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Research Article

CHARACTERIZATION OF UNDERLYING LAYER STABILIZATION MATERIAL FOR MECHANISTIC-EMPIRICAL DESIGN OF RIGID PAVEMENTS

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ABSTRACT

The Mechanistic-Empirical Pavement Design Guide (MEPDG) is applied to calculate pavement responses against the cumulative damage over time, taking into account the general properties of materials, traffic, environmental conditions and pavement structure. The procedure described in the guide was used in this paper to provide appropriate design alternatives for the existing conditions. The two most common types of rigid pavements for highways, Continuously Reinforced Concrete Pavement (CRCP) and Jointed Plain Concrete Pavement (JPCP) were considered in the design. The base layer material was chosen in such a way that a reasonable design life and distress level can be obtained. For each type of chemical stabilization techniques of the underlying layers, the satisfactory design cases were proposed based on the M-E design procedure. For CRCP, the results were also compared with those obtained from the procedure suggested by Texas Department of Transportation (TxDOT) pavement design manual.

Keywords: Pavement; MEPDG; Stabilization; Cracking; Faulting; IRI.

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1. INTRODUCTION

Since 1891, when Portland Cement Concrete (PCC) was firstly used as a wearing surface in North America [1], the need and use of rigid pavements have been increasing. Although asphalt pavements have been used since mid-18th century as roads or sidewalks before concrete pavements were introduced [2], this is not the only reason that more than 80 percent of the highway infrastructure is constructed with asphalt concrete or commonly known as flexible pavement. There are other reasons such as available materials and technologies which influence the pavement type [3]. In terms of the design life, design life of rigid pavements is typically considered to be 30 years of service life with minimal maintenance required for the first 20 years of service life while flexible pavement is designed for 15 years. Few pavements with exceeding 30 years of performance data were included in the past calibration processes [4]. Hence, even though the initial cost of a rigid pavement is higher than that for a flexible pavement, using rigid pavement will result in less subsequent construction and maintenance costs due to less distributed load over the subgrade and high structural capacity of pavement layers.

More than 50% of the annual construction and maintenance budget of Texas Department of Transportation (TxDOT) is currently spent on pavements, from which, only a portion of pavement-related needs can be addressed due to funding limitations. The pavement design process aims at guiding the District Pavement Engineer (DPE) towards selecting an appropriate pavement type capable of carrying traffic loads with minimum physical deterioration, maximum safety and maximum ride comfort through an approved design method [5]. Therefore, implementation of properly calibrated design methods and performance models to local conditions of Texas is essential for reliable pavement and overlay designs. In recent years, several mechanistic and numerical methods have been emerged as advanced frameworks for structural simulation and analysis to provide civil engineers with innovative procedures of addressing construction issues [6-15]. However, the new Mechanistic-Empirical Pavement Design Guide (MEPDG) was specifically developed for prediction of the pavement conditions over time with a significant benefit over the AASHTO 1993 [16] design guide, taking into account the traffic, climate and pavement structure. Furthermore, MEPDG provides a means for evaluating design variability and reliability in network level. Recently, TxDOT proposed an implementation and calibration plan for transition from previous empirical-based design to the new MEPDG. The research conducted by Ha et al. [17] has led to the development of a CRCP design procedure based on M-E design principles. The proposed methodology was calibrated using field data from CRCP sections in Texas as well as theoretical structural analysis.

Regarding to the strength of underlying layers of a pavement, chemical stabilization can be utilized as a moisture barrier in areas with problematic soil to prevent water from penetrating into the pavement structure [18-20]. From practical standpoint, cement stabilization, asphalt treatment and lime stabilization are among the most common chemical stabilization techniques in Texas. In order to evaluate the effectiveness of the stabilization techniques in the pavement performance, the MEPDG provides the designer with option of performance assessment of a pavement with any chemically stabilized base.

