TECH**BRIEF**

Estimation of Key PCC, Base, Subbase, and Pavement Engineering Properties from Routine Tests and Physical Characteristics

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This document is a technical summary of the Federal Highway Administration report, *Estimation of Key PCC, Base, Subbase, and Pavement Engineering Properties from Routine Tests and Physical Characteristics* (FHWA-HRT-12-030).(1)

This TechBrief presents models developed by statistical methods to predict key material properties for portland cement concrete (PCC), chemically stabilized materials, and unbound base, subbase, and subgrade materials. It also presents models to predict design inputs specific to the *Mechanistic-Empirical Pavement Design Guide* (MEPDG).(2) The models were developed under the Long-Term Pavement Performance (LTPP) data analysis study, *Estimation of Key PCC, Base, Subbase, and Pavement Engineering Properties from Routine Tests and Physical Characteristics*.(1) The predictive models were developed using data from the LTPP database as well as data generated from analyses used in the calibration of the MEPDG distress models under National Cooperative Highway Research Program Project 1-40D.(3,4)

Introduction

Material characterization is a critical component in all aspects of pavement engineering—analysis, design, construction, quality control (QC) and quality assurance (QA), pavement management (PM), and rehabilitation. At each stage during the life of a project, the influence of fundamental engineering material parameters on the long-term performance of the pavement can be predicted using advanced tools like the MEPDG.(2) Measuring the properties directly is preferable, but it is often not practical or possible. Consequently, there is a need for reliable models that can be used to estimate key parameters and provide more information about material properties, which is addressed to only a limited extent with currently available laboratory and field testing resources.

Reliable correlations between material properties and a combination of mix design parameters, physical characteristics, and index properties offer a cost-effective alternative and are equivalent to the level 2 inputs used in the MEPDG. The LTPP database offers an opportunity to develop correlation equations to estimate material properties.(3)

The Long-Term Pavement Performance (LTPP) program is a large research project for the study of in-service pavements across North America. Its goal is to extend the life of highway pavements through various designs of new and rehabilitated pavement structures, using different materials and under different loads, environments, subgrade soil, and maintenance practices. LTPP was established under the Strategic Highway Research Program and is now managed by the Federal Highway Administration.

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Therefore, it served as the primary source of data in developing the models presented here. To develop models for design feature parameters specific to the MEPDG, LTPP data were combined with data generated from MEPDG analyses of LTPP sections.

Material Properties Identified for Model Development

In selecting key material properties that required predictive models, the following parameters were considered:

- Input requirements for the MEPDG design procedure and the sensitivity of the specific parameter for performance prediction.
- Typical agency needs for determining material properties for QA and PM.
- Challenges involved in determining the material property of interest directly through laboratory testing.
- The specific material property's relationship with material parameters, physical properties, routine test results, and typical index properties.
- The potential to develop a predictive model.
- Likelihood that the actual value of the material property would deviate from typical values or assumed defaults and the significance of such a deviation in predicting performance.
- Data availability in the LTPP database.

Predictive models were developed for PCC compressive strength, PCC flexural strength, PCC elastic modulus, PCC tensile strength, lean concrete base modulus, and unbound materials resilient modulus. In addition, rigid pavement design feature input properties were developed using the MEPDG calibration data. These include the jointed plain concrete pavement (JPCP) and the continuously reinforced concrete pavement (CRCP) *deltaT* parameter, which is defined as the equivalent temperature differential that corresponds to the effective permanent curl-warp locked into the pavement. For all PCC material properties, multiple models were developed for use under different project situations.

Development of Prediction Models

In developing the models, a uniform set of statistical criteria were used to select independent parameters to define a relationship as well as to mathematically formulate prediction functions. The analyses examined several statistical parameters in choosing the optimal model and determining the predictive ability of the model. In general, the optimal set of independent variables (Mallows coefficient, C_p), the interaction effects (variance inflation factor), the significance of the variable (p-value), and the goodness of fit (R^2) were verified. Additionally, the study validated and/or refined existing models and developed new relationships. In the statistical analyses, the following tasks were accomplished:

