REVIEW OF ROLLER-COMPACTED CONCRETE (RCC) PAVEMENT DESIGN METHODS

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ABSTRACT

Current RCC pavement design methods incorporate fatigue-based models that rely solely on exterior loading for the determination of stress. By neglecting variables such as the temperature gradients and load placement, these designs may be inadequate for the actual conditions the pavement endures.

This paper summarizes some current RCC pavement design methods and describes the development of an alternative design method that incorporates temperature gradients and wheel wander in a fatigue-based design. This inclusion of temperature effects tended to increase the design thickness of RCC pavements.

Although it was found that load transfer efficiency did not impact the critical slab tensile stress used for the alternative fatigue-based design, issues such as adjusting the thickness or increasing load transfer were investigated to limit the stress on the subgrade.

OVERVIEW OF CURRENT RCC PAVEMENT DESIGN

As RCC pavements respond similarly to conventional concrete pavements mechanically, the design procedures for both are similar. In general, RCC pavement design procedures are based on limiting flexural stresses and the corresponding fatigue damage caused by wheel loads. With this in mind, all concrete pavements have different stress and deflection responses depending on wheel load placement. Generally, wheel loads near the edge of a pavement create higher stresses than those placed at the interior of a pavement away from discontinuities [1]. Two predominant design procedures currently exist for RCC pavements. One design method was developed by the Portland Cement Association (PCA), while the other method was developed by the U.S. Army Corps of Engineers (USCoE)

PCA Method

The PCA's RCC pavement design method is intended for use in the design of industrial RCC pavements [2], although it can be used for similar paving operations [1]. This procedure utilizes Westergaard interior stress calculations due to a wheel load as the critical stress, thereby ignoring any degree of load transfer at either natural cracks or engineered joints [3]. If loads are to be located at the edge of the slab, the PCA method recommends a 20 percent increase in the designed slab thickness [2]. The PCA procedure does not give any recommendations on contraction joint spacing, but only notes that natural cracks will form [3].

For the analysis of fatigue life, the PCA method utilizes the concept of the stress ratio. The stress ratio is defined as the stress of the design load divided by the flexural strength of the RCC used in the pavement. This procedure then relates the design stress ratio to the expected load repetitions until failure of the RCC pavement using either equation (1) or (2):

$$\mathbf{SR = 118.31 - 10.73(\log_{10}(NA)) \quad \text{for } NA \leq 600{,}000 \text{ load repetitions} \quad (1)}$$

or

$$\mathbf{SR = 40 \quad \text{for } NA \leq 600{,}000 \text{ load repetitions} \quad (2)}$$

where:

SR = stress ratio (ratio of interior stress due to the design wheel load to the 28 day flexural strength of the RCC).

NA = number of load applications until failure.

This equation was derived from a series of laboratory fatigue tests on RCC beams using the rupture of the beams as the failure criteria. A conservative factor was then incorporated into the equation to account for uncontrollable construction and environmental variables [4].

USCoE Method

The USCoE method for the design of RCC pavements uses a conservative version of its conventional concrete pavement design procedure. The conventional concrete pavement design assumes load transfer at joints and cracks resulting in a 25% maximum bending stress reduction. However, the RCC design method assumes that no load transfer capability exists, resulting in no maximum stress reduction when wheel loads are placed near cracks and joints. Design tensile stresses are calculated using the Westergaard free edge stress equations. If utilized, transverse contraction joint spacings are recommended to be between 9 to 18 m for airfields and 15 to 23 m for roads, streets, parking areas, and open storage areas to control unpredictable natural crack patterns [3].

In this design procedure, the fatigue life is calculated from a transfer function that was developed using behavioral data from pavement test sections on which accelerated aircraft loads were simulated. The criterion for failure was defined as at least one-half of the slabs in the pavement test sections exhibiting one or more structural cracks [4].

Comparison and Contrast

Neither the PCA or USCoE RCC design method incorporates the benefit of load transfer at discontinuities in the RCC pavement slab or provides recommendations on transverse joint spacing. The USCoE method incorporates physical conventional concrete pavement test section data into their fatigue performance model. While the mechanics of conventional concrete and RCC pavements are similar, this assumes that their fatigue life is also similar. In contrast, the PCA RCC design method incorporates RCC flexural test data with the beam rupture stress as failure. Although this model may help in predicting fatigue cracking in RCC pavements, this occurrence generally does not signal the end of the performance life of a pavement.

GUIDE TO ALTERNATIVE RCC PAVEMENT DESIGN

To incorporate the effects of wheel wander and temperature gradients in the RCC layer, a modified RCC pavement design method was developed. The design steps of this method are outlined in the sections following and a flowchart of the design methodology can be seen in Figure 1.

