Development of a Roller-Compacted Concrete (RCC) Fatigue Curve with a Reliability Component from Published RCC Beam Fatigue Data

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Abstract

The roller-compacted concrete (RCC) fatigue curve most commonly used in design and referenced in literature at current was developed approximately 30 years ago and is based on a limited set of 23 beams from 4 RCC mixtures. Since this first RCC fatigue curve was published, two additional studies have published RCC fatigue test results for 118 additional beam specimens from 8 RCC mixtures, but these two studies did not present an updated RCC fatigue curve for design. All of the 141 published RCC beam fatigue data points were utilized in a Kaplan-Meier survival analysis and with an advanced model fitting software to develop an RCC fatigue curve with a reliability component. Comparison of this RCC fatigue model to that published in 1987 suggests that the newer model is useful in removing some of the over-conservatism built into the 1987 RCC fatigue curve.

Introduction

The most commonly accepted fatigue curve for roller-compacted concrete (RCC) was developed from 4 RCC mixtures and 23 beam fatigue tests conducted approximately 30 years ago as one part of a comprehensive study investigating the engineering properties of RCC (Tayabji and Okamoto 1987). A stress ratio (SR) limiting design approach using this fatigue curve was then presented as the first formal and rational thickness design procedure for RCC pavements (Tayabji and Halpenny 1987). This 1987 RCC fatigue curve also serves as the basis of the Portland Cement Association's (PCA's) RCC-PAVE software (PCA 2002), a commonly referenced RCC thickness design program.

Since the first RCC fatigue curve was published in 1987 and as the use of RCC has expanded, two studies have published an additional 118 beam fatigue test results from 8 RCC mixtures (SEM 2003; Okamoto 2008), but these two recent studies did not present updated RCC fatigue curves for use in design. This paper presents an RCC fatigue curve with a reliability component based on all 141 published RCC fatigue data points. The proposed model, named here as the American Concrete Pavement Association (ACPA) RCC fatigue curve, provides a significant improvement to RCC thickness designs by removing unnecessary conservatism in design as was introduced in the assumptions made in develop of the 1987 RCC fatigue curve.

[1] PNA Construction Technologies, http://www.pna-inc.com/
[2] American Concrete Pavement Association (ACPA), http://www.acpa.org/

Published RCC Fatigue Data and Models

Tayabji and Okamoto 1987; Tayabji and Halpenny 1987 **–** 23 *sawed* 6 in. x 6 in. (15 cm x 15 cm) beams from 4 RCC mixtures were fatigue tested at varying SRs to determine the load applications to failure. Figure 1 shows the 23 fatigue beam test results and the 50% curve based on a least-squares linear regression. Figure 2 shows the 50% curve, the 95% curve, and a design curve that was set approximately 15% below the 95% curve to make the design purposefully conservative; the RCC Design Curve in Figure 2 is referred to as the 1987 RCC fatigue curve in this paper because it served as the design basis. Note that the 1987 RCC fatigue curve was truncated at a stress ratio of 0.4 (e.g., unlimited load repetitions were assumed at a stress ratio equal to or less than 0.4) despite a lack of support for this simplification in the beam fatigue test data.

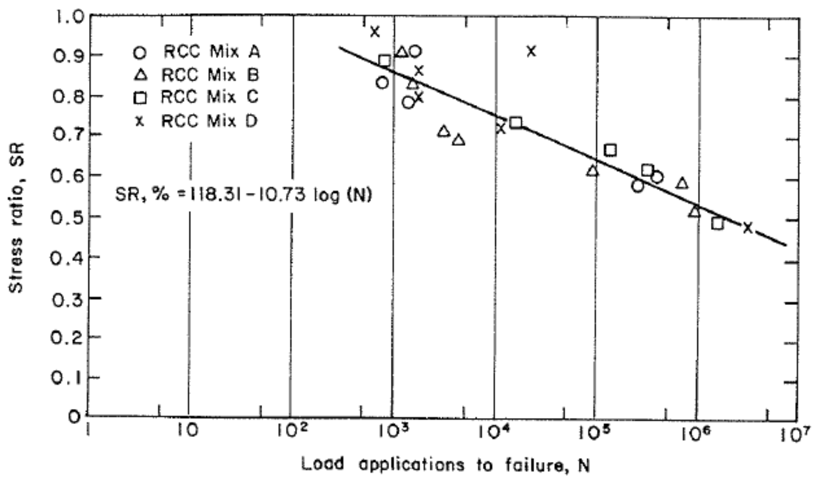

Figure 1. Proposed fatigue relationship for RCC (Tayabji and Okamoto 1987).

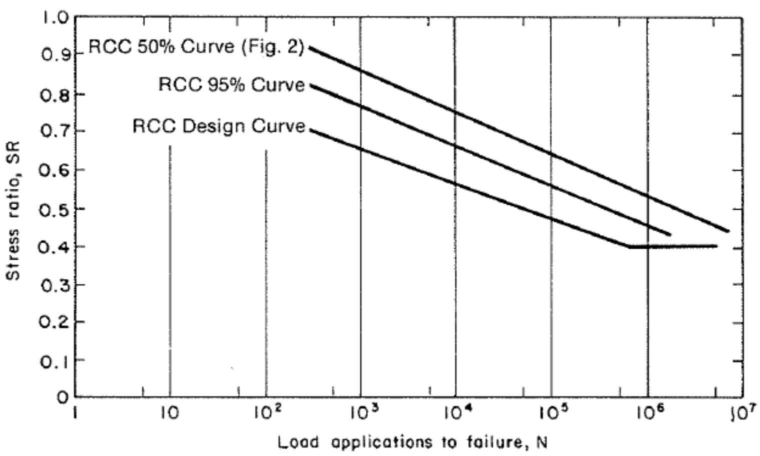

Figure 2. Proposed RCC fatigue curves (Tayabji and Halpenny 1987).

SEM 2003 **–** Fatigue tests were conducted on 37 *cast* 4 in. x 4 in. (10 cm x 10 cm) beams for 5 RCC mixtures, with all results reported in a tabular manner. Not all beams were tested to failure because all tests were stopped at 1,000,000 load repetitions. This report did not present a fatigue model/equation based on the data.

