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Behavioral Analysis of Rigid Pavements Utilizing Recycled Base Layers

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Abstract

Sustainable pavement design requires a balanced consideration of economic, environmental, and social impacts. In line with Federal Highway Administration (FHWA) guidelines for sustainable roadway infrastructure, incorporating recycled materials such as reclaimed asphalt pavement (RAP), recycled pavement material (RPM), recycled asphalt shingles (RASs), and warm-mix asphalt (WMA) has been shown to reduce natural resource depletion while promoting circular construction practices. This study investigates the structural performance of Portland cement concrete (PCC) pavements constructed on RAP and RPM base layers. A series of design scenarios was modeled using site-specific laboratory and field data—particularly subgrade soil properties and climatic conditions—from El Paso and San Antonio, Texas. The analysis incorporates unsaturated soil parameters and follows the performance thresholds set by the Mechanistic-Empirical Pavement Design Guide (MEPDG). Findings indicate that concrete mixture design, pavement structure, and local weather conditions are the primary drivers of distress in jointed plain concrete pavements (JPCPs). However, subsoil characteristics have a significant impact on joint faulting in JPCP and punchout occurrences in continuously reinforced concrete pavements (CRCPs), especially in thinner sections. Notably, the use of up to 50% recycled material in the base layer had minimal adverse effects on pavement performance, underscoring its viability as a sustainable design strategy for rigid pavements.

Keywords: recycled asphalt pavement; MEPDG; transverse cracking; joint faulting; punchout; IRI

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1. Introduction

Sustainable development represents a guiding framework that seeks to balance human progress with the preservation of environmental systems necessary to support life and economic activity. It emphasizes the responsible use of resources to meet present needs without compromising the ability of future generations to meet theirs. Recognizing its importance, the United Nations General Assembly adopted the 2030 Agenda for Sustainable Development in 2015, introducing 17 interlinked Sustainable Development Goals (SDGs) aimed at addressing global challenges across environmental, social, and economic dimensions. Within this global agenda, the transportation sector plays a crucial role, particularly through the concept of sustainable transport—defined as the planning and operation of transportation systems in a manner that minimizes environmental

degradation, reduces the consumption of non-renewable resources, and supports broader sustainability objectives [1,2].

In the realm of road infrastructure, the extraction and production of traditional construction materials have long been associated with high energy consumption, greenhouse gas emissions, and land resource depletion. As a result, incorporating recycled and reclaimed materials into roadway construction has emerged as a viable strategy to promote sustainable construction practices. Federal and state transportation agencies, including the Federal Highway Administration (FHWA), have increasingly encouraged the use of alternative materials such as reclaimed asphalt pavement (RAP), recycled asphalt shingles (RASs), recycled pavement material (RPM), and warm-mix asphalt (WMA) to conserve natural resources and reduce construction impacts [3–5]. For instance, recycling rates for RAP have significantly improved over time: in 1993, approximately 80% (73 million tons) of RAP was reused [6], and by 2010, this figure had risen to over 99%, with most of the material incorporated into hot mix base and shoulder layers [7].

The widespread use of these materials underscores a shift toward more environmentally responsible infrastructure development. However, successful implementation depends not only on the availability of recycling technologies but also on the ability of recycled materials to meet structural performance criteria and design specifications at a reasonable cost. Consequently, research has focused on evaluating the feasibility and performance of recycled materials, particularly in lower pavement layers, such as subbase and base courses, where large volumes are required [8,9]. While some studies have explored their use in upper pavement layers [10–17], the base and subbase layers remain the most promising applications due to the structural demands and economic benefits.

Several recent investigations have highlighted the potential of RAP and similar materials in pavement foundations. Hoy et al. [18] explored the mechanical behavior of RAP–fly ash geopolymer mixtures, demonstrating favorable results for base layer applications. Huo et al. [19] demonstrated that cement-stabilized RAP enhances strength and durability in road base applications. Rinya and Pal [20] investigated the influence of residual asphalt binder on the mechanical performance of soil–reclaimed asphalt pavement (RAP) mixtures. They found that residual binder reduced strength across all RAP contents, but the addition of 2% cement significantly improved strength, suggesting viability for base and subbase applications. Zulfiqar et al. [21] evaluated the resilient modulus values of virgin aggregate and recycled aggregate base layers and provided numerical models that accurately capture the strength properties of recycled materials. Titi et al. [22] characterized the physical properties of recycled aggregates recovered from in-service pavement base layers using standardized ASTM testing methods. Their findings confirmed the material's suitability in terms of durability for reuse in future base layer applications. Zhang et al. [23] evaluated the effects of substituting natural limestone with RAP at various percentages in asphalt. They demonstrated that mixtures containing RAP substitutions achieved acceptable modulus results, supporting their feasibility for sustainable pavement applications. These studies have paved the way for the integration of recycled materials into mechanistic pavement design frameworks.

The Mechanistic-Empirical Pavement Design Guide (MEPDG) [24] represents a significant advancement in pavement engineering, enabling the analysis of pavement performance by integrating material properties, traffic loading, climate conditions, and structural configurations. It provides a scientifically grounded approach for evaluating design variability and reliability at both project and network levels. In response to this evolving methodology, the Texas Department of Transportation (TxDOT) has adopted an implementation and calibration plan to transition from empirical to mechanistic-empirical pavement design, particularly for rigid pavement systems [25]. Ha et al. [26] contributed a TxDOT-

based design procedure for continuously reinforced concrete pavement (CRCP), leveraging localized data to improve design accuracy.

While extensive research has been conducted on the use of RAP and other recycled materials in pavement systems, further investigation is needed to advance their effective implementation. A key limitation of prior studies lies in the lack of regional calibration within mechanistic-empirical pavement design models. This study addresses that gap by leveraging locally available materials, construction practices, and region-specific specifications from ongoing projects to develop models that more accurately predict site-specific pavement performance. Another shortcoming in existing research is the treatment of design input parameters in isolation, often neglecting interactions between variables. This simplification can lead to inaccurate performance predictions. The current study improves upon this by incorporating interdependencies among input parameters into the modeling process, enhancing the reliability of the outcomes. Beyond its localized focus, this research also provides generalized design guidance for the use of recycled materials in pavement systems. It identifies the most influential design parameters and offers a framework for their systematic consideration, supporting more uniform and effective application across similar projects. In doing so, the study overcomes several limitations observed in prior works and contributes to the broader goal of sustainable infrastructure development.

This study focuses on the M-E design of rigid pavements—CRCP and jointed plain concrete pavement (JPCP)—by incorporating different reclaimed base materials (RAP and RPM) with or without milling. These materials were assessed under two distinct traffic loading conditions in Texas using MEPDG performance criteria such as transverse slab cracking, mean joint faulting, international roughness index (IRI), and both top–down and bottom–up cracking. The interaction of design variables was explored to optimize pavement design, and MEPDG outputs were compared with those from TxDOT's design framework. In contrast to conventional practices, where many design parameters are determined based on historical precedents and empirical assumptions, this study advocates for a data-driven, performance-based approach to future pavement design. Specifically, it emphasizes the parametric optimization of input parameters for recycled pavement foundation materials considering interactions among key design inputs to enhance structural performance and sustainability. This research validates results against TxDOT's CRCP-ME tool. The inclusion of up to 50% recycled material in the base layer further highlights the feasibility of sustainable pavement design without compromising performance.