This study, therefore, focuses on the M-E design of both rigid pavement types (JPCP and CRCP) with chemically stabilized base, located in Texas. The material properties of the base layer vary to model cement-treated base (CTB) and asphalt-treated base (ATB) according to the previous experimental works and the values suggested by the MEPDG. Various thicknesses of pavement as well as base layer with or without total thickness of layers were considered. In case of CRCP, the design procedure proposed by Ha et al. [17] has also been followed to compare a calibrated approach with the general framework of MEPDG.

2. PROBLEM STATEMENT

The design consists of a jointed plain or continuously reinforced concrete pavement for a period of 20 years in El Paso, Texas. The project begins in Februray 2018 and after a construction period of four months, the section will be opened to traffic in June 2018. This primary arterial will be constructed towards East with the length of 15 miles. According to MEPDG, it is expected that at the end of design life, JPCP has no more than 15% transverse slab cracking, 0.20 in. joint faulting at the reliability level of 90% and terminal IRI (International Roughness Index) of 200 in./mile at the reliability level of 95%. For CRCP, the pavement will have no more than 10 punchouts per mile and terminal IRI of 200 in./mile at the reliability level of 90%.

2.1. Traffic

One of the most important factors in the pavement design, traffic (including loading magnitude, configuration and number of load repetitions), is considered in this section. Although the equivalent single axle load (ESAL) approach is not used for traffic characterization in MEPDG, it is applied in current procedure for design of CRCP pavements in Texas [17]. In the case of CRCP, the ESAL value of 4 million will be considered. For all cases in the MEPDG design of rigid pavements, a two-lane highway with estimated average annual daily truck traffic (AADTT) of 2200 trucks in both directions during first year of service is considered. The percent of truck in the design lane is 90% with equal distribution in both directions. The operational speed was considered as 60 mph. The normalized truck volume distribution is according to TTC (Truck Traffic Classification) group 2 in the MEPDG consisting of high percentage of single trailer trucks, determined from the LTPP (Long-Term Pavement Performance) sites (see Table 1). The spacing of the axles was selected based on the recorded WIM (Weigh-in-Motion) data in MEPDG. It is assumed constant for standard truck. For tandem axle, tridem axle and quad axle, the spacing is equal to 51.6 in., 49.2 in., and 49.2 in., respectivley. It was assumed that the traffic pattern remains constant throughout the year and increases by 4% of the preceding year on compound annually basis. Average axle width and spacing as well as tire spacing were assumed as the default values in the MEPDG.

Table 1. Truck class distribution default values included in the design

Vehicle class	Class 4	Class 5	Class 6	Class 7	Class 8	Class 9	Class 10	Class 11	Class 12	Class 13
Truck class distribution (%)	2.4	14.1	4.5	0.7	7.9	66.3	1.4	2.2	0.3	0.2

2.2. Climate

The climate data can be extracted from available database provided from stations around the world [21]. In this study, therefore, the climate data used for the design were taken from the weather station in El Paso (31.811 N, 106.376 W) near the airport so that the temperature, precipitation and relative humidity can be implemented in predicting the pavement distress. The depth of water table was set to 15 ft. to take into consideration the changes in the resilient modulus of the aggregate layers and foundation soils over time.

2.3. Drainage

If enough attention is not paid to the drainage properties of the underlying pavement layers, infiltration of water may cause issues regarding the strength of unbound materials such as pumping, shoulder deterioration and heaving of swelling soils. In this study, the drainage properties are defined as 2% of highway cross slope, length of drainage path of 12 ft. from the centerline to the edge and surface shortwave absorptivity of 0.85.

2.4. Foundation and Subgrade Soils

In this study, the performances of two rigid pavement types (JPCP and CRCP) were investigated. For JPCP, two cases of constant pavement depth (rigid pavement plus underlying layer equal to 15 in.) with varying pavement depths (ranging between 3 and 9 in. for each layer) were considered. The base material was assumed to have the properties of cement-treated base (CTB) or asphalt-treated base (ATB) with near the minimum suggested values based on TxDOT design manual to consider the critical conditions. For the subgrade soil, two types of coarse-grained soil (A-1-a) and fine-grained soil (A-7-6) were taken into account. The material properties for each of these cases are illustrated in Fig. 1 and listed in Table 2.