Okamoto 2008 – Fatigue tests were conducted on 37 *cast* 4 in. x 4 in. (10 cm x 10 cm) beams and 44 *cast* 6 in. x 6 in. (15 cm x 15 cm) beams from 3 RCC mixtures. Beam fatigue test results and proposed 50% and 95% reliability equations are shown in Figure 3 for the 4 in. x 4 in. (10 cm x 10 cm) beams and Figure 4 for the 6 in. x 6 in. (15 cm x 15 cm) beams. While the aggregate material (dolomite, gravel, or limestone) was considered during this testing, aggregate type is typically an unknown variable during the design stage of a project so this variable was not considered in the ACPA RCC fatigue curve development, which is consistent with the approach taken by other concrete fatigue model development.

The beam fatigue test results were used to develop a conversion from 4 in. x 4 in. (10 cm x 10 cm) beams to 6 in. x 6 in. (15 cm x 15 cm) beams as a strength multiplier (Figure 5).

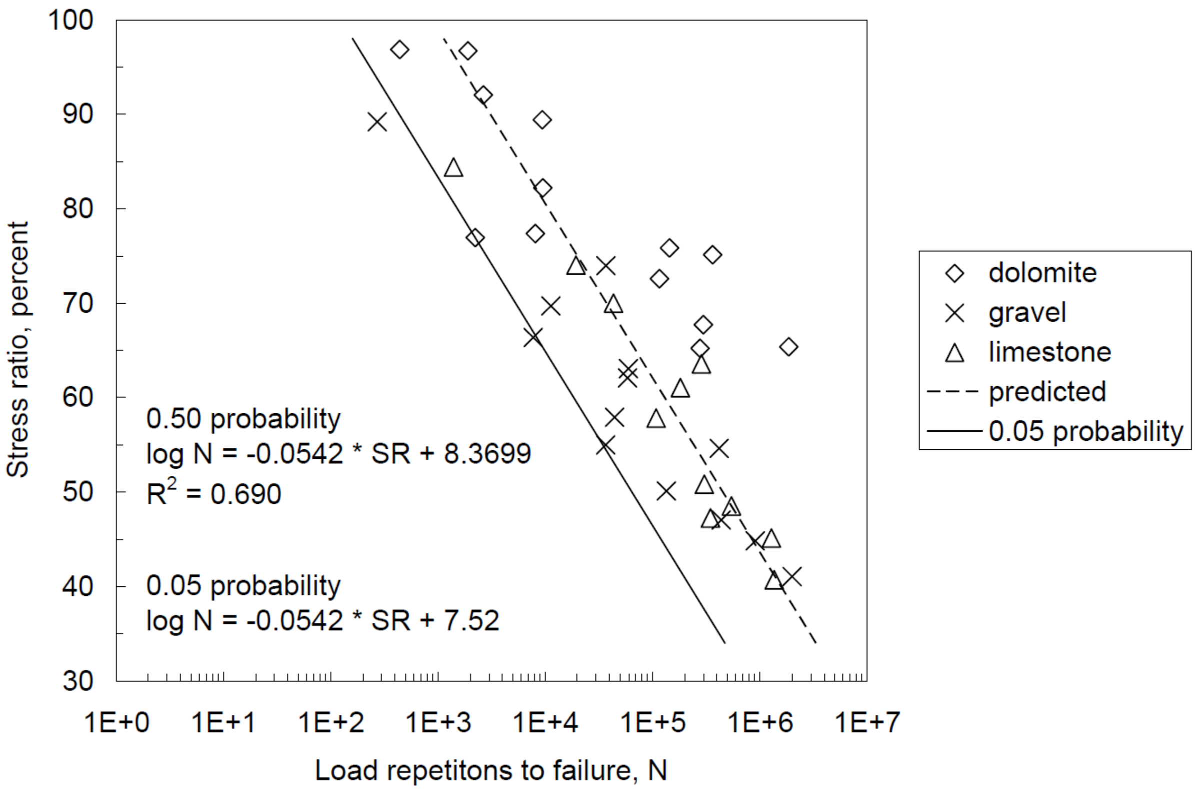

Figure 3. 4 in. x 4 in. (10 cm x 10 cm) beam fatigue test results (Okamoto 2008).

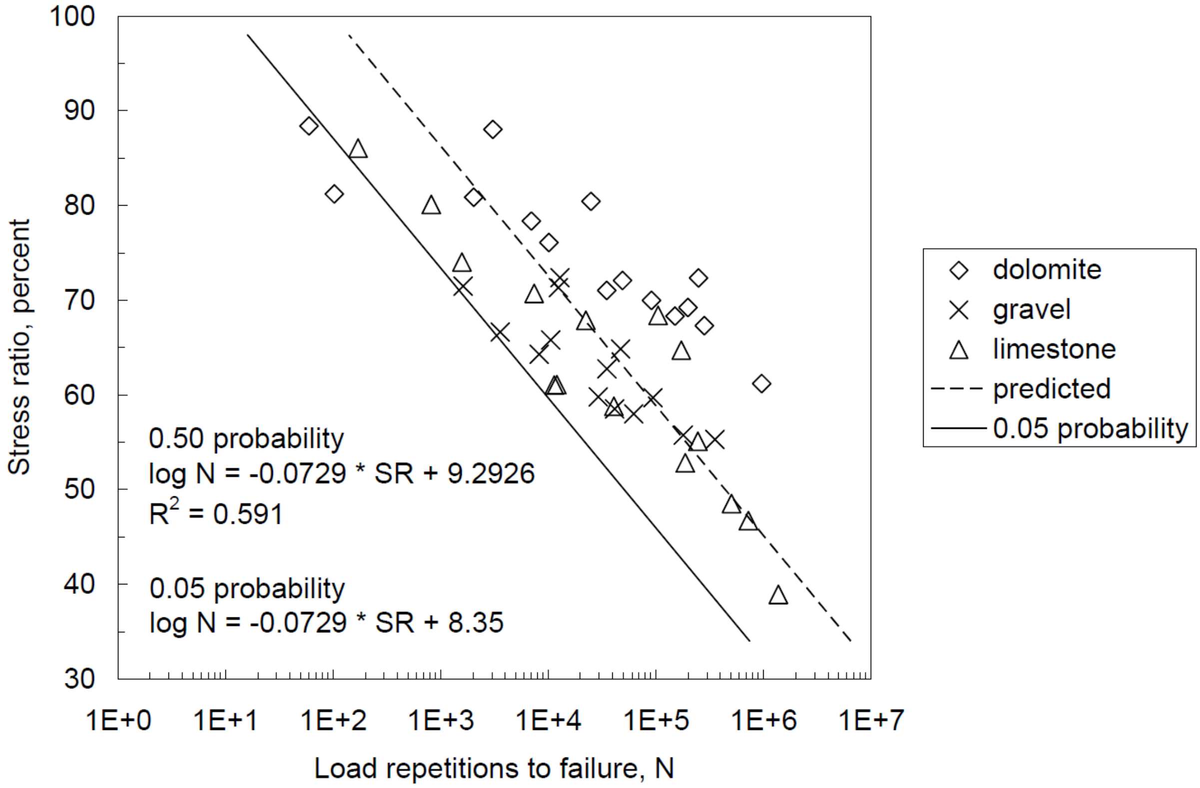

Figure 4. 6 in. x 6 in. (15 cm x 15 cm) beam fatigue test results (Okamoto 2008).