- PCC compressive strength was correlated with mix design parameters and aggregate properties. It was found to increase with decreasing water/cementitious materials (w/c) ratio, increasing cementitious materials content (CMC), increasing curing time, increasing unit weight, decreasing maximum aggregate size for a given level of w/c ratio, and decreasing fineness modulus of the sand.
- PCC flexural strength and compressive strength were correlated using a power model. While similar relationships are used in the industry, they were validated and refined using the LTPP data that make them appropriate for paving mixes. It was also correlated to the w/c ratio, unit weight, and CMC for predictions at different ages. The correlations were improved significantly in these new models with the inclusion of additional parameters. The flexural strength increased proportionally with all parameters listed except w/c ratio, with which it bears an inverse relationship.
- PCC elastic modulus, compressive strength, and unit weight were correlated using a power model, as has been done in past studies. These relationships were validated and modified with the data used in this study. Prediction models were also developed based on aggregate type, unit weight, compressive strength, and age. The elastic modulus increased with an increase in magnitude of all parameters listed in this item. However, the predictive ability of the elastic modulus models was marginal, and users are advised to use them with caution or verify them using laboratory testing for smaller samples.
- PCC splitting tensile strength and compressive strength were correlated using a power relationship.
- The coefficient of thermal expansion (CTE) of PCC was most sensitive to the coarse aggregate type and the volumterics of the mix design. CTE recommendations are made for each aggregate type, and a correlation to mix volumetrics was developed.
- JPCP *deltaT* negative gradient was found to increase with an increase in temperature range at the project location for the month of construction and slab width and was found to decrease with a decrease in PCC thickness, unit weight, w/c ratio, and latitude of the project location.

- CRCP *deltaT* negative gradient was found to increase with an increase in maximum temperature at the project location for the month of construction and maximum temperature range and was found to decrease with the use of chert, granite, limestone, and quartzite.
- The modulus of lean concrete base and its 28-day compressive strength were correlated based on a power model.
- The prediction of granular base or subgrade material resilient modulus was possible using parameters k_1, k_2, and k_3 of the constitutive model as follows:
    - The parameter k_1 was found to increase with a decrease in percent passing the $^1/_2$-inch sieve, an increase in liquid limit, and a decrease in optimum moisture content.
    - The parameter k_2 was found to increase with a decrease in percent passing the No. 80 sieve, liquid limit, and percent gravel and an increase in the maximum particle size of the smallest 10 percent of the soil sample.
    - The parameter k_3 was dependent on the soil classification (i.e., coarse-grained versus fine-grained materials).

Summary of Models Developed

This section provides a summary of the models. Refer to the corresponding main report, *Estimation of Key PCC, Base, Subbase, and Pavement Engineering Properties from Routine Tests and Physical Characteristics*, for detailed information about the quality of the predictive models and the range of data that can be applied to each model.(1) Figure 1 through figure 5 present the PCC compressive strength models, figure 6 through figure 8 present PCC flexural strength models, figure 9 through figure 11 present PCC elastic modulus models, figure 12 presents a PCC indirect tensile strength model, and figure 13 and figure 14 present PCC CTE models. Note that the elastic modulus models yielded a correlation with a low R^2 and need to be used with caution.

The applications for figure 1 are 28-day strength for design and QA.

Figure 1. Compressive strength model 1 for 28-day cylinder strength.

$$f_{c,28d} = 4{,}028.41841 - 3{,}486.3501 \times w/c + 4.02511 \times CMC$$

The applications for figure 2 are design, QA, PM, and opening strength for ages less than 1 year.

Figure 2. Compressive strength model 2 for short-term cylinder strength.

$$f_{c,t} = 6{,}358.60655 + 3.53012 \times CMC - 34.24312 \times w/c \times uw + 633.3489 \times \ln(t)$$

The applications for figure 3 are design, QA, PM, and opening/in situ strength for ages less than 1 year.

Figure 3. Compressive strength model 3 for short-term core strength.

$$f_{c,t} = 98.92962 + 5.70412 \times CMC + 28.48527 \times uw + 2{,}570.13151 \times MAS \times w/c - 199.84664 \times FM + 611.30879 \times \ln(t)$$

The applications for figure 4 are design, QA, PM, and in situ strength at any age.

Figure 4. Compressive strength model 4 for all ages core strength.

$$f_{c,t} = -6{,}022.44 - 854.46 \times w/c + 4.8656 \times CMC + 68.5337 \times uw + 533.15 \times \ln(t)$$

The applications for figure 5 are rehabilitation design and in situ strength for ages greater than 5 years.