2. Materials and Methods

In order to conduct pavement design using MEPDG, the designer first considers the site conditions (traffic loading, environmental conditions, material strength, and quality from historical pavement condition data, such as the pavement management system, PMS) and then evaluates for adequacy against performance criteria (i.e., prediction of distresses and smoothness). To take into account the sustainability of the design, environmental impacts must be considered through the most important stages of the process (Figure 1).

The design problem consisted of a jointed plain or continuously reinforced concrete pavement for a period of 20 years in El Paso and San Antonio, Texas. The project began in February 2019 and, after a construction period of three months, the section was opened to traffic in May 2019. This primary arterial road was constructed toward the North with a length of 10 miles. According to MEPDG, it is expected that at the end of its design life, JPCP will have no more than 15% transverse slab cracking, 0.20 in. joint faulting at a reliability level of 90%, and a terminal IRI of 200 in./mile at a reliability level of 95%. For CRCP, the pavement will have no more than 10 punchouts per mile and a terminal IRI of 200 in./mile at a reliability level of 90% [27].

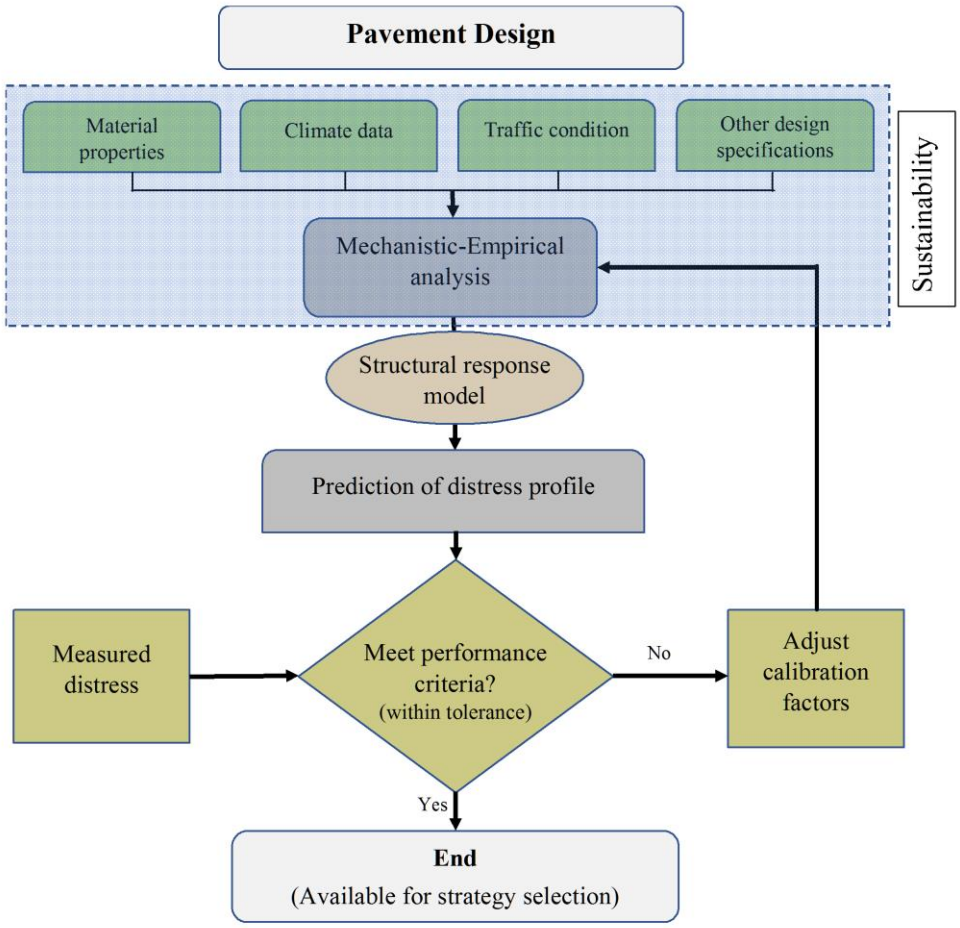


Figure 1. Schematic image of improvement of the M-E design process by taking into account sustainability.

2.1. Traffic

The overall growth of the industry and population of cities has led to a wide variety of traffic loads from different vehicle classes. Thus, traffic load is a key parameter in structural analysis and design of road pavement. To take into account the traffic load, the previous guide for pavement design [28] used the ESAL approach for traffic characterization. Although the new M-E design process employs axle load spectra instead of ESAL, it is used in the current procedure for the design of CRCPs in Texas [29]. The axle load spectra have been determined according to weighing-in-motion (WIM) data based on the loading magnitude, configuration, and number of load repetitions.

However, in this study, a two-lane highway with an estimated average annual daily truck traffic (AADTT) of 2200 trucks in both directions during the first year of service was considered for the M-E design and an ESAL value of 25 million was used for the design of CRCP based on the TxDOT guide. The percentage of trucks in the design lane was 90%, with equal distribution in both directions. The operational speed was assumed to be 60 mph. The normalized truck volume distribution was according to TTC (Truck Traffic Classification) groups 2 and 10 in MEPDG, corresponding to high percentages of single-trailer trucks (heavy traffic load) and mixed trucks (medium traffic load), respectively, determined from LTPP sites (see Figure 2). It was assumed that the traffic pattern remained constant throughout the year and increased by 4% of the preceding year on an annually compounded basis. Axle load configuration (average axle width and spacing as well as tire spacing) was taken from the WIM database for the standard truck class, as mentioned in MEPDG [27].

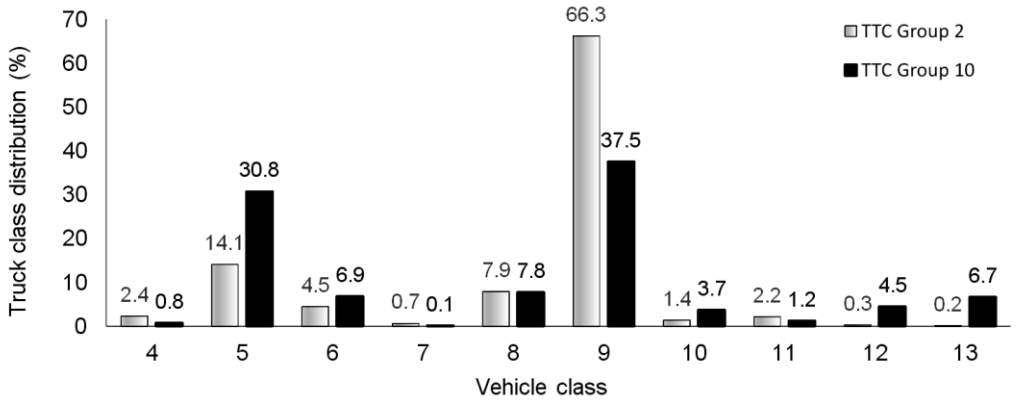


Figure 2. AADTT distribution by vehicle class included in the design [30].

2.2. Climate

The climate data used in the design of this project were taken from weather stations in El Paso (31.811 N, 106.376 W) and San Antonio (29.533 N, 98.464 W), near the city airports, so that the average daily temperature, precipitation, and wind speed, relative humidity, frost depth, and number of freeze–thaw cycles could be implemented in predicting pavement distress. According to the available geotechnical reports, the depth of the ground water table was set to 10 ft. for San Antonio and 30 ft. for El Paso to take into consideration changes in the resilient modulus of aggregate layers and foundation soils over time [27].

