Using the mechanistic-empirical pavement design guide for material selection

Uso de la guía mecanicista - empírica de diseño de pavimentos para selección de materiales

Armando Orobio[*1], *John P. Zaniewski*[2]

[1]School of Civil Engineering and Geomatics. University of Valle. Street 13 Nº 100 - 00, Building 350, 2nd floor. Cali, Colombia.

[2]Department of Civil and Environmental Engineering. West Virginia University Morgantown WV 26506-6103. PO Box 6103.

(Recibido el 28 de septiembre de 2010. Aceptado el 30 de agosto de 2012)

Abstract

The general design approach in the Mechanistic-Empirical pavement Design Guide (MEPDG) is to compare the performance of several trail structures over the design period against previously defined performance criteria to choice the best alternative after life cycle and constructability analyses. The material properties are selected from laboratory testing, correlation or typical values depending on the hierarchical levels defined by the designers. Layers in a flexible pavement structure are built with different materials and different asphalt mix types. The MEPDG predicted performance of pavement structures varies with variations of the material properties and material properties combination in the different layers. The effect on pavement performance from variations of material properties in the different layers of a pavement structure is analyzed in this study using MEPDG. The study showed that results from sensitivity studies of MEPDG to material properties can be used in selection of pavement materials for better performance.

----------- *Keywords:* Pavement materials, pavement design, sensitivity analysis, MEPDG, M-E PDG

Resumen

El procedimiento general de diseño en la Guía Mecanicista–Empírica para el Diseño se Pavimentos (MEPDG por sus siglas en ingles) incluye la comparación de la durabilidad de varias estructuras de prueba con unos criterios de desempeño previamente definidos. Esta comparación se hace

* Autor de correspondencia: teléfono: + 57 + 2 + 339 24 20, fax: + 57 + 2 + 339 20 86, correo electrónico: armando.orobio@correounivalle.edu.co (A. Orobio)

durante el periodo de diseño para escoger la mejor alternativa después de un análisis de ciclo de vida y un análisis de constructibilidad. Las propiedades de los materiales se seleccionan a partir de ensayos de laboratorio, correlaciones ó valores típicos dependiendo de los niveles jerárquicos definidos por los diseñadores. Las capas de la estructura de los pavimentos flexibles son construidas con diferentes materiales y diferentes tipos de mezclas asfálticas. La durabilidad de las estructuras de pavimento predicha por MEPDG varia con las variaciones de las propiedades de los materiales y la combinación esas propiedades de materiales en las diferentes capas. El efecto en una estructura de pavimento de las variaciones de las propiedades de los materiales en las diferentes capas de la estructura es analizado en este estudio usando MEPDG. El estudio mostró que resultados de estudios de sensibilidad de MEPDG a las propiedades de los materiales, pueden ser usados en la selección de materiales en procura de mayor durabilidad de los pavimentos.

--------- *Palabras clave:* Materiales para pavimentos, diseños de pavimentos, análisis de sensibilidad, MEPDG, M-E PDG

Introduction

MEPDG is an improved procedure of pavement design which highly depends on material characterization [1]. Flexible pavements are built with combination of layers made of different material types. In other words, pavements structures are combination of layers with different material properties. The pavement performance is highly depending of material properties and the interaction of pavement layers with traffic and environmental loads. The effect of interactions among pavement structure, pavement layers, traffic and environment is complex. It has been shown that the effect of material properties on pavement performance depends not only on the material properties itself, but also on the depth in the pavement structure where the material is located [2]. A material property may have large effect on pavement performance in a layer while having little effect in another layer [3].

The sensitivity of MEPDG to material properties was study in a flexible pavement structure and the results were used to investigate the effect of different combination of material properties in the different layers of the pavement structure using MEPDG. The study reveals that a suitable combination of material properties in the different layers of a pavement structure leads to a better predicted pavement performance from MEPDG. Consequently, MEPDG may be used in assessment materials for a better choice.

The sensitivity study

MEPDG is a complex pavement design procedure which has been a major change in pavement design. MEPDG uses pavement response and performance models to analyze pavement performance considering several input factors. In general terms, the input factors are structure, traffic, and climate.