Figure 5. Compressive strength model 5 for long-term core strength.

$$f_{c,LT} = -3{,}467.3508 + 3.63452 \times CMC + 0.42362 \times uw^2$$

Where:

$f_{c,28d}$ = Compressive strength at 28 days.
$f_{c,t}$ = Compressive strength at time t, days.
$f_{c,LT}$ = Long-term compressive strength.
w/c = Water/cementitious materials ratio.
CMC = Cementitious materials content, lb/ft^3.
uw = Unit weight, lb/ft^3.
t = Age, years.
MAS = Maximum aggregate size, inch.
FM = Fineness modulus of fine aggregate.

The applications for figure 6 are design and PM when compressive strength at a given age is available.

Figure 6. Flexural strength model 1 based on compressive strength.

$$MR = 22.7741 \times f'_c{}^{0.4082}$$

The applications for figure 7 are design and PM when index properties are available and predicting for any age.

Figure 7. Flexural strength model 2 based on age, unit weight, and w/c ratio.

$$MR_t = 676.0159 - 1{,}120.31 \times w/c + 4.1304 \times uw + 35.74627 \times \ln(t)$$

The applications for figure 8 are design and PM when index properties are available and predicting for any age.

Figure 8. Flexural strength model 3 based on age, unit weight, and CMC.

$$MR_t = 24.15063 + 0.55579 \times CMC + 2.96376 \times uw + 35.54463 \times \ln(t)$$

Where:

MR = Flexural strength, psi.
MR_t = Flexural strength at age t years, psi.
f'_c = Compressive strength determined at the same age, psi.
w/c = Water/cementitious materials ratio.
CMC = Cementitious materials content, lb/yd^3.
uw = Unit weight, lb/ft^3.
t = Pavement age, years.

The applications for figure 9 are design and PM when compressive strength at given age and aggregate type are available.

Figure 9. Elastic modulus model 1 based on aggregate type.

$$E_c = (4.499 \times (uw)^{2.3481} \times (f'c)^{0.2429}) \times D_{agg}$$

The applications for figure 10 are design and PM when compressive strength at a given age is available (predicts for any age).

Figure 10. Elastic modulus model 2 based on age and compressive strength.

$$E_{c,t} = 59.0287 \times (f'c_t)^{1.3} \times \left(\ln\left(\frac{t}{0.03}\right)\right)^{-0.2118}$$

The applications for figure 11 are design and PM when 28-day compressive strength is available (predicts for any age).

Figure 11. Elastic modulus model 3 based on age and 28-day compressive strength.

$$E_{c,t} = 375.6 \times (f'c_{28\text{-}day})^{1.1} \times \left(\ln\left(\frac{t}{0.03}\right)\right)0.00524$$

Where:

E_c = PCC elastic modulus, psi.
E_t = Elastic modulus at age t years.
$E_{c,t}$ = Elastic modulus at age t years.
$f'c_t$ = Compressive strength at age t years.
uw = Unit weight, lb/ft^3.
$f'c$ = Compressive strength at same age, psi.
$f'c,_{28\text{-}day}$ = 28-day compressive strength.
t = Age at which modulus is determined, years.
D_{agg} = Regressed constant depending on aggregate type: andesite (1), basalt (0.9286), chert (1.0079), diabase (0.9215), dolomite (1.0254), granite (0.8333), limestone (1), quartzite (0.9511), and sandstone (1).

The application for figure 12 is design when compressive strength is available.

Figure 12. PCC indirect tensile strength model based on compressive strength.

$$f_t = 8.9068 \times (f'c)^{0.4785}$$

Where:

f_t = Indirect tensile strength of the PCC material.
$f'c$ = Compressive strength of the mix determined at the same age.

The applications for figure 13 are design, QC, and PM when coarse aggregate rock type is available.

Figure 13. CTE model 1 based on aggregate type.

Basalt (4.86), Chert (6.9), Diabase (5.13), Dolomite (5.79), Gabbro (5.28), Granite (5.71), Limestone (5.25), Quartzite (6.18), Andesite (5.33), Sandstone (6.33)

The applications for figure 14 are design, QC, and PM when coarse aggregate rock type and mix design proportioning are available.

Figure 14. CTE model 2 based on mix volumetrics.

$$CTE_{PCC} = CTE_{CA} \times V_{CA} + 6.4514 \times (1 - V_{CA})$$

Where:

CTE_{PCC} = CTE of the PCC material, x10^{-6} inch/inch/°F.
V_{CA} = Volumetric proportion of the coarse aggregate (0 to 0.6).
CTE_{CA} = Constant determined for each aggregate type (basalt (3), chert (6.4), diabase (3.4835), dolomite (5.1184), gabbro (3.75), granite (4.7423), limestone (3.2886), quartzite (6.1), andesite (3.6243), and sandstone (4.5)).