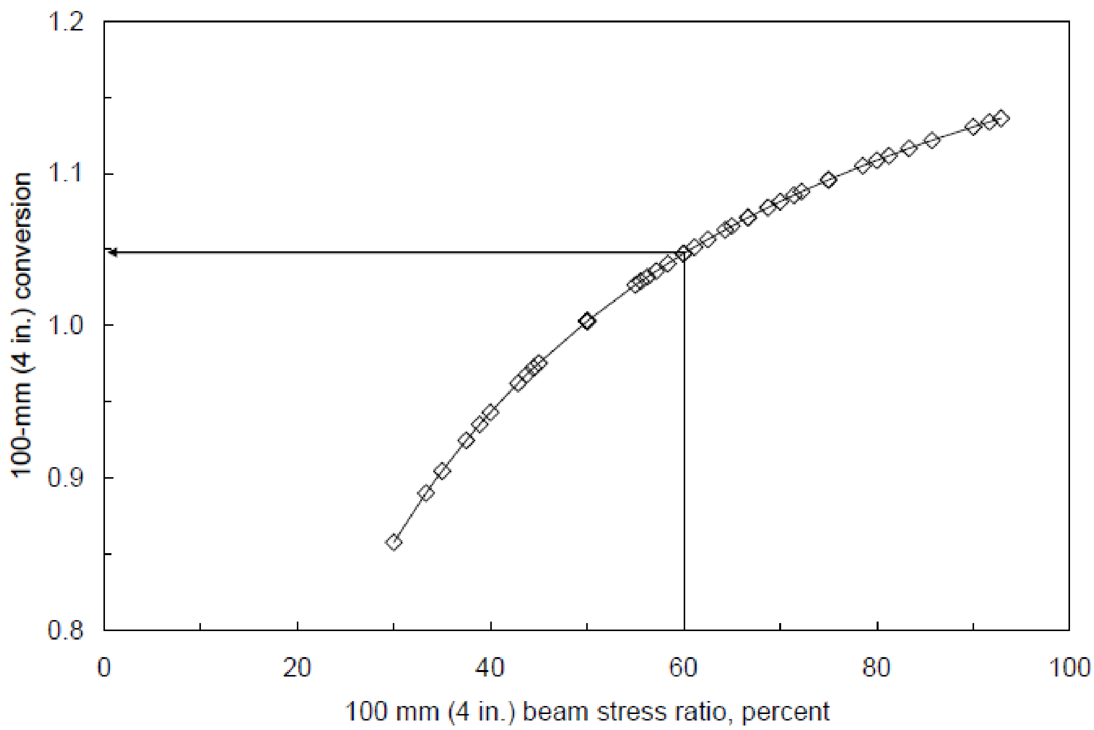

Figure 5. Strength multiplier to convert 4 in. x 4 in. (10 cm x 10 cm) beams to 6 in. x 6 in. (15 cm x 15 cm) beams (Okamoto 2008).

ACPA RCC Fatigue Curve Development

Data Assembly **–** All RCC beam fatigue data points published in the referenced research reports were considered in development of the ACPA RCC fatigue curve.

> ***Native 6 in. x 6 in. (15 cm x 15 cm) Data*** **–** Tayabji and Okamoto 1987 and Okamoto 2008 provided 67 *sawed* or *cast* 6 in. x 6 in. (15 cm x 15 cm) RCC beam fatigue data points (Figure 6).
>
> ***4 in. x 4 in. (10 cm x 10 cm) Conversion to 6 in. x 6 in. (15 cm x 15 cm)*** **–** The strength multiplier conversion developed by Okamoto 2008 was used to convert all 4 in. x 4 in. (10 cm x 10 cm) SEM 2003 and Okamoto 2008 data to 6 in. x 6 in. (15 cm x 15 cm) data. Because this is a strength multiplier conversion, the stress ratio and strength of the material were required to conduct the conversion for each particular mixture tested in each respective study. Figure 7 shows the 37 SEM 2003 and 37 Okamoto 2008 data points before and after this conversion.

Altogether, 141 RCC fatigue data points were utilized in the development of the ACPA RCC fatigue curve, as shown in Figure 8. *NOTE: An RCC fatigue curve using only the native 6 in. x 6 in. (15 cm x 15 cm) data was also develop but it was determined that inclusion of the converted 4 in. x 4 in. (10 cm x 10 cm) data resulted in a fatigue curve that better modeled the expected asymptotic nature of material fatigue at low stress ratios.*

