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The Effects of Slab Size on Pavement Life Cycle Cost

Timothy A. Parsons * Jim W. Hall, Jr*

Abstract

The purpose of this study was to determine the effect of expansion joint spacing (slab size) on the life cycle costs of owning Portland Cement Concrete (PCC) airfield pavements. Previous research has shown that slab size has a statistically significant impact on pavement performance. A probabilistic life cycle cost analysis was performed to determine if the effect of slab size on pavement performance would affect the total cost of ownership of PCC pavements. Data from 48 Pavement Condition Index (PCI) inspections of military and civilian airfields were used to develop probability-of-distress-by-condition curves, which were then used to develop probabilistic cost-of-repair-by-condition curves. A present worth life cycle cost analysis was then performed for various slab sizes, using construction costs, rehabilitation costs, and maintenance costs. Maintenance costs were determined by assuming a condition deterioration rate appropriate for each slab size and applying the cost-by-condition curves. The probabilistic cost-of-repair-by-condition curves indicated that smaller slabs are more expensive to repair on a unit cost basis. Life cycle cost analysis showed that larger slabs have a higher total cost of ownership than smaller slabs due to a faster rate of deterioration.

INTRODUCTION

Previous research has shown that joint spacing (slab size) in Portland cement concrete (PCC) has a statistically significant impact on pavement performance [1]. In general, smaller slabs deteriorate slower than larger slabs. While this indicates that pavements consisting of smaller slabs will last longer, it does not necessarily follow that pavements consisting of smaller slabs will be less costly. This research examines the relationship between slab size, pavement deterioration rate, and various repair types and their associated costs to determine the total cost of ownership of a pavement through a 50-year life cycle.

Pavement deterioration rates for various slab sizes were calculated and then used to calculate pavement life cycle costs. Pavements were divided into three groups for analysis: 4.6m (15ft) slabs, 6.1m (20ft) slabs, and 7.6m (25ft) slabs. Slabs larger than 7.6m were neglected due to the small sample size.

A probabilistic cost-by-condition model was developed for this analysis. Pavement management techniques are unable to accurately predict the development of individual distresses; therefore, maintenance costs for a 50-year life cycle could not be directly estimated from the unit cost of repair of the various distresses. Any cost-by-condition model should account for any differences in distress types occurring on the various size slabs; therefore, a single cost model for all three analysis groups would be inadequate.

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* Applied Research Associates

The model was based on the probability of a given distress occurring at a given Pavement Condition Index (PCI) value [2] and the average density of the distress when it did occur. These data were combined with unit cost of the appropriate repair for each distress type to determine the overall cost-by-condition relationship. This method considers the possibility that different distresses, with different repair costs, occur at different rates for different slab sizes.

Maintenance costs were determined by selecting an appropriate deterioration rate for each slab group and calculating the PCI of the pavement for each year of a 50-year life cycle. Calculated PCI values were then used to estimate maintenance costs using the probabilistic cost-by-condition relationship. Construction and reconstruction costs were determined from historical United States Air Force (USAF) historical cost data [3]. Salvage value was determined as initial construction cost pro-rated for the remaining life of the pavement. Life cycle costs for each analysis group were then calculated by summing all construction, maintenance, and reconstruction costs, then subtracting the salvage value of the pavement.

All calculations were performed using year 2004 costs of construction and maintenance.

PROBABILISTIC COST-BY-CONDITION MODEL

A probabilistic cost model was developed to determine the relationship between pavement condition as determined by the PCI and maintenance costs for each analysis group. The probabilistic model was based on the equation

$$C_{dp}=P*g*C_s \qquad \text{Eq. 1}$$

for any PCI X, where:

C_{dp} is the probable cost at any given PCI X due to distress D

P is the probability of distress D occurring at PCI X

g is the average density of distress D occurring at PCI X

C_s is the cost of repair per slab for the treatment of distress D

Values of P and g were calculated from historical inspection data of 48 airfields in the continental United States. Approximately 4200 inspections of pavement sections were sorted by PCI value. Probability P of distress D occurring at PCI X was calculated by determining the number of sections at PCI X with distress D present and comparing it to the total number of sections with PCI X. Density γ of distress D at PCI X was then calculated by determining the average density of distress D in sections with PCI X where distress D is present.