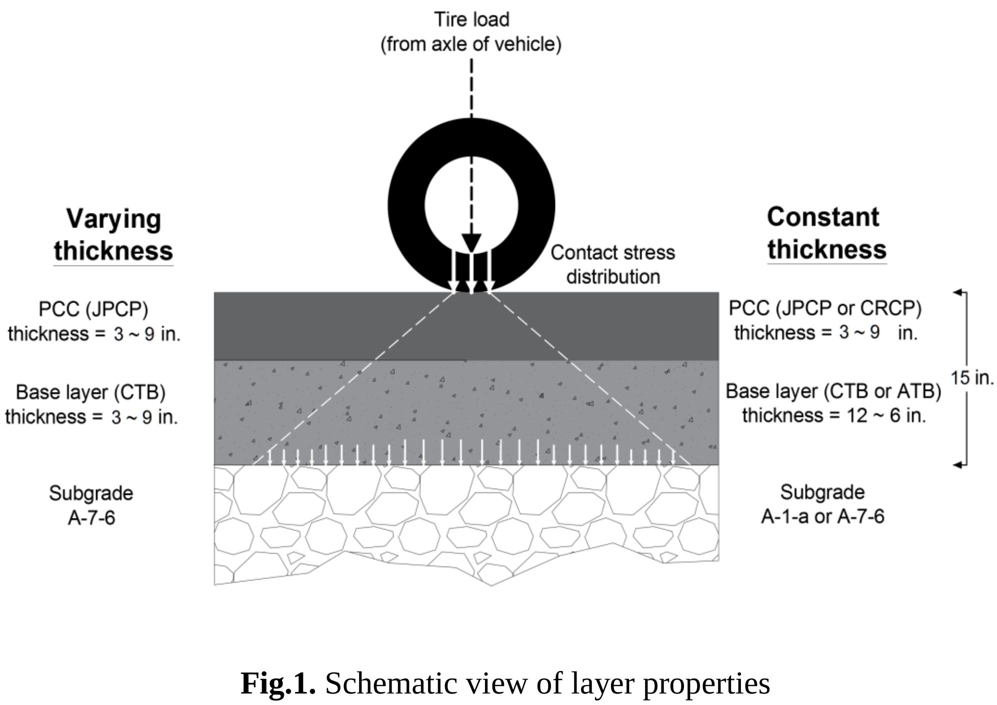


Fig.1. Schematic view of layer properties

Table 2. Pavement material properties

PCC	Unit weight: 140 (pcf) Poisson's ratio: 0.20 Cement: type I W/C: 0.45 28-day modulus of rupture for JPCP: 840 psi 28-day modulus of rupture for CRCP: 680 psi Elastic modulus for JPCP: 5,200 ksi Elastic modulus for CRCP: 4,000 ksi Coefficient of thermal expansion for JPCP: 6.3 in./in./°F $\times 10^{-6}$ Coefficient of thermal expansion for CRCP: 4.9 in./in./°F $\times 10^{-6}$ Surface shortwave absorptivity: 0.8 Thermal conductivity: 1.25 BTU/hr.-ft.-°F Heat capacity: 0.28 Lane width: 12 ft. Dowel diameter and spacing (JPCP): 1.25 and 12 in., respectively Bar diameter and depth (CRCP): 0.62 and 4 in., respectively Reinforcement (CRCP): 0.6%	
Base	CTB	Unit weight: 150 (pcf) Poisson's ratio: 0.15 Elastic modulus: 200 ksi (TxDOT: 100 ~ 700 ksi) Thermal conductivity: 1.25 BTU/hr.-ft.-°F Heat capacity: 0.28
	ATB	Unit weight: 150 (pcf) Poisson's ratio: 0.35 Binder content: 10% Air void: 8% Elastic modulus: 100 ksi (TxDOT: 100 ~ 400 ksi)
Subgrade	SG1 (A-1-a)	Poisson's ratio: 0.35 Resilient modulus: 18 ksi PI, LL and P_{200}: 2%, 7% and 9%, respectively
	SG2 (A-7-6)	Poisson's ratio: 0.35 Resilient modulus: 13 ksi PI, LL and P_{200}: 30%, 51% and 79%, respectively