The pavement response model is used to determine the structural response of pavements under traffic loads and climate conditions, the outputs from the pavement response models are stresses, strains, and displacements in the pavement layers. The pavement responses at critical points of the pavement structure are used as inputs in the pavement performance models to predict pavement distress through the pavement life. The design period is divided into shorter analysis periods or increments and the critical stresses, strains, and displacements for each increment are converted to incremental distresses. The incremental distresses are summed over all increments and the output at the end of the design period [1].

Due to the complexity of the design procedure, the general approach for sensitivity analyses of MEPDG has been the variation of the inputs of interest to analyze the pavement performance prediction at the end of the design period. This approach that has been used successfully in many research works [4 - 11, 13] appears to be the best way to evaluate the sensitivity of MEPDG to input parameters. A simply mechanistic analysis would have no meaning in MEPDG sensitivity.

The most common approach for sensitivity analysis of MEPDG has been the technique of varying the parameters one at time while keeping the others unchanged [4, 14, 15, 16]. The literature also reports a study using factorial experiments [10]. Due to the large number of input parameter in MEPDG, these methodologies would require a large number of runs to study the large possibility of input values combination in MEPDG. Therefore, these approaches are very impractical when a large number of parameters are included in the analysis. Additionally, MEPDG is computer code; any time it is run with the same set of input parameters, the same output is obtained. Hence, there is no experimental error. The current statistical methodologies for physical experiments may not be suitable for analysis of computer codes [17]. Consequently; statistical methodologies for computer experiments are better approaches for sensitivity analysis of MEPDG [2]. In that sense, a study using Monte Carlo Simulation and Pearson's and Spearman's coefficients to analyze the sensitivity of the outputs in MEPDG was found in the literature [18].

A research by Orobio [2] used space-filling computer experiments with Latin Hypercube Sampling (LHS), Standardized Regression Coefficients (SRC), and Gaussian stochastic processes (GSP) to study the sensitivity of MEPDG to material properties. Parts of the results from that study are used in here to identify the most suitable combination of material properties for good performance using MEPDG. In the study, the researcher [2] analyzed the sensitivity of MEPDG to material properties on the pavement structure in figure 1.The material properties with input ranges used in the analysis are displayed in table 1. Li (with i=1,2,3,4,5) at front of the name of each material property identifies the layer in the pavement structure. For example, L1 refers to layer 1which is the top layer and L5 refers to layer 5 (subgrade) in the pavement structure. The results of sensitivity are summarized in figure 2.

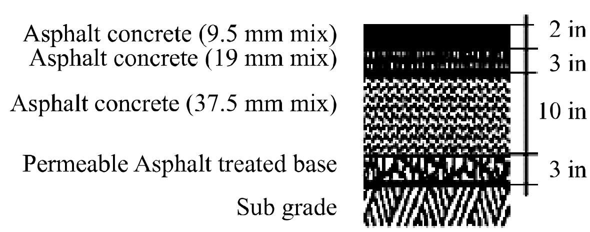

Figure 1 Pavement structure in the sensitivity study

Table 1 Input Parameters and Ranges

Layer	*Parameter*	*Units*	*Range*
L1	Surface short-wave absorptive		0.8 - 0.9
L1	L1 Effective binder content	%	4.5 - 6.5
	L1 Air Voids	%	3 - 10
	L1 Total unit weight	pcf	145 - 150
	L1 Poisson's ratio	-	0.25 - 0.4
	L1 Thermal conductivity asphalt	BTU/hr-ft-Fo	0.5 - 0.8
	L1 Heat capacity asphalt	BTU/lb-Fo	0.22 - 0.5

Layer	Parameter	Units	Range
L2	L2 Effective binder content	%	3.5 - 6
	L2 Air voids	%	3 - 10
	L2 Total unit weight	pcf	145 - 150
	L2 Poisson's ratio	-	0.25 - 0.4
	L2 Thermal conductivity asphalt	BTU/hr-ft-Fo	0.5 - 0.8
	L2 Heat capacity asphalt	BTU/lb-Fo	0.22 - 0.50
L3	L3 Effective binder content	%	2.5 - 4.0
	L3 Air voids	%	6 - 12
	L3 Total unit weight (pcf)	pcf	145 - 150
	L3 Poisson's ratio	-	0.25 - 0.4
	L3 Thermal conductivity asphalt	BTU/hr-ft-Fo	0.5 - 0.8
	L3 Heat capacity asphalt	BTU/lb-Fo	0.22 - 0.5
L4	L4 Effective binder content	%	2 - 3
	L4 Air voids	%	15 - 20
	L4 Total unit weight	pcf	145 - 150
	L4 Poisson's ratio	-	0.25 - 0.4
	L4 Thermal conductivity asphalt	BTU/hr-ft-Fo	0.5 - 0.8
	L4 Heat capacity asphalt	BTU/lb-Fo	0.22 - 0.50
L5	L5 Poisson's ratio	-	0.3 - 0.4
	L5 Coefficient of lateral pressure Ko	-	0.5 - 0.7
	L5 Modulus	psi	5000 - 9000
	Tensile strength	psi	500 - 1500
	Mix coefficient of thermal contraction	in/in/oF	2.2E-5 - 3.4E-5

