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PCC Materials Input Values for Mechanistic-Empirical Pavement Design Guide

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PCC Materials Input Values for Mechanistic-Empirical Pavement Design Guide

by

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EXECUTIVE SUMMARY

The new Mechanistic-Empirical Pavement Design Guide (MEPDG) requires a number of materials-related inputs, many of which are not typically measured or tracked. For rigid pavement design, such inputs include the Portland cement concrete (PCC) coefficient of thermal expansion (CTE), Poisson's ratio, and elastic modulus. For this study, three replicate specimens were prepared for each of 24 concrete/cement paste mixtures and tested at various ages ranging from 7 to 90 days. Aggregates included in the study represented the major aggregate types typically used in Arkansas. Results from the testing effort were collected into a materials library/catalog to be accessed by pavement designers using the MEPDG for Level 1 design efforts. The results show that MEPDG Level 3 default values for CTE are generally suitable for most design applications; values for Poisson's ratio should be taken from the PCC materials catalog for design; and that default strength-gain curves embedded in the MEPDG, while generally sufficient for design, could be improved. Regression coefficients governing the MEPDG strength gain algorithm were optimized for Arkansas using the data generated in the study.

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CHAPTER 1. INTRODUCTION

Research Project TRC-0302 performed at the University of Arkansas for the Arkansas State Highway and Transportation Department (AHTD) demonstrated that rigid pavement distress models contained in the new Mechanistic Empirical Pavement Design Guide (MEPDG) were sensitive to a number of Portland cement concrete (PCC) materials inputs, particularly the coefficient of thermal expansion (CTE) and Poisson's ratio (*1*). However, the CTE had not been included as a variable in materials specifications or in the structural design of concrete pavements though it has long been known to have an effect on joint movement, crack formation, curling stresses and thermal deformations in jointed plain concrete pavement (JPCP) and continuous reinforced concrete pavement (CRCP) (*2*).

Hundreds of cores taken from Long-Term Pavement Performance (LTPP) sections throughout the United States were tested for the CTE at the Turner-Fairbank Highway Research Center laboratory using the AASHTO TP 60 test procedure as part of studies conducted by FHWA (*2*). The results were then used in the MEPDG to determine the significance of the measured CTE on concrete pavement performance. The CTE of concrete was found to vary widely, depending on the predominant aggregate type used in the concrete. Further sensitivity analysis showed that the CTE had a pronounced effect on slab cracking and, to a lower degree, on joint faulting. Its effect on smoothness was also noted (*2*). Since pavement performance predictions are sensitive to the CTE input value, and because the CTE value varies with factors such as aggregate type, particle size, cement type, water cement ratio and relative humidity, it is imperative that the specific value of the CTE for each of the concrete mixtures be made available to designers.

In addition, the Poisson's ratio of concrete, which is not often tested in most laboratories, also has a significant influence on the distress model analysis of PCC using the MEPDG (*2*). Research is needed to characterize these two properties, coefficient of thermal expansion and Poisson's ratio, in which the concrete modulus of elasticity and compressive strength can also be determined for typical Arkansas pavement PCC mixtures in order to provide guidance for designers in selecting materials input values for rigid pavement design using the Mechanistic Empirical Pavement Design Guide.

CHAPTER 2. BACKGROUND AND REVIEW

2.1 NEED FOR MECHANISTIC EMPIRICAL PAVEMENT DESIGN GUIDE

The pavement design guide currently in practice is the AASHTO 1993 “Guide for Design of Pavement Structures”, which is based on the empirical equations derived from the AASHO Road Test (1958-60). The test conditions from which the empirical equations derived for the AASHTO guide was limited to the modest traffic levels used in the road test, one set of climate data, limited structural conditions and materials typically found in Illinois (*3*). This makes the existing method less applicable to the new materials used in pavement construction, variable climatic conditions, fluctuating traffic loadings and varied locations -demanding the need for a new design not entirely based on the empirical data but also based on a mechanistic structural response.

The AASHTO Joint Task Force on Pavements (JTFP) proposed a research program to develop a design guide based on numerical models calibrated with pavement performance data from the LTPP program which is both mechanistic and empirical. National Cooperative Research Project (NCHRP) conducted the research with the cooperation of the state departments of transportation, industry groups and the Federal Highway Administration (FHWA) in from 1996-2004 (*3*).

Figure 1 represents the different processes of MEPDG design method. The end result of this new method is predicted pavement response to a given set of loading and climatic conditions. The MEPDG software includes the pavement condition prediction over time. It accounts for traffic, climate and pavement structure interaction and allows the exceptional loadings with multiple tiers or axles and provide means for evaluating design variability and reliability (*3*). Since the output of the MEPDG design is the pavement response, it helps analyze the present pavement condition to help find the best rehabilitation methods.

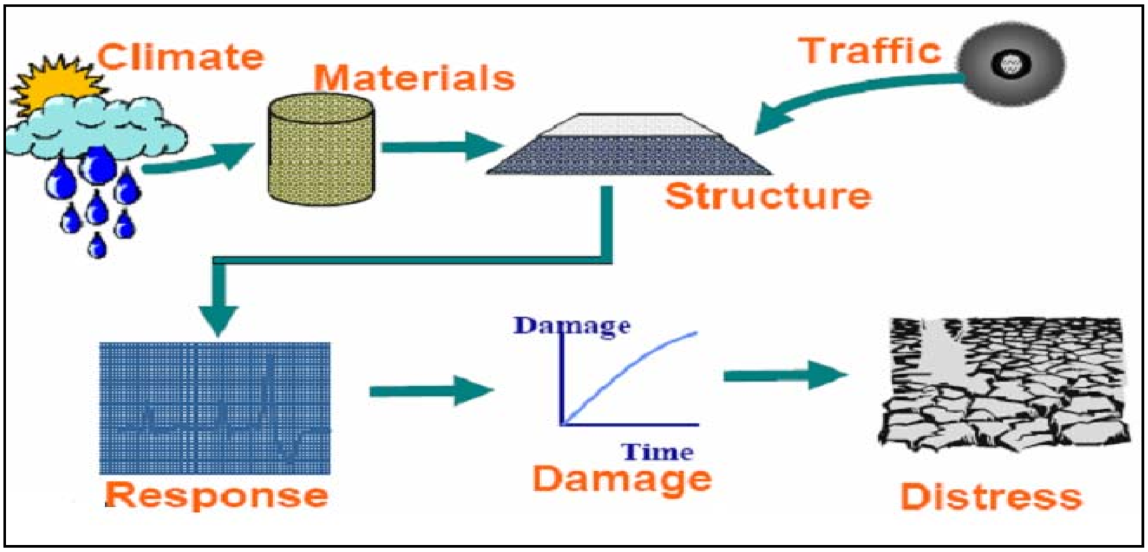


Figure 1 Schematic Representation of Different Processes of the MEPDG (*3*)

2.1.1 Components of MEPDG

The major components of the MEPDG software are project information, input data, analysis and the output file as shown in Figure 2. The first part of the design software is to collect the general project information including the design life of the pavement and project details which will help retrieve the design in the future.

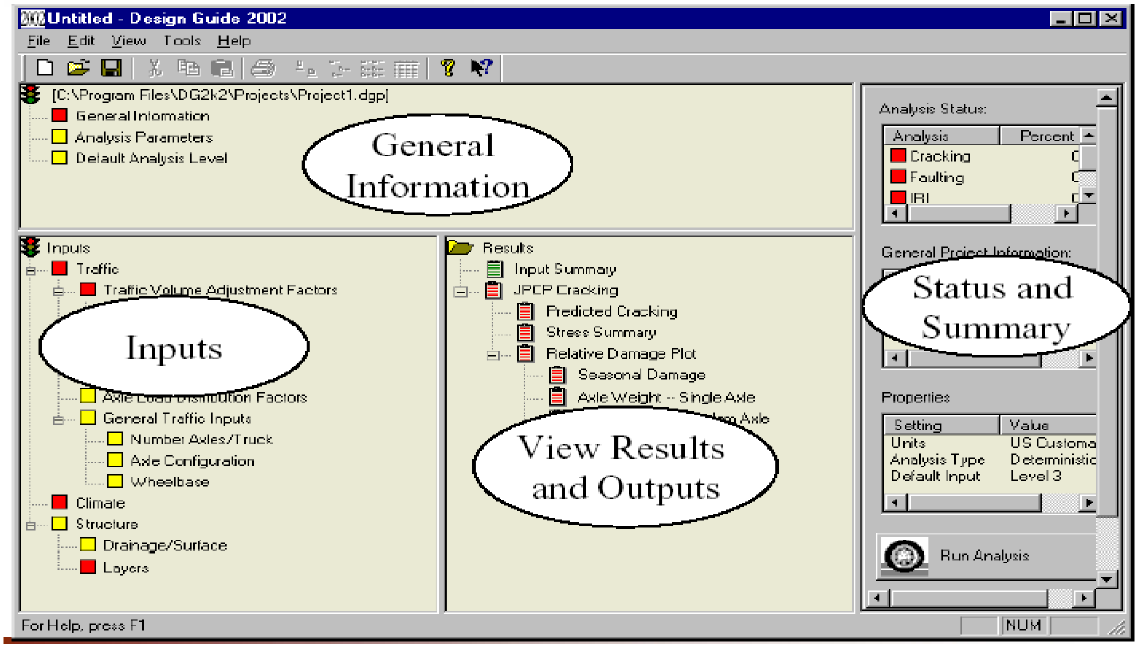


Figure 2 Layout of Different Components in MEPDG Software

2.1.1.1 Input Data

The main part of the pavement design is the data input for each major section of traffic, climate and structure including material type. A database for the input parameters for traffic, climate and structure including the material type, which the MEPDG recognizes as the primary factors that affect pavement performance was developed primarily using data from the LTTP Project.