Stress Ratio and Allowable Stress

The first step in the design of the RCC slab thickness is to determine the stress ratio as a function of load repetitions from Figure 2. This figure illustrates relationships between stress ratio and allowable repetitions in RCC pavements developed by PCA [2] as well as Tayabji and Halpenny [5]. Tayabji and Halpenny's RCC pavement fatigue relationship encompasses a larger range of stress ratios. A comparison of both relationships shows that the PCA model for fatigue of RCC pavements is more conservative than that of the Tayabji and Halpenny model, resulting in thicker pavements. Engineering judgment should be employed to determine which fatigue relationship to utilize.

Using equation (3), the allowable stress can be determined from the stress ratio and the design modulus of rupture of the RCC for either fatigue relationship.

$$\sigma_{\text{allowable}} = SR * MOR \quad \textbf{(3)}$$

where:

$\sigma_{\text{allowable}}$ = allowable design stress
SR = stress ratio (found from Figure 2)
MOR = modulus of rupture of RCC

Temperature Gradients

Three temperature differentials of 0, -8.3, and +8.3°C were selected for use in the fatigue-based RCC thickness design to account for curling in the slabs. For simplicity in modeling, all temperatures differentials in this analysis were assumed to change linearly with depth of the RCC pavement slab. Since the temperature differentials were held constant at the three values stated above, the temperature gradients (defined as the temperature differential across the depth of the slab divided by the depth of the slab) changed as the thicknesses of the RCC pavement slabs changed.

The subgrade in this analysis was assumed to be a Winkler foundation. A Winkler, or dense liquid, foundation models the subgrade as a set of independent springs. The deflection of each "spring" is proportional to the force at that point and independent of all forces elsewhere [6]. By assuming an RCC pavement to be a rigid plate supported by this type of foundation, additional stresses will transpire due to lift-off of the slab from the underlying layers caused by curling.

Lateral Load Location

Current RCC pavement design methods assume that the design load position is either at the edge of the pavement slab or at the interior of the pavement slab. In reality, the location with respect to the longitudinal slab edge (or shoulder) varies with each pass of an axle due to drifting of vehicles. Over time, the accumulation of these passes result in a lateral load distribution as illustrated in Figure 3. Figure 3 represents a normal frequency distribution with an expected value (E[x]) of 0.6 m and standard deviation (σ_{dev}) of 0.254 m from the slab edge for a 3.6 m lane width. The zero point on the horizontal axis represents the slab edge and all positive values along this axis represent distances from the slab edge. This distribution was assumed after examination of many field tests [7-12] that attempted to characterize the wheel wander distributions of many different vehicle types for a variety of pavements.

As axles drift towards the slab edge, increased tensile stresses transpire in the slab. This drifting towards the slab edge would underestimate the design stress if an interior slab loading condition were employed in design. Conversely, if the edge loading condition were used for design, it would overestimate the design stress and result in a conservative slab thickness. To assess the effect of wheel wander on RCC slab thickness design, a level of lateral load reliability can be chosen as defined in equation (4).

$$R = (1 - P[F]) \times 100\% \qquad \textbf{(4)}$$

where:

R	=	reliability, %
P[F]	=	probability of failure

As the level of lateral load reliability is increased, the probability that the level of design stress will be surpassed is decreased. If the chosen level of reliability is 70% (or 0.70), the probability that a random wheel positioning would be closer to the slab edge than designed for would be 1 - 0.70 = 0.30 or 30%. The level of lateral load reliability chosen for any particular pavement design should be related to the use and expected life of the facility in question. If a pavement is to be used as low volume roadway, this reliability value should be at a low level. Conversely, if the pavement is to be traversed by vehicles requiring a better ride quality, a higher lateral load reliability should be designed for.

Figure 4 represents the cumulative distribution for the lateral load distribution data shown in Figure 3. A level of reliability near 100% is achieved if the edge loading condition is utilized. On the other hand, the reliability level is only 50% when using E[x] = 0.6 m from the slab edge.

Table 1 lists the levels of lateral load reliability for different distances from the slab edge as well as a list of "c" values which are associated with certain levels of reliability for this particular wheel wander distribution. These "c" values can be used to design RCC pavement thicknesses for an assumed lateral load reliability level. These "c" values were developed through a random series of iterations using a finite element program to determine the effect of the lateral load placement on the critical tensile stress and are only approximate values. The "c" value is defined by equation (5).

$$c = \frac{(\sigma_{\mathrm{R}} - \sigma_{24})}{(\sigma_{\mathrm{edge}} - \sigma_{24})} \quad \textbf{(5)}$$

where:

c	=	"c" value, from Table 1
σ_{R}	=	tensile stress for lateral load reliability level in question
σ_{24}	=	tensile stress for load placed at slab edge
σ_{edge}	=	tensile stress for load placed 0.6 m from slab edge

Many RCC pavement applications are unlike highway pavements, as the traffic does not follow a consistent pattern. These types of facilities include freight yards, airport aprons, and parking lots. In this case, a "c" value of 1.0 can be used to project all loads at the slab edge or 0.0 for all interior load conditions. This "c" value can be based on the level of service required at the designed facility using proper engineering judgment.