3. RESULTS AND DISCUSSION

This study investigates the performance of JPCP and CRCP with varying thicknesses constructed on cement- and asphalt-treated base over two different subgrades. To predict performance and design life of pavement, MEPDG presents a series of distress models and subsequently, accumulates the data from them to International Roughness Index (IRI), which proposes the smoothness and necessity for repair or rehabilitation. As mentioned before, the major distresses observed in JPCP are transverse cracking and faulting and also the common distress in CRCP is punchout. There are various relationships for distress in different regions depending on the pavement performance data. However, the final validated and calibrated models for IRI using LTPP field data which relate distresses in JPCs and CRCPs are as follows [4]:

$$IRI = IRI_0 + C_1 \times Crk + C_2 \times Spall + C_3 \times TFault + C_4 \times SF \qquad (1)$$

where IRI is the predicted IRI (in./mile), IRI_0 is the initial smoothness (in./mile), Crk is the percentage of slabs with transverse cracks, $Spall$ is the percentage of joints with spalling, $TFault$ is the total joint faulting cumulated per mile (in.), SF is the site factor, $C_1 = 0.8203$, $C_2 = 0.4417$, $C_3 = 0.4929$ and $C_4 = 25.24$.

For each distress type, there is a threshold value on the basis of estimated design life and reliability level beyond which the pavement is assumed to be failed. The results from analysis of pavement for constant and various thicknesses and also comparison with TxDOT regulations are presented in the following sections.

3.1. Constant Thickness

In this case, the total thickness of rigid pavement of the base layer was assumed as constant value of 15 in. (see Fig. 1). The estimated distress for JPCP in terms of predicted mean joint faulting is illustrated in Fig. 2, where the red horizontal line indicates the threshold value for the failure specified in MEPDG. As mentioned in section 2, the studied road is a primary arterial road in El Paso, for which the maximum value for mean joint faulting at the end of design life is 0.20 inch.

Since the performance of pavement with constant thickness is investigated in this section, each thickness in Fig. 2 corresponds to a certain case. The pavements over cement-treated base are illustrated by squares and pavements on the asphalt-treated base are shown by circles. The hollow and solid shapes (either squares or circle) in this figure are associated with subgrade 1 (A-7-6) and subgrade 2 (A-1-a), respectively.