2.3. Drainage and Surface Properties

The design needs to include positive measures to minimize the potential for reduced service life due to saturated structural layers or pumping caused by inadequate subsurface drainage, particularly in PCC pavements where the drainage analysis or past performance indicates that potential. If enough attention is not paid to the drainage properties of the underlying pavement layers, the infiltration of water may cause issues regarding the strength of unbound materials, pumping and shoulder deterioration, and heaving of swelling soils. Therefore, in this study, the drainage properties were defined as 2% of the highway cross-slope, a length of the drainage path of 12 ft. from the centerline to the edge, and a surface shortwave absorptivity of 0.85 [27].

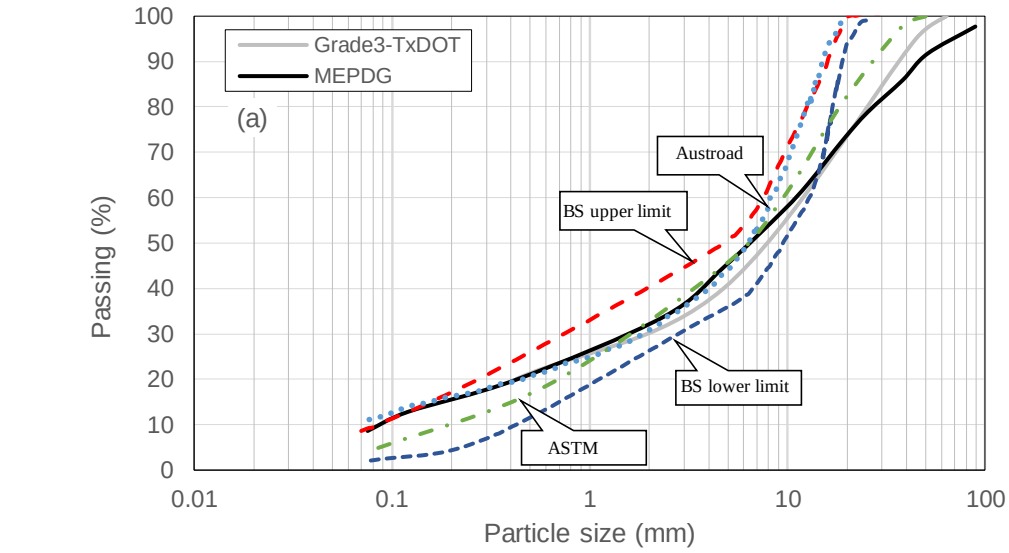
2.4. Material Properties

In this study, the pavement structure comprised three layers, including PCC slab (JPCP or CRCP), recycled base material (RAP or RPM, with or without milling, respectively), and subgrade (El Paso coarse-grained soil A-1-a and fine-grained soil A-6; San Antonio coarse-grained soil A-1-a and fine-grained soil A-7-6). The performance of two rigid pavement types was investigated in two cases of constant pavement depth (rigid pavement plus underlying layer equal to 16 in.), where the thickness of PCC ranged from 5 to 12 in. (as recommended by TxDOT). Table 1 lists the initial configuration, strength, and material properties of the rigid pavements, mostly derived from a certain concrete mix in Texas based on the TxDOT pavement manual. Some of the listed parameters were changed later to conduct a parametric study. It was assumed that the concrete was cured using the compound method, and the main aggregate type of the mixture was dolomite. The values of zero-stress temperature and ultimate shrinkage were calculated according to the equations presented in MEPDG.

Table 1. PCC mixture design inputs.

Properties	JPCP	CRCP
Unit weight (pcf)	145	145
Poisson's ratio	0.2	0.2
Cement type	Type I	Type I
Water to cement ratio	0.42	0.40
28-day modulus of rupture (psi)	850	690
Elastic modulus (ksi)	5000	4200
Coefficient of thermal expansion $(\text{in./in./}^{\circ}\text{F} \times 10^{-6})$	6.3	5
Surface shortwave absorptivity	0.85	0.85
Thermal conductivity (BTU/hr.-ft.-°F)	1.25	1.25
Heat capacity	0.28	0.28
Lane width (ft.)	12	12
Dowel diameter and spacing (in.)	1.25–12	-
Joint spacing (ft.)	15	-
Bar diameter and depth (in.)	-	0.63–4
Reinforcement (%)	-	0.6

As discussed earlier, the use of reclaimed materials in road construction avoids the energy and emissions associated with processing construction materials, saving natural resources (e.g., gravel, limestone, oil) for necessary applications, increasing the service life of infrastructures, and minimizing life cycle costs (economic sustainability). Successful applications of recycled pavement materials for use in base and/or subbase courses in Texas (excellent applications in San Antonio and El Paso) have been reported [31]. Figure 3 illustrates the grain size distribution of recycled pavement materials and recycled asphalt pavement according to the recommendations of MEPDG [24] and TxDOT specifications for flexible bases [31], which are used for modeling in the parametric study. The standard grading envelope specified in BS 4987 [32], as well as the particle size distribution itemized by ASTM D2940-15 [33] and Austroads (Sydney, Australia) [34], are demonstrated in the figure for comparison. As indicated, the grain size distribution suggested by TxDOT matches well with that from MEPDG, which requires using high percentages of coarse-grained materials in the mixture. Interestingly, the particle size distribution proposed by Austroads practically falls between the limits suggested in BS. In addition to the particle size distribution, the liquid limit and plasticity index of the base materials were correspondingly set as 6% and 1% for RPM and 40% and 12% for RAP [24,32], respectively. A maximum dry unit weight of 125 pcf and Poisson's ratio of 0.3 were used in the analyses. The resilient modulus of the base layer was modified by the temperature/moisture conditions (level 3); however, variant initial values from 30 to 40 ksi for the RPM base and 25 to 35 ksi for the RAP base were respectively used for the parametric study. These values were obtained from laboratory tests conducted at the University of Texas at El Paso on a conventional mixture of recycled materials with virgin material (10 to 50% recycled material in the mixture).





(**b**)



(**c**)

Figure 3. (**a**) Comparison of grain size distribution of RPM/RAP used in this study with other specifications [24,32,33,35]. (**b**) Photo of recycled pavement material (RPM). (**c**) Photo of recycled asphalt pavement (RAP).

For the subgrade soil, for each area of study, two types of coarse-grained soil (A-1-a) and fine-grained soil (A-7-6 in San Antonio and A-6 in El Paso) were selected. In order to estimate the material properties of subgrade soil, the procedure proposed by Fredlund and Xing [36], according to the Soil–Water Characteristic Curve (SWCC), was employed, which defines the relationship between water content and suction of any particular soil. It is worth noting that this approach was also implemented in the "Environmental Effects" section of report NCHRP 1-37A [36]. Thus, four SWCC model parameters, a_f, b_f, c_f, and h_r, needed to be calculated based on the following equations, which were obtained from non-linear regression analyses and correlated with $P_{200} \times PI$ and D_{60} [36].

If $P_{200} \times PI > 0$

$$\begin{aligned} a_f &= \frac{0.00364(P_{200}PI)^{3.35} + 4(P_{200}PI) + 11}{6.895} \text{ psi} \\ \frac{b_f}{c_f} &= -2.313(P_{200}PI)^{0.14} + 5 \\ c_f &= 0.0514(P_{200}PI)^{0.465} + 0.5 \\ \frac{h_r}{a_f} &= 32.44e^{0.0186(P_{200}PI)} \end{aligned} \quad (1)$$

If $P_{200} \times PI = 0$

$$\begin{aligned} a_f &= \frac{0.8627(D_{60})^{-0.751}}{6.895} \text{ psi} \\ b_f &= 7.5 \\ c_f &= 0.1772 \ln(D_{60}) + 0.7734 \\ \frac{h_r}{a_f} &= \frac{1}{D_{60}+9.7e^{-4}} \end{aligned} \quad (2)$$

where P_{200} is the percentage of soil particles passing sieve number 200 (%), PI is the plasticity index of the soil (%), and D_{60} defines the diameter that 60% of soil particles by weight are smaller than.