2.1.1.1.1 Environment. The MEPDG directly accounts for the effect of climate on the pavement. In addition to temperature, the moisture gradient in a PCC slab is also demonstrated to influence warping/ curling in PCC slabs or stress/strain distribution in HMA structures. The three elements of incorporating the effects of environment in MEPDG are material specific thermal properties, heat transmission algorithm (based on the Enhanced Integrated Climatic Model (EICM) developed at the University of Illinois) and a site specific environmental data (*3*). The software includes a set of environmental data collected at various locations across the United States that brackets the different climatic conditions prevalent in the country. But this data set may be insufficient to make use of the site-specificity of the software.

2.1.1.1.2 Traffic. Considering the complex nature of the load applications, while developing the MEPDG it was recognized that the method of representing volume of load as Annual Average Daily Traffic (AADT) and Equivalent Single Axle Load (ESAL) is not sufficient to differentiate the effect of different axle load configurations on pavement performance. The alternate method introduced in the MEPDG is "Traffic Load Spectra", where the anticipated traffic is classified as axle type with axle weight distribution (*3*). It also allows further distribution of traffic in terms of daily, weekly, monthly or seasonal volume, which gives a more realistic approach of the actual distribution of axle types, weights and occurrence in time. Since these data are site specific, the designers are required to input the traffic data in MEPDG specific to each project.

2.1.1.1.3 Materials. As with any pavement design procedure it is required to define the structural data of materials including their thickness, properties and sequence, but more specific inputs, including non structural data, are required for a more realistic design. The structural properties of concrete materials mostly include the Modulus of Elasticity and Poisson's ratio, which allows the structural analysis algorithms to calculate the maximum stresses and strains within the pavement under critical loading conditions (*3*). Non-structural input values include properties related to conduction and transmission phenomenon, such as the heat capacity, thermal conductivity, and hydraulic conductivity. It also includes specific gravity and the PCC slab dimensions, including the reinforcement details. These values are further taken into account while computing the curling and warping of PCC slabs, moisture, and freezing interface movements.

2.1.1.2. Analysis

Depending on time specific conditions, the structures are modeled under various loadings and vary with the type of pavement. In the MEPDG a rigid pavement, finite element model, ILLISLAB, is used with an Artificial Neural Network (ANN) for faster performance (*3*). The analysis computes and sums the load related and load independent stresses and strains at each time increment. These instantaneous stresses and strains are then combined and integrated over each time increment with the calibrated distress models to estimate the accumulated damage to the pavement structure. Application of the MEPDG to regional and local conditions requires calibration, and it is expected that these models will be improved over the years upon further research.

2.1.1.3. Output

The output of the MEPDG is predicted pavement response over the design period for the projected load applications - not the pavement structure material or thickness. It is the designer who evaluates whether the projected distress are within an acceptable level, and redo the analysis if necessary. For altering the design the designer should be aware of cause of each distress, and use practical experience and understanding of pavement behavior for appropriate adjustments.

2.1.2 Hierarchical Level of Design Input in MEPDG

The MEPDG has a hierarchical approach of data input allowing the designer to choose the level of reliability of input data, providing three levels of design (Level 1 to Level 3).

Level 1 provides project or segment specific data, which is more precise and accurate, and used when there is a need for higher level of reliability. In routine design, Level 2 input values typically use data available regionally, possibility from a state highway agency database or input values based on regression correlation equations. The least accurate data, which are default values, is considered as Level 3 inputs. This level of input is used only when there are minimal consequences of early failure.

Figure 3 illustrates the accuracy of performance estimates obtained using the 1993 AASHTO Guide, nationally calibrated MEPDG, and Iowa calibrated MEPDG. This figure clearly shows that the performance estimates of AASHTO based design guide varies greatly from the actual measured pavement response.

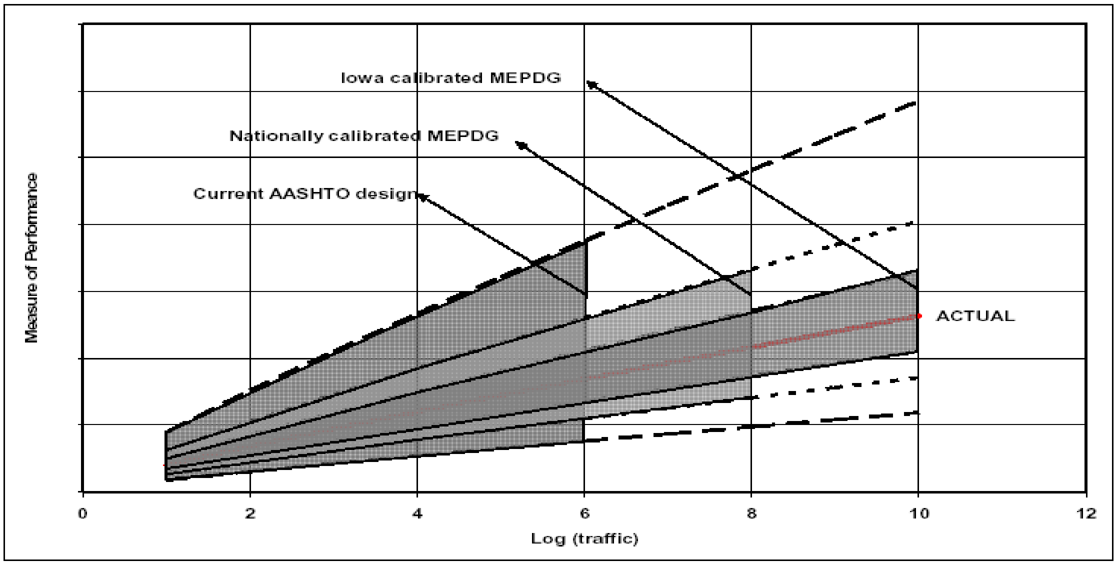


Figure 3 Comparison of Design Pavement Performance to Actual (*3*)

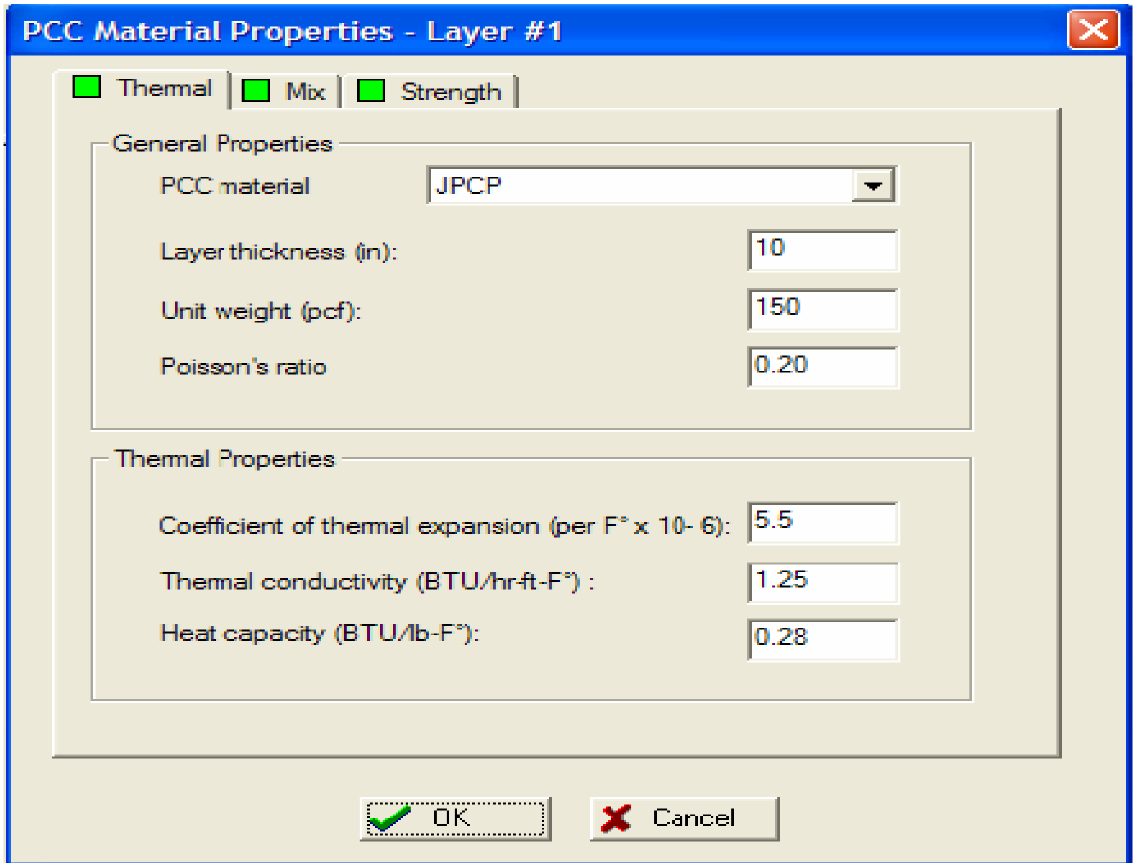
Region specific calibrated MEPDG based pavement performance fits more closely to the actual responses, compared to the nationally calibrated MEPDG. This research project conducted in Iowa has demonstrated the need for more specific material input values of

Level 1 accuracy to obtain a pavement performance prediction closer to that of the actual pavement performance (*3*).

2.1.3 PCC Material Input Parameters MEPDG

Characterizing the material properties of each pavement component is a tedious process whether it is flexible or concrete pavement. As a part of applying the MEPDG at a regional level, studies are being conducted to characterize the common materials used in pavement construction. Due to its complexity, studies have also been performed to find those input parameters which are most sensitive for MEPDG design. It is found that certain material properties are too sensitive not to be ignored for safe and economic pavement design (*1*). This research includes factors to which MEPDG performance predictions for PCC pavements are quite sensitive.

