BONDED CONCRETE OVERLAY OF ASPHALT PAVEMENTS MECHANISTIC-EMPIRICAL DESIGN GUIDE (BCOA-ME)

VALIDATION STUDIES

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Prepared for:
FHWA Pooled Fund Project: TPF-5-165

August 2013

BCOA-ME Validation Studies

Design Examples and Sensitivity Analysis

The Bonded Concrete Overlay on Asphalt Mechanistic-Empirical (BCOA-ME) design procedure requires validation to investigate whether or not the results produced can be considered reasonable. First, design examples are employed to compare known prediction and performance data with comparable design predictions made by the BCOA-ME. Predictions using the Colorado Department of Transportation (CDOT) Procedure and the American Concrete Pavement Association (ACPA) Procedure will also be compared in these design examples. Following the discussion of design examples, a sensitivity analysis of the input variables will be presented to ensure that the BCOA-ME is not especially sensitive to any single input parameter. These sensitivity results are also presented to compare the sensitivity of the BCOA-ME to the comparable CDOT and ACPA design procedures to allow for further validation of these reasonable procedures.

Design Examples

Introduction

In order to validate the BCOA-ME design examples were employed to compare predicted design PCC thicknesses from the BCOA-ME with known performance and distress data from field construction. Design examples were selected as representative samples from a variety of climates (both with different sunshine and AMDAT zones) and with 4 ft × 4 ft, 6 ft × 6 ft, and 10 ft × 12 ft joint spacing. Each design example will be discussed, and the inputs and design outputs from the BCOA-ME will be given, which will then be compared to the design outputs from existing whitetopping procedures depending on the inferred failure mode based on the slab size. Limited data was available and parameters presented in italics have been estimated based on standard values or field assumptions.

Design Example 1

The following design inputs were taken from a road segment of Highway 2 in Cumberland County, IL.

Road Segment		Highway-2
Location		Cumberland County, IL
Traffic	Design Life, years	10
	One-way ADT	1,050
	Estimated Design ESALs	*300,000*
Existing Structure Properties	*HMA Layer Condition*	*Adequate*
	Post Milling HMA Thickness, in	3.5
	HMA Poisson's Ratio	*0.35*
	Modulus of Subgrade Reaction, psi/in	*170*
PCC Overlay Properties	*Average 28-day flexural strength, psi*	*650*
	Estimated PCC Elastic Modulus, psi	*3,930,000*
	Coefficient of Thermal Expansion, 10-6 in/ ℉/in	*3.8*
Joint	Spacing, ft	6 × 6

The BCOA-ME calculated a PCC design thickness of 4.5 in. The CDOT Procedure predicted a thickness of 8.0 in, the maximum design thickness for the CDOT Procedure. The actual constructed PCC thickness of this road segment was 5.75 in, which exhibited only 0.3% cracks after 3 years of service. Because this level of cracking after this amount of service is relatively low, it is feasible that the original constructed thickness was conservative and a thinner slab could also fulfill design purposes. Therefore, the BCOA-ME could provide a reasonable design thickness of 4.5 in for this roadway segment but would otherwise be too thin for this roadway segment.

Design Example 2

The following design inputs were taken from a road segment of NY 408 and SH-622 in Rochester, NY.

Road Segment		NY-408 and SH-622
Location		Rochester, NY
Traffic	Design Life, years	10
	One-way ADT	5,250
	Estimated Design ESALs	*810,000*
Existing Structure Properties	*HMA Layer Condition*	*Marginal*
	Post Milling HMA Thickness, in	9.5
	HMA Poisson's Ratio	*0.35*
	Modulus of Subgrade Reaction, psi/in	*250*
PCC Overlay Properties	*Average 28-day compressive strength, psi*	*5,000*
	Estimated PCC Elastic Modulus, psi	*4,040,000*
	Coefficient of Thermal Expansion, 10-6 in/°F/in	*6.0*
Joint	Spacing, ft	4 × 4

The BCOA-ME calculated a PCC thickness of 4.0 in. The ACPA Procedure predicted a thickness of 3.0 in, the minimum design thickness allowed by this procedure. The constructed PCC layer thickness was only 4.0 in and after 6 years of service exhibited only a few corner cracks. However, the actual ESALs measured on this roadway segment during service were only 460,000 ESALs: slightly more than half of the design ESALs predicted and consequently used in the BCOA-ME. The lack of distress in this thinner slab could be attributed to this difference in design ESALs and measured ESALs. Therefore, the BCOA-ME's estimate of a PCC design thickness of 4.0 in for 810,000 ESALs could be reasonable.

Design Example 3

The following design inputs are taken from Cell 95 of MnROAD in Minneapolis, MN, which contained synthetic structural fibers. To compare the effect of including synthetic structural fibers on the BCOA-ME's design outputs, PCC design thicknesses were calculated for two separate cases: with and without structural fibers. The input values for designing without structural fibers are given as follows:

Road Segment		Cell 95, MnROAD
Location		Minneapolis, MN
Traffic	Estimated Design ESALs	4,800,000
Existing Structure Properties	HMA Layer Condition	Adequate
	Post Milling HMA Thickness, in	10
	HMA Poisson's Ratio	*0.35*
	Modulus of Subgrade Reaction, psi/in	150
PCC Overlay Properties	Average 28-day flexural strength, psi	650
	Estimated PCC Elastic Modulus, psi	*3,930,000*
	Coefficient of Thermal Expansion, 10-6 in/°F/in	*4.8*
Joint	Spacing, ft	6 × 6

The BCOA-ME calculated a PCC layer thickness of 4.0 in when not considering structural fibers. All design parameters were then kept identical except the inclusion of 25 lb/yd^3 of synthetic structural fibers. The resulting BCOA-ME calculated thickness was 2.5 in. The CDOT Procedure does not account for the included fibers and predicted a PCC thickness of 4.0, the minimum design thickness, for both cases.

The actual constructed segment did contain synthetic structural fibers and was constructed with a PCC thickness of 3 in and experienced 20% of slabs cracked after 7 years of service. The BCOA-ME estimated thickness of 2.5 in is slightly thinner than the built value. While reasonably close, this difference could be indicative of possible inaccuracies of the BCOA-ME when predicting PCC thicknesses with structural fibers. The inclusion of fibers reduced the design thickness by 1.5 in and could potentially be under designed.

Design Example 4

The following design inputs were taken from a road segment of Highway 4 in Piatt County, IL.

Road Segment		Highway 4
Location		Piatt County, IL
Traffic	Design Life, years	10
	One-way ADT	2000
	Estimated Design ESALs	*137,000*
Existing Structure Properties	*HMA Layer Condition*	*Adequate*
	Post Milling HMA Thickness, in	4
	HMA Poisson's Ratio	*0.35*
	Modulus of Subgrade Reaction, psi/in	*170*
PCC Overlay Properties	Average 28-day flexural strength, psi	600
	Estimated PCC Elastic Modulus, psi	*3,700,000*
	Coefficient of Thermal Expansion, 10-6 in/ ℉/in	*5.3*
Joint	Spacing, ft	5.5 × 5.5

The BCOA-ME calculated a PCC thickness of 4.5 in and the CDOT Procedure calculated a PCC thickness of 6.2 in. The constructed thickness of this roadway segment was 5 in and exhibited 0.2% cracks after 4 years of service; however, the measured ESALs were only 40,000. Given this low level of fatigue, it is possible that the BCOA-ME, predicting close to the design thickness of 5.0 in, would provide a reasonable estimate since the measured distress percentage was very low. However, since the measured ESALs were much lower than the design ESALs, it is also possible that the BCOA-ME estimate is slightly under designed.

Design Example 5

The following design inputs were taken from a road segment of US 60 in Neosho, MO.

Road Segment		US 60
Location		Neosho, MO
Traffic	Design Life, years	10
	One-way ADT	3,800
	Estimated Design ESALs	*395,000*
Existing Structure Properties	HMA Layer Condition	Marginal
	Post Milling HMA Thickness, in	4.5
	HMA Poisson's Ratio	*0.35*
	Modulus of Subgrade Reaction, psi/in	*200*
PCC Overlay Properties	Average 28-day compressive strength, psi	5,000
	Estimated PCC Elastic Modulus, psi	*4,040,000*
	Coefficient of Thermal Expansion, 10-6 in/ ℉/in	*3.8*
Joint	Spacing, ft	4 × 4

The BCOA-ME calculated a PCC thickness of 4.5 in while the ACPA Procedure calculated a thickness of 3.5 in. The constructed slab thickness varied between 4.5 and 5.2 in and 2.2% cracks were observed after 10 years. Therefore, the design thickness suggested by the BCOA-ME is consistent with the constructed thicknesses. Given the relatively low amount of measured distresses, a thinner slab could be appropriate here. Therefore, while the predicted PCC thickness of the BCOA-ME is consistent with the built design, it may be slightly overdesigned for this design case.

Design Example 6

The following design inputs taken from a road segment of SR 30 in Lancaster, PA.

Road Segment		SR-30
Location		Lancaster, PA
Traffic	Design Life, years	10
	One-way ADT	8,741
	Estimated Design ESALs	*1,900,000*
Existing Structure Properties	HMA Layer Condition	Marginal
	Post Milling HMA Thickness, in	9.5
	HMA Poisson's Ratio	*0.35*
	Modulus of Subgrade Reaction, psi/in	*170*
PCC Overlay Properties	*Average 28-day flexural strength, psi*	*650*
	Estimated PCC Elastic Modulus, psi	*3,930,000*
	Coefficient of Thermal Expansion, 10-6 in/°F/in	*6.0*
Joint	Spacing, ft	3 × 3

The BCOA-ME calculated a PCC layer thickness of 4.5 in while the ACPA Procedure predicted a PCC thickness of 3.0 in, the minimum design thickness for the ACPA Procedure. The constructed PCC layer thickness was 3.0 in but distress data is not available. Therefore, the BCOA-ME prediction is consistent with the constructed PCC layer thickness but without distress data, the quality of this estimate cannot be determined.

Design Example 7

The following design inputs are taken from SH 121 in Denver, CO. To compare the effect of the HMA layer condition, the same roadway segment was designed changing only the

HMA layer condition between ‘adequate’ and ‘marginal’. The design inputs used for both are as follows:

Road Segment		SH 121
Location		Denver. CO
Traffic	Estimated Design ESALs	1,270,000
Existing Structure Properties	HMA Layer Condition	Adequate Marginal
	Post Milling HMA Thickness, in	5.5
	HMA Poisson’s Ratio	*0.35*
	Modulus of Subgrade Reaction, psi/in	*500*
PCC Overlay Properties	Average 28-day flexural strength, psi	575
	Estimated PCC Elastic Modulus, psi	*3,590,000*
	Coefficient of Thermal Expansion, 10-6 in/°F/in	*6.0*
Joint	Spacing, ft	6 × 6

For the ‘adequate’ HMA condition, the BCOA-ME calculated a PCC thickness of 4.0 in. The ‘marginal’ HMA condition calculated a PCC thickness of 4.0 in. Therefore, the quality of the HMA layer alone had little effect on design thickness. The actual constructed PCC thickness was 4.4 in but no distress or performance data is available. The condition of the HMA layer is described as “existing milled” which could align with the adequate HMA condition. In this case, the BCOA-ME estimate for PCC thickness would be slightly thinner than the constructed PCC thickness, but without distress data, the quality of this estimate cannot be determined.