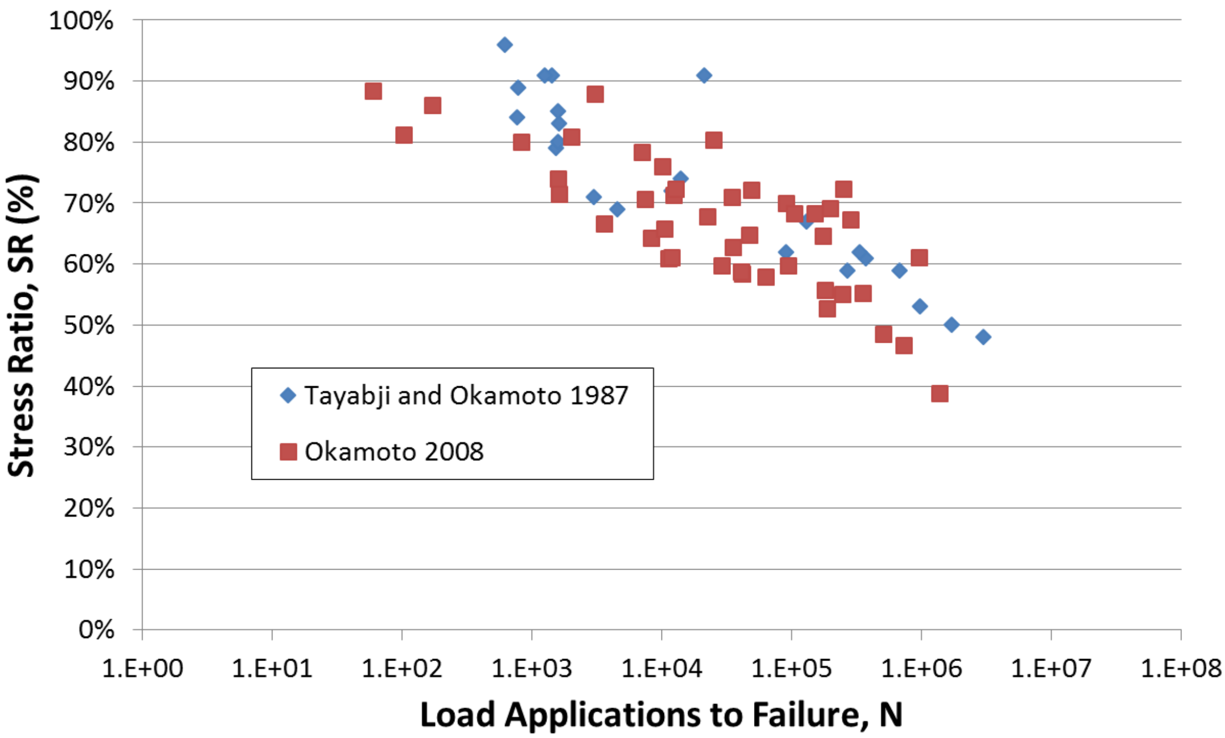

Figure 6. 6 in. x 6 in. (15 cm x 15 cm) RCC beam fatigue test results from Tayabji and Okamoto 1987 and Okamoto 2008.

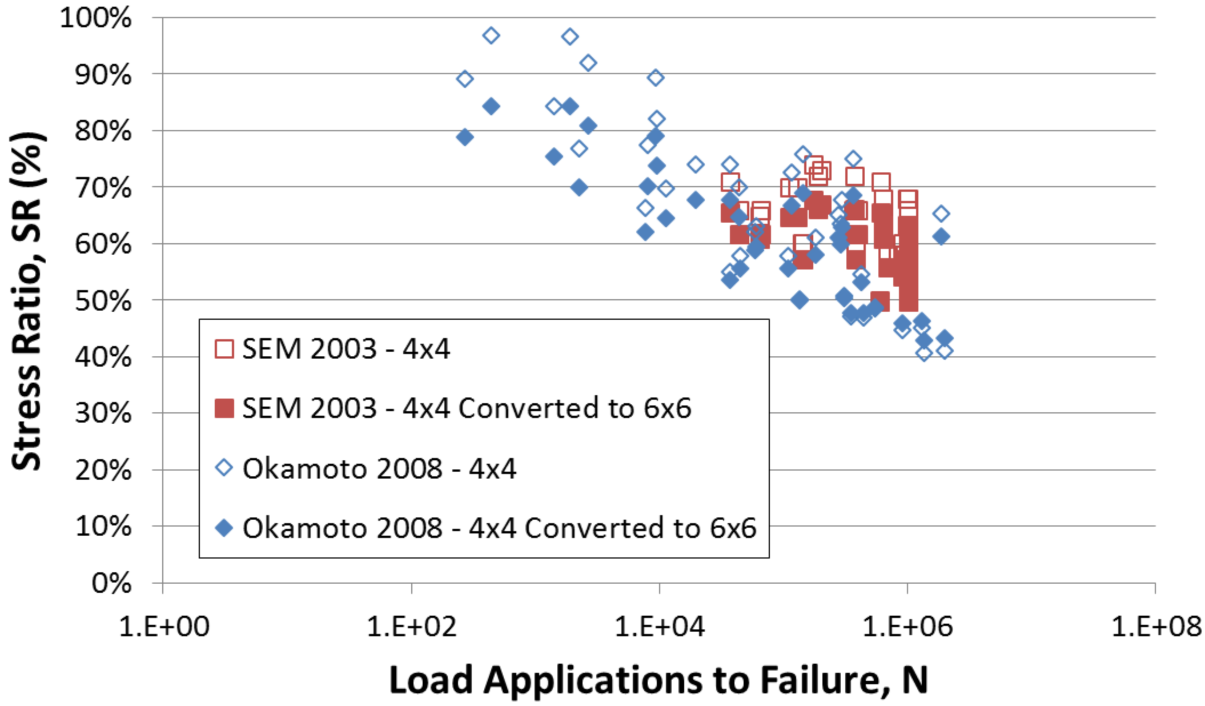

Figure 7. 4 in. x 4 in. (10 cm x 10 cm) RCC beam fatigue test results from SEM 2003 and Okamoto 2008, and the equivalent 6 in. x 6 in. (15 cm x 15 cm) RCC beam fatigue test results using the Okamoto 2008 conversion.