The cost of repair C_s for a given distress is dependent upon the repair method selected for a distress, the amount of repair to be performed in an affected slab, and the unit cost of the repair. Appropriate repairs were selected for each distress, and repair costs were determined from USAF historical costs. The selected repairs, associated unit costs, and amount of repair in an affected slab are listed in Table 1. The corresponding costs for 4.6m, 6.1m, and 7.6m slabs are shown in Table 2. Repair amounts were based on typical distress size.

The probable cost C_{dp} was calculated for each distress and PCI combination. The total probable cost at any PCI X, C_p, was then calculated by summing C_{dp} for all distresses at each PCI such that

$$C_P = \sum_{distresses} C_{dp} \qquad \text{Eq. 2}$$

for each PCI from 55 to 100. The entire process was performed for each analysis group of pavement. These values were then plotted as shown in Figure 1. PCI values below 55 were not used due to the lack of data in the 0 to 55 range. In general, smaller slabs cost more per slab to

Table 1. Repairs and associated unit costs for PCC distresses

Distress	Severity	Repair	Work Unit	Unit Cost (US$/unit)	Repair Area
BLOW-UP	High	Slab Replacement - PCC	m^2	98.06	Whole slab
BLOW-UP	Medium	Patching - PCC Full Depth	m^2	96.65	Slab width*.3m
CORNER BREAK	High	Patching - PCC Full Depth	m^2	96.65	2.3m^2
CORNER BREAK	Medium	Patching - PCC Full Depth	m^2	96.65	2.3m^2
LINEAR CR	High	Patching - PCC Full Depth	m^2	96.65	Slab Width*0.3m
LINEAR CR	Medium	Crack Sealing PCC	m	9.94	Slab width
DURABIL. CR	High	Patching - PCC Full Depth	m^2	96.65	Slab area*.25
DURABIL. CR	Medium	Patching - PCC Full Depth	m^2	96.65	Slab area*.10
JT SEAL DMG	High	Joint Seal (Localized)	m	6.89	Slab width*2
JT SEAL DMG	Medium	Joint Seal (Localized)	m	6.89	Slab width*2
SMALL PATCH	High	Patching - PCC Partial Depth	m^2	284.71	0.46m^2
SMALL PATCH	Medium	Crack Sealing - PCC	m	9.94	1.5m
LARGE PATCH	High	Patching - PCC Full Depth	m^2	96.65	1.85m^2
LARGE PATCH	Medium	Crack Sealing - PCC	m	9.94	6m
SCALING	High	Slab Replacement - PCC	m^2	98.06	Whole slab
SCALING	Medium	Patching - PCC Partial Depth	m^2	284.71	0.46m^2
FAULTING	High	Slab Replacement - PCC	m^2	98.06	Whole slab
FAULTING	Medium	Grinding (Localized)	m	12.50	Slab width
SHAT. SLAB	High	Slab Replacement - PCC	m^2	98.06	Whole slab
SHAT. SLAB	Medium	Patching - PCC Full Depth	m^2	96.65	Slab width*2
JOINT SPALL	High	Patching - PCC Partial Depth	m^2	284.71	0.46m^2
JOINT SPALL	Medium	Patching - PCC Partial Depth	m^2	284.71	0.46m^2
CORNER SPALL	High	Patching - PCC Partial Depth	m^2	284.71	0.46m^2
CORNER SPALL	Medium	Patching - PCC Partial Depth	m^2	284.71	0.46m^2