Design Example 8

The following design inputs are taken from Cell 97 at the MnROAD test facility in Minneapolis, MN.

Road Segment		Cell 97
Location		Minneapolis, MN
Traffic	Estimated Design ESALs	9,800,000
Existing Structure Properties	HMA Layer Condition	Adequate
	Post Milling HMA Thickness, in	7
	HMA Poisson’s Ratio	*0.35*
	Modulus of Subgrade Reaction, psi/in	*150*
PCC Overlay Properties	Average 28-day compressive strength, psi	6,100
	Estimated PCC Elastic Modulus, psi	*4,460,000*

	Coefficient of Thermal Expansion, 10-6 in/ °F/in	*4.8*
Joint	Spacing, ft	10 × 12

The BCOA-ME calculated a PCC layer thickness of 3.3 in while the CDOT Procedure predicted a PCC thickness of 1.6 in. Both procedures produced the minimum values of the procedure: 4.5 and 4.0 in for the BCOA-ME and CDOT procedures, respectively. The constructed PCC layer thickness was 6.0 in and distress data indicated that after 9.8 million ESALs, 21% of mid-slab longitudinal cracking was present. Therefore, both the BCOA-ME and CDOT procedures appear to under-predict the necessary PCC thickness for the overlay, indicating that more performance data is needed to better calibrate the larger slab sizes.

Conclusion

The design examples presented indicate that the BCOA-ME is able to provide reasonable predictions for a variety of realistic whitetopping applications. For several of these examples, the BCOA-ME's lessened sensitivity toward existing HMA thickness and PCC modulus of rupture allows for the production of more realistic estimates than those given by the existing ACPA and CDOT Procedures. While some possible inaccuracies were identified, such as possible difficulty in predicting PCC design thickness with structural fibers, overall, most design example estimates were reasonable and consistent with existing field data.

Sensitivity Analysis

Introduction

The design model of the BCOA-ME will be additionally validated by the use of a sensitivity analysis. This sensitivity analysis will measure the model response to variation of selected input parameters, chosen based on their potential influence to the PCC design thickness. Seven variables were considered: traffic (as measured through 18-kip ESALs), PCC modulus of rupture, PCC coefficient of thermal expansion, HMA layer thickness, HMA layer quality (as measured through the elastic modulus of the HMA layer, E_{HMA}), the subgrade k-value and the climate conditions.

Climate sensitivity was of particular interest to this analysis as the BCOA-ME differs most greatly from the CDOT and ACPA Procedures with respect to climate parameters. The BCOA-ME utilized a monthly HMA modulus based on the site-specific region coupled with EELTG calculations to account for the temperature gradient, whereas the ACPA and CDOT Procedures used constant HMA modulus values and required a user-inputted temperature gradient.

The 2004 CDOT Procedure sensitivity analysis revealed the strongest sensitivities to the E_{HMA} and the PCC modulus of rupture. The ACPA Procedure sensitivity analysis revealed sensitivities to the HMA layer thickness and moderate sensitivity to the E_{HMA}. As the BCOA-ME's prediction equations are adapted from the ACPA method for 4 ft × 4 ft slabs, similar sensitivities would be expected between these two procedures. Likewise, the BCOA-ME's prediction equations for 6 ft × 6 ft and 12 ft × 12 ft slabs are adapted from the CDOT design procedure and some sensitivity is expected to be inherited from this model base.

The PCC design thicknesses from all three procedures are bound by established design limits. The BCOA-ME PCC designs for 4 ft × 4 ft slabs range from 2.5 in to 5.5 in, the design thicknesses for the 6 ft × 6 ft slabs range from 3 in to 7.5 in and the design thicknesses for the 12 ft × 12 ft slabs range from 4.5 to 7.5 in. The ACPA Procedure designs are bound between 3 in and 5 in while the CDOT Procedure designs are bound between 4 in and 8 in. Plots presented reflect these design limits with several exceptions noted where the limitation is removed to better observe trends.

The sensitivity of the BCOA-ME to each of the seven parameters is discussed below. The response to five of the sensitivity parameters is measured through the resulting design PCC thickness as a function of the remaining two parameters: traffic levels as expressed through design ESALs and HMA thickness. Therefore, for each sensitivity parameter, plots were produced as functions of either design ESALs or HMA layer thickness vs. PCC design thickness. For clarity, only data points for the BCOA-ME are included in the plots and one plot for each slab size is given. The sensitivity values are also compared to calculated values using either the ACPA Procedure or the CDOT Procedure, depending on the inferred failure mode based on slab size. BCOA-ME predictions for smaller slabs are compared to the predictions for the ACPA method, both of which are dominated by corner cracking as a failure mechanism while the BCOA-ME predictions for larger slabs are compared to the predictions for the CDOT method, both of which are governed by transverse cracking. For each variable, the BCOA-ME was used with the standard inputs shown in Table 1, varying only one of the sensitivity parameters for each section. For the sensitivity plots, traffic was varied between 1,000 and 10,000,000 ESALs and HMA thickness was varied between 3 in and 7.5 in.

Table 1. Summary of standard input values for sensitivity analysis parameters

Climate	Station	Minneapolis, MN
	Latitude (degree)	44.53
	Longitude (degree)	-93.14
	Elevation (ft)	874
	AMDAT Region ID	1
	Sunshine Zone	5
Traffic	Design ESALs	1,000,000
Existing Structure Properties	Existing HMA Condition	Adequate
	Post Milling HMA Thickness (in)	6
	HMA Poisson’s Ratio (default 0.35)	0.35
	Modulus of Subgrade Reaction (psi/in)	250
PCC Overlay Properties	Average 28-day flexural strength (psi)	650
	Estimated PCC Elastic Modulus (psi)	3,930,000
	Coefficient of Thermal Expansion (10-6 in/ °F/in)	5.5
Joint	Spacing, ft × ft	4 × 4 6 × 6 12 × 12

These standard input values can then be used to produce Figures 1 and 2 which indicate the base predictions of the sensitivity analysis as a function of design ESALs in Figure 1 and HMA layer thickness in Figure 2. In Figure 1, it appears the BCOA-ME for the larger slabs aligns well with the CDOT Procedure as a function of ESALs while the BCOA-ME for smaller slabs consistently predicts thicker slabs than the ACPA Procedure. Predictions from all methods increase as traffic levels increase. Figure 2 indicates PCC thickness as a function of HMA thickness and the shallower slopes indicate that the BCOA-ME is less sensitive to existing HMA thickness than both the ACPA and CDOT Procedures, the design plots of which have much steeper slopes.

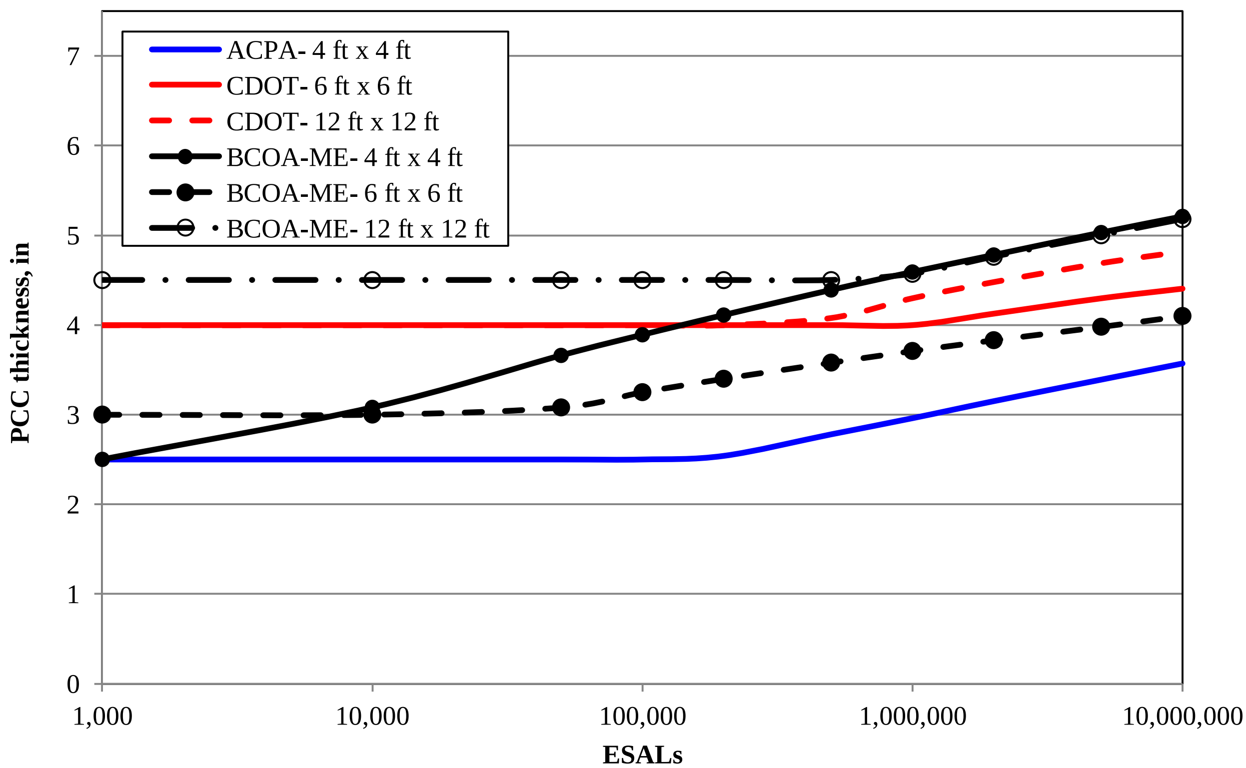

Figure 1. PCC thickness sensitivity to joint spacing with respect to design ESALs