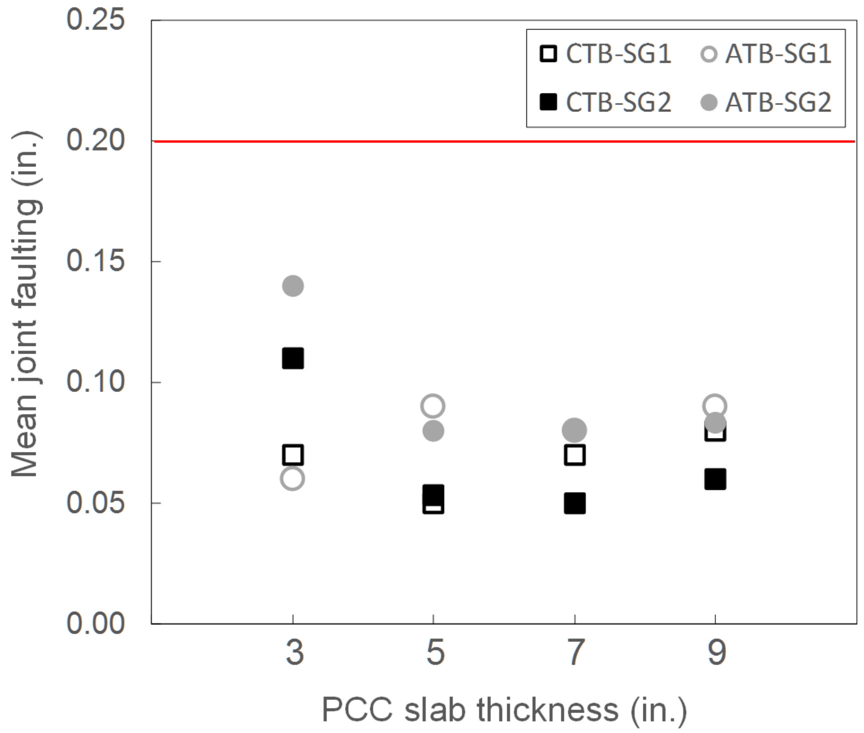


Fig.2. Performance criteria (mean joint faulting) for JPCP with constant thickness

Joint faulting in JPCPs is generally influenced by the characteristics of the underlying material. As can be seen in Fig. 2, the faulting requirement in all cases was satisfied, which means that the pavement will not fail in less than 20 years due to joint faulting. The effect of subgrade material properties is more prominent in pavements with low thicknesses. As expected, the distress in pavement is generally decreasing as the pavement thickness increases. The application of ATB has led to comparatively more joint faulting in pavement.

Fig. 3 illustrates variation of JPCP transverse cracking with the thickness of pavement for different subgrades and stabilized bases. The maximum value for transverse cracking for this primary arterial road in El Paso is 15 percent slab at the end of design life according to MEPDG. From this figure, it can be understood that for JPCPs thicker than 7 in., transverse cracking from temperature gradient and/or drying gradient shrinkage stresses can not be a significant problem; however, for thinner pavements, it can cause high levels of distress, especially for pavements over ATB.

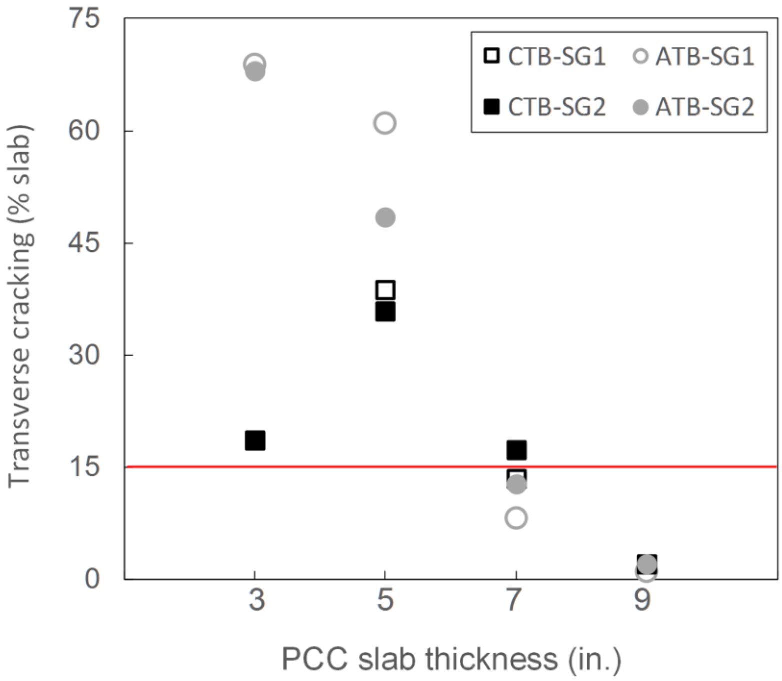


Fig.3. Performance criteria (transverse cracking) for JPCP of constant thickness

In Fig. 4, the effect of CRCP thickness and stabilization agent on the variation of punchouts per mile is shown, which has a maximum value of 10 per mile based on MEPDG. Interestingly, CRCPs with the thickness lower than 7 in. show high level of distress for PPC thickness lower than 9 in., beyond which there is a considerable reduction of pavement distress. This means that by using PCC slabs with thickness lower than 9 in., the pavement will fail due to fatigue cracking. For thin pavements over ATB, the amount of distress (in terms of puchout) is relatively higher (around 40%) than that one over CTB, which is basically due to the considerable effect of temperature and low load transfer efficiency. Beyond the thickness of 5 in., the effect of stabilization agent type on the punchouts in pavement decreases and thus, both base types show the same behaviour.