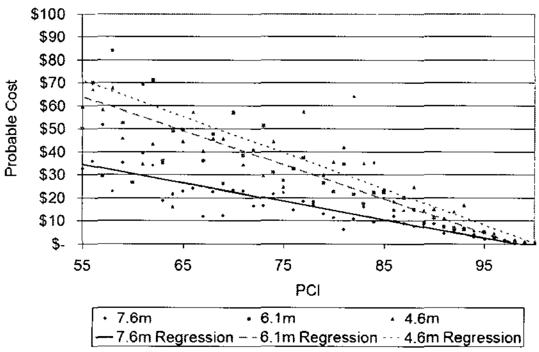

Figure 1. Cost of repair per slab by PCI

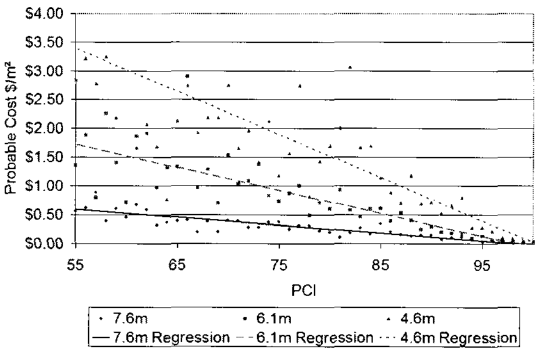

Figure 2. Unit cost of repair by PCI

Table 2. Cost of repair per slab for various distresses and slab sizes

Distress	Severity	Repair	Cost per Slab (US$)		
			4.6m	6.1m	7.6m
BLOW-UP	High	Slab Replacement - PCC	2050	3644	5694
BLOW-UP	Medium	Patching - PCC Full Depth	135	180	225
CORNER BREAK	High	Patching - PCC Full Depth	225	225	225
CORNER BREAK	Medium	Patching - PCC Full Depth	225	225	225
LINEAR CR	High	Patching - PCC Full Depth	135	180	225
LINEAR CR	Medium	Crack Sealing - PCC	45	61	76
DURABIL. CR	High	Patching - PCC Full Depth	505	898	1403
DURABIL. CR	Medium	Patching - PCC Full Depth	202	359	561
JT SEAL DMG	High	Joint Seal (Localized)	63	84	105
JT SEAL DMG	Medium	Joint Seal (Localized)	63	84	105
SMALL PATCH	High	Patching - PCC Partial Depth	132	132	132
SMALL PATCH	Medium	Crack Sealing - PCC	15	15	15
LARGE PATCH	High	Patching - PCC Full Depth	180	180	180
LARGE PATCH	Medium	Crack Sealing - PCC	61	61	61
SCALING	High	Slab Replacement - PCC	2050	3644	5694
SCALING	Medium	Patching - PCC Partial Depth	132	132	132
FAULTING	High	Slab Replacement - PCC	2050	3644	5694
FAULTING	Medium	Grinding (Localized)	57	76	95
SHAT. SLAB	High	Slab Replacement - PCC	2050	3644	5694
SHAT. SLAB	Medium	Patching - PCC Full Depth	269	359	449
JOINT SPALL	High	Patching - PCC Partial Depth	132	132	132
JOINT SPALL	Medium	Patching - PCC Partial Depth	132	132	132
CORNER SPALL	High	Patching - PCC Partial Depth	132	132	132
CORNER SPALL	Medium	Patching - PCC Partial Depth	132	132	132

maintain.

Because the probabilities are based on the number of slabs, not area, Figure 1 represents the probable cost of repair per slab. Figure 2 shows the probable cost by PCI by area, which was calculated by dividing the cost per slab by the area of a single slab. As shown, the trend of smaller slabs costing more to maintain strengthens when the comparison is made on a unit-cost basis.

LIFE CYCLE COST ANALYSIS

Life cycle costs were calculated by estimating construction costs, maintenance costs, reconstruction costs, and salvage value of a hypothetical 9290m^2 (100,000ft^2) PCC pavement section for a period of 50 years. All costs were summed, and the salvage value deducted from the costs to determine the total 50-year cost of ownership.

Construction costs were determined from historical

USAF construction cost data. Initial construction was assumed to consist of clearing and grubbing, construction of the base course, and construction of the PCC surface layer. The cost for these items was estimated at US$123.78/m^2, or US$1.15 million for a 9290m^2 section.

Maintenance costs were estimated using pavement deterioration rates and probabilistic cost-by-condition curves developed from historical inspection data. Deterioration rates appropriate for each slab size were selected using a regression analysis [1]. Deterioration rates used are listed in Table 3. Condition of the pavement section was estimated for each year of a 50-year period. Maintenance costs for each year were then calculated using the cost-by-condition relationship, and summed over the analysis period.