With respect to the foregoing explanations, the data collected by Puppala et al. [37] were employed to determine the SWCC model parameters. According to their study, for El Paso clay, P_{200} = 88% and PI = 16%, while for San Antonio clay, P_{200} = 83% and PI = 36%. The available geotechnical reports revealed that D_{60} values for El Paso and San Antonio coarse-grained soil could be estimated as 11 and 14 mm, respectively. Therefore, the properties of the subgrade soil are summarized in Table 2. The soil resilient modulus was adjusted based on the temperature and moisture characterization. The thickness of the subgrade soil was set to 12 ft. to avoid the boundary effect.

Table 2. Subgrade soil properties.

Properties	El Paso		San Antonio	
	A-6	**A-1-a**	**A-7-6**	**A-1-a**
Resilient modulus, M_r (ksi)	13	16	12	18
Unit weight, γ (pcf)	105	120	100	130
Poisson's ratio, ν	0.35	0.30	0.35	0.30
Specific gravity, G_s	2.70	2.67	2.70	2.67
SWCC parameters (Equations (1) and (2))	a_f = 1.677 b_f = 1.688 c_f = 0.520 h_r = 54.546	a_f = 0.757 b_f = 7.500 c_f = 1.198 h_r = 0.089	a_f = 1.769 b_f = 1.612 c_f = 0.529 h_r = 57.697	a_f = 0.908 b_f = 7.500 c_f = 1.241 h_r = 0.070

The durability of the recycled base material was assessed in a separate study. Overall, based on that study, the durability of the material in terms of water absorption and tensile strength due freeze–thaw suggested that RAP does not disproportionately affect the durability of the pavement foundation.

3. Results and Discussion

A parametric study taking into consideration different variables for the M-E design of JPCP and CRCP in El Paso and San Antonio was conducted. In this section, the results of approximately 1500 runs in the AASHTOWare program version 2.3 are presented and discussed to find the most significant design factors in each design case.

It is noteworthy that, as one advantage of this study, the correlations and interactions between input parameters were taken into account, which eliminated the significant shortcomings in previous studies [38,39] and led to obtaining a more realistic set of input parameters that would avoid producing unreliable results. For example, in the case of investigating the effect of the concrete modulus of rupture, the elastic modulus and other mixture properties of the concrete were subsequently adjusted.

In this section, for cases where a given factor is investigated, the average amount for other parameters was assumed. For instance, in exploring the effect of the modulus of rupture, a PCC thickness of 9 in. (base thickness of 7 in.), a modulus of the RAP base of

30 ksi, high traffic 1 (TTC group 2), and subgrade type 1 (columns 2 and 4 in Table 2) were considered.

3.1. Joint Faulting

Figure 4 summarizes the significance of the studied factors on the mean joint faulting of JPCP in El Paso and San Antonio. These factors include PCC thickness, modulus of rupture of concrete, coefficient of thermal expansion, joint spacing, shoulder condition, modulus of the base layer, subgrade layer material, and traffic classification. The range of values of the design parameters was taken from the typical values suggested in the literature.

The analysis highlights that slab-related parameters—specifically slab thickness, coefficient of thermal expansion (CTE), and joint spacing—exert a more significant influence on PCC pavement performance than recycled base layer properties or traffic loading. According to MEPDG criteria, the acceptable threshold for mean joint faulting is 0.2 inches, under which all simulated scenarios fell, indicating satisfactory performance. Consequently, other distress parameters, such as transverse cracking and surface smoothness, will be more critical in governing the final design.