Figure 2 shows the SRC for all material properties in the study for roughness (IRI), rutting, and cracking predicted from MEPDG. The SRC are indicators of the sensitivity of MEPDG to material properties. The lager the SRC, higher the effect on MEPDG outputs from variations of input values. Some material properties have negative SRC while others have positive SRC. A positive SRC indicates that the corresponding MEPDG output increases as the input value for the material parameter increases, and vice versa. A negative SRC indicates that the corresponding MEPDG output decrease as the input value for the material parameter increases, and vice versa. A star at front of a bar indicates that the material property is significant at a significance level of 0.05.

The largest effects on IRI are due to resilient modulus of subgrade (L5), effective binder content of layer 4, Poisson's ratio of surface (L1), and as-built air voids of layers 1, 2, and 3. Other significant parameters on IRI predicted from MEPDG are surface short-wave absorptive, effective binder content of layer 1, 2, and 3, and Poisson's ratio of layers 2, 3 and 4. The other parameters in the study did not significantly affect the predicted IRI from MEPDG.

Resilient modulus of subgrade (L5), Poisson's ratio of surface (L1), and as-built air voids of layers 1 and 2 have the largest effects on predicted rutting from MEPDG. Other significant parameters on MEPDG predicted rutting are surface short-wave absorptive, effective binder content of layers 1 and 2, Poisson's ratio of layer 2, heat capacity of asphalt of layer 1 and 2, and thermal conductivity of asphalt of layer 1. The other parameters in the study have no significant effect on predicted rutting from MEPDG.

The largest effects on predicted cracking from MEPDG are due to as-built air voids of layer 3, resilient modulus of subgrade and effective binder content of layers 3 and 4. Other parameters with significant effect on MEPDG predicted cracking are Poisson's ratio of layers 1, 2,3 and 4, as-built air voids of layers 1 and 3, surface short-wave absorptive, effective binder content of layers 1 and 2 and total unit weight. The other parameters in the study do not significantly affect MEPDG predicted cracking.

Out of 30 parameters, 13 are significant for IRI, 11 are significant for rutting, and 13 are significant for cracking.

The results from this sensitivity study can be used to identify the most suitable combination of input parameters in order to design a pavement structure which performances well.