Table 3. Pavement deterioration rates by slab size

Slab Size	Deterioration Rate
4.6m	0.4720 points/year
6.1m	0.6417 points/year
7.6m	0.7640 points/year

Reconstruction costs were also determined from historical USAF construction cost data. For purposes of life cycle cost analysis, pavements were assumed to be reconstructed the first year after the PCI fell to 70. A PCI of 70 is a commonly accepted value that will trigger pavement rehabilitation. Reconstruction was assumed to consist of demolition of the old pavement and construction of a new PCC surface layer. The cost for these items was estimated at US$155.48/m^2, or US$1.44 million for a 9290m^2 section. The 4.6m slab pavement did not require reconstruction during the 50 year analysis period. The 6.1m slab pavement required reconstruction in year 47. The 7.6m slab pavement required reconstruction during year 40.

Construction and reconstruction cost variations due to different joint spacing layouts were neglected because research of cost estimating guides indicated that joint spacing is not a concern when estimating PCC construction costs. No references were available that directly addressed additional costs of construction due to smaller slab sizes.

Salvage value was determined by pro-rating the initial construction value by the remaining life of the pavement at year 50. Remaining life was defined as the difference between the final PCI of the pavement and the reconstruction trigger value (70) divided by the difference between the PCI of new pavement (100) and the reconstruction trigger value.

$$S = \frac{PCI_{50} - 70}{100 - 70} V_i \qquad \text{Eq. 3}$$

where:

S is the salvage value

PCI_{50} is the PCI at year 50

V_i is the initial value (construction cost) of the pavement

If a pavement had a PCI of 76 at year 50, the salvage value would be (76-70)/(100-70)V_i =0.2V_i, or 20% of the initial construction cost.

Table 4 shows the results of the life cycle cost analysis. Reconstruction costs are included in maintenance costs. As shown, the smallest slabs have the highest maintenance costs, but the lowest total cost of ownership for a 50-year period. The largest slabs have the highest total cost of ownership.

Table 4. Life cycle cost analysis results for a 50-year period

Slab Size	4.6m	6.1m	7.6m
Construction Cost	$1,150,000	$1,150,000	$1,150,000
Maintenance Cost	$424,320	$232,811	$62,496
Reconstruction Cost	$0	$1,444,000	$1,444,000
Salvage Value	$245,333	$1,076,205	$857,133
Total Cost	$1,328,987	$1,750,606	$1,799,362

CONCLUSIONS

The data indicate smaller slabs generally cost more to maintain on a per-unit cost-by-condition basis. The 6.1m-slabs cost twice as much per square unit to maintain than 7.6m-slabs. The 4.6m-slabs cost twice as much per square unit to maintain as 6.1m-slabs. The difference in unit maintenance cost between larger and smaller slabs is likely due to the differences in the types of distresses that were more probable on smaller slabs as opposed to those that occurred on larger slabs. Further analysis is required to determine precisely which distresses are more likely on smaller slabs as opposed to larger slabs.

Even though smaller slabs cost more to maintain on a per-unit basis, their slow deterioration rate results in a lower total cost of ownership over time. While small slabs cost more to maintain than large slabs at a given condition, smaller slabs remain in better condition longer. The superior economic performance of smaller slabs is the result of two factors.

The first factor is the lower maintenance costs resulting from higher condition, i.e., pavements in good condition need less maintenance than pavements in bad condition. This alone is not sufficient to explain the lower life cycle cost of smaller slabs due to the higher unit cost of maintenance for smaller slabs. As shown in Table 4, maintenance costs are significantly higher for smaller slabs than for larger slabs.

The second factor is the extended service life of the smaller slabs. Service life is quantified in economic terms by depreciation. Pavement decreases in value until the point it is no longer serviceable. Depreciation is the "cost" to the owner due to loss of serviceability in the asset. The smaller slabs deteriorate slower, which is expressed as a lower annual depreciation cost. Table 5 shows the average annual depreciation and maintenance costs for the various slab sizes over a 50-year period. Average annual depreciation was calculated as the cost of initial construction divided by the time the pavement takes to deteriorate to a PCI of 70.

Construction using smaller slabs results in a pavement with a depreciation value low enough to offset increased maintenance costs.

Table 5. Annual maintenance and depreciation costs by slab size

Slab Size	Maintenance (US$/year)	Life Span (years)	Depreciation (US$/year)	Total Cost (US$/year)
4.6m	8,486	64	18,093	26,579
6.1m	4,656	47	24,599	29,255
7.6m	1,250	39	29,287	30,537

ACKNOWLEDGEMENTS

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