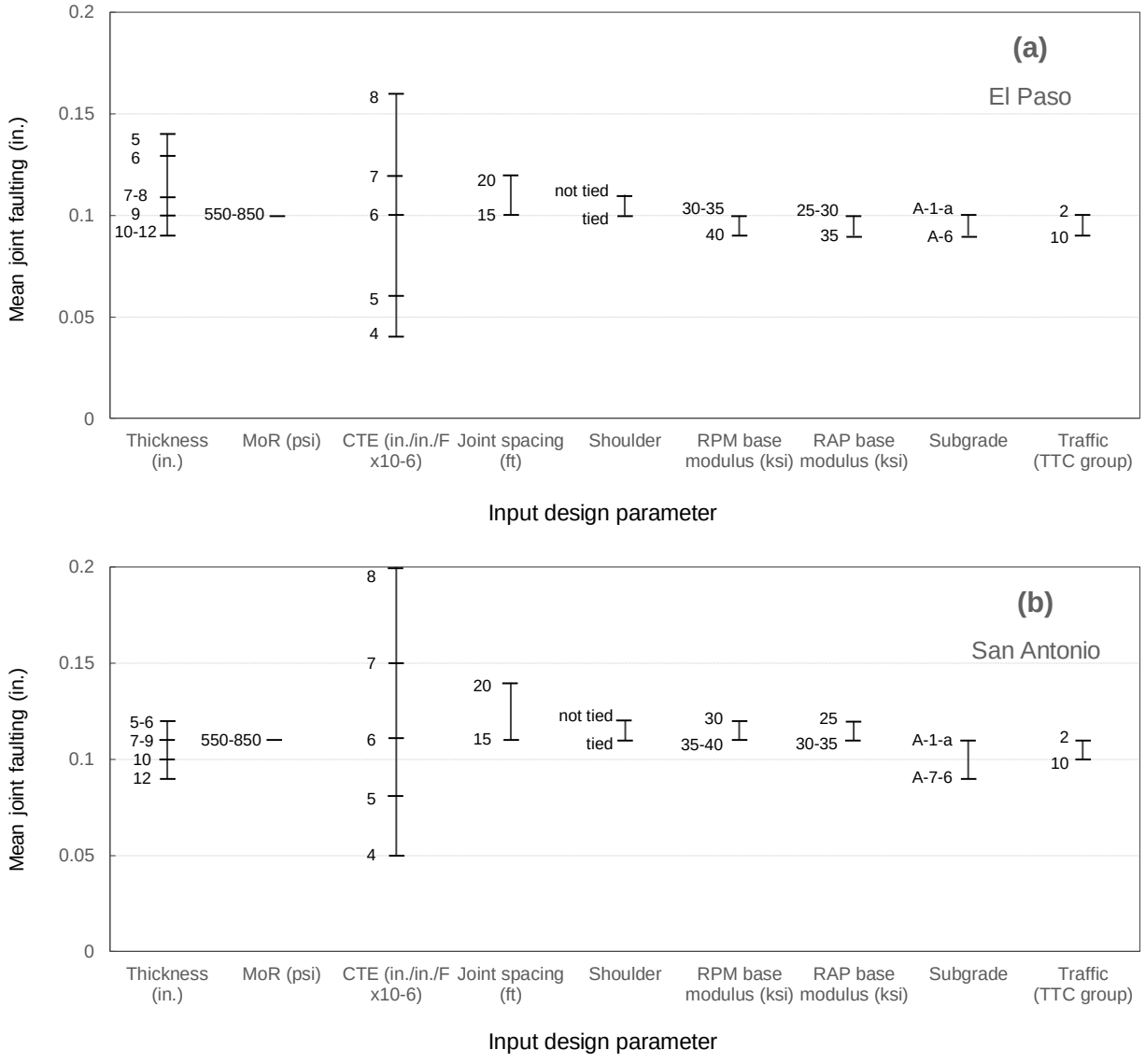


Figure 4. *Cont.*

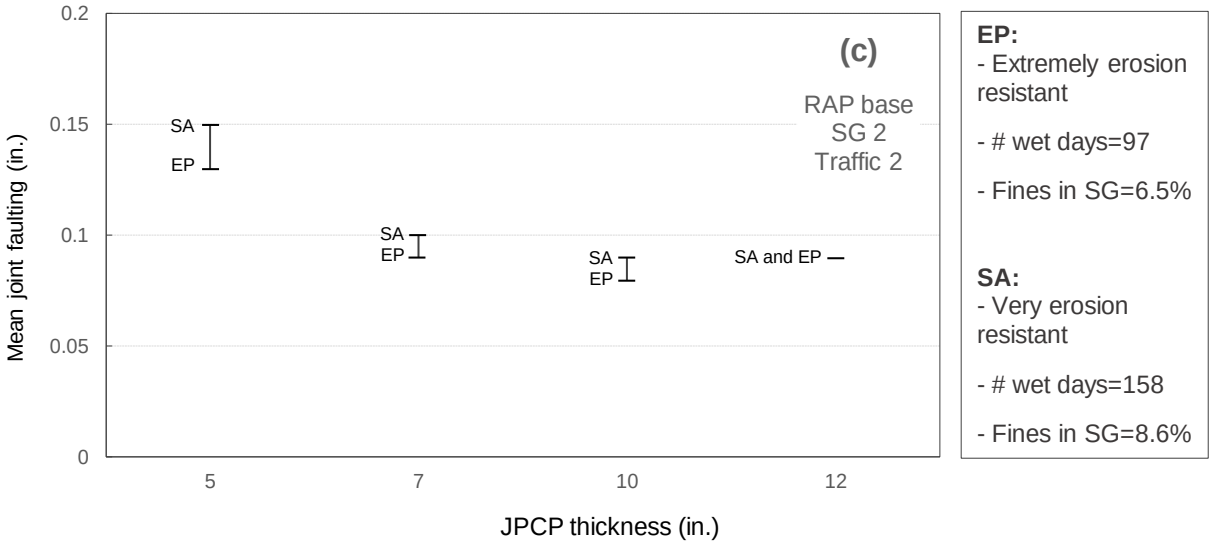


Figure 4. Effects of design input parameters on the mean transverse joint faulting of JPC pavements in (**a**) El Paso and (**b**) San Antonio. (**c**) Effect of parameters considered in joint faulting calculation for pavements of different thicknesses.

While increasing the slab thickness reduced the mean joint faulting by approximately 30% in San Antonio and 35% in El Paso due to enhanced aggregate interlock from a larger load transfer area across transverse joints, this approach should not be adopted as a primary design variable. Instead, optimizing slab thickness is crucial for cost effectiveness, as even a reduction of 0.5 inches can result in substantial savings in pavement construction.

The effect of concrete mix design, particularly the coefficient of thermal expansion, was also evident. As the CTE increases, larger joint openings and reduced aggregate interlock occur, thereby decreasing load transfer efficiency. This phenomenon is most pronounced under negative temperature gradients, where slab curling further exacerbates faulting. Accordingly, higher mean joint faulting was observed in San Antonio compared to El Paso, attributed to lower average nighttime temperatures in the former, which intensified slab curling effects.

As expected, extending joint spacing to reduce construction costs leads to increased joint faulting. A 33% increase in joint spacing resulted in approximately 20% higher mean joint faulting at both sites. The presence of tied concrete shoulders in the baseline design offered improved lateral support and reduced edge stresses. However, designs incorporating untied shoulders demonstrated only a marginal effect on performance, suggesting that untied shoulders may be a viable option depending on required load transfer efficiency.

Regarding the contribution of subsoil layers to pavement performance, the inclusion of up to 50% recycled material in the base layer was found to slightly increase joint faulting (by around 10%) due to a reduced base modulus. Nevertheless, this trade-off is acceptable given the cost savings and sustainability benefits associated with recycled materials. The influence of the recycled material source differed slightly between the two sites, resulting in variations in the base modulus and associated faulting levels.

Subgrade properties exhibited a more pronounced effect on pavement response in San Antonio. Comparative analysis indicated that El Paso's coarse-grained, erosion-resistant subgrade led to lower joint faulting, while San Antonio's finer-grained subgrade with higher moisture susceptibility (i.e., more wet days and higher fines content) increased faulting, particularly in thinner PCC slabs. These findings suggest that thicker rigid pavements can mitigate the influence of adverse climate and subgrade conditions, enhancing overall structural resilience.

3.2. Transverse Cracking

According to M-E design guidelines, transverse slab cracking is considered as bottom–up (BUC) and top–down (TDC) modes of fatigue cracking. The former is the result of tensile strain at the bottom of the PCC slab exceeding a threshold value, leading to the initiation of cracks that propagate upward to the slab surface due to repeated load application. The latter is mainly attributed to the combination of loading at both slab transverse edges simultaneously: upward curling of the slab due to the presence of a negative temperature gradient and bottom layer settlement [37]. Using this concept, utilizing the higher thickness to avoid critical tensile strain at the bottom of the slab needs to be justified such that the appearance of load-related TDC in thick PCC layers can be eliminated. Although construction-related TDC may contribute to the ultimate cracking behavior of pavement as a result of the segregation of the concrete mixture or loss of bonding between concrete lifts, critical design scenarios take into account load-related TDC as they are associated with material properties (e.g., modulus and failure properties), pavement structure, traffic, and climate. Therefore, the influence of these design variables on pavement transverse cracking in El Paso is presented in Figure 5a and the ratios of top–down to bottom–up cracking contributing to the pavement cracking behavior are characterized in Figure 5b,c for both construction sites.

As illustrated in Figure 5a, slab properties and traffic conditions have more prominent effects on pavement transverse cracking than base and subgrade layer properties, which is beneficial to the use of high amounts of recycled materials being mixed with virgin material in the base layer. However, the use of a stabilized base layer can significantly affect the cracking response [40]. A similar trend was observed for the pavement modeled in San Antonio, which is not presented here for the sake of brevity. As recommended by MEPDG, transverse slab cracking should not exceed 15% of the slab for primary highways. According to this figure, the thickness of the PCC slab considerably affects the transverse cracking behavior, such that only pavements thicker than 9 in. met the minimum design requirement. In contrast to mean joint faulting, transverse cracking of JPCP is highly affected by the concrete modulus of rupture. It can be seen that by modifying the concrete mixture, the level of distress in terms of cracking can be controlled. A similar conclusion can be made for changing the coefficient of thermal expansion with the concrete mixture, where a smaller CTE value decreases the vulnerability of the slab to curling and warping. Using shorter slabs (less joint spacing) leads to less curling and warping, which can effectively reduce transverse cracking. The effect of traffic loading on transverse cracking should be taken into account since the loading configuration based on TTC group 2 indicated twice as much cracking as that from TTC group 10.