Determination of Design Tensile Stress

The next step in the RCC pavement design is to determine tensile stresses for the specific design wheel load and modulus of subgrade reaction for a variety of thicknesses. These stresses should be determined for both the edge and interior loading condition if the lateral load distribution is to be considered. These values can be entered into a RCC pavement design worksheet similar to Table 2 from a set of previously tabulated values.

After this has been completed, the assumption of the percentage of time that the pavement will be under each temperature gradient must be addressed. As previously stated, this design method only accommodates temperature differentials of 0, -8.3, and +8.3°C. While positive and negative gradients do exist a majority of the time in concrete pavements, the assumption that no gradient occurs a majority of the time helps balance out periods when the assumed temperature differential is greater than +8.3°C. Ideally, more temperature differential values would better model the effect of curling on the design stresses. Example values are also entered into the top of Table 2.

The next step is to use these temperature differential assumptions to compute the weighted values of tensile stress for all thicknesses and in both loading position cases as seen in the example in Table 2. After this, the differential between the weighted tensile stresses for each loading position can be computed by subtracting the weighted stress when the load is 0.6 m from the edge from the weighted edge stresses. These values were found for a variety of thicknesses and entered in the column in the upper portion of Table 2.

To determine the design stresses for each RCC pavement thickness when considering the lateral load distribution, the "c" value must be used. The design stresses can be computed by multiplying the differential of the weighted stresses by this "c" value and adding that to the weighted stress found for when the load is located 0.6 m from the edge as seen in Table 2.

The final step is to choose the thickness of the RCC pavement using the allowable stress value calculated and the design stresses for each RCC thickness found in Table 2. The minimum thickness such that the design stress does not exceed the allowable stress should be selected.

Limiting Subgrade Stress

From a slab tensile stress standpoint, the load transfer efficiency at cracks and joints has little effect on the maximum tensile stress. The "maximum" tensile stress is almost always experienced when the axle is midway between the transverse joints or cracks, along the edge of the slab. When the load is at or near a discontinuity, the slab tensile stress is affected by the load transfer efficiency but not to the point where the "maximum" tensile stress is exceeded. In some cases where a negative temperature gradient (temperature at the bottom of the RCC slab is higher than the top of the slab) existed, the "maximum" stress was due to a load at the joint or crack instead of at the mid-slab edge. In these few cases, the critical tensile stress occurred at the top of the RCC slab whereas the vast majority of scenarios resulted in a critical tensile stress at the bottom of the RCC slab.

One way that load transfer efficiency aids in the pavement performance is by controlling the subgrade stress. When the underlying layers of a concrete pavement system are stressed, the probability of pumping in the underlying materials increases. This can result in premature cracking in the corners of the slabs by creating a cantilever effect at the slab corner. Faulting and spalling are also distresses that can develop with low load transfer capacities.

The design method incorporates an optional design check against an excessive subgrade stress. This design check was developed using finite element analysis by modeling an 80 kN single axle load at a joint or crack, although no temperature gradients were utilized. As the load transfer efficiency was increased, the subgrade stress was found to decrease. This effect promotes the use of joints at distances less than 9 m in order to keep the cracks tight and promote higher load transfer between slabs. Figure 5 was developed from RCC pavement field data in [3] and shows that increasing crack spacings lead to lower load transfer. Similar data on cut joints in RCC pavements exhibited a comparable trend. A decrease in subgrade stress was also exhibited when the RCC thickness was increased.

Engineered joints are not normally utilized in RCC pavements in order to save on initial construction and sealant maintenance costs. Due to volumetric instability and curling effects, natural transverse crack spacings develop, usually ranging from 9 to 24 m for conventional RCC pavement sections. These large crack spacings can result in wide crack openings with low load transfer. If a pavement is to be designed without engineered joints, the engineer should note that increased stresses could develop when loads are at these cracks.

It is important to note that the use of retrofit dowels analytically reduced the subgrade stress for a given thickness and modulus of subgrade reaction. The subgrade stress was significantly higher when only aggregate interlock was utilized than when the crack/joint was retrofitted with dowels, although this may prove to be impractical from a design standpoint. While no particular threshold is recommended to limit the subgrade stress, this should provide a check for the designer in order to deem the design thickness as adequate for long-term protection of the underlying layers. It may also indicate the need for retrofit dowels for in-service pavements that indicate low load transfer at the cracks or joints. Figure 6 shows a graphical example of how load transfer efficiency analytically affects the subgrade stress before and after retrofit dowels.