The material input values for PCC in the MEPDG comprise general PCC properties, thermal, mixture, and strength properties. The general properties of PCC include layer thickness, unit weight of concrete and Poisson's ratio, which are used primarily in predicting mechanistic pavement responses. The thermal properties comprise the coefficient of thermal expansion, thermal conductivity and heat transfer, which are required predominantly in predicting slab deformations and temperature profile. Figure 4 represents the input screen of MEPDG for general and thermal properties of concrete. The mixture properties include the cement type, cementitious content, water content, aggregate type and curing type, concrete set temperature, and strength gain over time. The input screen for the mixture properties in MEPDG is shown in Figure 5. Strength properties are needed in precisely predicting the strength gain over time and mechanistic response.



General Properties

PCC material: JPCP

Layer thickness (in): 10

Unit weight (pcf): 150

Poisson's ratio: 0.20

Thermal Properties

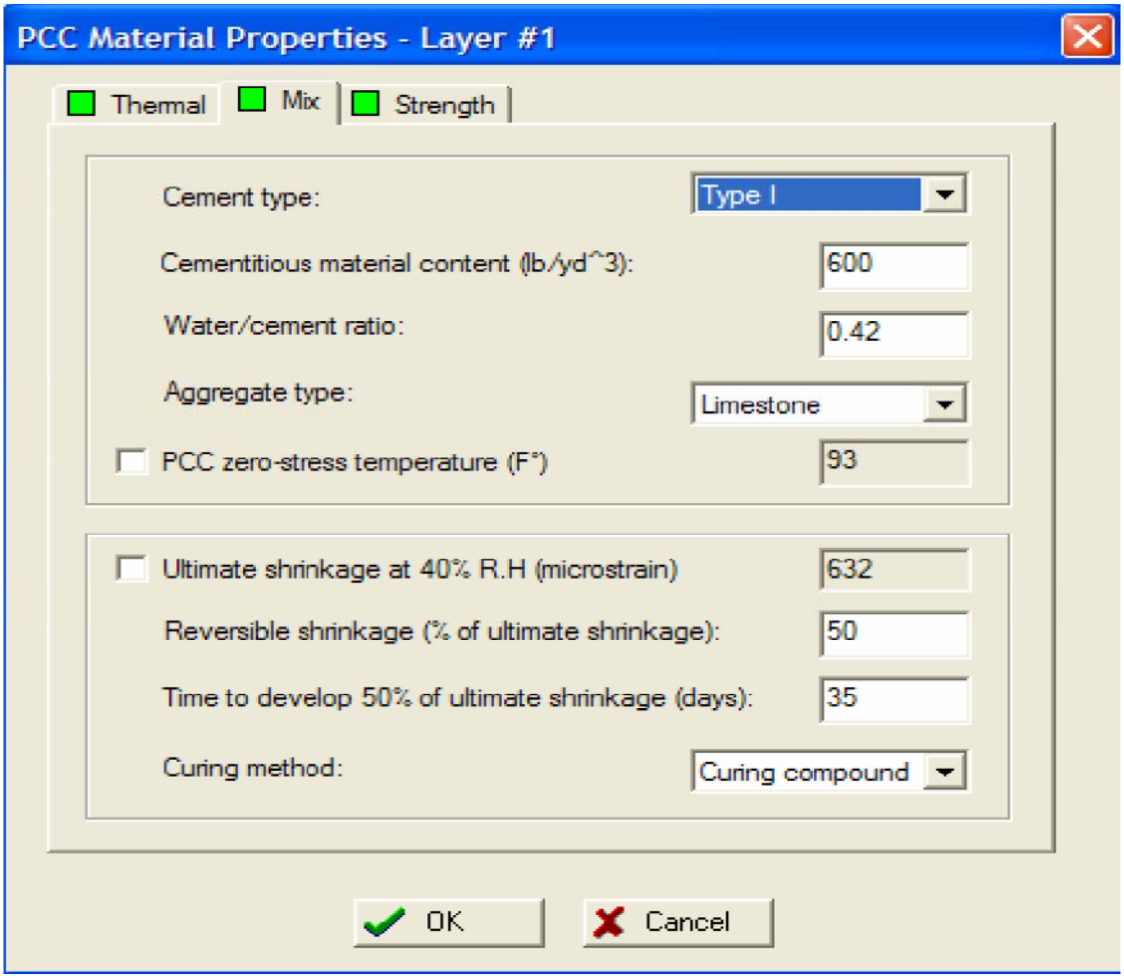
Coefficient of thermal expansion (per F° x 10- 6): 5.5

Thermal conductivity (BTU/hr-ft-F°) : 1.25

Heat capacity (BTU/lb-F°): 0.28

Figure 4 General & Thermal PCC Material Properties Input Screen of MEPDG

The MEPDG includes recommended values for all the thermal, mixture and strength properties, which allows the designer to obtain an acceptable level of distress and roughness while designing. But it does not bracket all the construction materials available for construction, particularly the materials that are locally available. Hence to apply the MEPDG regionally it is recommended that the state DOT’s should have the set of material properties of all the locally available construction material, so as to obtain more precise results in designing pavement using MEPDG.



Cement type: Type I

Cementitious material content (lb/yd^3): 600

Water/cement ratio: 0.42

Aggregate type: Limestone

☐ PCC zero-stress temperature (F°) 93

☐ Ultimate shrinkage at 40% R.H (microstrain) 632

Reversible shrinkage (% of ultimate shrinkage): 50

Time to develop 50% of ultimate shrinkage (days): 35

Curing method: Curing compound

Figure 5 Mixture PCC Material Properties Input Screen of MEPDG

The MEPDG allows the strength properties of PCC to be input based on the accuracy of the available data. For level 1 input, the required values are the Modulus of Elasticity (E) and Modulus of Rupture (MR) at 7, 14, 28, and 90 days and the ratio of 20 year to 28 day strength. Level 2 inputs allow taking the compressive strength at 7, 14, 28, and 90 days and the 20 year to 28 day ratio (*3*). For level 3 inputs, it allows the user to input either 28 day modulus of rupture or compressive strength, along with or without the 28 day modulus of elasticity.

2.2 SENSITIVE PCC MATERIAL INPUT PARAMETERS OF MEPDG

The pavement performance models contained in the MEPDG have been found to be very sensitive to certain PCC material properties compared to other parameters and hence require further attention, including understanding the factors affecting the changes in those properties. Steven Beam studied the 29 PCC-related input parameters for the sensitivity of the distress models and found that 6 parameters are sensitive to all the three distress models of faulting, cracking and smoothness (*1*). Table 1 notes the sensitivity of performance models to each input parameter. It is noted that 4 of these sensitive parameters are structural properties and 2 are non structural properties. Also observed is the sensitivity of pavement performance to thermal properties. The temperature related properties, coefficient of thermal expansion and curl/warp effective temperature difference, are found to be sensitive to faulting, cracking and smoothness but thermal conductivity to be sensitive only for the cracking model. It is also found that the primary structural properties used in stress- strain analysis, the Poisson's ratio, Modulus of Elasticity and compressive strength are also found to be sensitive to distress models of cracking and smoothness. This emphasizes the need for more research on these material related properties.

Table 1 Significance of PCC Material inputs in MEPDG Summary (*1*)

JPCP Concrete Material Charateristics	Performance Models		
	Faulting	Cracking	Smoothness
Curl/Warp Effective Temperature Difference	S	S	S
Joint Spacing	S	S	S
Sealent type	I	I	I
Dowel Diameter	S	I	S
Dowel Spacing	I	I	I
Edge Support	S	S	S
PCC-Base Interface	I	I	I
Erodability Index	I	I	I
Surface short wave absorptivity	I	S	I
Infiltration of surface water	I	I	I
Drainage path length	I	I	I
Pavement cross slope	I	I	I
Layer thickness	S	S	S
Unit weight	S	S	S
Poisson's ratio	I	S	I
Coefficient of thermal expansion	S	S	S
Thermal conductivity	I	S	I
Heat capacity	I	I	I
Cement type	I	I	I
Cement content	I	I	I
Water/Cement ratio	I	I	I
Aggregate type	I	I	I
PCC set temperature	I	I	I
Ultimate shrinkage at 40% R.H	I	I	I
Reversible shrinkage	I	I	I
Time to develop 50% of ultimate shrinkage	I	I	I
Curing method	I	I	I
28-day PCC modulus of rupture	I	S	S
28-day PCC compressive strength	I	S	S

S = Significant to the performance models

I = Insignificant to the performance models

2.3. COEFFICIENT OF THERMAL EXPANSION

Coefficient of thermal expansion (CTE) is a measure of a material's expansion or contraction per unit length per degree of temperature change. It is usually expressed in terms of micro strains per unit temperature change. Concrete expands slightly as temperature rises and contracts as temperature falls, although it can expand slightly as free water in the concrete freezes (*4*). Temperature changes may be caused by environmental conditions or by cement hydration. An average value for the coefficient of thermal expansion of concrete is about 10 millionths per degree Celsius, although values range from 6 to 13 millionths per degree Celsius. This amounts to a length change of 5 mm for 10 m of concrete subjected to a rise or fall of 50°C (*4*). The coefficient of thermal expansion for structural low-density concrete varies from 7 to 11 millionths per degree Celsius.

2.3.1. Factors Affecting Coefficient of Thermal Expansion of Concrete

Thermal expansion and contraction of concrete varies with factors such as aggregate type, cement content, water cement ratio, temperature range, concrete age, and relative humidity. Of these, it is observed that the aggregate type has the greatest influence on the variability of coefficient of thermal expansion (*4*). The variation in the value of coefficient of thermal expansion of different types of concrete with different aggregates is shown in Table 2, obtained from experimental data. The data were obtained from tests on small concrete specimens in which all factors were the same except testing factor-aggregate type or cement type.