Figure 15 lists the *deltaT* model for JPCP for rigid pavements. Because of the limitations of the model developed for CRCP *deltaT*, this model is not included in this document. The applications are design and PM when mix design and construction weather information are available.

Figure 15. *deltaT* JPCP design.

$$\begin{gathered} deltaT/inch = -5.27805 - 0.00794 \times \\ TR - 0.0826 \times SW + 0.18632 \times PCCTHK \\ + 0.01677 \times uw + 1.14008 \times w/c \\ + 0.01784 \times latitude \end{gathered}$$

Where:

deltaT/inch = Predicted gradient in JPCP slab, °F/inch.
TR = Difference between maximum and minimum temperature in construction month, °F.
SW = Slab width, ft.
PCCTHK = JPCP slab thickness, inch.
uw = Unit weight of PCC used in JPCP slab, lb/ft^3.
w/c = Water/cementitious materials ratio.
latitude = Latitude of the project location, degrees.

Figure 16 shows the lean concrete base elastic modulus model. The applications are design and PM when 28-day compressive strength information is available.

Figure 16. *deltaT* JPCP design. Lean concrete base elastic modulus model.

$$E_{LCB} = 58{,}156\sqrt{f'_{c,28d}} + 716{,}886$$

Where:

E_{LCB} = Elastic modulus of the lean concrete base layer.
$f'_{c,\ 28d}$ = 28-day compressive strength of the lean concrete base material.

Figure 17 shows the model developed for resilient modulus for coarse- and fine-grained base layers and soil. The applications are design, QA, and PM when gradation, Atterberg limits, and moisture content are known.

Figure 17. Resilient modulus for coarse- and fine-grained base layers and soils.

$$M_r = k_1\left(\frac{\theta}{P_a}\right)^{k_2}\left(\frac{\tau_{oct}}{P_a}\right)^{k_3}$$

The parameters in figure 17 are defined in figure 18 through figure 20 as follows where:

M_r = Resilient modulus, psi.
θ = Bulk stress ($\sigma_1 + \sigma_2 + \sigma_3$).
σ_1 = Major principal stress.
σ_2 = Intermediate principal stress = σ_3 for M_r test on cylindrical specimen.
σ_3 = Minor principal stress/confining pressure.
τ_{oct} = Octahedral shear stress = $\frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2}$.
P_a = Normalizing stress (atmospheric pressure).
k_1, k_2, and k_3 = Regression constants (obtained by fitting M_r test data to this model form.

Figure 18. Prediction model for k1.

$$\begin{gathered} k_1 = 1{,}446.2 - 4.56764 \times PCTHALF + 4.92 \\ \times LL - 27.73 \times OPTMOIST \end{gathered}$$

Figure 19. Prediction model for k2.

$$\begin{gathered} k_2 = 0.45679 - 0.00073376 \times PCTNO80 - \\ 0.00269 \times LL + 0.00060555 \times \\ PCTGRVL + 12.97 \times D_{10} \end{gathered}$$

Figure 20. Prediction model for k3.

$$\begin{gathered} k_3 = -0.188 \text{ (for fine-grained soils)} \\ k_3 = -0.153 \text{ (for coarse-grained materials)} \end{gathered}$$

Where:

PCTHALF = Percent passing the $^1/_2$-inch sieve.

LL = Liquid limit, percent.
OPTMOIST = Optimum moisture content, percent.
*PCTNO*80 = Percent passing No. 80 sieve.
PCTGRVL = Percent gravel fraction (0.078- to 2.36-inch size).
D_{10} = Maximum particle size of the smallest 10 percent of soil sample.

Conclusions

Material characterization is critical to pavement analysis, design, and performance prediction. While the availability of the MEPDG has allowed great flexibility in the evaluation of as-designed and as-built pavements, the need for extensive input data can be a challenge for agencies adopting the MEPDG. The ability to develop prediction models for material properties and design features was explored under this study. It was found that information on mix constituents, their physical characteristics, and index properties could be used to develop correlations to predict material properties for PCC materials, stabilized materials, and unbound bases and subgrade materials.

References

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