In order to clarify the contributions of top–down and bottom–up cracking to the overall cracking behavior of JPCP at different sites and climate conditions, the scattered plots of all the results in Figure 5b,c need to be considered. As discussed earlier and can be seen in this figure, by increasing the thickness of the slab, the ratio of top–down to bottom–up cracking increases, so that the TDC/BUC ratio becomes greater than 1 for a PCC slab thicker than 10 in., i.e., transverse cracking for those pavements is mainly controlled by top–down cracking. Generally speaking, it can be said that the TDC/BUC ratio in San Antonio was greater than the corresponding values for El Paso, which can be explained by different climate conditions and thus variant thermal gradients within the concrete pavements. One may discuss the effects of recycled material properties from different sources at these construction sites.

Another interesting observation is that the schematic data cloud analogy indicates a larger discrepancy of datapoints in San Antonio compared to El Paso. In other words, the results indicate that the distance from the mean increases with changing the site and

climate conditions in San Antonio and, therefore, more investigation is required at this site to eliminate the degree of uncertainties in the design.

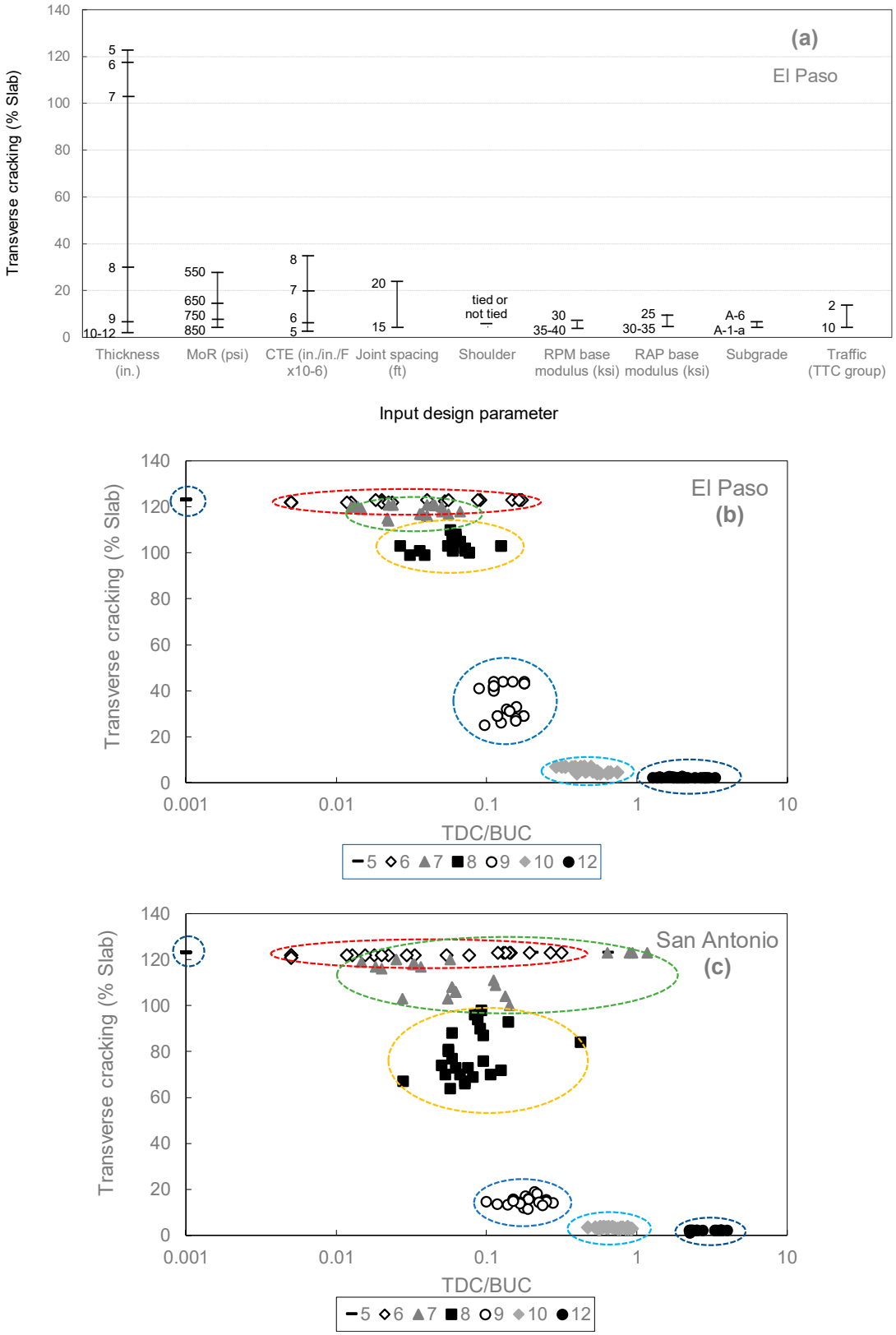


Figure 5. (**a**) Effects of design input parameters on the mean transverse joint faulting of JPC pavements in El Paso. (**b**,**c**) The contributions of top–down cracking (TDC) and bottom–up cracking (BUC) to the transverse cracking of JPCP.

3.3. Punchouts

In continuously reinforced concrete pavement (CRCP), the two primary categories of distress are spalling and punchout. In the context of Texas roadways, punchouts encompass various forms of localized damage, including distress at transverse construction joints, horizontal cracking, construction-related deficiencies, and inadequate load transfer at longitudinal joints [28]. Although structurally induced punchouts develop gradually over time, addressing their root causes requires more than simply increasing slab thickness.

Key factors influencing punchout formation include the modulus of rupture of the concrete, percentage of longitudinal steel reinforcement, and subgrade soil properties, as illustrated in Figure 6. According to MEPDG guidelines, the allowable limit for punchouts is 10 occurrences per mile. The analysis indicates that increasing the amount of longitudinal steel reinforcement can significantly reduce the number of punchouts—by up to 60% at both study sites (El Paso and San Antonio). However, this relationship was assessed at a slab thickness of 9 inches. Since thicker slabs (e.g., >10 inches) generally met the performance criteria, an optimal combination of slab thickness and steel percentage must be determined to balance performance, constructability, and cost. Excessive steel content can lead to additional cracking and practical challenges during construction.