Table 2 Coefficient of Thermal Expansion for various types of Concrete (*5*)

Aggregate Type (from single source)	Concrete CTE (using this aggregate)	
	Per 1°F	per 1°C
Quartz	6.60	11.90
Sandstone	6.50	11.70
Gravel	6.00	10.80
Granite	5.30	9.50
Basalt	4.80	8.60
Limestone	3.80	6.80

Studies done in this field showed that, being the main constituent of concrete, the variation in the value of coefficient of thermal expansion of aggregates causes wide variations in the thermal coefficients of concrete.

Aggregates are often complex in terms of type and mineral content and hence the thermal coefficients cannot be neatly classified by rock or mineral type (*5*). Table 3 lists the value of coefficient of thermal expansion of various aggregates. It is considered that the main factor influencing the thermal expansion of rock, and therefore of concrete, is the proportion of quartz present. Rocks with high quartz content, such as quartzite and sandstone, have the highest coefficients whereas rocks containing little or no quartz, such as limestone, have the lowest coefficient of thermal expansion (*5*).

Table 3 Coefficient of Thermal Expansion for Various Types of Aggregates (*5*).

Aggregate Type	Aggregate CTE	
	per 1° F	**per 1° C**
Marble	0.6 to 0.9	1.1 to 1.60
Gravel, Chert	4.1 to 7.3	7.4 to 13.0
Quartzite	7.300	13.100
Gravel	5.9 to 7.1	10.6 to 12.8
Sands	6.0 to 7.0	10.8 to 12.6
Granite	1 to 6.6	1.8 to 11.9
Sandstone	6.600	11.9
Limestone	1.9 to 6.4	3.4 to 11.5
Slag	5.100	9.2
Traprock	4.3 to 4.7	7.7 to 8.5
Basalt	4.5	8.1

The CTE for structural light weight concrete varies from 4.0 to 6.0 % per 1°F (7.0 to 11.0 per 1°C), depending on the aggregate type and the amount of natural sand (*5*). It is noted from Figure 6 that at a temperature higher than 40°C, the coefficient of coarse grained aggregate is more than the fine grained aggregates.

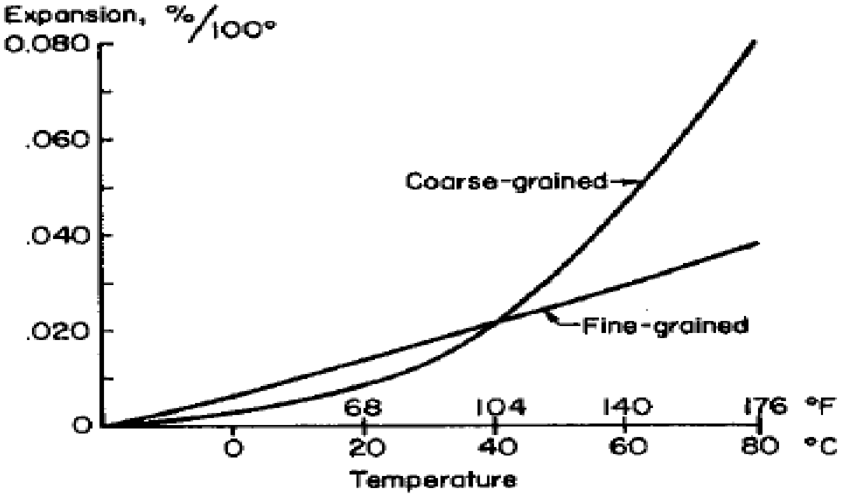


Figure 6 Graph of CTE Vs Temperature for Fine Grained & Coarse Grained Soils (*5*)

The thermal coefficient for cement paste may range from 0.060% to 0.090% per 100°F (10.8 to 16.2 per 1^{o}C). The difference in coefficients of mortar and aggregates is illustrated in Table 4. The Cement paste has a higher expansion coefficient than aggregate and as aggregate is added to the paste, the CTE drops. Hence, cement paste (cement plus water) has the highest coefficient, mortar (paste and sand) has a lower coefficient and Concrete (mortar and coarse aggregate) has the lowest coefficient (*6*).

Table 4 Difference Between CTE of Mortar & Coarse Aggregate (*6*).

Fine Aggregate in mortar	**Course Aggregate by itself**	**CTE**	
		per 1^{o} F	**per 1^{o} C**
Siliceous	Lime Stone	0.8 to 5.2	1.4 to 9.4
Glacial	Lime Stone	2.7 to 3.4	4.9 to 6.1
Limestone	Lime Stone	0.9 to 2.8	1.6 to 5.0
Syenite	Syenite	1.90	3.40
Siliceous	Quartzite	0.7 to 1.7	1.3 to 3.1
Siliceous	Traprock	1.9 to 2.8	3.4 to 5.0
Syenite	Traprock	1.70	3.10
Limestone	Traprock	0.8 to 1.1	1.4 to 2.0

Another variation of thermal expansion of concrete relates to the moisture content. Air-dry aggregate by itself may have a 10% higher coefficient of expansion than saturated aggregate (*5*). It is believed that the thermal coefficient of expansion of concrete is approximately equal to the weighted average of the coefficients of its ingredients. The thermal coefficient of expansion of concrete will vary for other reasons as well. One is called hydrothermal volume change, in which a change of temperature of concrete causes a migration of water between the gels and capillaries of the concrete. As a result, the damp or wet expansion of concrete will not be the same as for oven dry concrete. The absolute difference may be plus or minus 0.010%. However, the difference disappears within a half hour after the temperature stabilizes; the phenomenon yields its largest apparent thermal coefficients at about 68° F (20° C) (*5*).

The thermal expansion coefficient for a given aggregate may vary with different grain textures, moisture content, aggregate type, aggregate size, mix proportion etc with temperature. Thus it can be seen why the coefficient for concrete can also vary considerably with the temperature. This highlights the need for testing the aggregate or the concrete in critical situations.

2.3.2. Standard Test Method for Coefficient of Thermal Expansion

The test method for the measurement of CTE of PCC, adopted by AASHTO in the year 2000 as the standard test method of CTE (designated as TP 60-00), was developed by the portland cement concrete team. Shown in Figure 7 is the test equipment for CTE. This method determines the CTE of a cylindrical concrete specimen, under a saturated condition since the degree of saturation of concrete is known to have a major influence on its measured coefficient of thermal expansion. It measures the length change of the specimen due to a specified temperature change and corrected for any change in length of the measuring apparatus (previously determined). The CTE is then calculated by dividing the corrected length change by the temperature change and then the specimen (*6*).

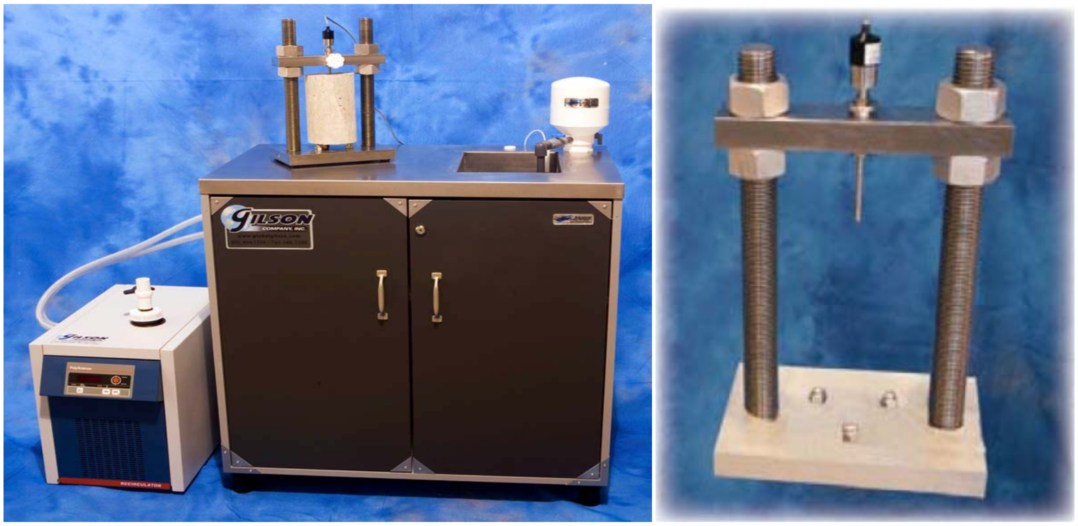


Figure 7 Coefficient of Thermal Expansion Testing Equipment

Test specimens consist of drilled 100-mm (4 in.) nominal diameter cores sampled from the concrete structure being evaluated, or 100-mm (4 in.) nominal diameter cylinders, obtained in accordance with ASTM test T 24 (*6*). The standard reference material used for calibration will be the same length as the test specimen so that the frame does not have to be adjusted between calibrations and testing (*6*). The sawed ends should be flat and parallel.

2.3.2.1. Procedure

The specimens stored in saturated limewater at 23 ± 2°C for not less than 48 hours until two successive weighing of the surface-dried sample at intervals of 24 hours show an increase in weight of less than 0.5 percent is used for CTE testing (*6*). Linear variable differential transducer (LVDT) attached measuring apparatus is placed inside the water bath which is filled with cold tap water enough to immerse the specimen. Temperature sensor reports the variation in temperature of the bath. Fully saturated specimen removed from the storage tank is measured for the length and diameter before placing in the measuring apparatus. Specimens are placed in the measuring apparatus located in the controlled temperature bath with the lower end of the specimen firmly seated against the support buttons also ensuring the LVDT tip seated against the upper end of the specimen (*6*).

The test equipment uses a software program automated to perform the standard test procedure. It sets the temperature of the water bath initially to 10°C until the thermal equilibrium of the specimen has been reached, indicated by consistent readings of the LVDT taken every 10 minutes over a one-half hour time period. Once the initial temperature readings from the sensor to the nearest of 0.1°C and the LVDT reading to the nearest 0.00025 mm are recorded, the temperature of water bath is set to 50°C and then again 10°C repeating the same process. The LVDT and temperature readings recorded at 50°C is the second set of readings and then again recorded at 10°C is the third and final set of readings.

