1.33	3.1	31
C	1.00	1.00	1.0	10

6. Multiply the combined ratios by the life of alternate C, which is estimated to be 10 years. The as-built depth of cover of most decks constructed from 1960 to 1965 varies significantly from the specified minimum of 3.2 or 3.8 cm ($1^1/_4$ or $1^1/_2$ in). Variations in as-built water-cement ratio from the specified maximum of 0.44 or 0.49 liters/kg (5 or $5^1/_2$ gal/sack) also are present. It is the author's judgment, based on observation of a number of these bridges on high traffic highways in northeastern Kansas, that 10 years is a reasonable estimate of the average time until serious spalling occurs for alternate C bridges. Serious spalling is defined here as spalling that receives maintenance in the form of patching. The estimated life of each alternate is given above.

Another procedure used to estimate life, with the same data, is as follows:

1. Calculate R_t values for each alternate by using equation 1 with K = 160 000 ppm (saturated solution).
2. Estimate the number of days during an average year in which a bare bridge deck in Kansas would be in a saturated condition. Based on average number of rain days of more than 0.25 cm (0.10 in) for the period 1941 to 1970, the number is estimated to be 50.
3. Multiply the R_t values from step 1 by 365/50.

These values are as follows:

Alternate	Life (years)
A	61
B	27
C	10

This method shows less difference between the alternates than the first method did because it is based only on equation 1, in which the effect of water-cement ratio is not so large as in equation 2 and Figure 1.

Analysis Based on Data of Clear and Hay

Figures 2 and 3 are taken directly from Clear and Hay (2) except that the results after 830 salt applications have been added. Clear and Hay state that 7 to 28 salt applications were required to induce rebar corrosion for a 2.5-cm (1-in) cover of concrete with a water-cement ratio of 0.50; this condition approximates alternate C. Interpolation by using Figure 2 indicates that rebar corrosion would not take place after 330 applications in alternate B or after 830 salt applications in alternate A under the test conditions. Clear and Hay's recommendations (dictated by interim findings, after 330 applications, of their research) were either (a) w/c = 0.40 concrete and 5 cm (2 in) of clear cover or (b) w/c = 0.50 concrete and 7.6 cm (3 in) of clear cover. They did not give a life expectancy in years for these combinations. One could infer, however, that alternate B would not be good enough and that alternate A would be better than necessary.

To convert the number of test applications to years until serious spalling occurs requires that the following factors be considered:

1. The amount of salt applied per year of bridge deck life versus a given number of test applications,
2. The effect of a given quantity of salt applied to a bridge deck under field conditions versus the same quantity applied in test applications,
3. The time lag between the start of corrosion and the time to serious spalling, and
4. The effect of not obtaining the specified maximum water-cement ratio or minimum depth of cover.

Based on estimates by maintenance personnel it is believed that Kansas bridge decks receive about 20 applications at 370 kg/2-lane km (1300 lb/2-lane mile) per year. In Clear and Hay's tests the top surface of the slabs was ponded to a depth of 0.5 cm ($^1/_{16}$ in) with a 3 percent solution of sodium chloride each afternoon. The slabs were flushed monthly with potable water. Most of the slabs were exposed to precipitation. From this information it was calculated that one test application places approximately the same amount of salt per unit area on the test slabs as one application by maintenance personnel does on Kansas bridge decks. Therefore, based on the quantity of salt, 20 test applications equal one year. Other equivalencies are as follows:

Test Applications (2)	Years of Salting Kansas Bridge Decks
830	41
330	16
7 to 28	½ to 1½

Clear and Hay discuss the difference between their procedure, which results in a wet-dry surface within a single day, and one involving continuous soaking. They base their discussion on the difference between those slabs protected from precipitation and those not protected. Preventing the natural washing action of precipitation and the evaporating action of the sun had a definite adverse effect. They state that a continuous soaking procedure is a more stringent (although not necessarily superior) test. One could infer from their discussion that test applications are more stringent than field applications.

Spellman and Stratfull (3) found that their test specimens reached active potential in about three-quarters of the time it took for visible evidence of reinforcing steel corrosion (cracking). This time lag is probably not independent of depth of cover. It would logically be greater with more cover. The cover provided in their tests was a minimum of 2 cm (⅞ in).

In real bridge decks there is a finite probability that the specified maximum water-cement ratio will be exceeded and that the specified minimum depth of cover will not be obtained. The factors determining this probability are numerous and difficult to evaluate. In this analysis it was assumed that the in-place deck would be within the following tolerances essentially all the time: 0.03 water-cement ratio and 0.6-cm (¼-in) depth of cover.

Having considered the Clear and Hay data in the light of the four factors just discussed, it was felt that they agree with the length of life estimated based on the Beaton, Spellman, and Stratfull data.