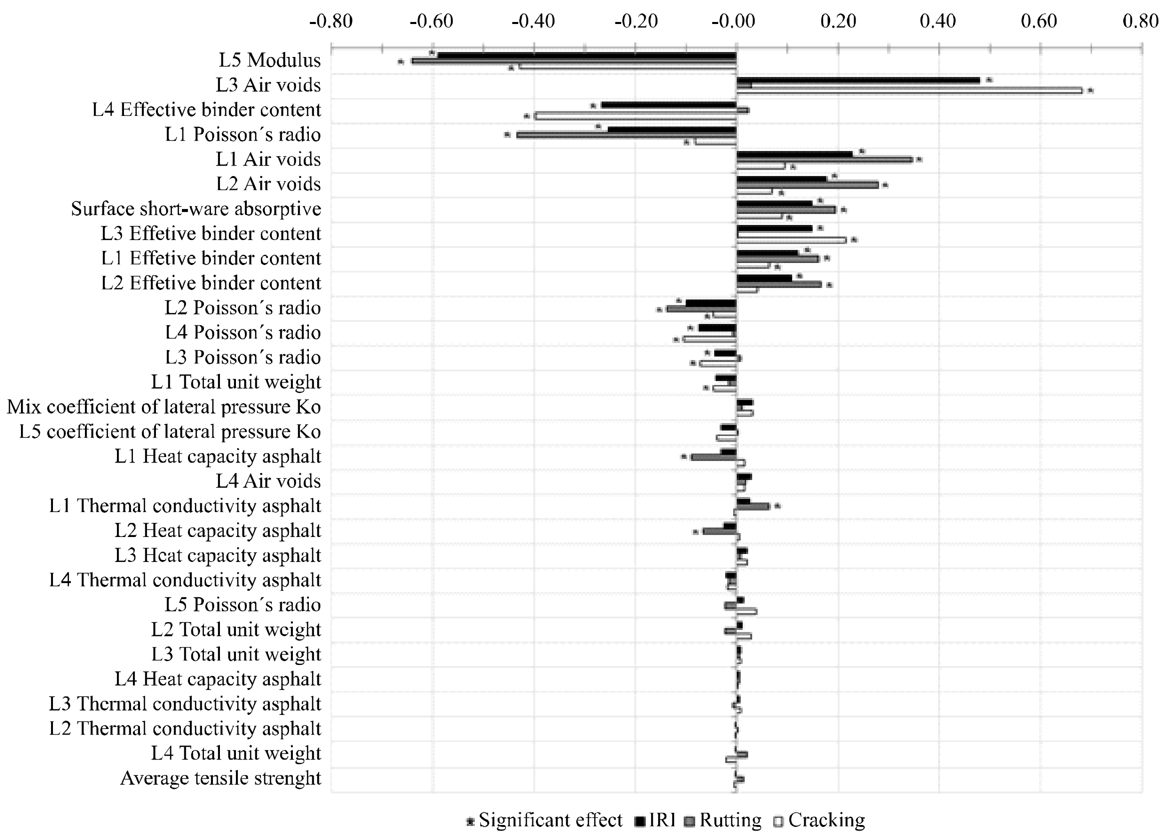

Figure 2 Standardized Regression Coefficients (SRC)

Material properties desirability

Pavement material desirability analysis intends to identify the best combination of material properties in order to design a structure that is predicted to perform well in field. Although, it is possible to identify desirable material properties using this methodology, it may not be easy to find materials to meet the desirable material properties. Designers may try to find the combination of material properties for construction as close to the desirable properties as possible.

The results of the sensitivity analysis explained above are used to introduce the procedure to identify the desirable material properties for the pavement structure in figure 1. Table 2 shows the results from the sensitivity analysis. The sign of the SRC are displayed in the table along with the lowest and highest values from the ranges used in the sensitivity analysis. A positive sign (+) indicates that the parameter is significant with a positive SRC. A negative sign (-) indicates that the parameter is significant with a negative SRC. Letter n indicates that the parameter is not significant. The signs of the SRC are used to define desirable input value for each MEPDG output (rutting, cracking, and IRI). A significant input parameter with positive SRC would require an input value close to the lowest side of its input range in order have better effect in performance. A significant input parameter with negative SRC would require an input value close to the highest side of its input range in order have better effect in performance. Columns under desirability in table 2 were defined with this concept.

Table 2 Material properties desirability

Layer	Parameter	Units	Range		Sign of src			Desirability			"Range side"	"Desirable input"
			Low	High	Rutting	Cracking	Iri	Rutting	Cracking	Iri		
L1	Surface Surface short-wave absorptive	-	0,8	0,9	+	+	+	0,8	0,8	0,8	Low	0,8
	L1 Effective binder content	%	4,5	6,5	+	+	+	4,5	4,5	4,5	Low	4,5
	L1 Air Voids	%	3	10	+	+	+	3	3	3	Low	3
	L1 Total unit weight	pcf	145	150	n	-	n	n	150	n	High	150
L1	L1 Poisson's ratio	-	0,25	0,4	-	-	-	0,4	0,4	0,4	High	0,4
	L1 Thermal conductivity asphalt	BTU/hr-ft-Fo	0,5	0,8	+	n	n	0,5	n	n	Low	0,5
	L1 Heat capacity asphalt	BTU/lb-Fo	0,22	0,5	-	n	n	0,5	n	n	High	0,5
	L2 Effective binder content	%	3,5	6	+	n	+	3,5	n	3,5	Low	3,5
	L2 Air voids	%	3	10	+	+	+	3	3	3	Low	3
	L2 Total unit weight	pcf	145	150	n	n	n	n	n	n	n	n
L2	L2 Poisson's ratio	-	0,25	0,4	-	-	-	0,4	0,4	0,4	High	0,4
	L2 Thermal conductivity asphalt	BTU/hr-ft-Fo	0,5	0,8	n	n	n	n	n	n	n	n
	L2 Heat capacity asphalt	BTU/lb-Fo	0,22	0,4	-	n	n	0,4	n	n	High	0,4