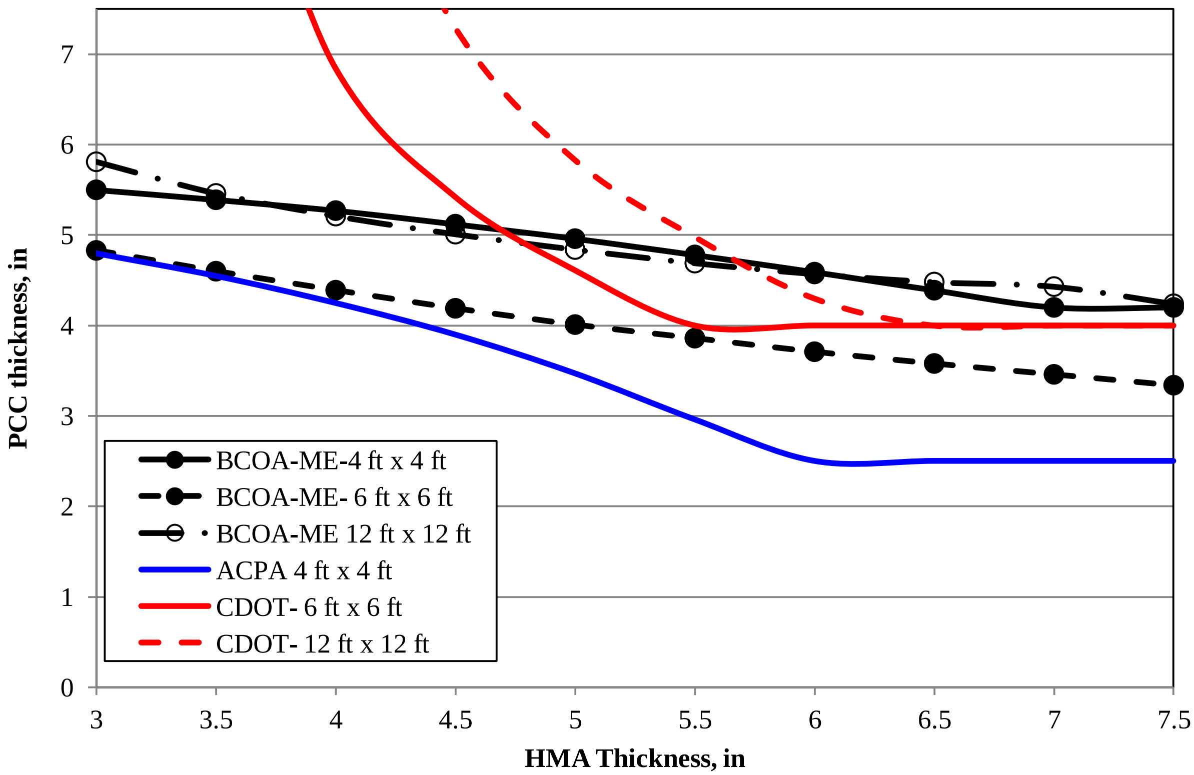

Figure 2. PCC thickness sensitivity to joint spacing with respect to HMA thickness

PCC Modulus of Rupture

All three design procedures exhibited sensitivity to the PCC layer modulus of rupture (MOR). The sensitivity analysis was completed with values of 550 psi and 750 psi, which were determined to be reasonable boundaries for constructed conditions.

The BCOA-ME PCC design thickness of 4 ft × 4 ft slabs, shown with respect to design ESALs in Figure 3, indicates sensitivity from the PCC modulus of rupture which increases as a function of design ESALs. The BCOA-ME consistently predicts larger PCC thicknesses for this slab size for both modulus of rupture values. The ACPA Procedure, however, exhibits greater sensitivity than the BCOA-ME, despite its smaller design thickness. At low ESALs, the BCOA-ME PCC thickness predictions did not differ and increased to 1 in at higher design ESALs. The ACPA Procedure did not predict a difference in PCC design thicknesses at lower design ESALs and increased to 3.5 in at higher design ESALs. The ACPA Procedure specifies a minimum modulus of rupture of 550 psi should be used with average values falling between 650 and 740 psi, if possible. Thus, the ACPA Procedure exhibits more sensitivity to this parameter and consistently designed thinner slabs.

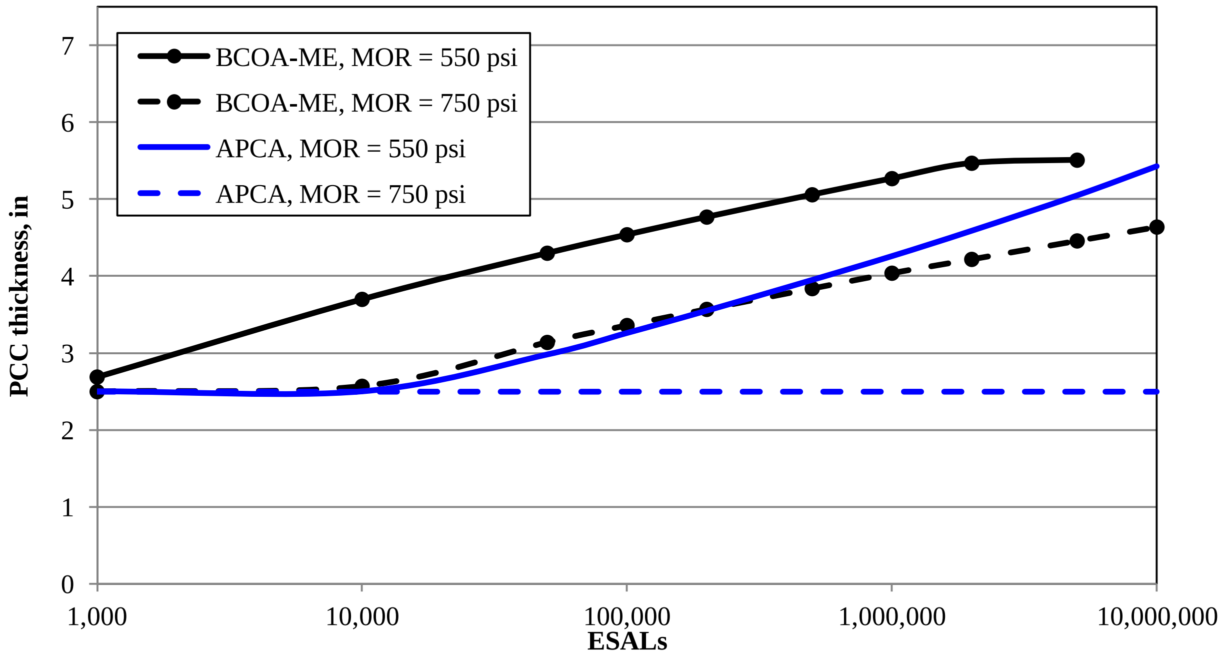

Figure 3. PCC thickness sensitivity to PCC modulus of rupture for 4 ft × 4 ft slabs with respect to design ESALs

The BCOA-ME PCC design thickness of 6 ft × 6 ft slabs with respect to design ESALs, shown in Figure 4, indicates that the BCOA-ME is slightly less sensitive to the PCC modulus of rupture for large slab sizes as compared to smaller slab sizes. The difference of predicted PCC thicknesses at low design ESALs is negligible and increases to 2 in for higher design ESALs. The CDOT Procedure exhibits less sensitivity and the difference of predicted PCC thicknesses at low design ESALs is negligible and it increases to 1.5 in at higher design ESALs. The BCOA-ME predicts a thinner slab than the CDOT for a higher modulus of rupture, but predicts comparable design thicknesses for a lower modulus of rupture value.

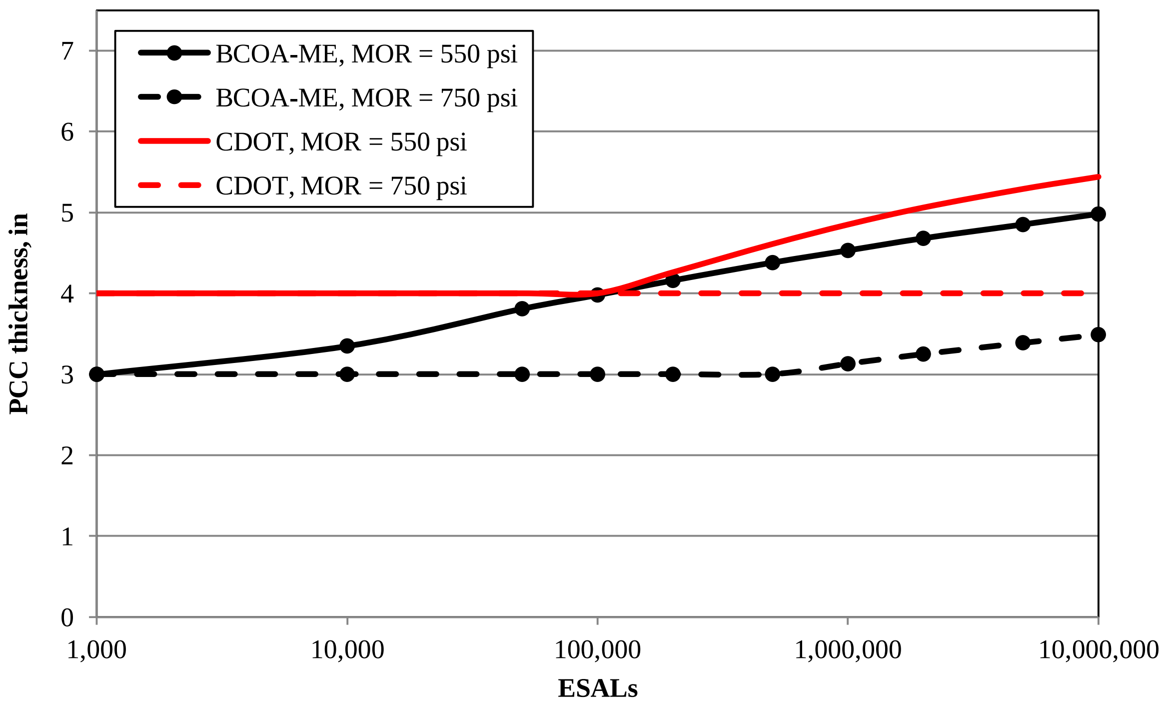

Figure 4. PCC thickness sensitivity to PCC modulus of rupture for 6 ft × 6 ft slabs with respect to design ESALs

The BCOA-ME PCC design thickness of 12 ft × 12 ft slabs with respect to design ESALs, shown in Figure 5, indicates that the BCOA-ME is slightly less sensitive to the PCC modulus of rupture (MOR) for large slab sizes as compared to smaller slab sizes. Both procedures exhibit the same trend of sensitivity to the modulus of rupture with increasing ESALs while the BCOA-ME procedure predicts slightly thicker predictions for low MOR concrete.