Fig. 5 summarizes the performance of JPCP and CRCP over CTB and ATB on two types of strong and weak subgrade soils. According to MEPDG, the maximum value for smoothness (IRI) for this primary arterial road in El Paso is 200 in./mile at the end of design life for both JPCP and CRCP. Obviously, by increasing the thickness of PCC, the amount of distress (in terms of roughness of road surface) decreases. As indicated, for cases with the same conditions, CRCPs show higher levels of distress. However, for thick pavements, JPCP and

CRCP show similar behaviours in terms of distress caused by roughness. As expected, the effect of subgrade soil type on the IRI is minimized. In most cases, pavements over CTB show better performance and lower distress in comparison with PCC over ATB.

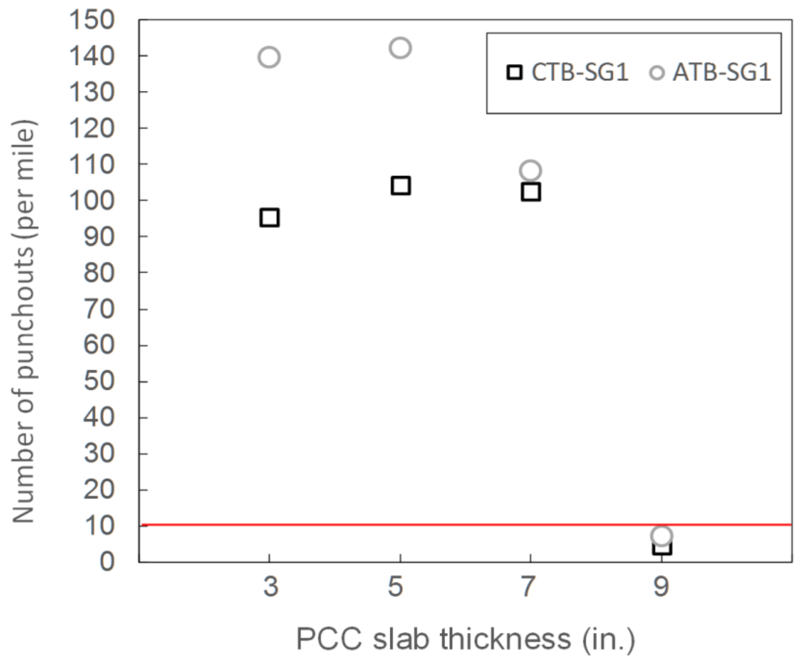


Fig.4. Performance criteria (number of punchouts) for CRCP of constant thickness

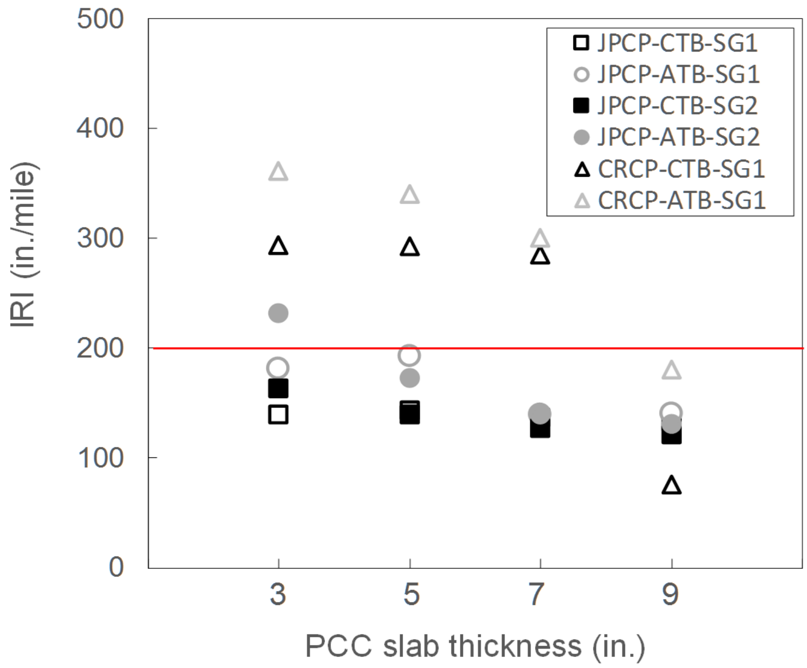


Fig.5. Performance criteria (IRI) for JPCP and CRCP of constant thickness