Layer	Parameter	Units	Range		Sign of src			Desirability			"Range side"	"Desirable input"
			Low	High	Rutting	Cracking	Iri	Rutting	Cracking	Iri		
L3	L3 Effective binder content	%	2,5	4	n	+	+	n	2,5	2,5	Low	2,5
	L3 Air voids	%	6	12	n	+	n	n	6	n	Low	6
	L3 Total unit weight (pcf)	pcf	145	150	n	n	n	n	n	n	n	n
	L3 Poisson's ratio	-	0,25	0,4	n	-	-	n	0,4	0,4	High	0,4
	L3 Thermal conductivity asphalt	BTU/hr-ft-Fo	0,5	0,8	n	n	n	n	n	n	n	n
	L3 Heat capacity asphalt	BTU/lb-Fo	0,22	0,5	n	n	n	n	n	n	n	n
L4	L4 Effective binder content	%	2	3	n	-	-	n	3	3	High	3
	L4 Air voids	%	15	20	n	n	n	n	n	n	n	n
	L4 Total unit weight	pcf	145	150	n	n	n	n	n	n	n	n
	L4 Poisson's ratio	-	0,25	0,4	n	-	-	n	0,4	0,4	High	0,4
	L4 Thermal conductivity asphalt	BTU/hr-ft-Fo	0,5	0,8	n	n	n	n	n	n	n	n
	L4 Heat capacity asphalt	BTU/lb-Fo	0,22	0,4	n	n	n	n	n	n	n	n
L5	L5 Poisson's ratio	-	0,3	0,4	n	n	n	n	n	n	n	n
	L5 Coefficient of lateral pressure Ko	-	0,5	0,7	n	n	n	n	n	n	n	n
	L5 Modulus	psi	5000	9000	-	-	-	9000	9000	9000	High	9000
	Average tensile strength at 14 oF	psi	500	1500	n	n	n	n	n	n	n	n
	Mix coefficient of thermal contraction	in/in/oF	2,2E-05	3,4E-05	n	n	n	n	n	n	n	n

The lowest or highest values of each parameter input range were defined as desirable for each MEPDG output. Where the parameter is no significant, n was placed in the corresponding cell in table 2. If the signs of the SRC are equal for all performance measures then the desirable input level is a low value for positive SRC or a high value for a negative SRC ignoring all no significant parameters. Inspection of table 2 shows the signs of SRC are equal for each parameter for all distresses. In case of different signs the desirable value should be selected to favor performance for the most critical distress.

The column Range Side is the general result from each input parameter after the analysis of all signs for all MEPDG outputs. Notice that, all sign are equal within parameter for this structure.

The better effect should be chosen in case of different signs for a given structure. Cells with n were not considered in the definition of the range side. The column desirable input was defined according to the range side. It is clear that the expected desirable input values need to be close to these values but not necessarily the same value.

Figure 3 displays the distribution of MEPDG outputs for all 300 runs in the sensitivity analysis. Outputs of runs 11 and 181 are extreme values with the highest IRI and cracking. These two runs are not extreme values for rutting. Runs 11 and 181 of the sensitivity analysis were evaluated using the concept of material property desirability. The column Runs in table 3 shows the input values for runs 11 an 181 used in the sensitivity analysis. A boundary of one third of the input range was used in order to check how far the original values are from the desirable values. Lowest value plus one third of the input range was defined as acceptable for the low rage side. Highest value minus one third of the input range was defined as acceptable for the high range side. Cells that meet these criteria were identified as “OK”, cells that fail to meet these criteria were identified with a “X”, and cells with no significant input parameters were identified with a “n”. Both 11 and 181 runs fail in most of the input parameters as seen in column Run Checking in table 3.