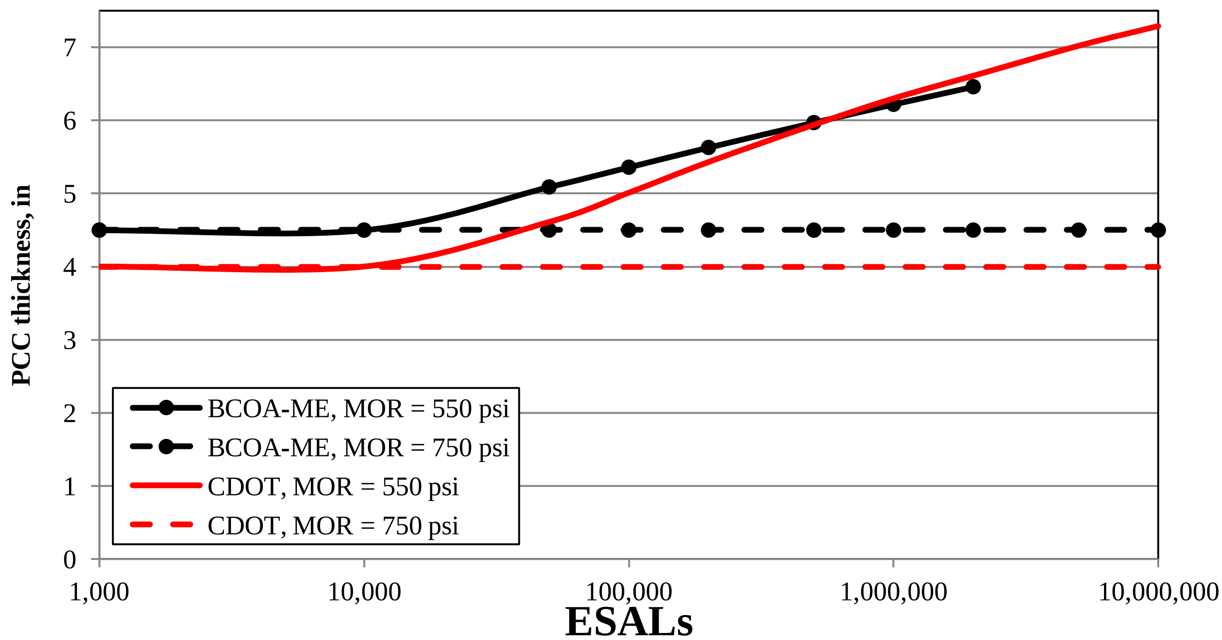

Figure 5. PCC thickness sensitivity to PCC modulus of rupture for 12 ft × 12 ft slabs with respect to design ESALs

PCC Coefficient of Thermal Expansion

The three design procedures all exhibited slight sensitivity to the PCC coefficient of thermal expansion (CTE). Neither of the previous procedures studied this parameter as a possible source of model sensitivity. A standard value of 5.5 10^{-6} in/□F/in was used for the standard sensitivity analyses, and the values used for the sensitivity analysis of the CTE were 4.0 and 6.0 10^{-6} in/□F/in.

The BCOA-ME exhibited some sensitivity toward the CTE as a function of design ESALs for 4 ft × 4 ft slabs. Shown in Figure 6, the difference in predicted PCC thickness for the BCOA-ME is negligible at low design ESALs and increases to approximately 1 in for high design ESALs. The ACPA Procedure exhibits a similar trend but for overall thinner design thicknesses with much less sensitivity.

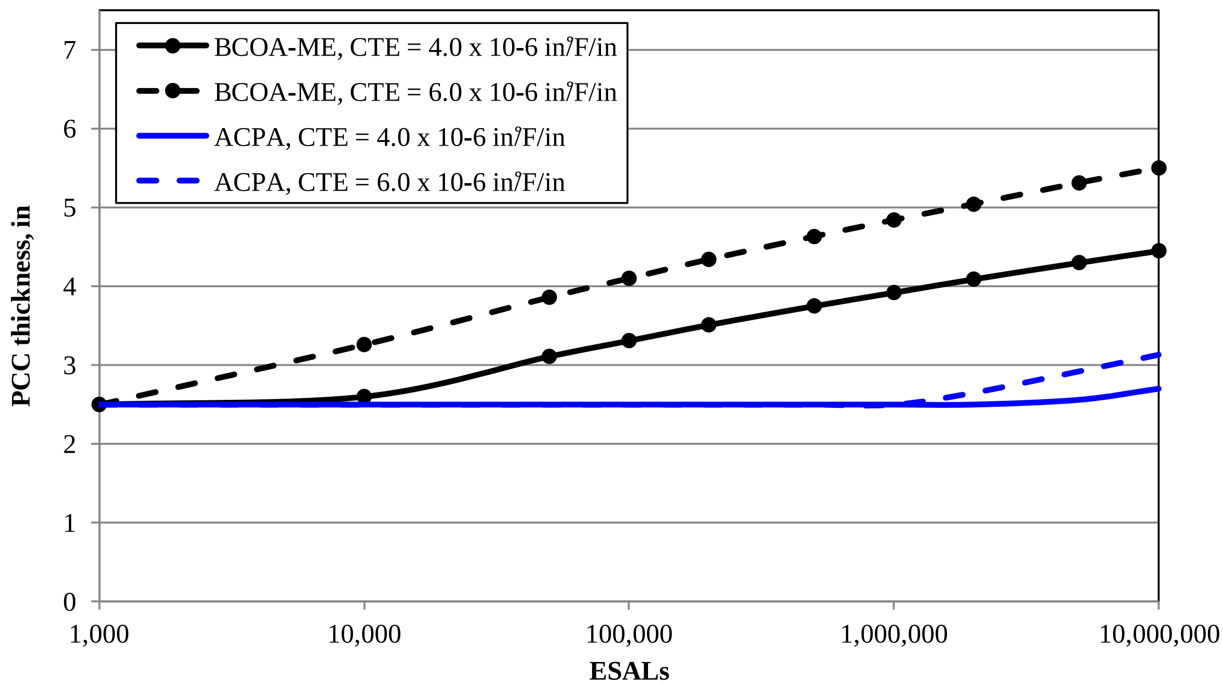

Figure 6. PCC thickness sensitivity to coefficient of thermal expansion for 4 ft × 4 ft slabs with respect to design ESALs

The BCOA-ME PCC design thickness of 6 ft × 6 ft slabs with respect to design ESALs, shown in Figure 7, indicates that the BCOA-ME does not exhibit any sensitivity to the CTE for larger slab sizes. Likewise, the CDOT predictions are also identical regardless of CTE. Because of the minimum thickness requirements, the CDOT method consistently predicts a slab of the minimum design thickness of 4 in while the BCOA-ME predicts a slightly thinner slab due to the 3 in minimum design thickness for 6 ft × 6 ft slabs.

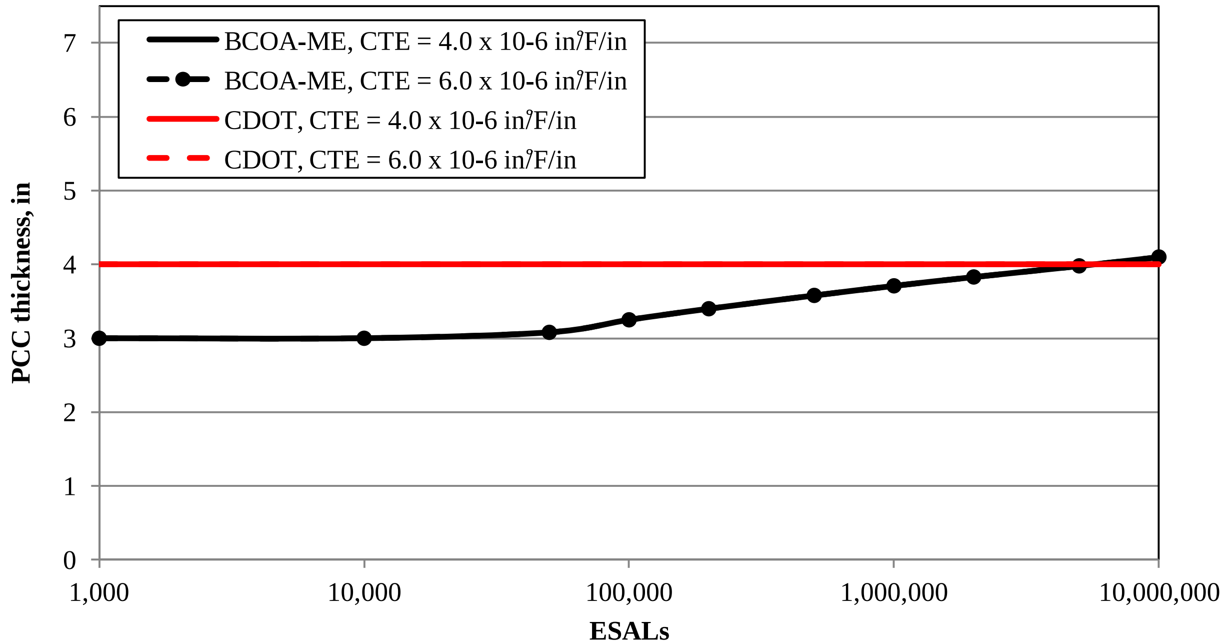

Figure 7. PCC thickness sensitivity to coefficient of thermal expansion for 6 ft × 6 ft slabs with respect to design ESALs

The BCOA-ME PCC design thickness of 12 ft × 12 ft slabs with respect to design ESALs, shown in Figure 8, indicates that the BCOA-ME does not exhibit any sensitivity to the CTE for larger slab sizes. Likewise, the CDOT predictions are also identical regardless of CTE. The BCOA-ME procedure exhibits slightly more sensitivity to design ESALs and is shown predicting a slightly thicker slab for ESALs above 100,000.