Generally, beyond the slab thickness of 7 in., where other performance indicators (transvers cracking and IRI) are basically satisfied, a different pattern was observed. Indeed, taking into account the CRCP, the pavement with the thickness of 9 in. has passed the failure criteria for the constant thickness cases considered in this study.

3.2. Varying Thicknesses

In this case, by changing the total thickness of pavement and base layer with one type of subgrade (Fig. 1), the performance of rigid pavements over cement-stabilized base was estimated. The difference between this case and constant one is the material properties of the cement-treated base, which has the elastic modulus of 1,000 ksi. Fig. 6 demonstrates the smoothness (IRI) of JPCPs with varying pavement and base layer thicknesses, in which, almost all investigated cases passed the failure criteria. As opposed to the previous cases, an appropriate reliability level was achieved as a result of using stronger base layer and subsequently, the deficiency caused by the weakness of subgrade layer was overcome. As shown, the beneficial effect of using thicker base layer is just considerable for the thickness of 3 in., beyond which various base layers perform the same.

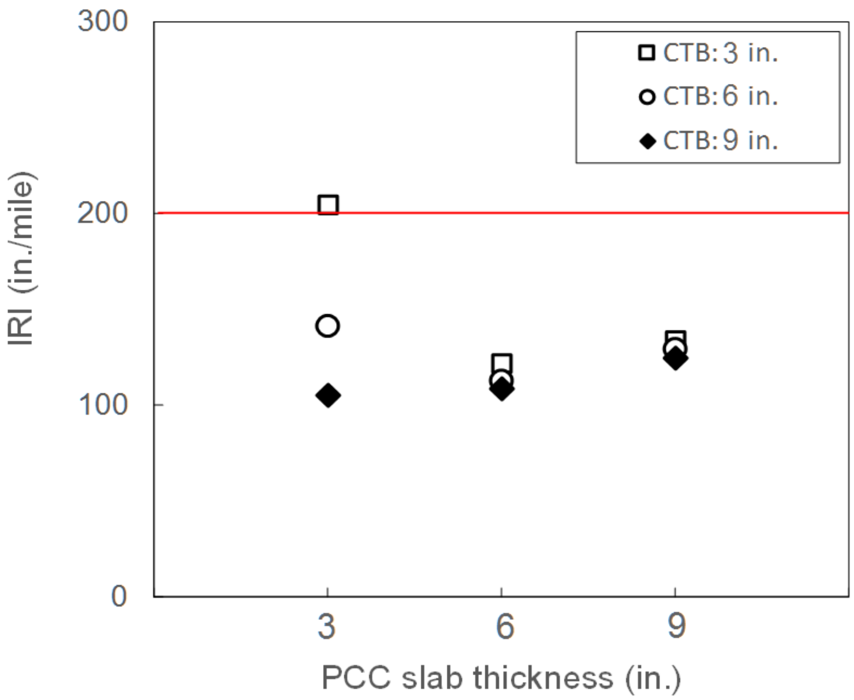
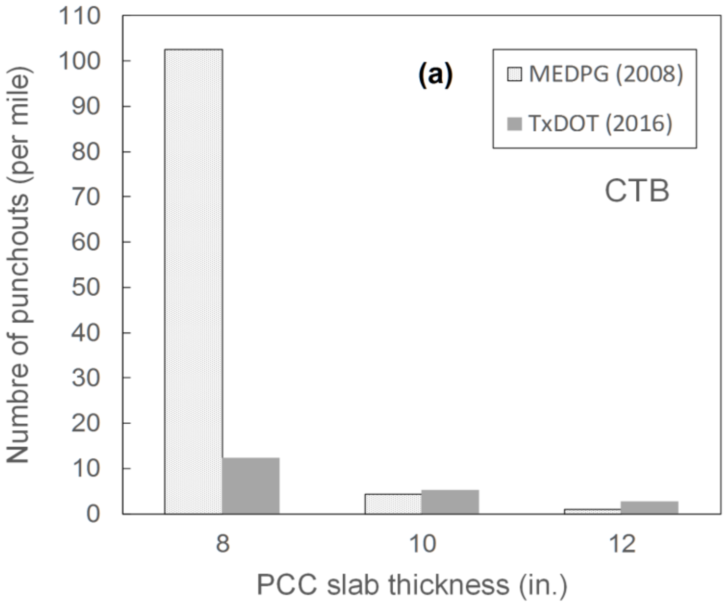