2.3.2.2. Calculations

Coefficient of thermal expansion is calculated by equation (1) and is reported in micro strains/°C (*6*):

$$\mathbf{CTE = (\Delta L_a / L_o) / \Delta T} \tag{1}$$

Where:

$\mathbf{\Delta La}$ = actual length change of specimen during temperature change, (See Equation 2)

$\mathbf{L_o}$ = measured length of specimen at room temperature, mm;

$\mathbf{\Delta T}$ = measured temperature change (average of the four sensors), °C

$$\Delta La = \Delta L_m + \Delta L_f \quad (2)$$

where:

ΔL_m = measured length change of specimen during temperature change, mm

ΔL_f =length change of the measuring apparatus during temperature change, (See Equation 3.)

$$\Delta L_f = C_f \text{ x } L_o \text{ x } \Delta T \quad (3)$$

where:

C_f = correction factor for change in length of apparatus temperature, in^{-6} / in / ^{o}C

For the expansion test segment, the initial and second readings are used in the calculations *(6)*. For the contraction test segment, the second and final readings are used in the calculations. The test result is the average of the two CTE values obtained from the two test segments provided the two values are within 0.3 micro strain/°C (0.5 micro strain/°F) of each other.

$$\mathbf{CTE = (CTE\ I + CTE\ 2) / 2} \quad (4)$$

2.3.2.3. Report

The report includes the identification number, specimen type, description and source, specimen dimensions, including length and diameter, mixture proportions and aggregate type (*6*). Figure 8 shows the test specimen in the water bath with attached LVDT measuring linear temperature variation using the testing equipment developed for the accurate measurement of coefficient of thermal expansion of concrete.

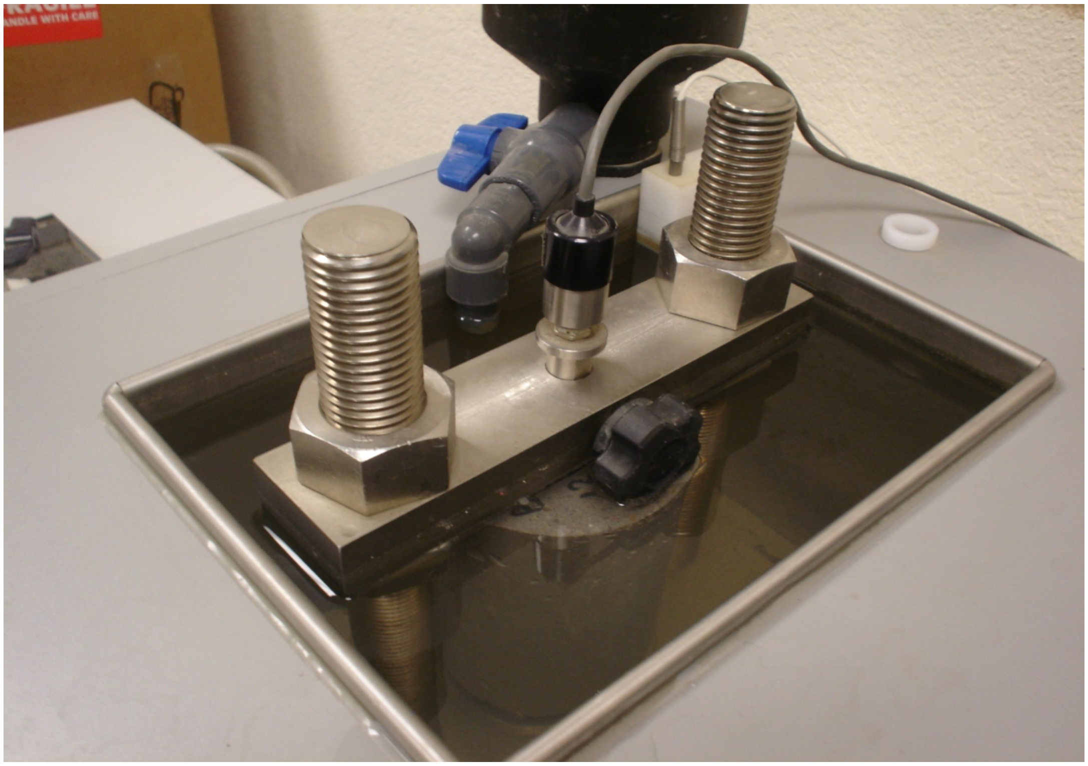


Figure 8 CTE Test setup showing specimen in water bath attached to LVDT (*8*).

If available, all temperature and length measurements collected during the test, all calculated values, including CTE data and the final CTE value, the frame's correction factor 'C' as well as the reference material used and its thermal coefficient, date of test, place of test, technician conducting test and any other pertinent information should be reported (*6*).

2.3.3 Role of CTE in PCC Material Characterization

The MEPDG considers the effects of PCC thermal expansion and contraction (*7*). LTPP research data may be used by future users of the guide to estimate appropriate CTE input values when material-specific data are not available.

The determination of CTE for different input levels is defined in the MEPDG. Level 1 of CTE determination involves direct measurement of the change in length of laboratory specimens subjected to changes in temperatures, using AASHTO TP60, *Standard Test method for CTE of Hydraulic Cement Concrete* (*7*). Level 2 of CTE determination uses a weighted average of the constituent values based on the relative volumes of the constituents of the concrete components. In this method, the CTE of PCC (α_{PCC}) is determined using linear, weighted average of the constituent CTE of aggregate and paste values based on the relative volumes of the constituents using Equation (5). Typical ranges of various common PCC mix components already tested and tabulated for CTE are contained in this level of design.

$$\boldsymbol{\alpha}_{\mathbf{PCC}} = \boldsymbol{\alpha}_{\mathbf{agg}} * \mathbf{V}_{\mathbf{agg}} + \boldsymbol{\alpha}_{\mathbf{paste}} * \mathbf{V}_{\mathbf{paste}} \qquad (5)$$

where,

α_{agg} = CTE of aggregate.

V_{agg} = Volumetric proportion of the aggregate in the PCC mix.

α_{paste} = CTE of cement paste.

V_{paste} = Volumetric proportion of the paste in the PCC mix.

Table 5 shows the tabulated values of CTE for concrete made with commonly used aggregates. The values of CTE used in LTTP pavement sections used for MEPDG calibration, is 4.0, 5.5 and 7.2 microstrain/^{o}F (minimum, mean and maximum respectively).

Table 5 Typical values of CTE for Second Level of Material Input Value (*8*)

Material Type	Aggregate CTE (10-6/°F)	CTE of Concrete (10-6/°F)
Aggregates		
Marbles	2.2–3.9	2.3
Limestones	2.0-3.6	3.4-5.1
Granites & Gneisses	3.2-5.3	3.8-5.3
Syenites, Diorites, Andesite, Basalt, Diabase	3.0-4.5	4.4-5.3
Dolomites	3.9-5.5	5.1-6.4
Blast Furnace Slag		5.1-5.9
Sandstones	5.6-6.7	5.6-6.5
Quartz Sands & Gravel	5.5-7.1	6.0-8.7
Quartzite, Cherts	6.1-7.0	6.6-7.1
Cement Paste (Saturated)		
w/c = 0.4 to 0.6	10.0-11.0	-
Concrete Cores		
Cores from LTTP pavement sections, many of which were used in calibration	NA	4.0-5.5-7.2 (Min-Mean-Max)

Level 3 of CTE estimation is based on historical data. The greatest potential for error is associated with this option, because PCC materials vary considerably (*7*). Realistic data for the types of materials being used in concrete mixtures are rarely available and, if available, are likely to be based on a specific PCC mix design or aggregate type. Thus, an agency should test typical mixes containing a range of aggregate types to obtain typical values for their materials.

2.3.4 Sensitivity of MEPDG Distress Models to CTE Material Input Value

The CTE is an important factor in optimizing concrete joint design, calculating stresses, joint sealant design, and selecting sealant materials in the process of pavement design as ascertained by the Research Project TRC-0302, sponsored by the Arkansas State Highway and Transportation Department (AHTD). This research was conducted by S. Beam (*1*) to assess the relative sensitivity of the models used in the MEPDG to inputs relating to Portland cement concrete (PCC) materials. In the analysis of jointed plain concrete pavements (JPCP), it is found that out of the 29 inputs, two of the PCC materials parameters to which the three distress models proved sensitive included the coefficient of thermal expansion (CTE) and the Poisson's ratio of the concrete neither of which are routinely measured in the laboratory prior to or during pavement construction or concrete mixture design.

Figure 9 shows the sensitivity of the performance models tested over a range of 3 $x10^{-6}$ to 9 $x10^{-6}$ per °F. As per the *MEPDG* range for typical values of a concrete pavement between 4 $x10^{-6}$ and 7 $x10^{-6}$ per °F, the faulting model is very sensitive to coefficient of thermal expansion (*1*). This is in line with the fact that this parameter greatly influences the curling stresses. These curling stresses can directly lead to faulting at the joints in addition to contributing to corner cracking.