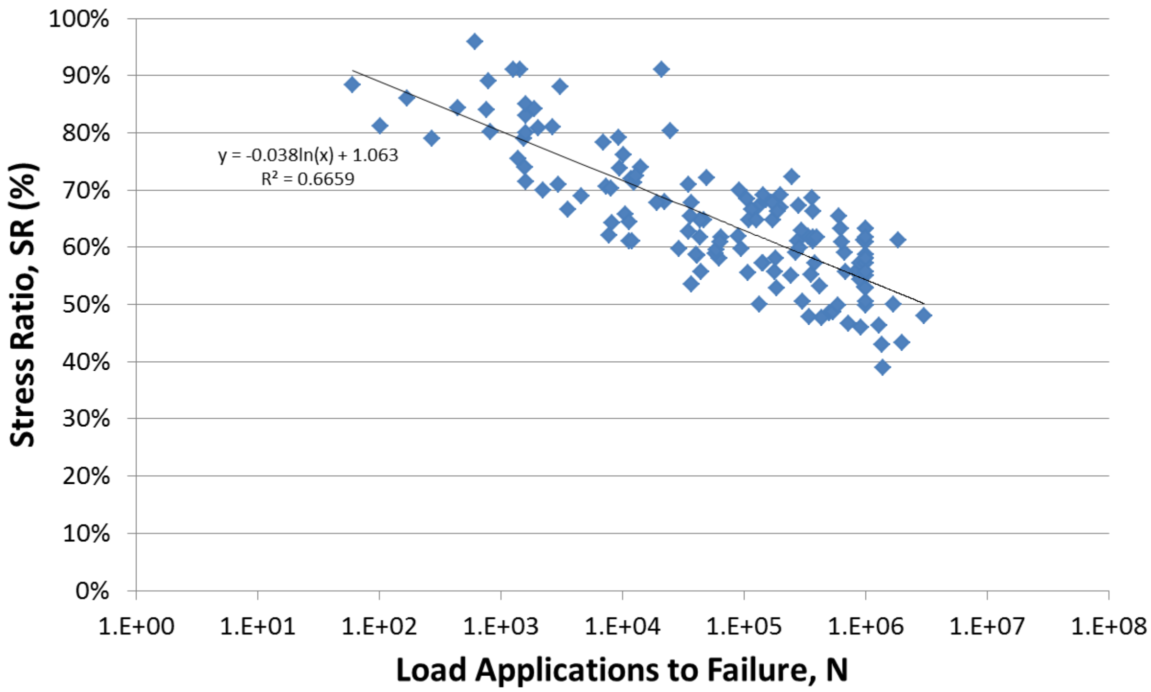

Figure 8. RCC beam fatigue test results from Tayabji and Okamoto 1987, SEM 2003, and Okamoto 2008 and a 50% curve.

Fatigue Model Form Selection – As shown in Figure 8, a 50% linear curve model does not well account for the asymptotic nature of RCC fatigue data. As such, a common PCC fatigue model form that incorporates reliability (McCall 1958) was considered:

$$\log N = \left[\frac{-SR^{-\alpha} \log(1-P)}{\beta} \right]^{\gamma}$$

where N = load repetitions to failure, SR = stress ratio, P = probability of failure, and α, β, and γ are model coefficients determined through regression.

TableCurve 2D (Systat 2013), a software that assists engineers and researchers in fitting a model to data by testing thousands of model forms against a dataset, also was used to determine if an alternate equation form might prove to be a better fit.

Fatigue Model Calibration

Grouping of Data – Data was grouped by SR, as shown in Table 1.

Table 1. Grouping of RCC Fatigue Data for Model Calibration

Class	SR Range	Mean SR	Number of Beams
A	SR < 0.55	49%	23
B	0.55 ≤ SR < 0.6	57%	25
C	0.6 ≤ SR < 0.65	62%	27
D	0.65 ≤ SR < 0.7	67%	26
E	0.7 ≤ SR < 0.8	73%	21
F	0.8 ≤ SR < 1.0	86%	19

Kaplan-Meier Survival Analysis – A Kaplan-Meier survival analysis was conducted with the groupings in Table 1. This approach is particularly useful because it can account for the data points where the test was stopped before failure occurred (e.g., SEM 2003 stopped all testing at 1,000,000 load repetitions; see Figure 7). This survival analysis essentially provides the probability of survival at any given number of load repetitions for each SR group considered, as shown in Figure 9.

McCall Model Fitting – The McCall model was fit using nonlinear regression, the results of which are shown in Figure 10 at a reliability of 50%, 95%, and 99% along with a 50% linear regression curve. Figure 11 shows a general goodness of fit using the McCall model.

TableCurve 2D Model Selection – The model with the best fit from the TableCurve 2D analysis is shown in Figure 12. Figure 13 shows that this model has a slightly better goodness of fit than does the McCall model. In comparing Figure 10 to Figure 12, the TableCurve 2D model has a more balanced consideration of the impact of reliability at both high and low level of load application to failure. As such, *the TableCurve 2D model is the model adopted as the ACPA RCC fatigue curve*.

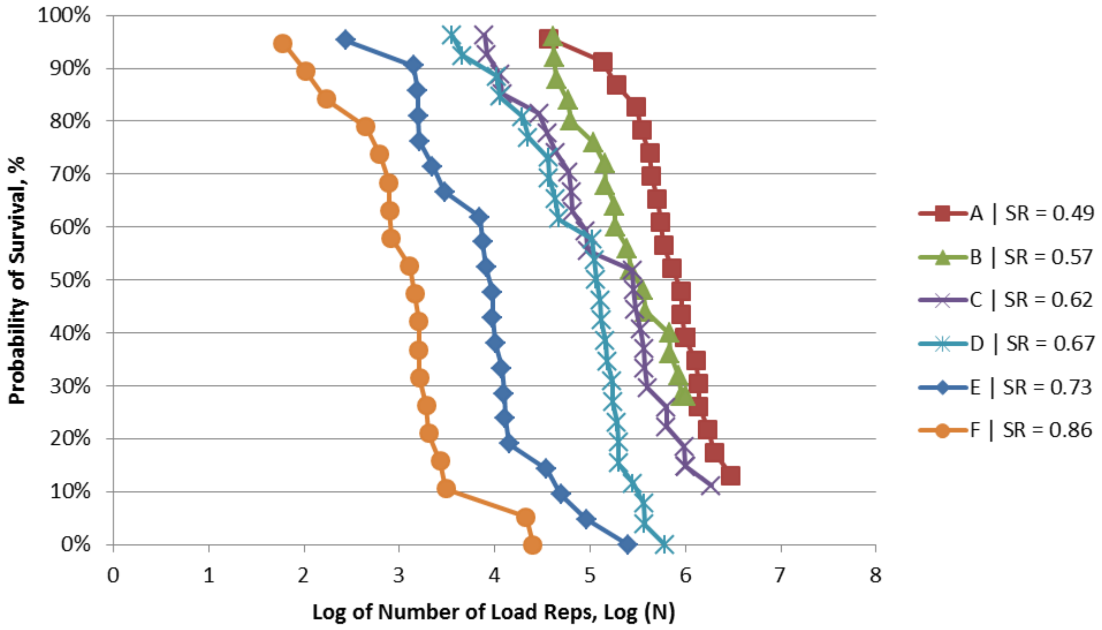

Figure 9. Probability of survival per the SR groups in Table 1.