Fig.6. Performance criteria (IRI) for JPCP of varying thickness

3.3. Comparison with TxDOT Procedure

In this section, the estimated distresses in CRCP are compared with those obtained from TxDOT procedure [5, 17]. As stated by Ha et al. [17], a program called TxCRCP-ME was developed by TxDOT for the design of CRCP, which works based on mechanistic finite element modelling of punchouts mechanism in accordance with the traffic, construction and distress data. Calibrated with field evaluation data, this program enables the prediction of the amount of distress in CRCP constructed in any region of Texas.



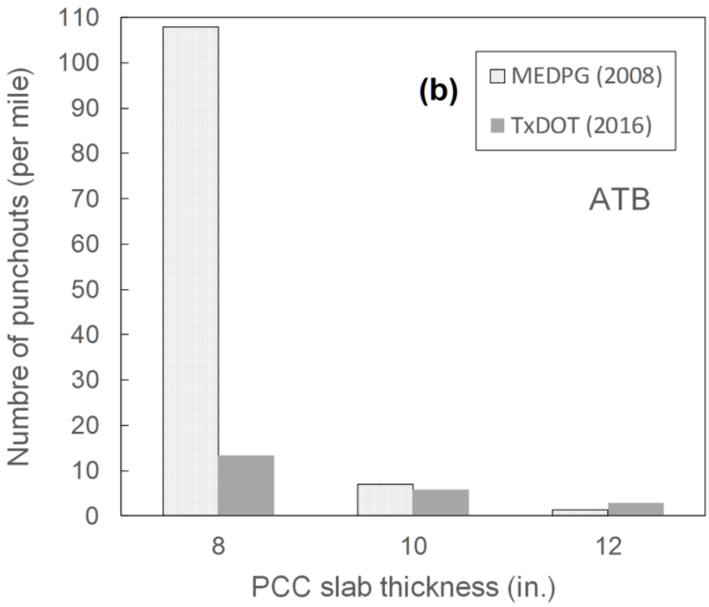


Fig.7. Comparison of punchouts in CRCP using MEPDG and TxDOT procedures

Although the proposed method by TxDOT has some limitations considering the thickness of layers, the constant thickness cases were properly modeled by some negligible modifications. However, the results would not be significantly affected by these assumptions. In Fig. 7, the predicted distresses from MEPDG [4] were compared with those from TxDOT manual [5] for CRCP of varying thicknesses.

As shown in Fig. 7, even though there is much difference between the predicted distresses by MEPDG and TxDOT, the slab with the thickness of 8 in. exceeds the limit number of punchouts of 10 in both cases (CTB or ATB). For CRCP with higher thickness, the mentioned procedures are in good agreement and the pavement can be considered as a design alternative in El Paso.

4. CONCLUSION

According to the procedure and guidelines described in MEPDG and TxDOT design manual, this study presents the results of a series of evaluations for the design of JPCP and CRCP on cement- and asphalt-treated base. Taking into account the recommended performance criteria, the effect of base stabilization on the design alternatives of various pavements was discussed. In most cases in this study, cement stabilization of base layer is more advantageous than asphalt treatment for pavements with low thickness. Moreover, no significant difference between the performance of thick pavements with CTB and ATB was observed.

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