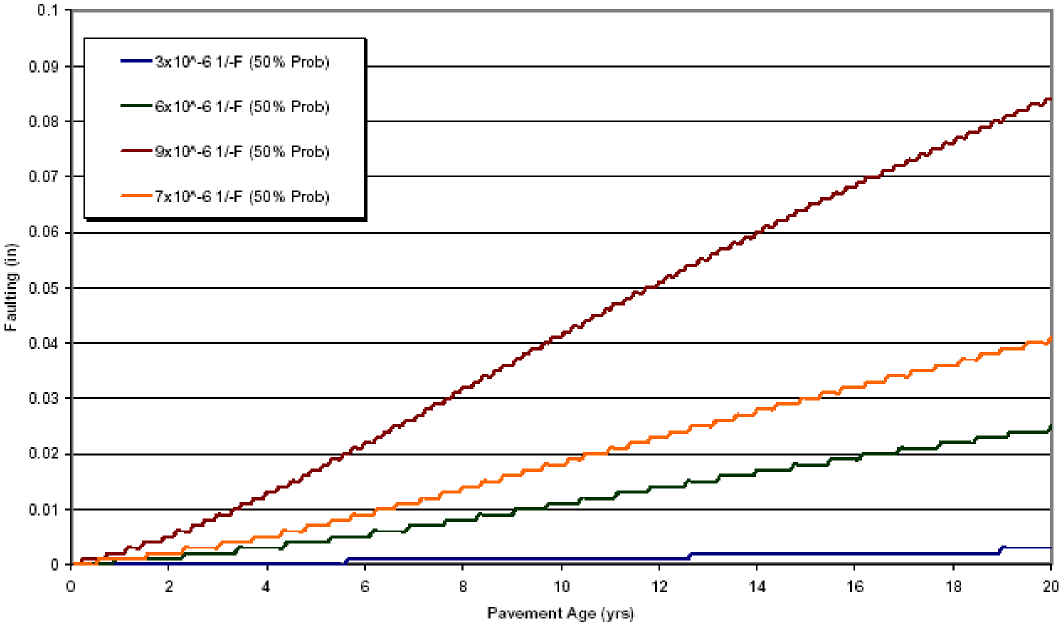


Figure 9 Sensitivity of Faulting to Coefficient of Thermal Expansion (*1*)

Figure 10 shows the influence of coefficient of thermal expansion in the cracking model. Though the influence is smaller within the range of typical values of MEPDG, between 4 x10^{-6} and 7 x10^{-6} per °F, cracking greatly increases for higher values of coefficient of thermal expansion (*1*). This gives the concrete mix designers the range of values of coefficient of thermal expansion for the materials used.

The same range of CTE values between x10^{-6} and 7 x10^{-6} per °F, when tested for the sensitivity of the roughness model did not show distress comparable to the cracking model. But it definitely showed the trend of increased roughness distress with increased value of CTE as illustrated in Figure 11.

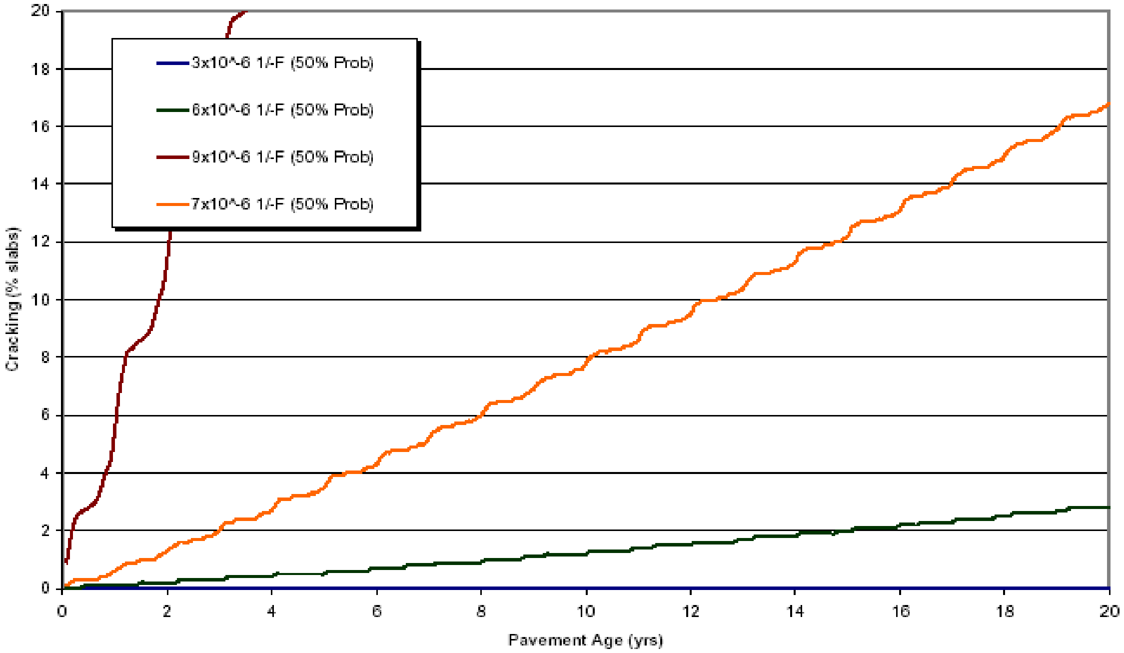


Figure 10 Sensitivity of Cracking to Coefficient of Thermal Expansion (*1*)

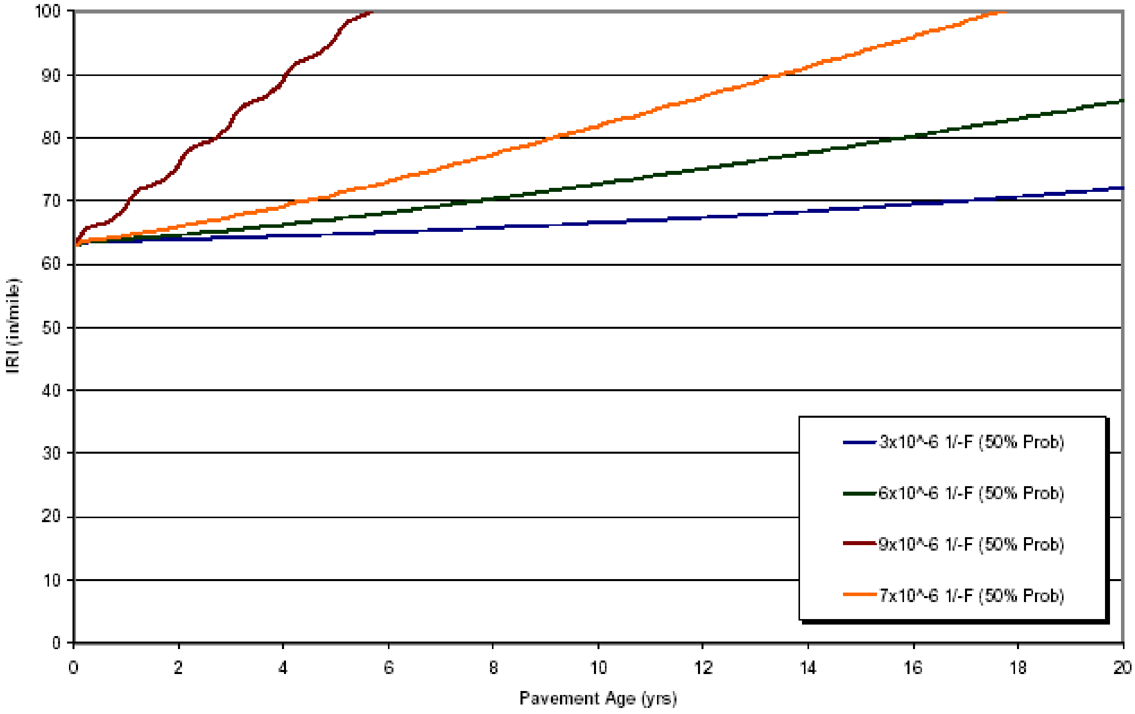


Figure 11 Sensitivity of IRI to Coefficient of Thermal Expansion (*1*)

2.4 POISSON’S RATIO AND ELASTIC MODULUS

An important material property used in elastic analysis of pavement systems is Poisson's ratio. It is defined as the ratio of transverse to longitudinal strains of a loaded specimen as illustrated in Figure 12 (*9*).

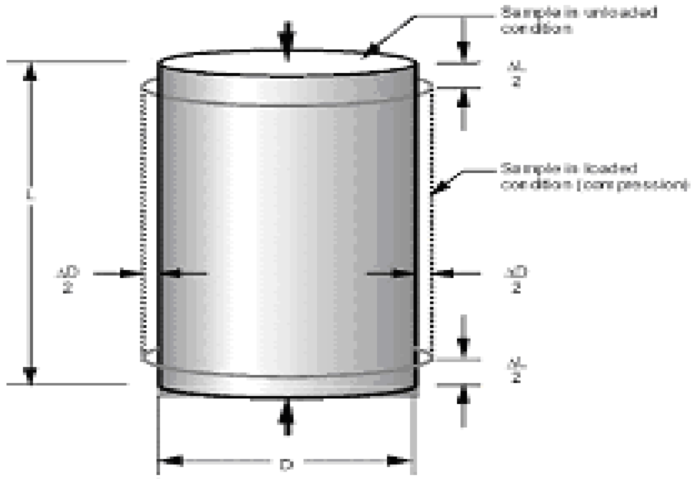


Figure 12: Volume Change on Load Application illustration diagram (*9*)

In realistic terms, Poisson's ratio can vary from initially 0 to about 0.5 (assuming no specimen volume change after loading). As shown in Table 6, a common value used is 0.20 to 0.21, but the value may vary from 0.15 to 0.25, depending upon the aggregate, moisture content, concrete age, and compressive strength. Generally, "stiffer" materials will have lower Poisson's ratios than "softer" materials. Poisson's ratios larger than 0.5 may be reported in the literature, however, this implies that the material was stressed to cracking, experimental error, etc (*10*).