COMPARISON OF RCC PAVEMENT DESIGN RESULTS

Five cases were analyzed using three separate RCC pavement design thickness methods ("new" method outlined in this paper, PCA method, and the USCoE method) to make comparisons between the results of each method. The "new" method was analyzed both with and without temperature gradients using both the PCA and Tayabji/Halpenny fatigue relationships summarized previously. The five cases are outlined in Table 3 and the results of the design method analysis are listed in Table 4.

In all cases, the "new" method using the conservative PCA fatigue relationship and incorporating temperature gradients resulted in the thickest RCC pavement sections. The same method and fatigue relationship were also utilized without a temperature differential across the depth of the pavement, resulting in 7-20% thinner pavements. The "new" method with the Tayabji/Halpenny fatigue relationship and temperature considerations resulted in 21-29% thinner pavements than designs using the same method with the PCA fatigue relationship. When temperature was not considered, the Tayabji/Halpenny fatigue relationship resulted in 14-23% thinner pavements than those cases designed using the PCA fatigue relationship.

In general, the PCA and USCoE RCC design methods predicted similar RCC thicknesses. In most cases, the PCA design method predicted a thickness of 13 mm greater than the USCoE method due to PCA's more conservative fatigue relationship. Both the USCoE and PCA design methods resulted in similar thicknesses when compared to the "new" method at 75 or 90% lateral load reliability and no temperature considerations. This seems logical since the "new" method is based on the same fatigue relationships used in the PCA design method, which does not incorporate temperature-related stresses.

SUMMARY

Current fatigue-based RCC pavement design methods were summarized and an alternative method was suggested in this paper. Current RCC pavement design methods assume no load transfer exists at cracks or joints and do not provide any recommendations on joint spacings, if utilized. While both employ different testing and failure criteria when developing fatigue transfer functions, the designs produce similar results for a given set of input parameters.

In developing this alternative design process, some conclusions were established as follows:

- With the exception of a few cases with extreme negative temperature gradients, the critical tensile stress occurred when the axle was placed midway between transverse cracks, immediately next to the slab edge. This load position, as well as a position 0.6 m from the longitudinal edge, was used in the development of an alternative fatigue-based design method for RCC pavements.

- The theory of using subgrade stress as a limiting factor in RCC pavement design was investigated. Increased load transfer efficiency and thickness helped limit subgrade stresses and influence the decision to reduce joint spacing or retrofit dowels. Joint spacing was recommended to be below 9 m in order to maximize load transfer at the discontinuities and reduce distresses near the joint.

- This alternative method of RCC pavement design tended to predict thicker RCC pavements in comparison to the PCA and U.S. Army Corps of Engineers methods. This is due to the accommodation of vehicle wander and temperature gradients in the design, which are not accounted for in other RCC pavement designs.

ACKNOWLEDGMENTS

The authors would like to thank the Portland Cement Association for sponsoring the research fellowship grant (PCA Fellowship No. F23-99) to fund this project as well as for providing technical assistance on this subject. The research reported in this paper was conducted by Michigan State University. The contents of this paper reflect the views of the authors, who are responsible for the facts and accuracy of the data presented. The contents do not necessarily reflect the views of the Portland Cement Association.