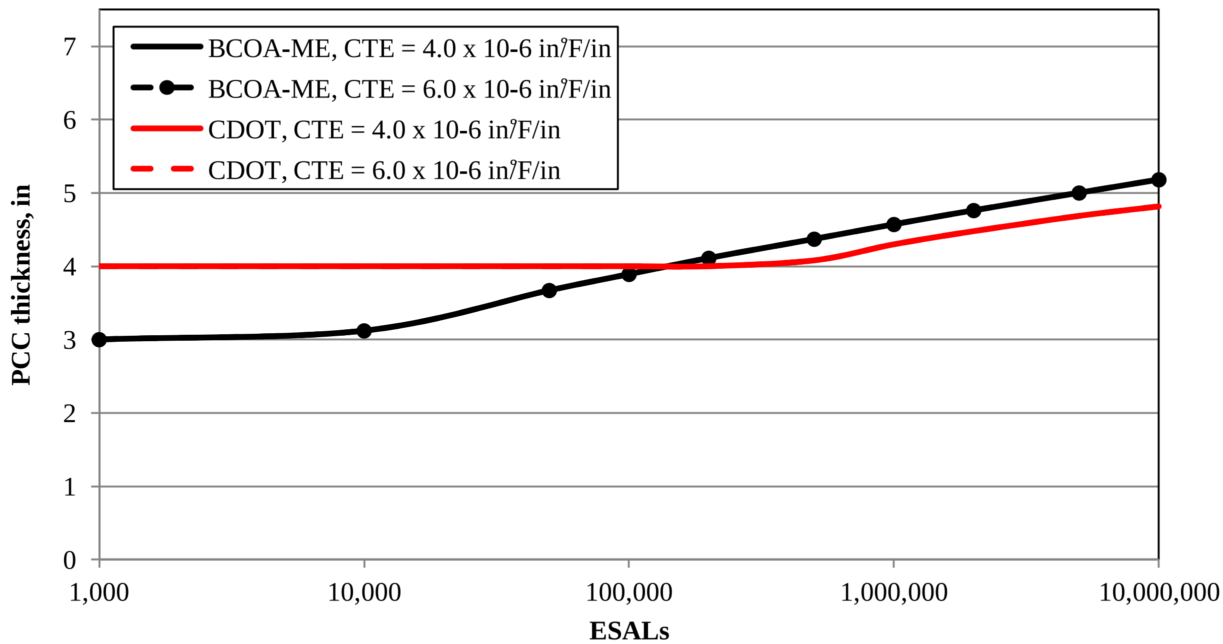

Figure 8. PCC thickness sensitivity to coefficient of thermal expansion for 12 ft × 12 ft slabs with respect to design ESALs

HMA Quality (measured through E_{HMA})

In the BCOA-ME, the quality of the HMA layer was quantified by reducing the E_{HMA} by a percentage based on the reported quality of the underlying asphalt. The existing HMA layer could be categorized as either 'adequate', which reduces the E_{HMA} by 5%, or 'marginal', which reduces the E_{HMA} by 13%. All E_{HMA} values are reduced in this procedure because an existing HMA layer in 'good' condition will likely not be a candidate for an overlay repair. The CDOT and ACPA Procedures complete sensitivity analyses with respect to the E_{HMA} modulus only and both concluded that extreme values, such as E_{HMA} values below 50,000 psi, increased the sensitivity of the model to other parameters; however, neither analysis incorporated adjustments for the quality of the existing HMA layer in terms of the E_{HMA}.

The BCOA-ME exhibited little sensitivity toward the E_{HMA} quality as a function of design ESALs for 4 ft × 4 ft slabs. Shown in Figure 9, the BCOA-ME predictions were nearly identical, but the prediction increased with increasing traffic. The effects of HMA quality were simulated in the ACPA Procedure by reducing the constant HMA elastic modulus by 50,000 psi, a reduction expected to be comparable to reductions taken by the BCOA-ME. The ACPA

Procedure also exhibited very little sensitivity toward the quality of the HMA layer, but more so than the BCOA-ME, and predictions also increased with increasing design ESALs. The ACPA Procedure also consistently predicted thinner slabs than the BCOA-ME for this smaller slab size.

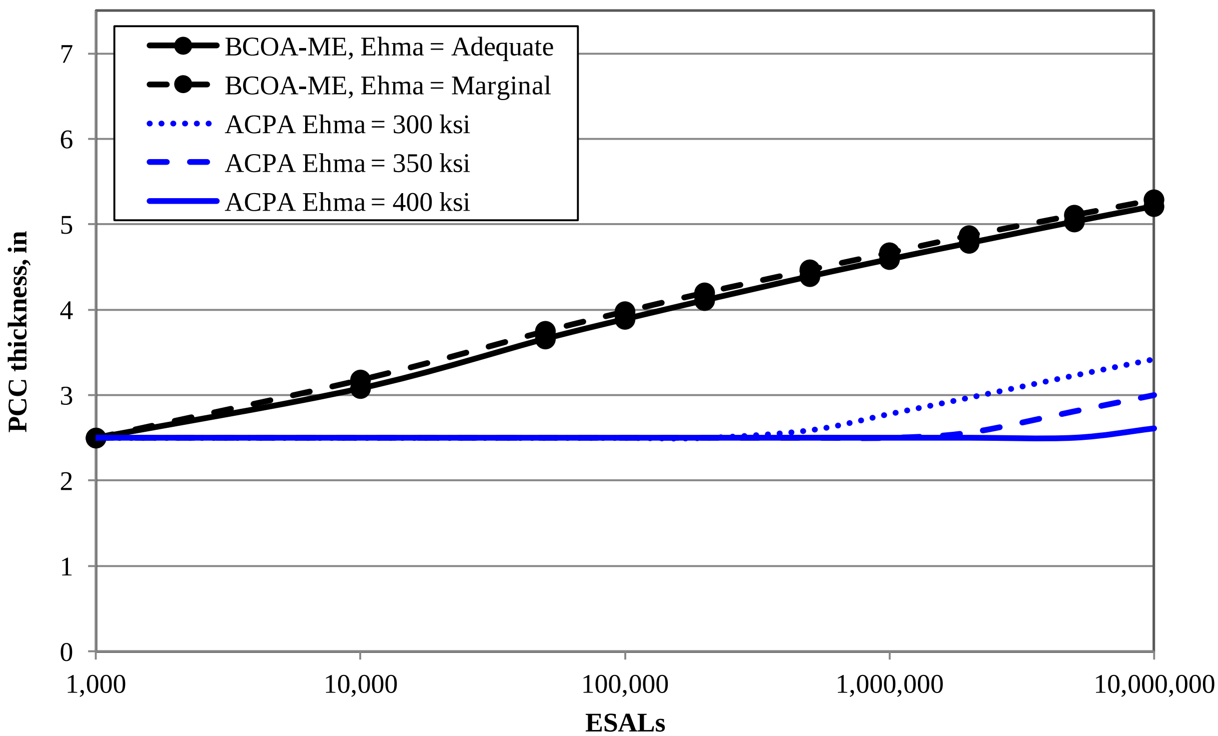

Figure 9. PCC thickness sensitivity to HMA quality for 4 ft × 4 ft slabs with respect to design ESALs

The BCOA-ME PCC design thickness of 4 ft × 4 ft slabs with respect to the HMA thickness, shown in Figure 10, indicates that the BCOA-ME does not exhibit any sensitivity to the HMA quality and only some sensitivity to HMA layer thickness where the difference in predicted values for higher and lower HMA thickness values varied by only 1.5 in. The ACPA Procedure also exhibited little sensitivity to the HMA quality but exhibited high sensitivity to the HMA layer thickness where the difference in predicted values for higher and lower HMA thickness values varied by 4 in. The ACPA Procedure consistently predicted thinner PCC thickness than the BCOA-ME for the smaller slab sizes but did exhibit greater sensitivity to both HMA quality and HMA layer thickness.

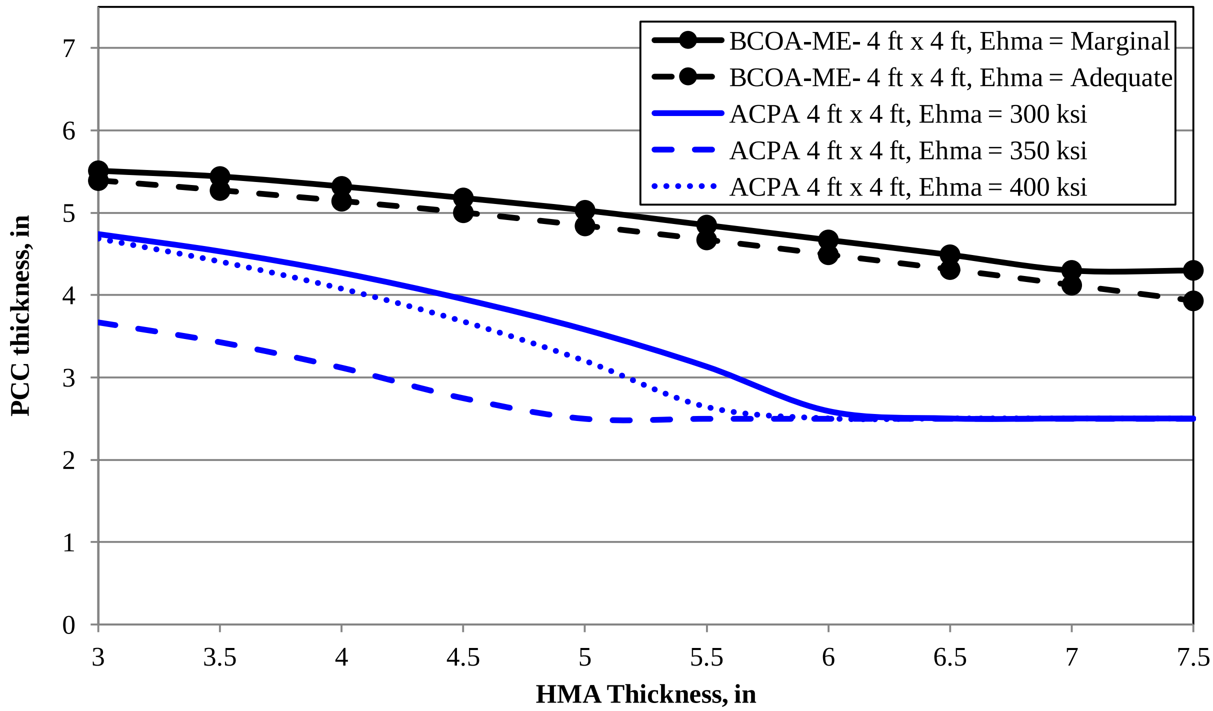

Figure 10. PCC thickness sensitivity to HMA quality for 4 ft × 4 ft slabs with respect to HMA thickness

The BCOA-ME PCC design thickness of 6 ft × 6 ft slabs with respect to the HMA thickness, shown in Figure 11, indicates that the BCOA-ME is much less sensitive to HMA quality than the CDOT Procedure for this slab size. The full extent of this sensitivity is displayed best in Figure 12, where the restraints of the CDOT Procedure minimum PCC design thickness of 4 in is removed. In Figure 12, the sensitivity trends with respect to HMA thickness are much more visible. Whereas the BCOA-ME design predictions varies by slightly less than 2 in with respect to changing HMA thickness, the CDOT Procedure exhibits high sensitivity to HMA thickness and the predictions differ up to 7 in. The predicted thicknesses between the two methods are comparable but in this case, the BCOA-ME is exhibiting much less sensitivity to both HMA quality as well as HMA layer thickness.