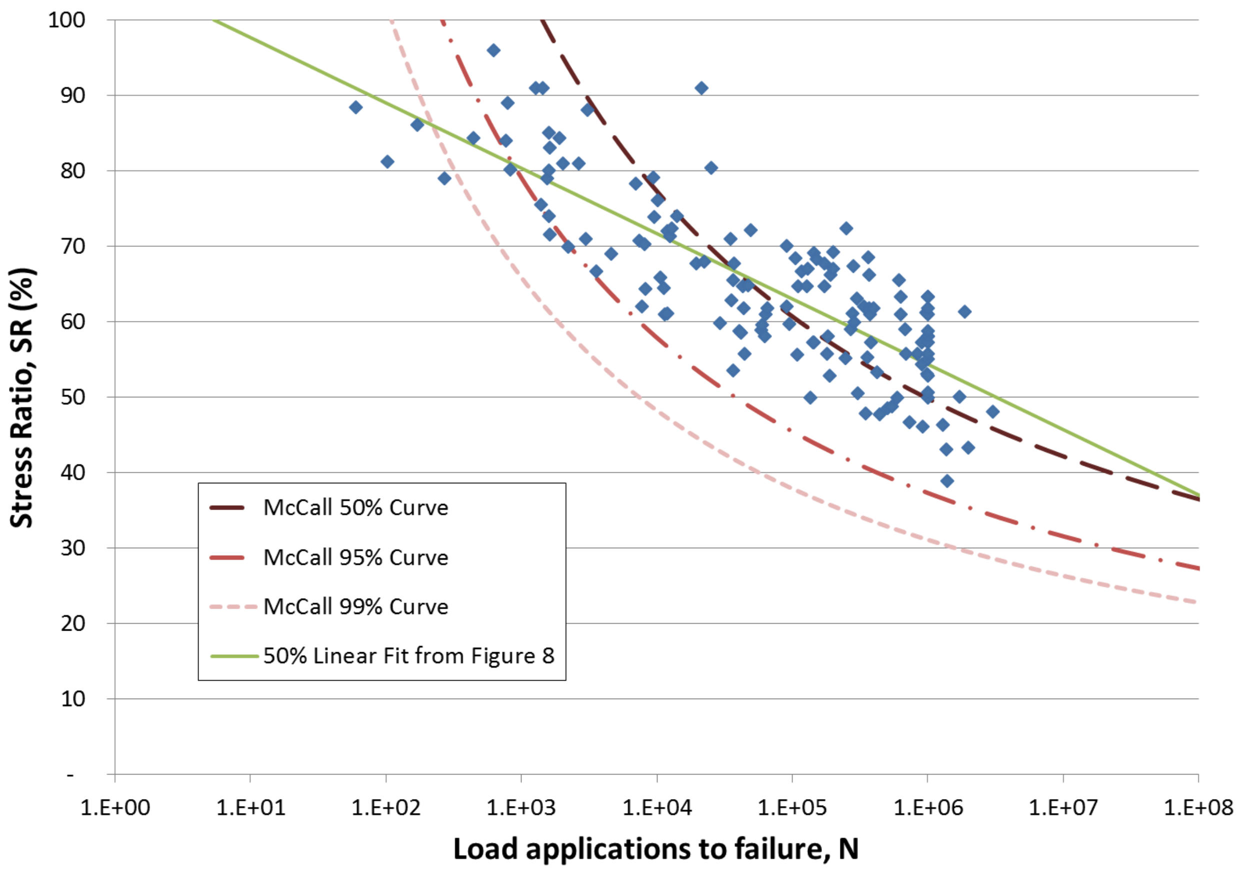

Figure 10. RCC fatigue curve based on the form suggested by McCall 1958.

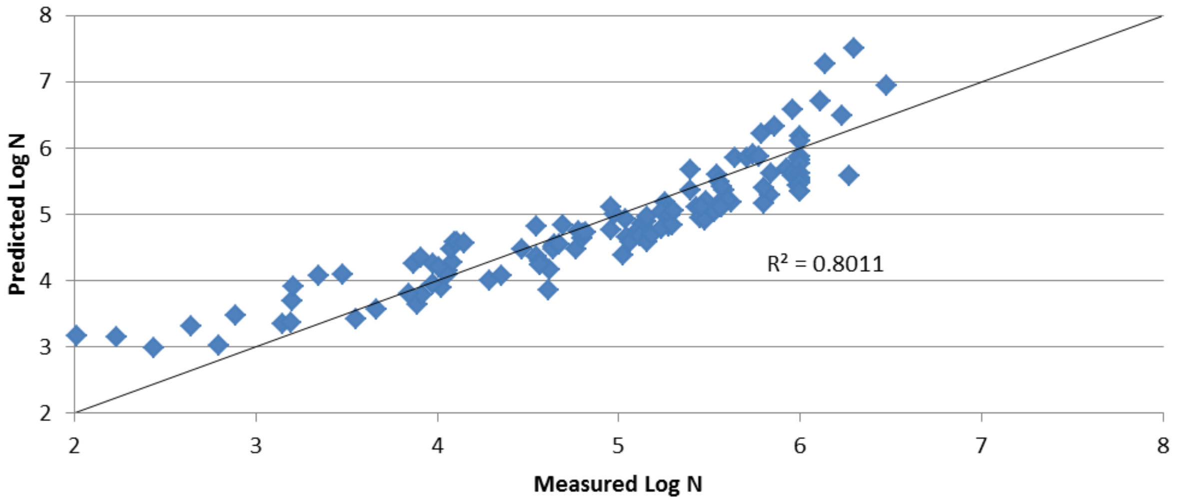

Figure 11. Measured vs. predicted log(N) for the McCall 1958 model.