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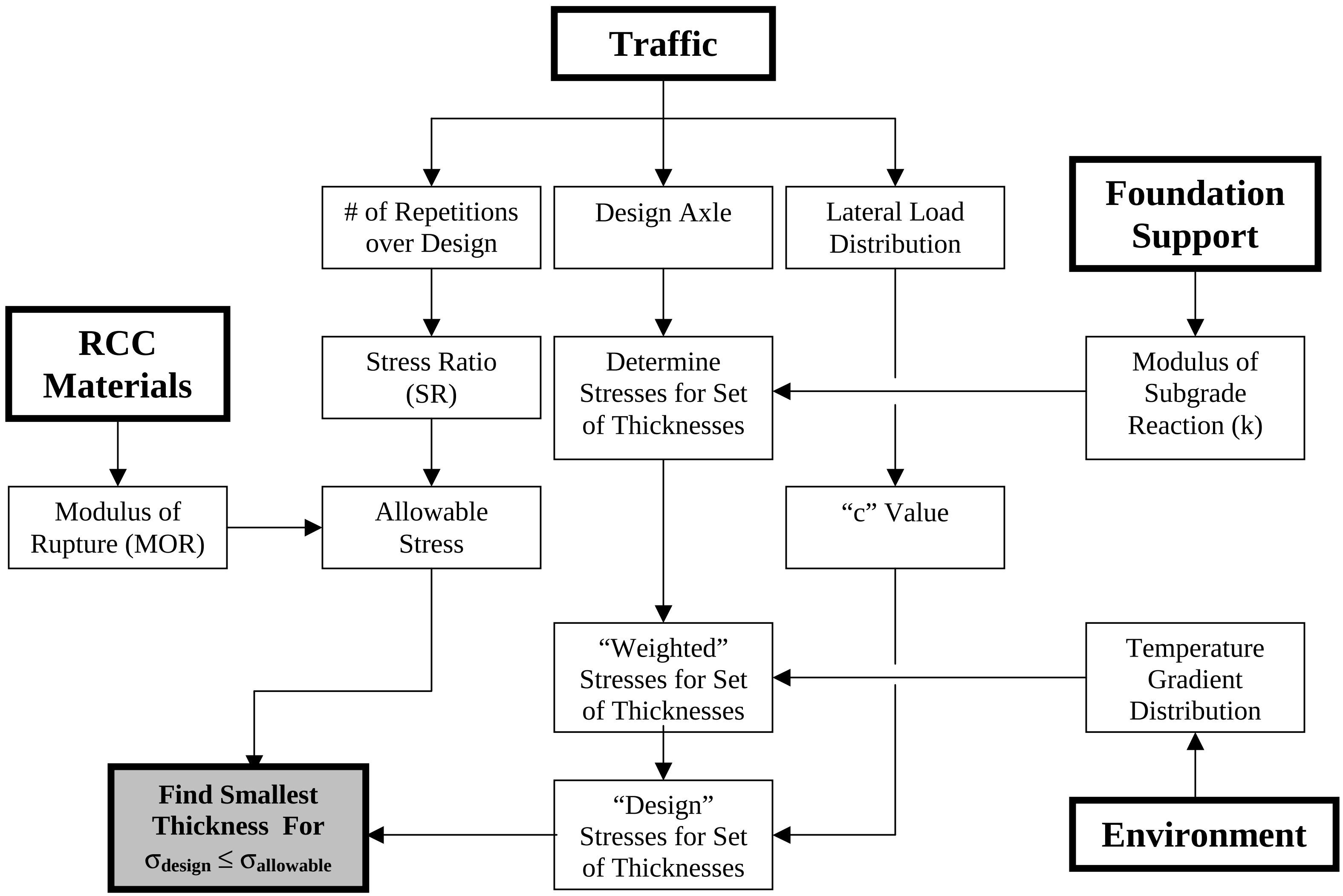

Figure 1. Flow Chart for Methodology of "New" RCC Pavement Design Process.

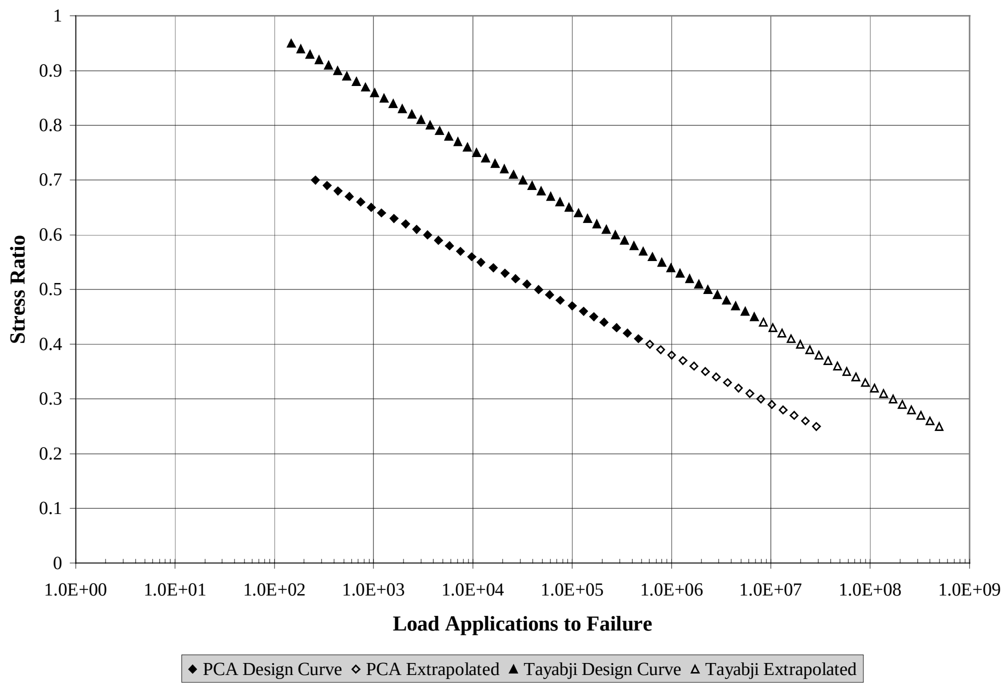

Figure 2. Comparison of PCA and Tayabji/Halpenny Fatigue Relationships.