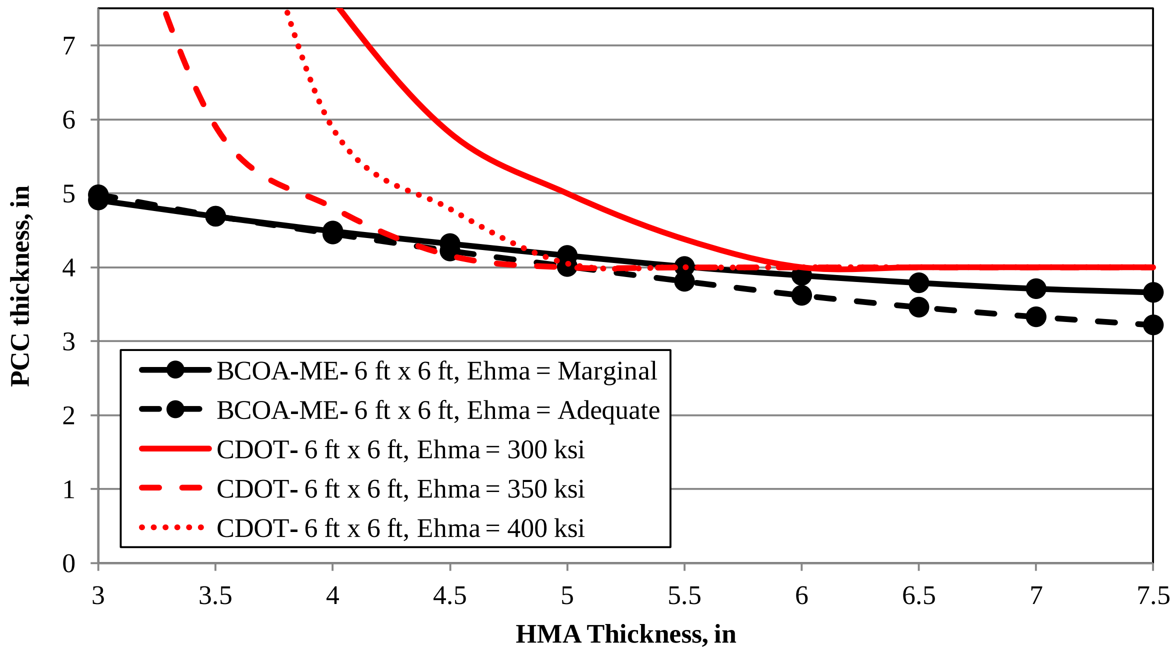

Figure 11. PCC thickness sensitivity to HMA quality for 6 ft × 6 ft slabs with respect to HMA thickness

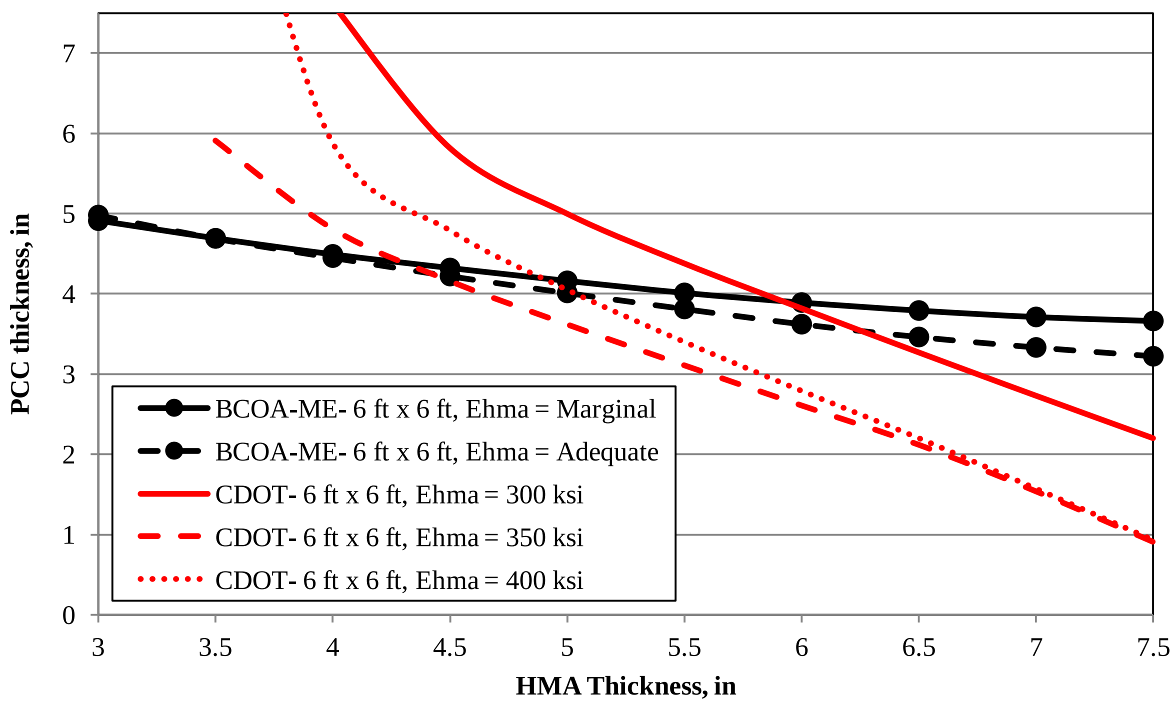

Figure 12. PCC thickness sensitivity to HMA quality for 6 ft × 6 ft slabs with respect to HMA thickness

The BCOA-ME PCC design thickness of 12 ft × 12 ft slabs with respect to the HMA thickness, shown in Figure 13, indicates that the BCOA-ME is approximately equally sensitive to HMA quality as the CDOT Procedure for this slab size. The full extent of this sensitivity is displayed best in Figure 14, where the restraints of the CDOT Procedure minimum PCC design thickness of 4 in is removed. In Figure 14, the sensitivity trends with respect to HMA thickness are much more visible. Whereas the BCOA-ME design predictions varies by slightly more than 1 in with respect to changing HMA thickness, the CDOT Procedure exhibits high sensitivity to HMA thickness and the predictions differ up to 7 in. The predicted thicknesses between the two methods are comparable but in this case, the BCOA-ME is exhibiting comparable sensitivity to both HMA quality as well as much less sensitivity to HMA layer thickness.

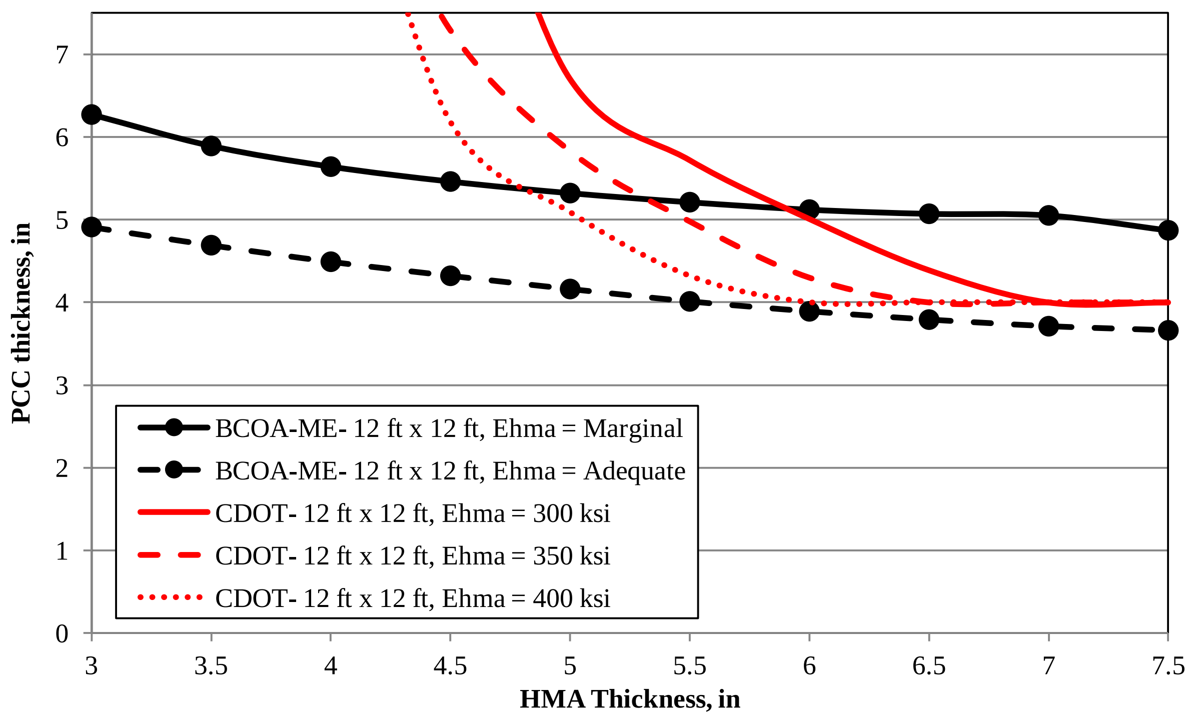

Figure 13. PCC thickness sensitivity to HMA quality for 12 ft × 12 ft slabs with respect to HMA thickness

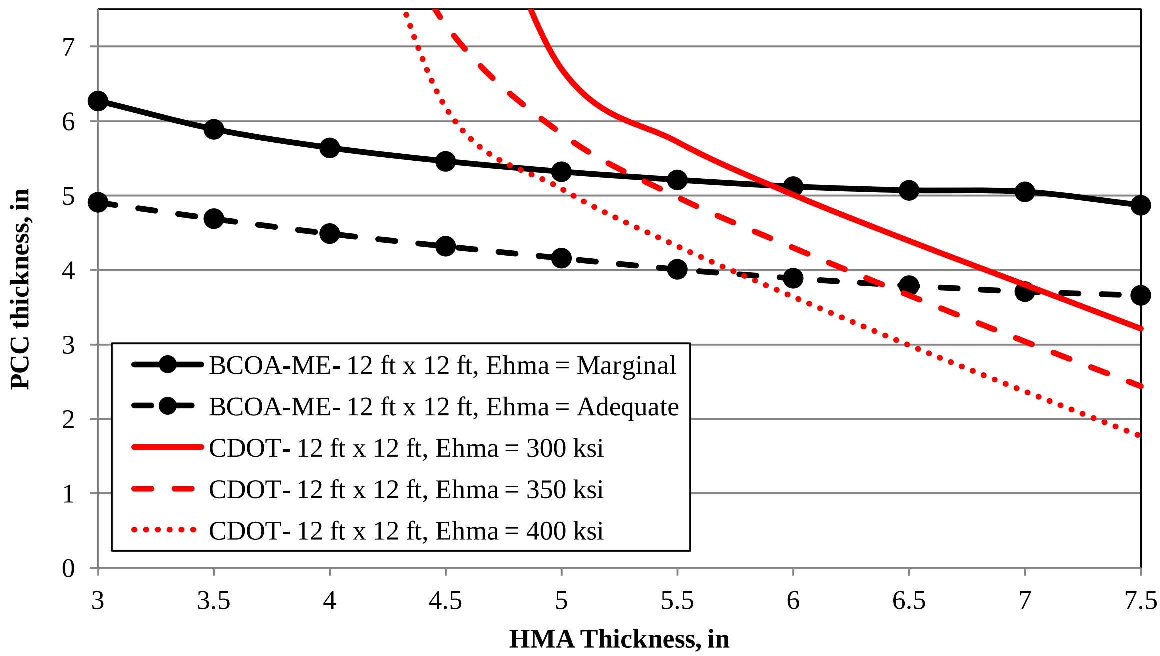

Figure 14. PCC thickness sensitivity to HMA quality for 12 ft × 12 ft slabs with respect to HMA thickness

Subgrade k-value

None of the three design procedures exhibited substantial sensitivity to the subgrade k-value. The previous sensitivity analyses for both the ACPA Procedure and the CDOT Procedure also found that adjustments in the k-value did not affect the PCC thickness and, as a result, the BCOA-ME was not expected to exhibit sensitivity to the subgrade k-value. Inputs used for k-value sensitivity were 100 psi/in and 350 psi/in, which provided reasonable boundaries compared to the 250 psi/in standard k-value input used for the other sensitivity models.