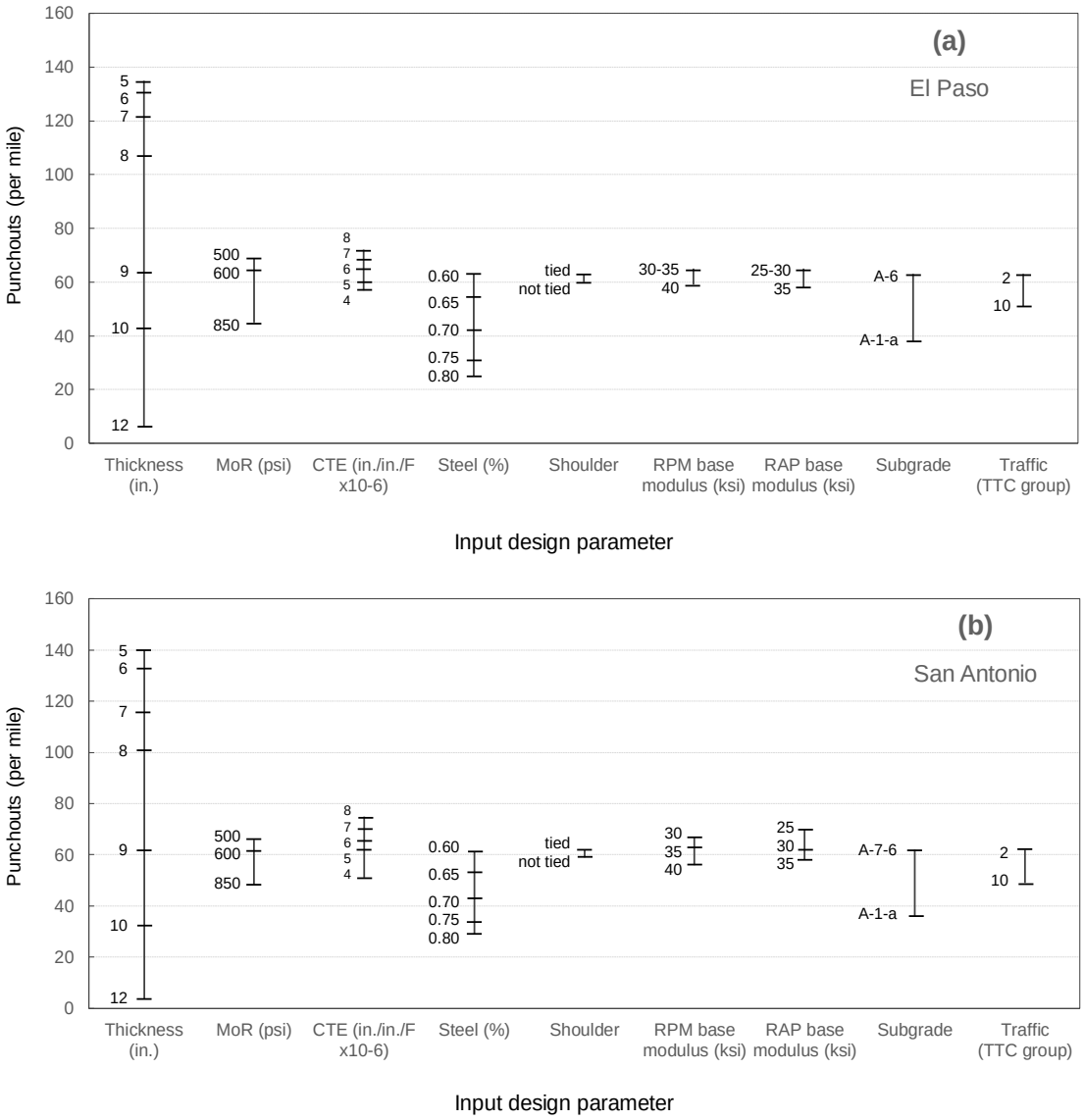


Figure 6. Effect of design input parameters on CRCP punchouts in (**a**) El Paso and (**b**) San Antonio.

Another notable observation is the impact of subgrade and base layer properties on CRCP performance, particularly in San Antonio. Here, the use of different blends of recycled and virgin aggregates in the base resulted in varying modulus values, which more strongly influenced the number of punchouts compared to El Paso. The subgrade itself plays a critical role: an increased fines content is associated with greater susceptibility to soil consolidation and erosion—two mechanisms that contribute directly to punchout formation.

While traffic loading is a well-recognized contributor to pavement cracking, its interaction with CRCP behavior becomes more complex in scenarios involving suboptimal steel placement (e.g., above mid-depth), weak bonding between steel and concrete, or poor-quality subsoil layers. Under such conditions, varying traffic loads may exacerbate structural deterioration and merit separate consideration during the design phase.

3.4. Smoothness

According to MEPDG, smoothness (IRI) is determined by taking into account the initial as-constructed profile of the pavement and other developed distress and movements that make any changes to the longitudinal profile. For JPCP, these distresses include cracking, spalling, and faulting, while the smoothness of CRCP is mainly affected by punchouts. The threshold value for IRI at the end of design life is 200 in./mile for both JPCP and CRCP. To assure the production of valid results, the IRI model was calibrated using LTPP data. Hence, Figure 7 summarizes the slab properties and subsoil conditions on the variations in IRI for JPCP and CRCP in El Paso and San Antonio. Regarding JPCPs, there was no major change to the IRI for pavements in San Antonio, except for the RAP base modulus, which increased the IRI for thin pavements. However, the RAP base modulus had a slight effect on the IRI of JPCPs in El Paso. At low thickness, increasing the coefficient of thermal expansion increased the IRI up to 35%, and at high thickness, the increase from decreasing the modulus of rupture (up to 50%) with respect to the primary model was more prominent. Therefore, by establishing a concrete mixture that balances the strength and thermal properties of the slab, the IRI value of JPCP can be justified to meet the design requirements. It should be noted that the trend of change in IRI with the thickness of JPCP needs to be investigated, as JPCP with a thickness of 9 in. in San Antonio met the design requirements, while a thickness of 10 in. was required in El Paso for satisfactory design. Taking into account the smoothness of CRCP at the two sites, no significant change was observed, neither in the trend nor in the values of IRI, by changing the design parameters, i.e., a CRCP thickness of more than 10 in. was required.