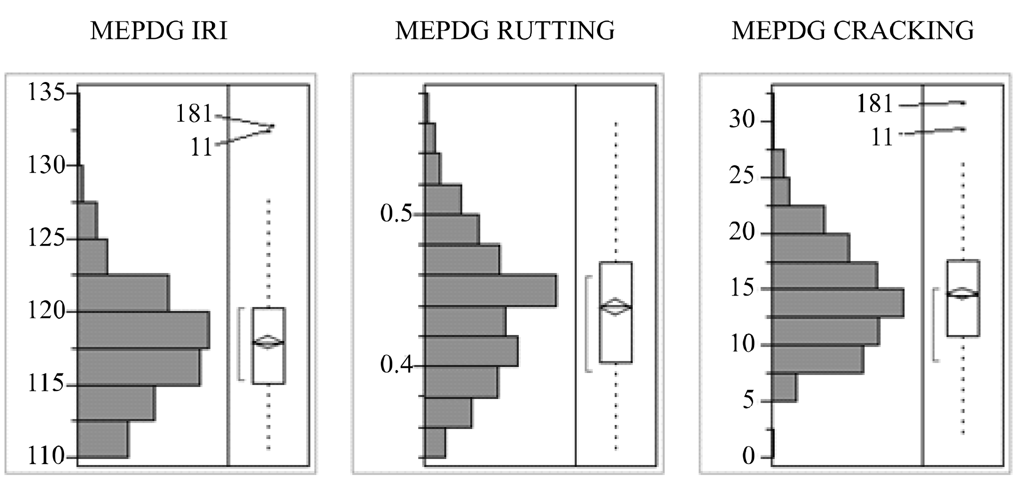

Figure 3 Distribution of MEPDG Outputs

New runs were defined in order to check run 11 and 181 with the desirable input values in MEPDG. Input values that fail to meet the desirable criteria were replaced with their corresponding desirable value.

Table 3 Checking runs 11 and 181

Layer	*Parameter*	*Units*	*Range*		*"Range side"*	*"Desirable input"*	*Runs*		*Run checking*		*New runs*	
			Low	***High***			***11***	***181***	***11***	***181***	***11***	***181***
L1	Surface Surface short-wave absorptive	-	0,8	0,9	Low	0,8	0,88	0,84	X	X	0,80	0,8
	L1 Effective binder content	%	4,5	6,5	Low	4,5	6,4	4,7	X	X	4,5	4,5
	L1 Air Voids	%	3	10	Low	3	9,9	8,2	X	X	3,0	3
	L1 Total unit weight	pcf	145	150	High	150	148,2	147,2	OK	X	148,2	150
L1	L1 Poisson's ratio	-	0,25	0,4	High	0,4	0,35	0,34	OK	X	0,35	0,4
	L1 Thermal conductivity asphalt	BTU/hr-ft-Fo	0,5	0,8	Low	0,5	0,66	0,70	X	X	0,50	0,5
	L1 Heat capacity asphalt	BTU/lb-Fo	0,22	0,5	High	0,5	0,27	0,33	X	X	0,50	0,5
	L2 Effective binder content	%	3,5	6	Low	3,5	5,8	5,2	X	X	3,5	3,5
	L2 Air voids	%	3	10	Low	3	7,3	9,1	X	X	3,0	3
	L2 Total unit weight	pcf	145	150	n	n	147,3	146,3	n	n	147,3	146,3
L2	L2 Poisson's ratio	-	0,25	0,4	High	0,4	0,26	0,35	X	OK	0,40	0,35
	L2 Thermal conductivity asphalt	BTU/hr-ft-Fo	0,5	0,8	n	n	0,70	0,68	n	n	0,70	0,68
	L2 Heat capacity asphalt	BTU/lb-Fo	0,22	0,4	High	0,4	0,36	0,31	OK	X	0,36	0,4
	L3 Effective binder content	%	2,5	4	Low	2,5	3,4	4,0	X	X	2,5	2,5
	L3 Air voids	%	6	12	Low	6	10,5	11,7	X	X	6,0	6
	L3 Total unit weight (pcf)	pcf	145	150	n	n	149,8	147,5	n	n	149,8	147,5
L3	L3 Poisson's ratio	-	0,25	0,4	High	0,4	0,39	0,32	OK	X	0,39	0,4
	L3 Thermal conductivity asphalt	BTU/hr-ft-Fo	0,5	0,8	n	n	0,74	0,69	n	n	0,74	0,69
	L3 Heat capacity asphalt	BTU/lb-Fo	0,22	0,5	n	n	0,29	0,35	n	n	0,29	0,35
	L4 Effective binder content	%	2	3	High	3	2,2	2,1	X	X	3,0	3
	L4 Air voids	%	15	20	n	n	16,8	19,5	n	n	16,8	19,5
	L4 Total unit weight	pcf	145	150	n	n	147,3	149,6	n	n	147,3	149,6
L4	L4 Poisson's ratio	-	0,25	0,4	High	0,4	0,29	0,39	X	OK	0,40	0,39
	L4 Thermal conductivity asphalt	BTU/hr-ft-Fo	0,5	0,8	n	n	0,68	0,53	n	n	0,68	0,53
	L4 Heat capacity asphalt	BTU/lb-Fo	0,22	0,4	n	n	0,31	0,33	n	n	0,31	0,33