As shown in Figure 15, for 4 ft × 4 ft slabs, the BCOA-ME exhibits no sensitivity to the k-value and the predicted PCC thicknesses for k-values of 100 psi/in and 350 psi/in are identical. Likewise, the ACPA Procedure also predicts identical values for both k-values of 100 psi/in and 350 psi/in. The BCOA-ME consistently predicted larger PCC design thicknesses than the ACPA Procedure.

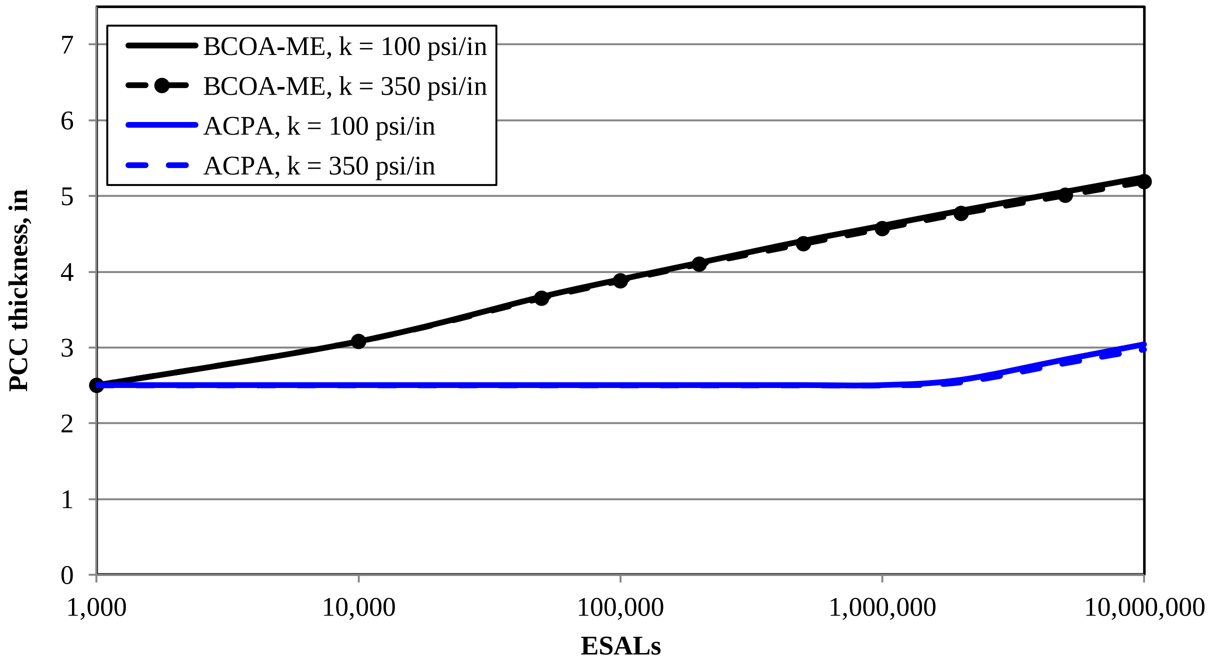

Figure 15. PCC thickness sensitivity to k value for 4 ft × 4 ft slabs with respect to design ESALs

Similarly, in Figure 16, for 6 ft × 6 ft slabs, the CDOT procedure exhibited no sensitivity to the subgrade k-value at all whereas the BCOA-ME procedure exhibited slight sensitivity with only approximately 0.5 in difference between k-value predictions. Overall, the BCOA-ME procedure exhibited slightly more sensitivity to ESALs than the CDOT procedure.

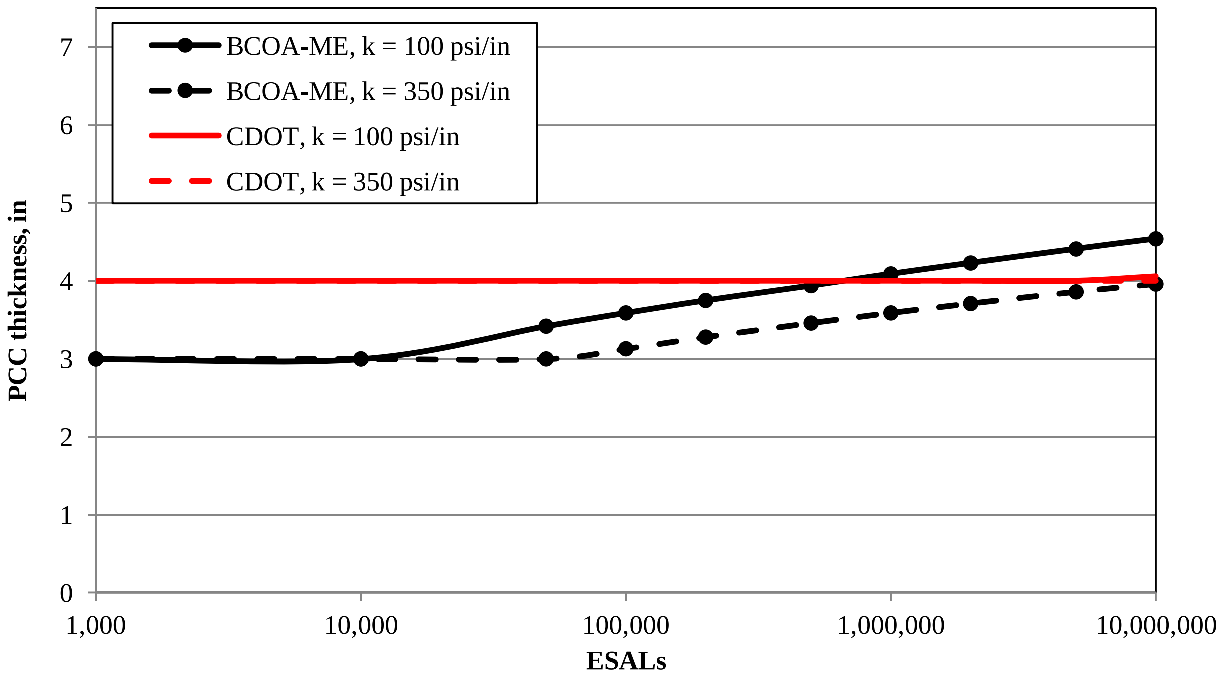

Figure 16. PCC thickness sensitivity to k value for 6 ft × 6 ft slabs with respect to design ESALs

In Figure 17, for 12 ft × 12 ft slabs, the CDOT procedure exhibited slightly more sensitivity to the subgrade k-value than the BCOA-ME procedure. The CDOT procedure predicted a difference of slightly less than 1 in while the BCOA-ME procedure predicted a difference in PCC overlay thickness of slightly more than 1 in at higher levels of ESALs.

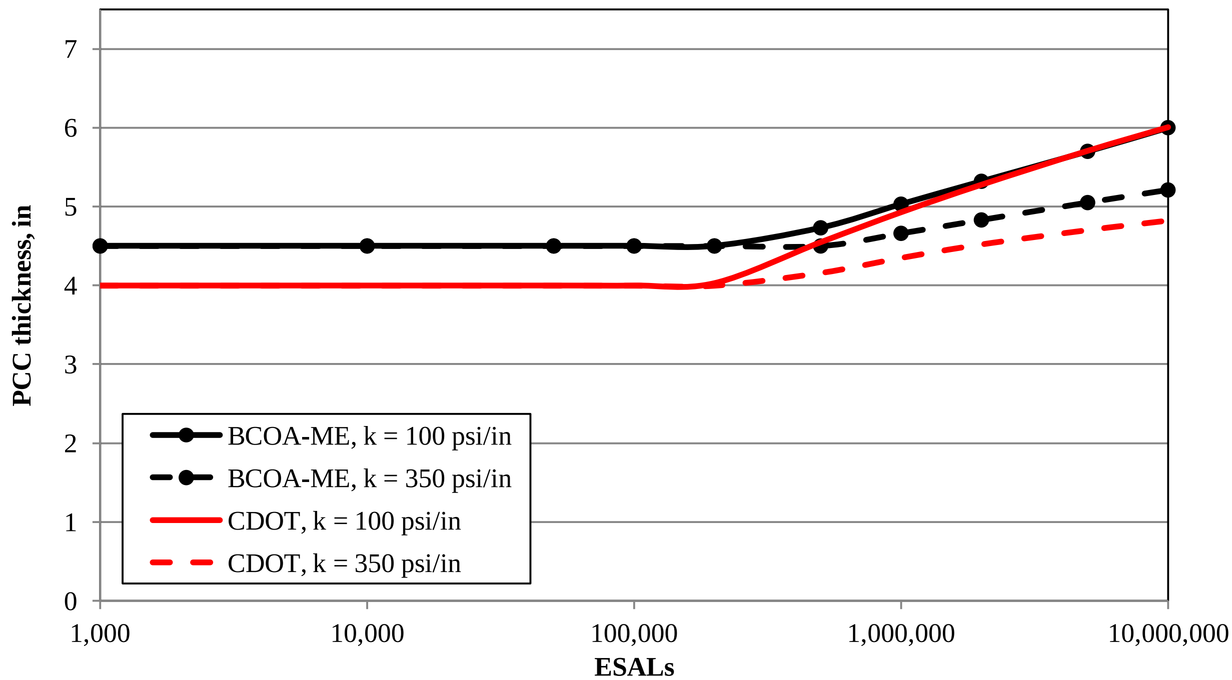

Figure 17. PCC thickness sensitivity to k value for 12 ft × 12 ft slabs with respect to design ESALs

Climate

Only the BCOA-ME was considered for climate sensitivity because the two comparable procedures accounted only for either a negative or positive temperature gradient rather than a true climate consideration. The BCOA-ME used climate parameters with a master curve to adjust the HMA dynamic modulus according to the appropriate climate, and used these HMA dynamic modulus values to develop a different temperature gradient. Four varying climates were compared for the climate sensitivity.

Several trends can be observed for 4 ft × 4 ft slabs as shown in Figure 18. The BCOA-ME predicted PCC design thicknesses in the following order of increasing design thickness: Seattle, Minneapolis, Phoenix, and Miami. The BCOA-ME exhibited only slight sensitivity with respect to climate.