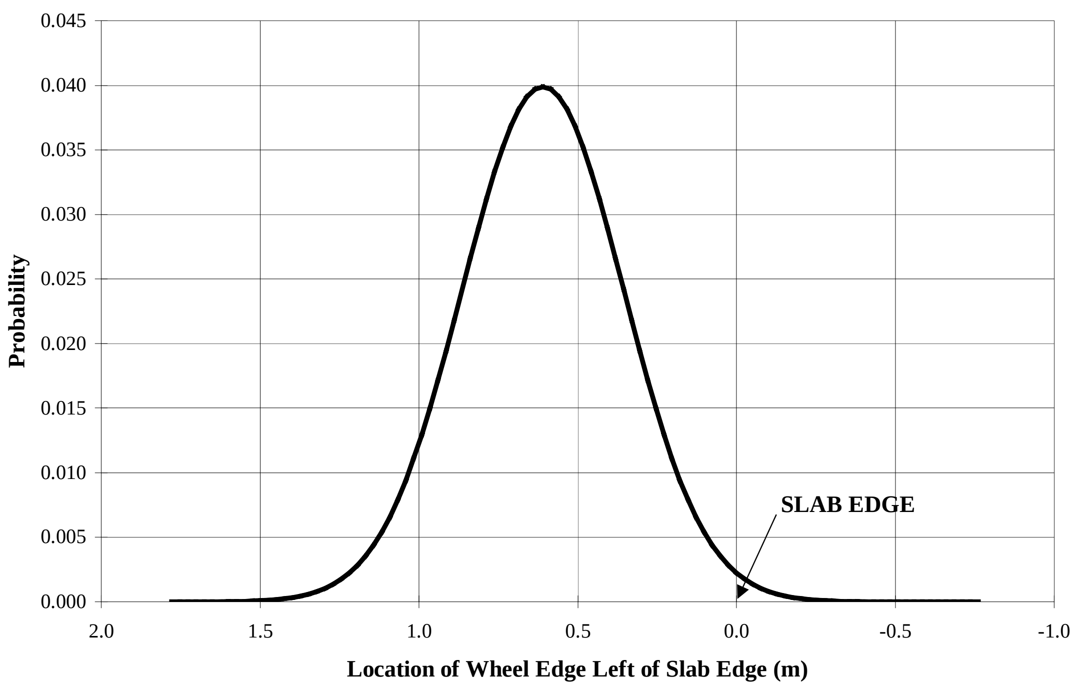

Figure 3. Typical Lateral Load Frequency Distribution for a 3.6 m Lane Width.

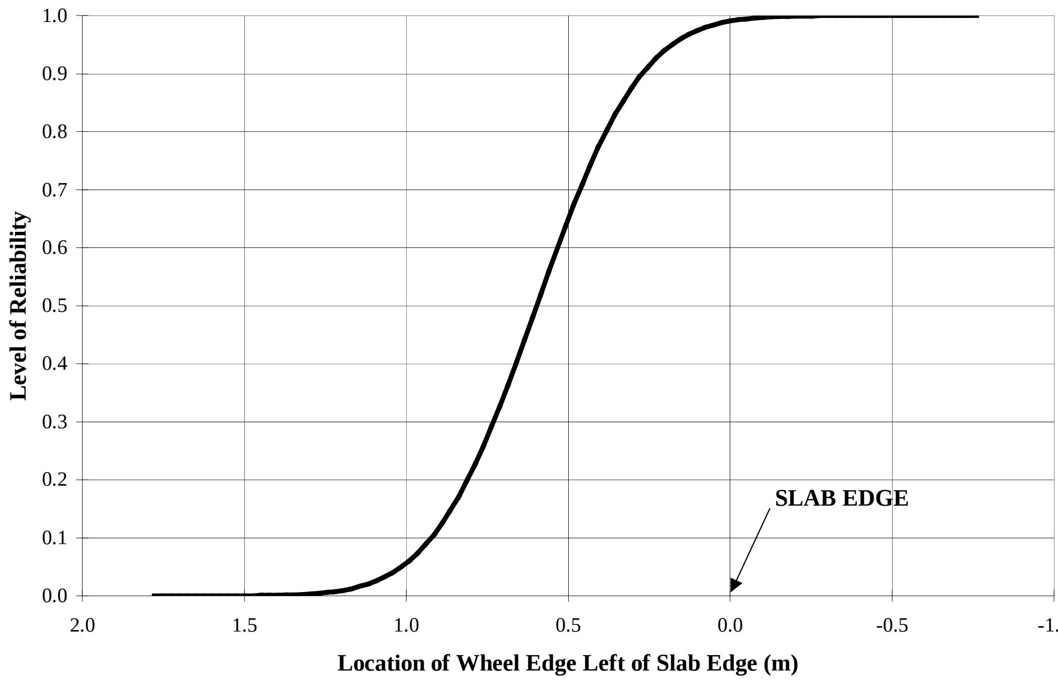

Figure 4. Typical Lateral Load Cumulative Distribution for a 3.6 m Lane Width.