Layer	Parameter	Units	Range		"Range side"	"Desirable input"	Runs		Run checking		New runs	
			Low	High			11	181	11	181	11	181
L5	L5 Poisson's ratio	-	0,3	0,4	n	n	0,37	0,34	n	n	0,37	0,34
	L5 Coefficient of lateral pressure Ko	-	0,5	0,7	n	n	0,50	0,50	n	n	0,50	0,5
	L5 Modulus	psi	5000	9000	High	9000	5202	5322	X	X	9000	9000
	Average tensile strength at 14 oF	psi	500	1500	n	n	1388,9	731,2	n	n	1388,9	731,2
	Mix coefficient of thermal contraction	in/in/oF	2,2E-05	3,4E-05	n	n	2,8E-05	3,0E-05	n	n	2,8E-05	3,0E-05

Input values that meet desirable criteria or are not significant were not altered. The columns New Runs in table 3 shows the new input values for runs 11 and 181. These new input values were used to run MEPDG and the outputs were analyzed with the distribution of the data from the sensitivity analysis.

Figure 4 displays the distribution of MEPDG output of IRI, rutting, and cracking for all 300 runs but the MEPDG outputs of runs 11 and 181 were replaced for the outputs with the desirable input values. Figure 4 shows very good predicted performance from MEPDG with the desirable input values. The new predicted performance is very low for IRI and rutting and there are not extreme values for cracking. There is a clear improvement in the performance of the pavement structure used in this analysis.

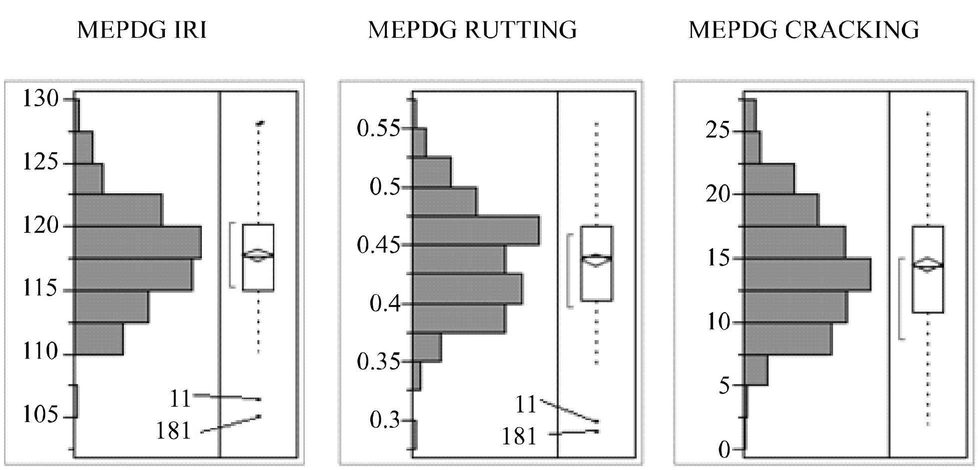

Figure 4 Distribution of MEPDG Outputs with the New Runs 11 and 181

Conclusions

This study shows that the complexity on the performance of pavement structures can be better understood using MEPDG analyses. MEPDG can be used in material assessment for a better choice. Comparison of available materials with the desirable materials may be a good idea during the design process. Additionally, this verification allows a better knowledge for the choice of materials in a given pavement structure.

This verification provides additional evidence that sensitivity of MEPDG to material properties is well identified using techniques for computer experiments as Latin Hypercube Sampling with metamodeling techniques as multiple regression analysis with standardized regression coefficient and Gaussian stochastic processes.

Generally the pavement design is completed before the contractor is selected. This essentially means that the designers must assume material properties rather than use the specific material for a project. The discontinuity between the pavement design process and the material design process should be reconsidered. This can be accomplish by using material design procedures with specifications developed to provide the desired levels base on the MEPDG analysis or refine the pavement design (layer thicknesses) after the material design process.