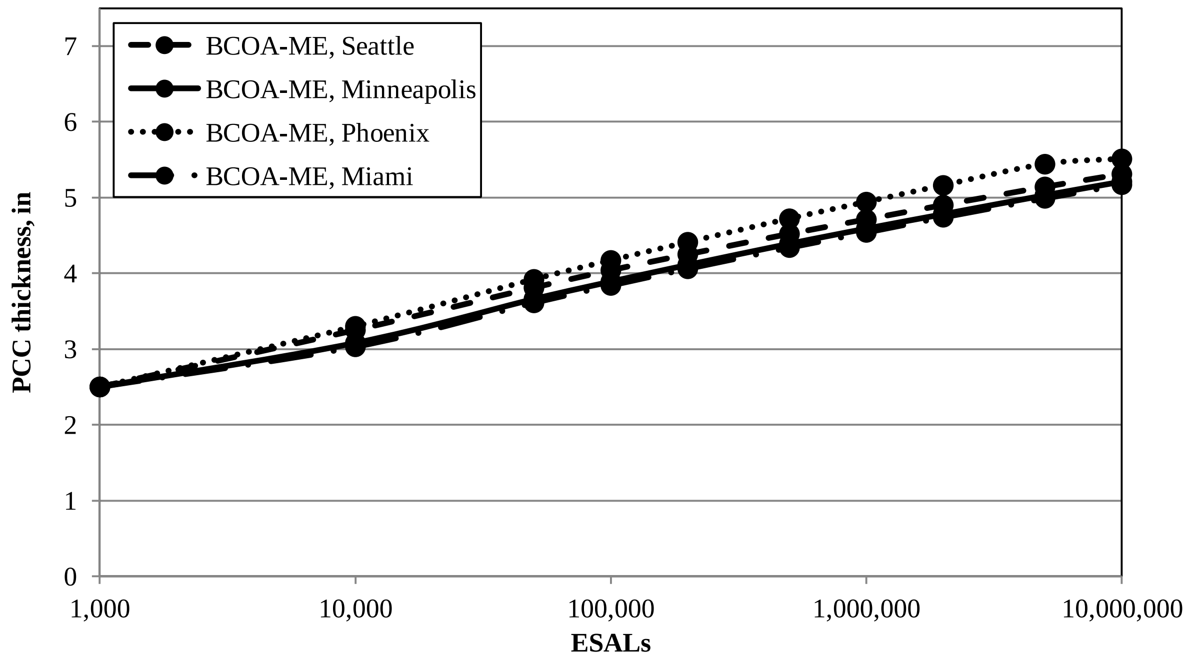

Figure 18. PCC thickness sensitivity to climate for 4 ft × 4 ft slabs with respect to design ESALs

Different trends are observed for 6 ft × 6 ft slabs in Figure 19. The overall sensitivity toward climate is less than for 4 ft × 4 ft slabs and predicted differences. Likewise, the BCOA-ME exhibits little sensitivity to increasing design ESALs as well and the design thickness increases only by 1 in as design ESALs increase rather than the 2 in increase exhibited by the 4 ft × 4 ft slabs with increasing design ESALs.

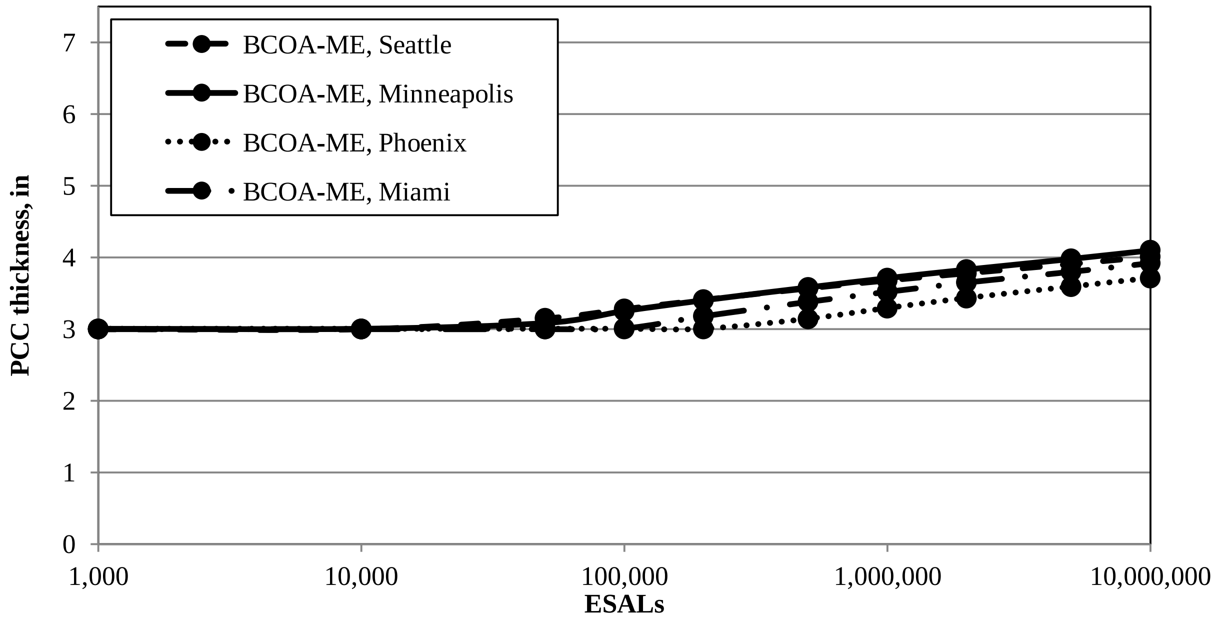

Figure 19. PCC thickness sensitivity to climate for 6 ft × 6 ft slabs with respect to design ESALs

Different trends are observed for 12 ft × 12 ft slabs as shown in Figure 20. Interestingly, the predictions for Minneapolis and Miami are both similar and are thicker than the predictions for both Phoenix and Seattle. This largest slab size appears to have higher sensitivity to climate based on the sunshine zone. Overall, the predictions still varied by less than 1 in at higher levels of design ESALs, indicating that the BCOA-ME sensitivity to climate is not substantial.

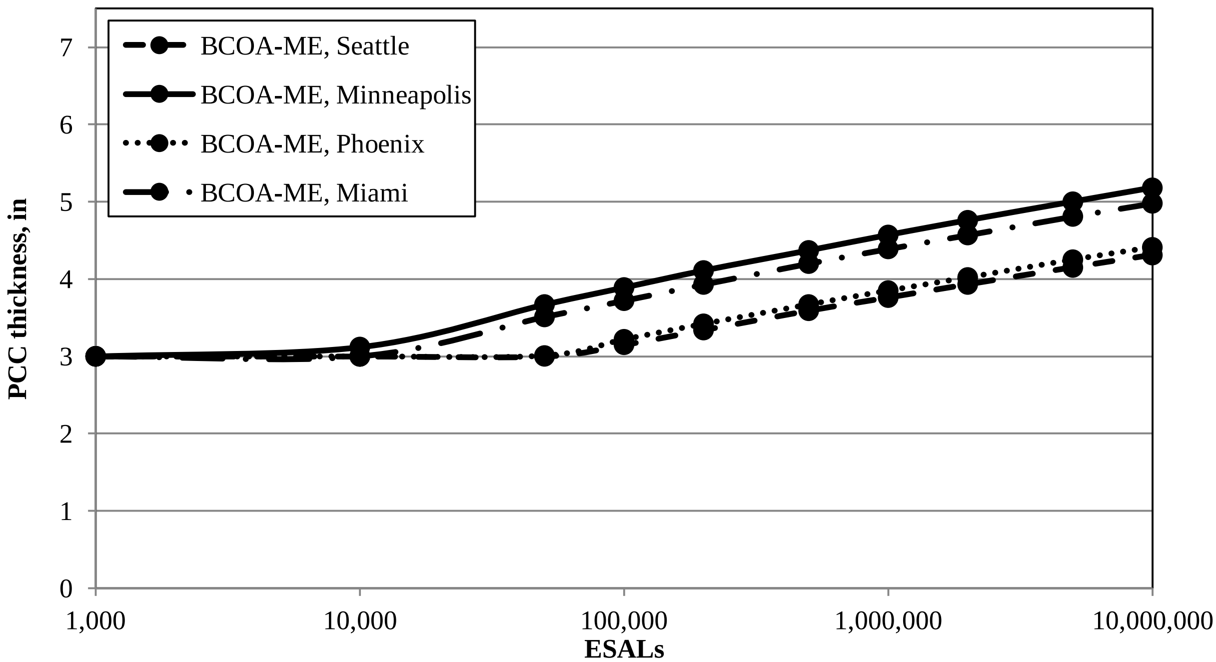

Figure 20. PCC thickness sensitivity to climate for 12 ft × 12 ft slabs with respect to design ESALs

Conclusion

This sensitivity analysis revealed that the BCOA-ME did exhibit some sensitivity toward several of the chosen parameters. Some of this sensitivity was expected to be inherited from the previous procedures (ACPA and CDOT) as both were used to develop the current BCOA-ME. The BCOA-ME exhibited the most sensitivity toward the PCC modulus of rupture and varying the modulus of rupture between 550 and 750 psi resulted in a design difference of up to 1.5 in. Slight sensitivity was observed for the PCC coefficient of thermal expansion, but the sensitivity was only present for the 4 ft × 4 ft slab size. Adjusting the PCC coefficient of thermal expansion between 4.0 and 6.0 10^{-6} in/□F/in resulted in a difference in design PCC thickness up to 1 in for the smaller slabs. The larger, 6 ft × 6 ft slabs did not exhibit any sensitivity to either the PCC coefficient of thermal expansion. The most extreme climate difference (between Minneapolis and Miami) resulted in a difference in PCC design thickness of less than 0.5 in for both the larger and the smaller slabs. The BCOA-ME did not exhibit any sensitivity toward the subgrade k-value. The largest slabs, 12 ft × 12 ft, exhibited sensitivity to HMA quality and PCC MOR. The

BCOA-ME procedure for this slab size did not exhibit substantial sensitivity toward k-value, PCC CTE or climate for this largest slab size.

Like the BCOA-ME, both the ACPA and CDOT Procedures exhibited high sensitivity to the PCC modulus of rupture and the HMA layer thickness, and this sensitivity could be inherited from the model base. It is important to note that the CDOT procedure exhibited much higher sensitivity to the HMA thickness than the BCOA-ME designs for comparable slab sizes. The ACPA Procedure exhibited sensitivity to the PCC coefficient of thermal expansion, while the CDOT Procedure did not. As the BCOA-ME for the 4 ft × 4 ft slabs was developed from the ACPA Procedure, the sensitivity of these two parameters to the smaller slab size can be explained. Like the BCOA-ME, neither the ACPA nor the CDOT Procedure indicated any sensitivity toward the k-value.