Table 1. Reliability Levels for Different Wheel Load Locations.

Distance of Wheel Edge from Slab Edge (m)	Level of Reliability (%)	"c" Values
0.60	50	0.00
0.44	75	0.07
0.28	90	0.16
0.19	95	0.31
0.02	99	0.90
0	99.5	1.00

Table 2. Worksheet for Example on Determination of RCC Thickness.

	ΔT_{RCC}	0°C	+8.3°C	-8.3°C	Weighted Stress Value (kPa)	Differential Between Weighted Stresses from Edge and 0.6m Away (kPa)	Design Tensile Stress (kPa)
	% Time Under Gradient	0.55	0.3	0.15			
RCC Thickness (mm)							
Load is 0.6m from edge	127	2318	3330	1724	2533	1245	2923
	152	1779	2786	1406	2025	934	2317
	178	1421	2424	1270	1699	709	1921
	203	1171	2177	1216	1480	582	1662
	229	987	2001	1160	1317	490	1471
	279	738	1762	1054	1092	365	1207
	330	579	1598	1032	953	281	1040
	381	471	1467	999	849	226	920
Load is at edge	127	3641	4544	2751	3778	k (kPa/mm)	68
	152	2820	3730	1924	2959	Lateral Load Reliability (%)	95
	178	2266	3185	1373	2408		
	203	1869	2806	1277	2062	"c" Value	0.31
	229	1575	2535	1203	1807	Allowable Stress (kPa)	2268
	279	1174	2165	1085	1458		
	330	916	1917	1032	1234	**Design Thickness (mm)**	**165**
	381	740	1727	999	1075		

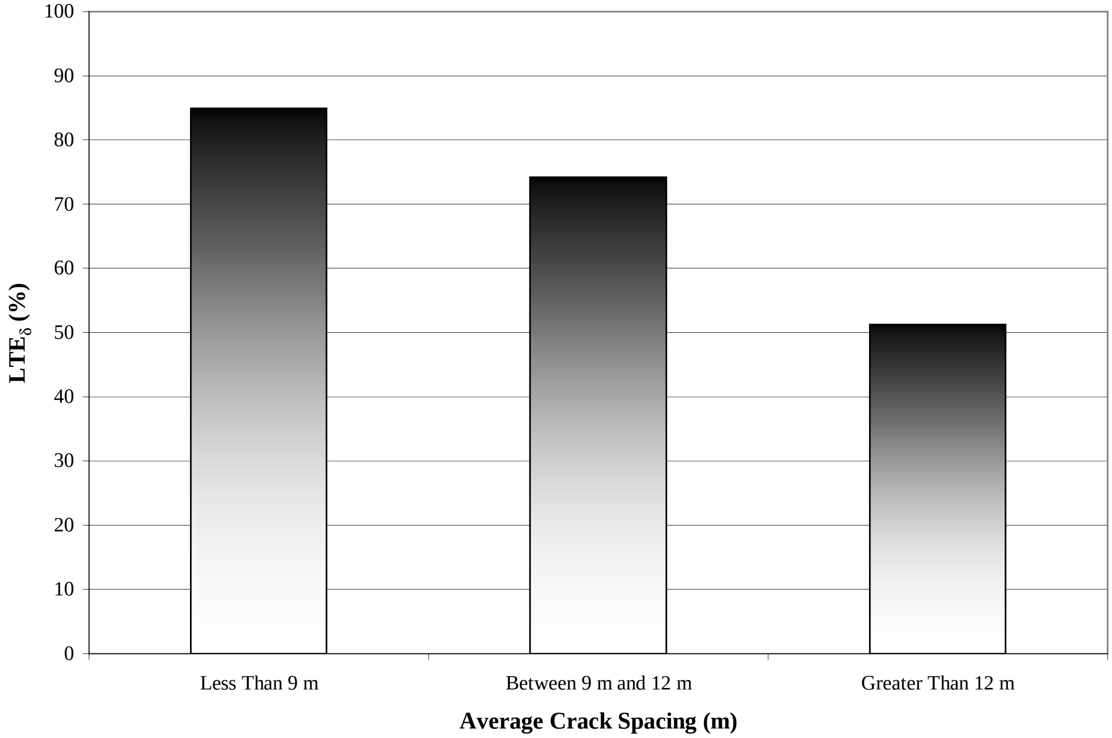

Figure 5. Correlation Between RCCP Transverse Crack Spacing and Load Transfer.