References

1. ARA, Inc. ERES Consultants Division. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Report, NCHRP Project 1-37A. Transportation Research Board of the National Academies, Washington, DC. 2004. Available in www.trb.org/mepdg/guide.htm.
2. A. Orobio. *Sensitivity Analysis of Flexible Pavement Performance Parameters in the Mechanistic-Empirical Design Guide.* Dissertation. West Virginia University. Morgantown. USA. 2010. pp.194.
3. A. Orobio, J. Zaniewski. "Sampling-Based Sensitivity Analysis of the Mechanistic–Empirical Pavement Design Guide Applied to Material Inputs". *Journal of the Transportation Research Board,* No 2226. 2011. pp. 85-93.
4. K. Hall, S. Beam. "Estimating the sensitivity of design input variables for rigid pavement analysis with a mechanistic - Empirical design guide". *Journal of the Transportation Research Board*. Vol. 1919. 2005. pp. 65-73.
5. S. Haider, R. Harichandran. "Effect of Axle Load Spectrum Characteristics on Flexible Pavement Performance". *Journal of the Transportation Research Board,* No 2095. 2009. pp. 101-114.
6. J. Li, L. Pierce, M. Hallenbeck, J. Uhlmeyer. "Sensitivity of Axle Load Spectra in the Mechanistic-Empirical Pavement Design Guide for Washington State". *Journal of the Transportation Research Board,* No 2093. 2009. pp. 50-56.
7. A. Papagiannakis, M. Bracher, J. Li, N. Jackson. "Sensitivity of NCHRP 1-37A Pavement Design to Traffic Input". J*ournal of the Transportation Research Board,* No 1945. 2006. pp. 49-55.
8. D. Timm, J. Bower, R. Turochy. "Effect of Load Spectra on Mechanistic-Empirical Flexible Pavement Design". *Journal of the Transportation Research Board,* No 1947. 2006; pp. 146-154.
9. A. Guclu, H. Ceylan, K. Gopalakrishnan, S. Kim. "Sensitivity Analysis of Rigid Pavement Systems Using the Mechanistic-Empirical Design Guide Software". *ASCE Journal of Transportation Engineering.* Vol 135. 2009. pp. 555-562.
10. Ws. Haider, B. Neeraj, C. Karim. *Simplified approach for quantifying effect of significant input variables and designing rigid pavements using M-E PDG. CD-ROM.* Transportation Research Board of the National Academies. Washington, DC. 2009. pp. 25.
11. V. Kannekanti, J. Harvey. Sensitivity analysis of 2002 design guide distress prediction models for jointed plain concrete pavement. *Journal of the Transportation Research Board,* No 1947. 2006. pp. 91-100.
12. S. Kim, H. Ceylan, K. Gopalakrishna. "Effect of M-E design guide inputs on flexible pavement performance predictions". *Road Materials and Pavement Design.* Vol 8. 2007. pp. 375-397.
13. R. Graves, K. Mahboub. "Pilot study in sampling-based sensitivity analysis of NCHRP design guide for flexible pavements". *Journal of the Transportation Research Board,* No 1947. 2006. pp. 123-135.
14. H. Ceylan, B. Coree, K. Gopalakrishnan. *Strategic Plan for Implementing Mechanistic-Empirical Pavement*

Design Guide in Iowa. In Proc. of the TRB 85th Annual Meeting. 22-26 Enero de 2006. Washington DC, USA. pp. 1-23.

15. Y. Kim, N. Muthadi. *Implementation Plan for the New Mechanistic–Empirical Pavement Design Guide*. NCDOT Final Report. Raleigh : North Carolina State University. Raleigh (USA). 2006. pp. 623.

16. S. Haider, N. Buch, K. Chatii. *Simplified approach for quantifying effect of significant input variables and designing rigid pavements using M-E PDG*. Presented at 88th Annual Meeting Transportation Research Board. Washington, DC. 2009. pp. 25.

17. J. Sacks, W. Welch, T. Mitchell, H. Wynn. "Design and Analysis of Computer Experiments". *Statistical Science*. Vol. 4. 1989. pp. 409-423.

18. R. Graves, K. Mahboub. "Pilot study in Sampling-Based sensitivity analysis of NCHRP design guide for flexible pavements". *Journal of the Transportation Research Board*. No. 1947. 2006. pp. 123-135.