COMPARISON OF ALTERNATES

Based on the preceding analysis of the research results (1, 2, 3, 4), two conclusions were reached:

1. For the frequency and rate of salt applications used in Kansas, spalling should be eliminated (for practical purposes) within a 50-year design life if alternate A is adopted.
2. Alternate A should last three times as long as current alternate B.

To determine the difference in cost of alternates A and B, two bridges were designed for each of the alternates A and B. Bridge 1 is a 15-m, 20-m, 15-m (48-ft, 64-ft, 48-ft) continuous reinforced concrete haunched slab with a 12-m (40-ft) roadway, and bridge 2 is a 16-m, 150-m, 16-m (54-ft, 93-ft, 54-ft) continuous welded deck girder with an 8.5-m (28-ft) roadway. These bridges were chosen because they are typical of Kansas bridges and represent extremes as far as the effect of the proposed changes on cost. AASHTO specifications (including 1974 interims) were used. The exterior dimensions of the alternates of each structure are identical and are taken from actual bridges recently built in Kansas. The bridges as originally designed and built were of the alternate B type: They used grade 40 reinforcing and working stress design method. So that the alternates could be compared under conditions more typical of those currently used, both alternates A and B were redesigned by using grade 60 steel and the load factor design method. The depth of cover for alternate A was increased to a 7.6-cm (3-in) minimum by lowering the top reinforcing steel 2.5 cm (1 in) relative to alternate B. In the design, alternate A had f_c' = 34.5 MPa (5000 psi) and alternate B had f_c' = 27.6 MPa (4000 psi). The cost of alternate C is irrelevant at this point inasmuch as Kansas and most other states have already abandoned it.

In the cost comparison, labor and materials were considered separately. The significant material costs that differ between alternates A and B are given in Table 1. Labor costs do not differ significantly between alternates A and B. The formwork is identical, and the concrete mixes are the same slump; the only difference in reinforcing is that the top steel (negative moment) is one bar size larger in alternate A. The increased steel costs are essentially due to the additional 2.5 cm (1 in) of cover, and the increased cement costs essentially are due to the lower water-cement ratio. Table 2 gives these costs.

IMPLEMENTATION

This system of bridge deck protection does not require any major adjustments in design or construction practices, at least in Kansas; hence, it is called conventional. It is only necessary to

1. Design bridges with a 7.5-cm (3-in) clear top cover instead of 5 cm (2 in); the thickness of decks should be the same.
2. Change the concrete specifications to a water-cement ratio of 0.35 instead of 0.44. Also, the specified minimum cement factors must be increased 25 to 30 percent so that mixes of the same slumps as currently being used will be obtained.

Contractors for the State Highway Commission of Kansas have constructed, by conventional methods, several bridge decks amounting to in excess of 7645 m^3 (10 000 yd^3) of the new concrete mixes. Several types of aggregate have been used, the weather has varied from winter to summer, and we have used both transit mix and remote central mix concrete. The in-place density and water-cement ratio have been checked extensively. This has shown that good consolidation (less than 2 percent entrapped air) is no more difficult to achieve with the new mixes than with the old. Likewise, it was shown that the probability of exceeding the specified maximum water-cement ratio is no greater for the new mixes than for the old. The only difficulty encountered that could be attributed to the new mix was in finishing. The top surface of the new mix does lose its wetness faster and is therefore more difficult to finish (at the same initial slump and under the same weather conditions). Two of the contractors adjusted their methods (no additional work force) and were able to achieve good finishes. The quality of the finish obtained by the third contractor was less than desirable on the new mix. Test cylinder strengths for the new mix after 28 days have averaged about 44.1 MPa (6400 lbf/in^2) (specified air content 6 percent ± 2).

Kansas is now designing most new decks with 7.5 cm (3 in) of top cover, but none of these has been constructed yet.

CONCLUSIONS

1. In Kansas conventional reinforced concrete bridge decks can be protected from spalling for a 50-year design life by providing a 7.5-cm (3-in) minimum cover over the reinforcing steel and specifying concrete with a maximum water-cement ratio of 0.35. This can be done at a cost increase of 2 percent or less over the current practice of providing 5-cm (2-in) minimum cover and specifying a maximum water-cement ratio of 0.44.
2. For other conditions of deicing salt exposure, adding concrete cover and reducing water cement ratio (within practical limits) are a cost-effective way of increasing the life of conventional bridge decks. When bridge decks with 7.5 cm (3 in) of cover and a water-cement ratio of 0.35 are compared with decks with 5 cm (2 in) of cover and a water-cement ratio of 0.44, it is found that life can be tripled for a 2 percent, or less, increase in construction cost.

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