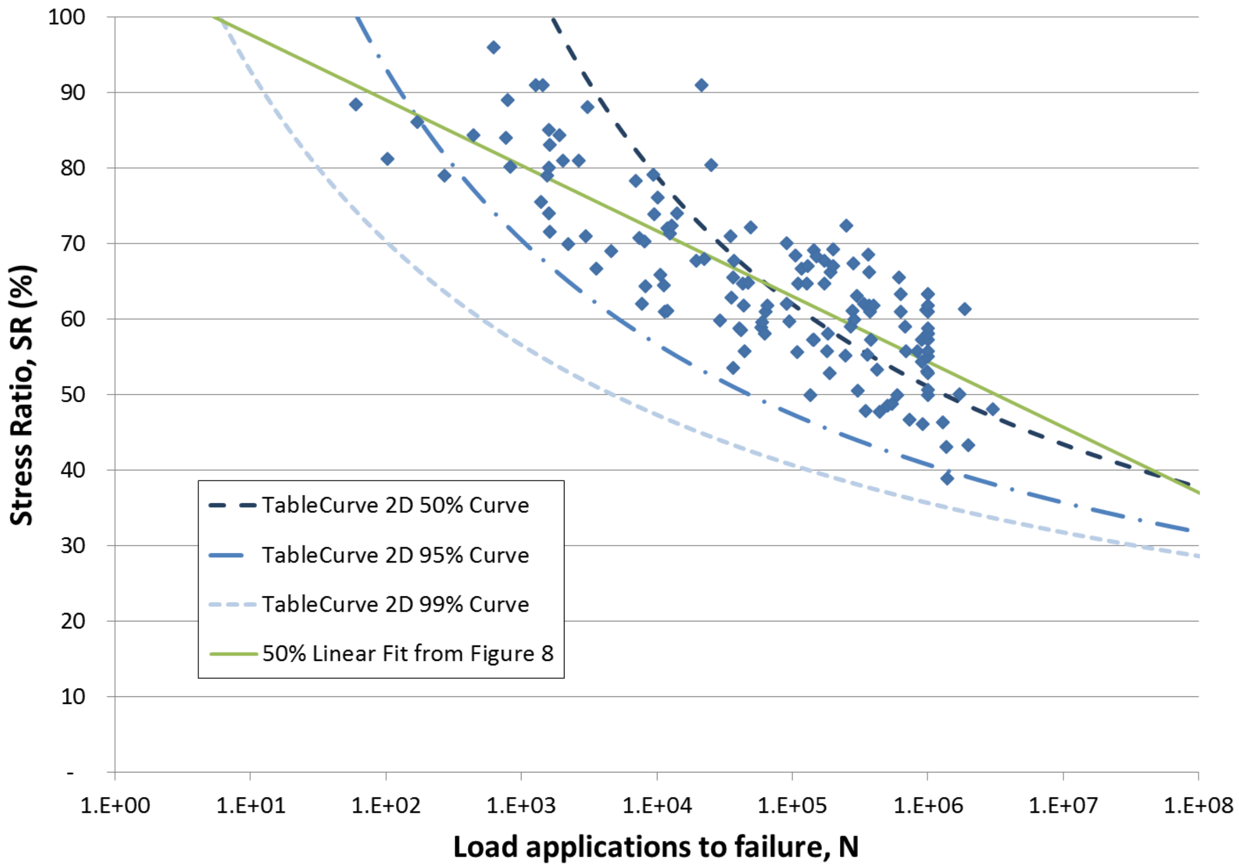

Figure 12. RCC fatigue curve based on the form selected from TableCurve 2D.

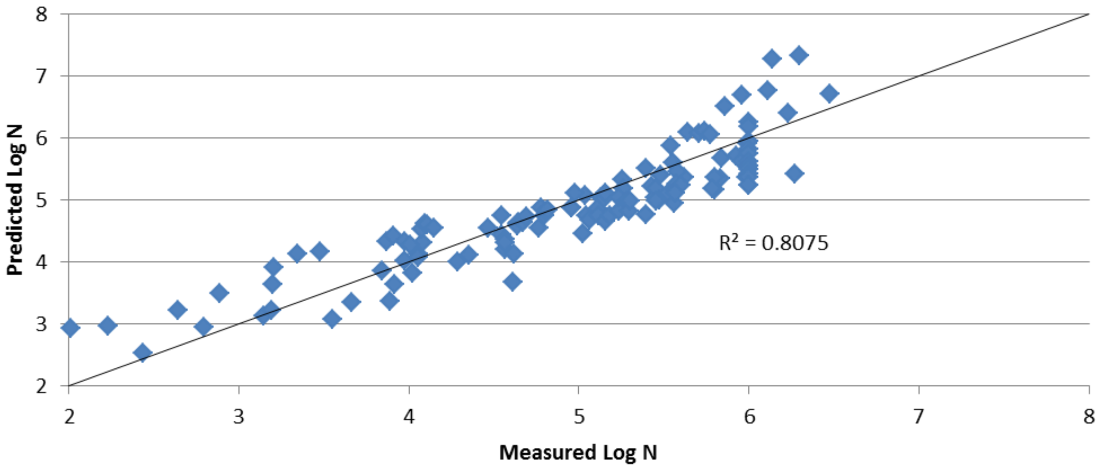

Figure 13. Measured vs. predicted log(N) for the TableCurve 2D model.

The ACPA RCC Fatigue Curve

As selected by the TableCurve 2D analysis, the ACPA RCC fatigue curve is:

$$\log N = \mathrm{A} + \frac{\mathrm{B}}{SR} + \mathrm{X} * \log(1 - R)$$

where N = load repetitions to failure, SR = stress ratio, R = reliability, and A, B, and X are fitting coefficients with the values of 0.76765451, 2.8922855, and 1.4405667, respectively.

Comparison of the ACPA and 1987 RCC Fatigue Curves

Figure 14 shows the 1987 50% and design RCC fatigue curves from Figure 2 as well as the ACPA RCC fatigue curve at 50% and 95% reliability. The primary difference between the two models is how reliability impacts the design and the shape of the curve, notably:

- While the 1987 design curve was at a set (e.g., reliability was not a design input) and presumably conservative position, the ACPA RCC fatigue curve allows for consideration of reliability in the design of any RCC pavement. For a reliability of less than 95%, the ACPA RCC fatigue curve will generally be above the 1987 design curve, meaning that a higher stress ratio is allowable for a given number of load repetitions in design and potentially leading to more optimized and less conservative thickness requirements for RCC pavements.
- When comparing the 1987 design curve to the ACPA RCC fatigue curve at a high reliability of 95%, the 1987 design curve is more conservative at a SR of approximately 55% or greater, similar from a SR of approximately 40-55%, and not conservative enough at a SR of approximately 40% or less due to the truncation of the 1987 design curve at a SR of 40%. The impact on thickness requirements will depend on load magnitude and will differ from a relatively low traffic volume application such as a port or intermodal facility to a high traffic volume application such as a highway.
- At a reliability of 50%, which can be used to model the average in-field performance expectation in a forensic manner, the ACPA RCC fatigue curve will generally suggest

a longer service life for a given thickness, load magnitude/geometry, and number of load applications.