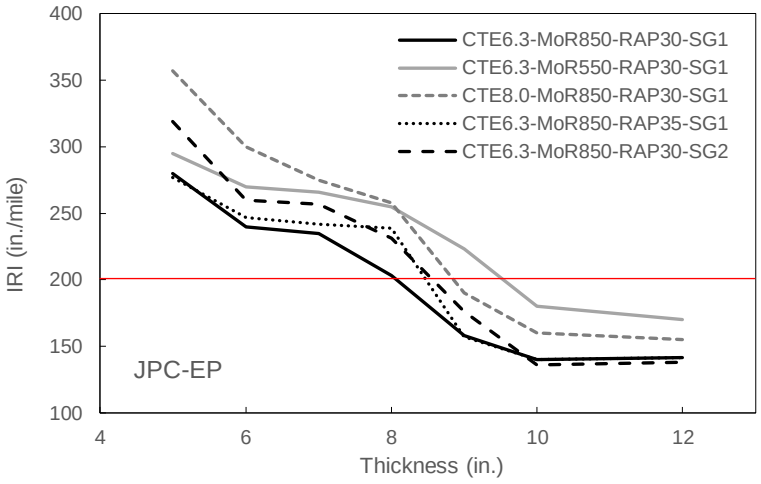


Figure 7. *Cont.*

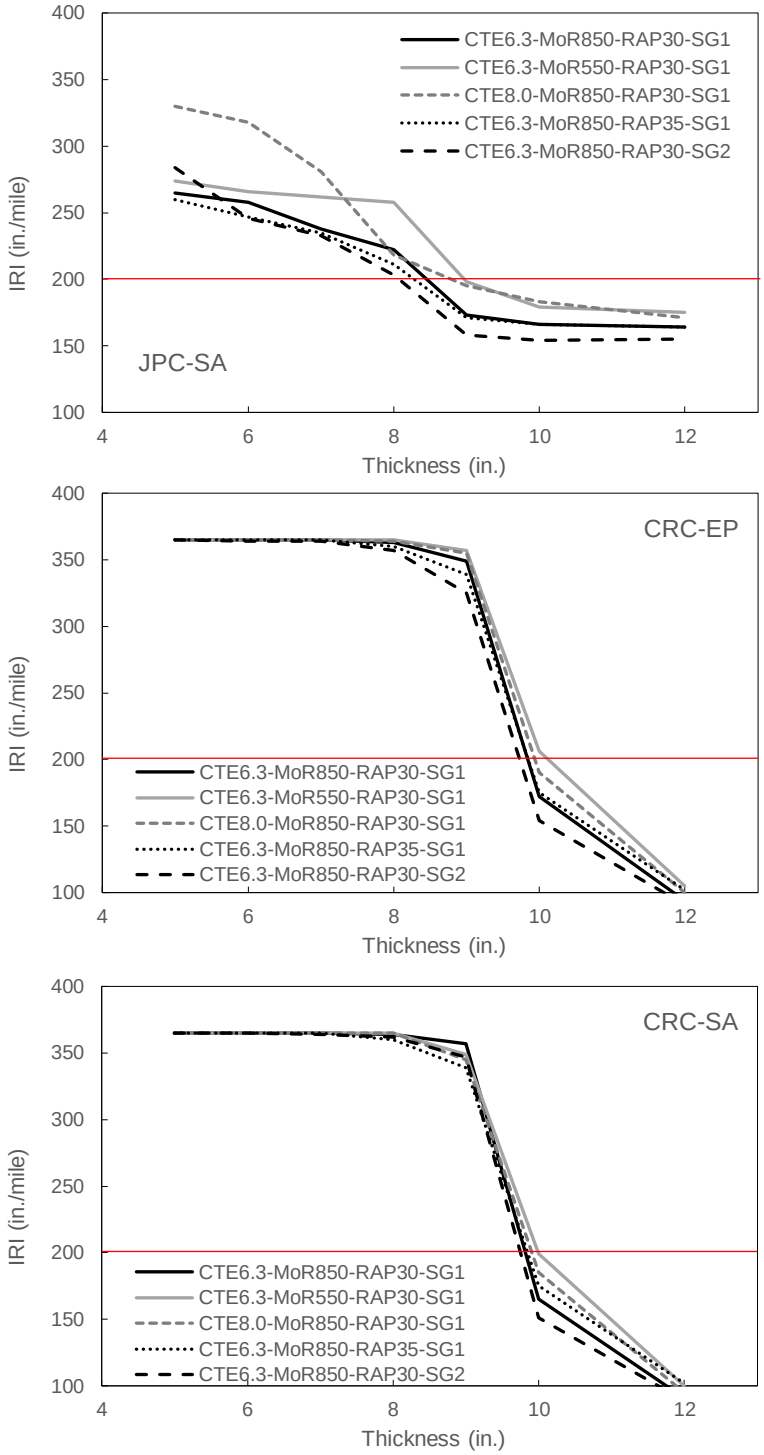


Figure 7. The variation in IRI with the thickness of JPCP and CRCP for different sublayer properties and concrete mixtures.

3.5. Comparison of MEPDG and TxDOT Guidelines

Since 2016, the Texas Department of Transportation (TxDOT) has recommended the use of the CRCP-ME spreadsheet tool for the mechanistic-empirical (M-E) design of continuously reinforced concrete pavements (CRCPs), as developed and documented by Ha et al. [26]. This tool is grounded in a comprehensive understanding of punchout mechanisms derived from field evaluations and employs a transfer function calibrated through mechanistic modeling of cumulative damage. The modeling relies on accurate and localized data related to traffic loading, construction practices, and pavement distress,

primarily sourced from TxDOT's Pavement Management Information System (PMIS). As a result, CRCP-ME serves as a locally calibrated and reliable predictive tool for evaluating CRCP performance across various Texas districts and counties.

To assess the consistency and applicability of nationally calibrated models, results from this study—derived using the Mechanistic-Empirical Pavement Design Guide (MEPDG)—were compared against predictions obtained using the CRCP-ME tool (see Figure 8). The comparison revealed a notable divergence in predicted punchouts for thin CRCP sections: MEPDG tended to yield more conservative estimates that may lead to overdesign, whereas CRCP-ME provided predictions more aligned with local performance data. By contrast, for thicker CRCP designs that satisfied performance criteria, the predictions from both methodologies showed strong agreement.

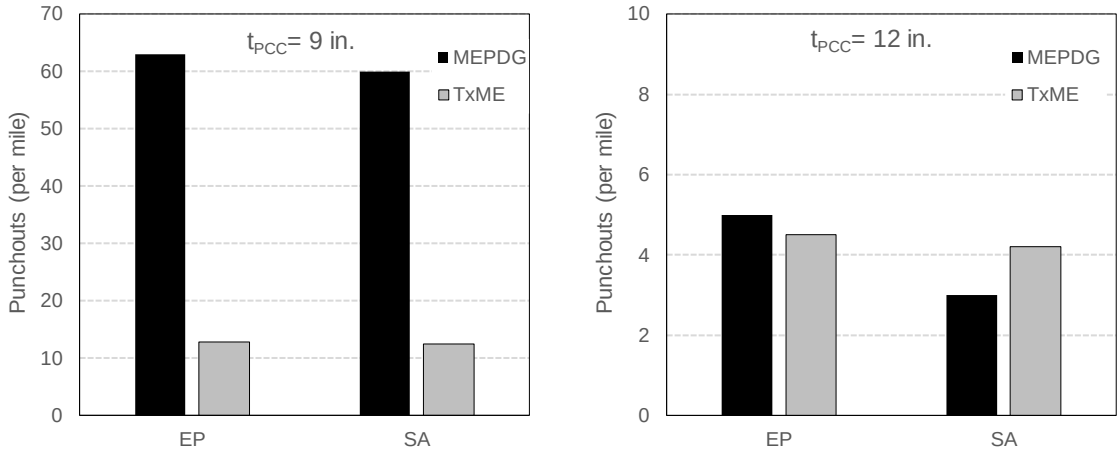


Figure 8. Comparison of CRCP distress based on MEPDG and TxCRCP-ME for El Paso and San Antonio.

This discrepancy is likely due to MEPDG's broader calibration scope, which introduced greater uncertainty for region-specific variables, particularly in the design of thinner pavements. Additionally, the MEPDG model adopted more conservative assumptions in these cases. Therefore, when MEPDG results suggest a thinner CRCP section—especially under specific combinations of traffic loading, service level requirements, and climatic conditions—it is advisable to conduct a more detailed validation using local field data or directly apply the CRCP-ME tool. Doing so enhances design accuracy and ensures conformance with TxDOT's performance expectations for CRCP structures.

4. Conclusions

This study investigates the performance of rigid pavements modeled using concrete mix design, subgrade soil conditions, recycled material properties, and the climate conditions of El Paso and San Antonio as representative dry and wet areas in Texas. Both jointed plain and continuously reinforced concrete pavements were modeled to check performance based on MEPDG criteria.

Based on the obtained results, concrete mixture and slab properties are the primary factors affecting PCC pavement performance. Due to the high cost of thick pavement and heavy steel use, subsoil properties and weather conditions were also evaluated. Changes in subgrade fines content, erosion resistance, and stiffness significantly influence joint faulting in JPCP and punchouts in CRCP, especially for thin pavements. Pavements in San Antonio showed greater bottom–up to top–down cracking ratio discrepancies compared to El Paso, warranting further study. JPCP smoothness in El Paso was more influenced by concrete properties than in San Antonio. MEPDG and TxDOT predictions aligned well

for thick CRCPs, but thin CRCP designs using MEPDG require closer scrutiny. The base modulus has limited impact on pavement distress, supporting the use of up to 50% recycled material in road construction near the study areas. This study recommends moving away from empirically-based designs to a data-driven, performance-based pavement design approach. The findings obtained using TxDOT's CRCP-ME tool, reinforcing the viability of sustainable designs using recycled materials, were validated.

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