Table 6 Poisson’s Ratio of different materials (*9*)

Material	Poisson's Ratio
Steel	0.25 - 0.30
Aluminum	0.33
PCC	0.15- 0.20*
Asphalt Concrete Flexible Pavement	0.35 (±)
Crushed Stone Flexible Pavement	0.40 (±)
Soils (fine-grained) Flexible Pavement	0.45 (±)
*Dynamic determination of μ could approach 0.25 for PCC (Neville, 1975)	

Elastic modulus (Ec) or Young's modulus of any material is a measure of the stress-strain behavior of the material. In the mechanistic pavement analysis, the PCC elastic modulus has a strong effect on pavement deflection and the stresses throughout the pavement structure. The recommended test procedure for obtaining Ec is ASTM Standard C 469, static modulus of elasticity and Poisson’s ratio of concrete in compression (*8*). The test provides a stress-strain ratio value (Ec) and Poisson's ratio of the lateral to longitudinal strain for hardened concrete at all ages and for all curing conditions. The Ec values obtained from this test are usually less than the moduli obtained from rapid load applications (dynamic or seismic testing conditions). The ratio is approximately 0.8 (*10*).

2.4.1. Factors Affecting Modulus of Elasticity and Poisson’s Ratio

Reliable information on the variation in Poisson’s ratio with age, strength or other properties of concrete is not available but generally Poisson’s ratio is lower for high strength concrete (*10*). The value of Modulus of Elasticity and Poisson’s ratio varies with factors such as moisture content, properties of aggregate materials, shape of the coarse aggregate particles, their surface characteristics, age of concrete and mix proportion of concrete (*10*). The higher the modulus of elasticity of aggregate the higher the value of modulus of resulting concrete. It is interesting to note that the two components of concrete, cement and aggregate, when tested individually, exhibited sensibly linear stress-strain relationship whereas concrete shows a curved relation which is attributed to the micro cracking of the composite interface material of cement and aggregate (*10*).

The strain increases at a faster rate than stress, which results in a lower value of Elastic Modulus. Concrete Modulus of elasticity increases for large percentages of aggregate content since the aggregates have higher modulus value than the cement paste. The age and the mix proportion of concrete influence the modulus of elasticity of concrete (*10*). The modulus value of the concrete increases with age and will have a higher value in the later stages than in the earlier period.

2.4.2. Test Method of Static Modulus of Elasticity and Poisson’s Ratio

In ASTM C469, the test apparatus consists of compression testing machine, compressometer and extensometer as shown in Figure 13. Test specimens consist of 6” x 12” Moist-cured concrete cylinders (capped) (*11*).

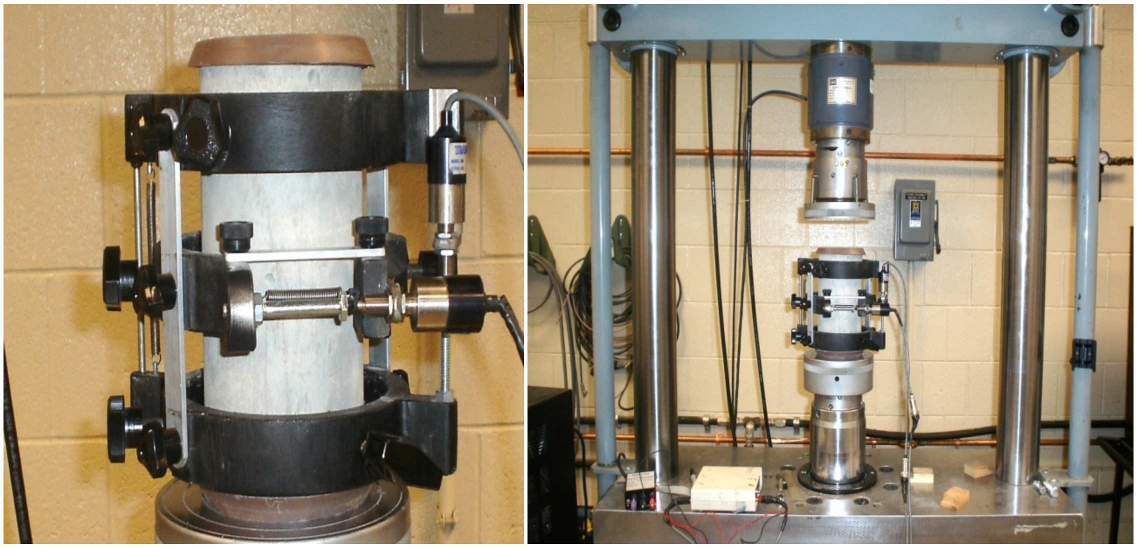


Figure 13 LVDT Attached capped concrete cylindrical specimen

2.4.2.1. Procedure

LVDT attached test specimen is placed on the lower platen of the test machine and aligned to the centerline of the upper thrust block of the crosshead. The sulphur capping assures a plane surface to avoid eccentric loading. The MTS testing machine is programmed to lower the crosshead to contact the specimen and start loading at a rate of 35 psi per second (990 lb/s) until a load of 40% of ultimate load is achieved. The 2 LVDTs attached to the specimen one horizontally and other vertically records the lateral and longitudinal strain. The software records the applied load and longitudinal deformation at set intervals without interruption. This loading cycle is repeated at least three times to obtain an average value. The recorded loading and deformation is used to calculate the stress and strain as noted below.

2.4.2.2. Calculation

Stress and longitudinal strain are calculated as follows (*11*):

Stress, $\sigma = P/A$ (5)

where

P = Applied load and

A = Cross-sectional area of the cylindrical specimen.

Strain, $\varepsilon_x = d/L_o$ (6)

where

L_o = Gage length is the distance between yokes generally equal to 8 in.

d = gl, Longitudinal specimen deformation and

where

g = The longitudinal dial gage reading and

$$l = \frac{e_1}{e_1 + e_2} \tag{7}$$

where

e_1 = Eccentricity of the compressometer pivot from the axis of the specimen and

e_2 = Eccentricity of the longitudinal dial gage from the axis of the specimen.

Plot the stress-strain curve (stress on the ordinate and strain on the abscissa) and Calculate E to the nearest 50,000 psi as follows:

$$E = \frac{\sigma_2 - \sigma_1}{\varepsilon_2 - 0.00005} \tag{6}$$

where

σ_2 = Stress corresponding to 40% of ultimate load

σ_1 = Stress corresponding to a strain of 0.00005 and

ε_2 = Strain at a stress of σ_2.

Calculate lateral (radial) strain as follows:

$$\text{Strain, } \varepsilon_y = d'/D, \tag{7}$$

where

D = Specimen diameter

d' = $g'I'$, Radial specimen deformation and.

where

g' = Radial dial gage reading and,

$$I' = \frac{e'_1}{e'_1 + e'_2} \tag{8}$$

where

e'_1 = Eccentricity of the extensometer pivot rod from the axis of the specimen and

e'_2 = Eccentricity of the radial dial gage from the axis of the specimen. If these eccentricities are equal, then $I'=0.5$.

Plot the lateral strain versus the longitudinal strain curve (lateral strain on the ordinate and longitudinal strain on the abscissa) and Calculate v to the nearest 0.01 as follows:

$$v = \frac{\varepsilon_{t2} - \varepsilon_{t1}}{\varepsilon_2 - 0.00005} \tag{9}$$

where

ε_{t2} = Lateral strain produced by stress σ_2

ε_{t1} = Lateral strain produced by stress σ_1

After loading to 40% and recording the load versus displacement data, unload the specimen and remove the compressometer (the compressometer may be left in place when appropriate to generate the entire stress vs. strain curve to failure). Perform an unconfined compression test in accordance with ASTM C 39. The specified loading rate is 35 psi/s (*11*).

2.4.2.3. Report

Report the compressive strength (nearest 10 psi) and unit weight of the concrete (0.1 pcf), Plot of the stress-strain diagram, measured value of Young's modulus (nearest 50,000 psi), measured value of Poisson's ratio (nearest 0.01).

2.4.3 Role of Modulus of Elasticity in PCC Material Characterization

The PCC modulus of elasticity is used as an input to characterize the performance of rigid pavement. It is a complex parameter influenced significantly by mix design parameters such as water cement ratio, paste aggregate proportion, aggregate type and by the mode of testing (*12*).

Aggregate characteristics are important in determining the elastic modulus of PCC due to their high elastic modulus and their control of the volumetric stability of the PCC (*12*). High aggregate content and high modulus aggregates like basalt, granite and dense limestone are associated with the high value of elastic modulus of PCC. As the water cement ratio increases, the porosity increases and modulus of elasticity decreases. Increased age and hydration results in decreased porosity and hence increased elastic modulus.

For a Level 1 design, the PCC modulus of elasticity and Poisson's ratio is determined through laboratory testing (ASTM C 469) (*8*). The modulus of elasticity of PCC will generally increase with time as the cement in the PCC continues to hydrate. As the modulus strength increases, so does the ability of the PCC to carry loads and therefore, it is important to account for this increase in load carrying capability.

For Level 2 designs, the modulus of elasticity is estimated from other concrete material testing such as compressive strength (*12*). PCC flexural strength is also an important parameter in the design of PCC pavements from which the Level 3 input value of modulus of elasticity is determined.

In MEPDG sensitivity analysis, the PCC elastic modulus has great influence on pavement deflection and stresses and hence the value of elastic modulus of PCC should be properly estimated (*8*). The characterization of the PCC elastic modulus varies as a function of pavement design type such as newly constructed, existing or fractured roads. Table 7 shows the three input levels according to accuracy of determining the value of PCC modulus of elasticity for a newly constructed road.