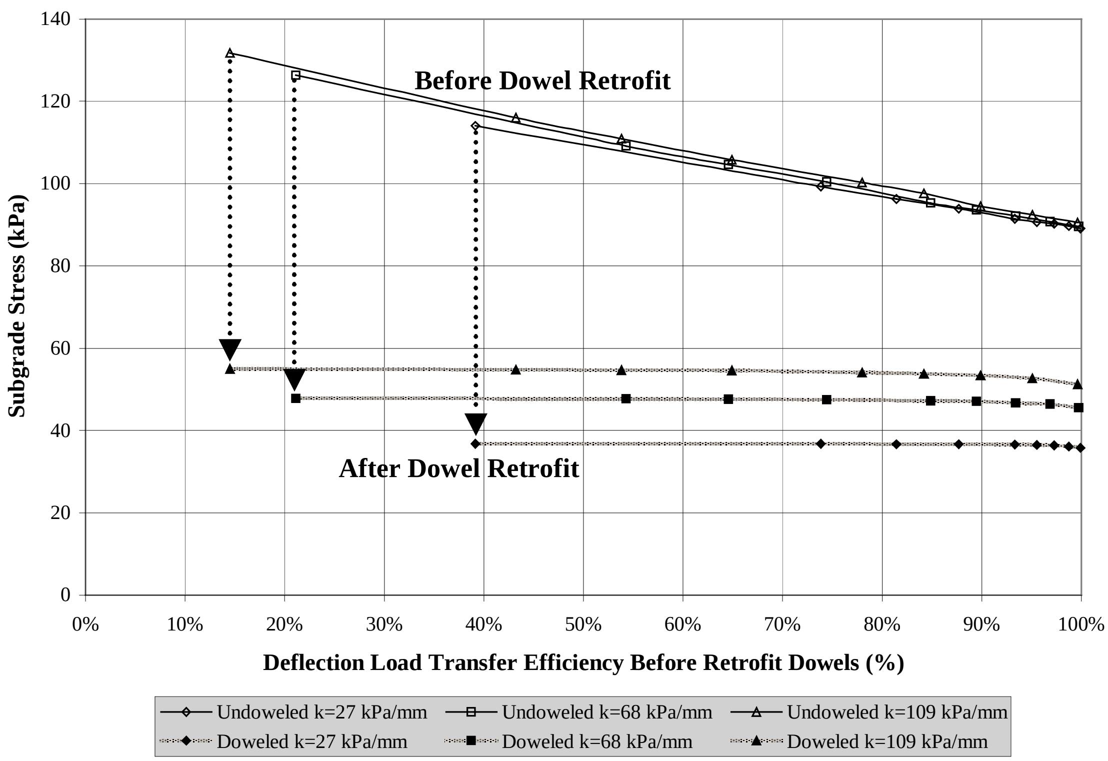

Figure 6. Example of Subgrade Stress For 80 kN Single Axle and 254mm RCC Pavement.

Table 3. Data to be Used in RCC Design Comparisons.

	Case No.				
	1	**2**	**3**	**4**	**5**
Design Axle (kN)	53	80	107	133	160
Single or Dual tired?	Dual	Dual	Dual	Dual	Dual
Single or Tandem Axle?	Single	Single	Tandem	Tandem	Tandem
Allowable Repetitions	200,000	300,000	300,000	400,000	1,000,000
k (kPa/mm)	27	68	109	68	27
RCC MOR (kPa)	2750	3450	5515	4825	4140
Positive gradient	25%	30%	35%	40%	45%
Negative gradient	10%	15%	20%	25%	30%
No gradient	65%	55%	45%	35%	25%
Lateral Load Reliability	75%	95%	90%	99%	99.5%

Table 4. RCC Thickness Results of RCC Design Comparison (in mm).

	Case No.				
Design Method	**1**	**2**	**3**	**4**	**5**
New Method[a] (with temp)	216	229	127[c]	178	305
New Method[a] (no temp)	178	203	127[c]	165	241
New Method[b] (with temp)	165	178	127[c]	140	216
New Method[b] (no temp)	152	165	127[c]	127	191
PCA Method	203	203	127	165	203
U.S. Army Corps of Engineers	191	191	114	152	203

[a] Using PCA fatigue relationship

[b] Using Tayabji/Halpenny fatigue relationship

[c] 127 mm is the thinnest RCC pavement section using this method