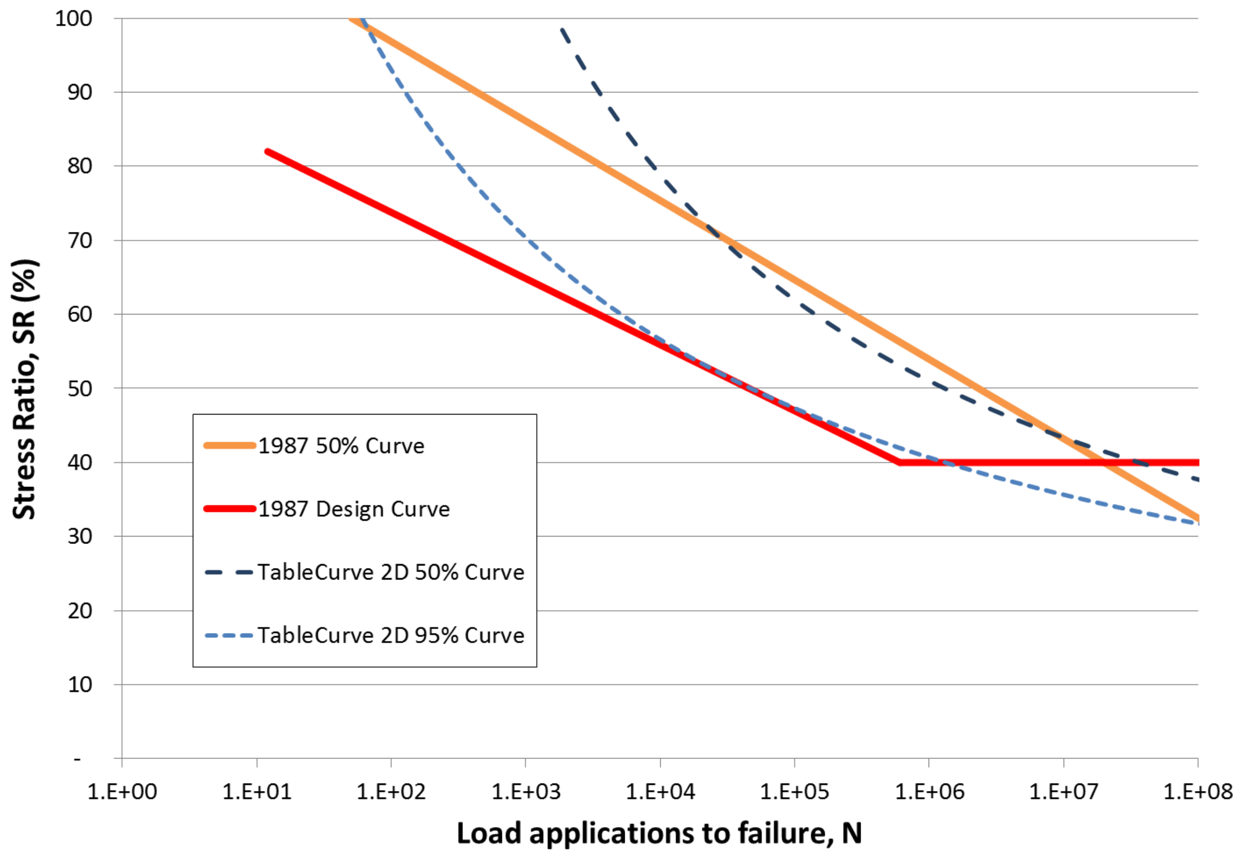

Figure 14. ACPA and 1987 RCC Fatigue Curve Comparison.

Conclusions and Future Research Needs

The ACPA RCC fatigue curve, developed from all published RCC beam fatigue data, is an incremental but significant improvement to the commonly referenced 1987 RCC fatigue curve. Through its consideration of reliability, specifically, the ACPA RCC fatigue curve can be leveraged to yield optimized RCC pavement thicknesses while considering the risk associated with early cracking failure of the pavement to best suit the needs of owners and agencies who consider RCC pavements.

Further improvement beyond the ACPA RCC fatigue model should be expected in the future as material selection, mixture design, construction, and testing methods continue to evolve in the application of RCC pavements. For example, as standardized testing methods for RCC beams and cylinders are only now becoming accepted, additional beam fatigue testing will be necessary to confidently tie the current testing practice with fatigue models. Also, testing of RCC beam fatigue is necessary beyond the 1,000,000 load application limit apparent in existing test data to refine RCC thickness design models for very high traffic applications.

References

American Concrete Pavement Association (ACPA), "StreetPave 12," Computer Software, ACPA Item Code SW02, http://www.acpa.org/streetpave/, 2012.

McCall, J.T., "Probability of Fatigue of Plain Concrete," Journal of the American Concrete Institute, vol. 30. no. 2, pp. 233-234, 1958.

Okamoto, P.A., "Roller Compacted Concrete Pavement Properties," PCA R&D Serial No. SN2996, Portland Cement Association, Skokie, IL, 2008.

Portland Cement Association (PCA), "RCC-PAVE," Computer Software, PCA Item Code MC043, 2002.

Service d'Expertise en Matériaux (SEM), "Rapport de l'étude des caractéristiques du béton compacté au rouleau routier," Association Canadienne du Ciment, Montréal, Québec, Canada, 2003.

Systat Software Inc., "TableCurve 2D," Computer Software, http://www.sigmaplot.com/products/tablecurve2d/tablecurve2d.php, 2013.

Tayabji, S.D. and Halpenny, D.J., "Thickness Design of Roller-Compacted Concrete Pavements," Transportation Research Record 1136, Transportation Research Boards, Washington, D.C., 1987.

Tayabji, S.D. and Okamoto, P.A., "Engineering Properties of Roller-Compacted Concrete," Transportation Research Record 1136, Transportation Research Board, Washington, D.C., 1987.

Vandenbossche, J., "Bonded Concrete Overlay on Asphalt – Mechanistic-Empirical (BCOA-ME)," Online Software, http://www.engineering.pitt.edu/Vandenbossche/BCOA-ME/, 2015.