Table 7 MEPDG Recommended PCC Elastic Modulus Estimation (*8*)

Material Group	Input Level	Description
PCC (Slabs)	1	• Modulus of elasticity (E_c) determined directly by laboratory testing using the method ASTM C 469 at various ages of 7, 14, 28 and 90 days. • Estimate the 20 year to 28 day (long term) elastic modulus ratio. • Develop modulus gain curve using the test data and long-term modulus ratio to predict E_c at any time over the design life.
	2	• Modulus of elasticity (E_c) determined indirectly from compressive strength testing at various ages (7, 14, 28, 90 days) using the recommended test of AASHTO T22. • Estimate the 20 year to 28 day compressive strength ratio. • Convert f'_c to E_c using the relationship, $E_c = 33\ \rho^{3/2}\ (f'_c)^{1/2}$ • Develop modulus gain curve using the test data and long term modulus ratio to predict E_c at anytime over the design life.
	3	• Modulus of elasticity (E_c) determined indirectly from 28 day estimate of flexural strength (M_R) or f'_c. M_R is determined using AASHTO T 97 and f_c using AASHTO T22 or from historical records. • If 28 day M_R is determined, then at time t, the M_R is determined by the equation, $M_R = (1 + \log_{10}(t/0.0767) - 0.01566*\log_{10}(t/0.0767)^2)*\ M_{R\ 28\ day}$ • Estimate the E_c (t) by first determining f'_c (t) from $M_R(t)$ and then converting fc(t) to E_c (t) using the relationship $f'_c = (M_R/9.5)^2$ psi and $E_c = 33\ \rho^{3/2}\ (f'_c)^{1/2}$ • If 28 day f'_c is estimated, first convert it to an M_R value using equation above and then project M_R (t) as above and from it E_c (t) over time.

2.4.4 Role of Poisson's Ratio in PCC Material Characterization

Poisson's ratio is the required input for the structural response computational models, although the effect on the computed pavement response is comparatively minor (*8*). Hence the value of this parameter is often assumed, with minimal regard to the mixture specific design, as it is rarely tested in a laboratory. As listed in Table 8, for input Level 1, the Poisson's ratio can be determined along with the modulus of elasticity using the ASTM C 469 laboratory test method. For level 2 inputs, a correlation with other material characteristics is not possible and hence is not applicable (*8*).

Table 8 PCC Input Levels for determination of Poisson's ratio (*8*)

Material Group	Input Level	Description
PCC (Slabs)	1	Poisson's ratio determined directly by laboratory testing using the method ASTM C 469
	2	Not Applicable – No relationship or correlation may be used to estimate Poisson's ratio from constituent materials characteristics or other tests.
	3	Typical values of Table 19 can be used

For the input value at Level 3 the values given in Table 9 and the value of Poisson's ratio is selected based on the material and construction type (*8*).

The typical range of Poisson's ratio values of PCC is 0.15 to 0.25. This range of values of Poisson's ratio is tested for the sensitivity of the three distress models of faulting, cracking and smoothness using the new MEPDG (*9*). The *MEPDG* states that the Poisson's ratio has little effect on the response models but required for computation of the stresses and strains within the pavement.

Table 9 PCC Input Level 3 values for the Poisson's ratio (*8*)

PCC Materials	Level 3 Range of values	Level 3 Typical values
PCC slabs newly constructed or existing	0.15- 0.25	0.2
Crack / Seat (Fractured Slab)	0.15- 0.25	0.2
Break / Seat (Fractured Slab)	0.15- 0.25	0.2
Rubbilized (Fractured Slab)	0.25- 0.40	0.3

2.4.5 Sensitivity of MEPDG Distress Models to Poisson's Ratio Input Value

The relation of Poisson's ratio with the stress - strain calculation of the concrete is further emphasized in the performance model response to variations in the value of Poisson's ratio. Though less sensitive, the faulting model, shows that the Poisson's ratio does have some effect (*1*). This is likely due to the mechanism of joint faulting being a vertical strain in the subgrade and has little to do with the concrete parameters aside from being able to support the bearing stress caused by the dowel bars (*1*). This is where the Poisson's ratio likely comes into play, and the effect is shown in Figure 14. The real effect of the Poisson's ratio on the predicted performance of a concrete pavement is reflected in Figure 15, which shows the sensitivity of the cracking model to the parameter.

Since cracking is the result of lateral strain created under vertical loading, the Poisson's ratio, by definition, would be extremely important in predicting a pavement's tendency to crack (*1*). This is reflected in the cracking model's sensitivity to the

Poisson's ratio. As the Poisson's ratio increases, meaning that the lateral strain in the pavement is higher relative to the longitudinal strain, the cracking model shows more cracking.

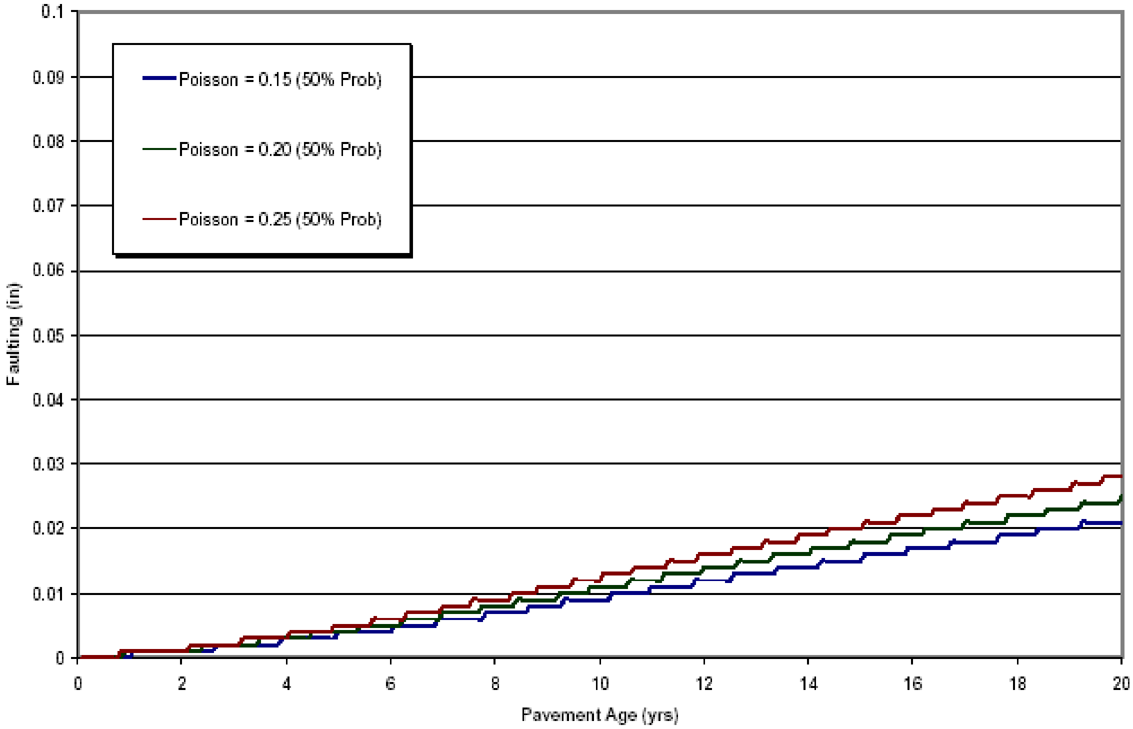


Figure 14 Sensitivity of Faulting to Poisson's Ratio (*1*)

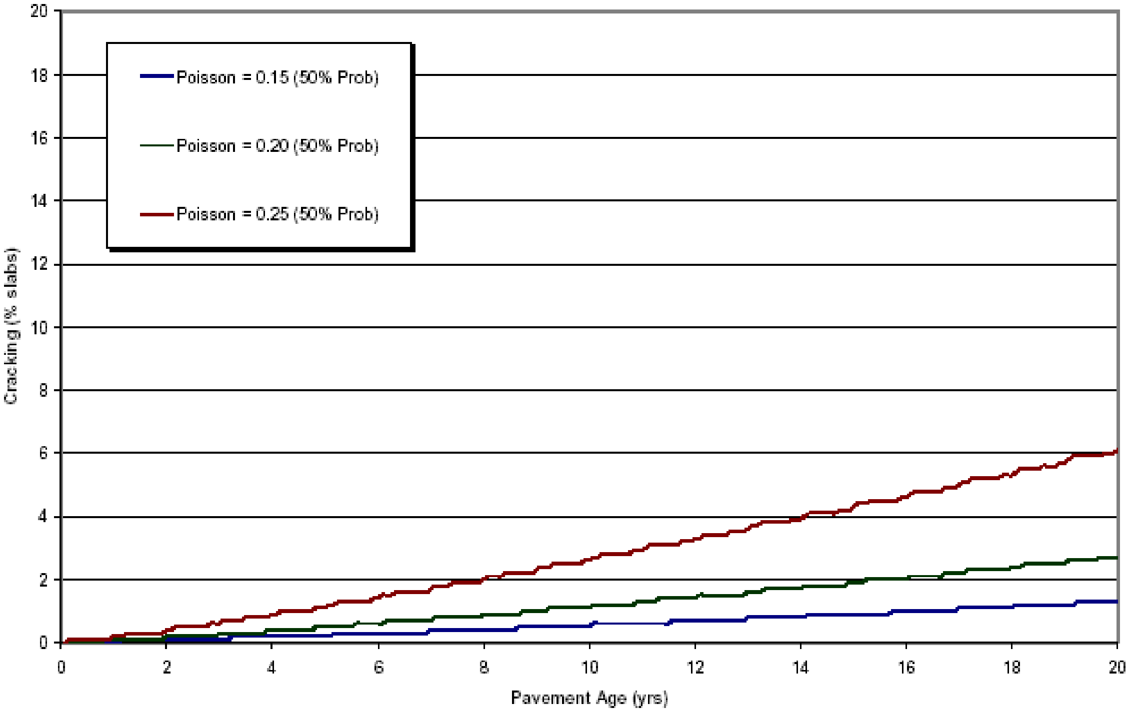


Figure 15 – Sensitivity of Cracking to Poisson's Ratio (*1*)

Figure 16 shows that the IRI model is only slightly sensitive to the Poisson's ratio, despite the fact that the cracking model is so sensitive to the Poisson's ratio. This is because, as has already been stated, the smoothness model is much more sensitive to the faulting than the cracking in the pavement, as it should be. Since the faulting is not very sensitive to variations in the Poisson's ratio, the smoothness model is not as sensitive.

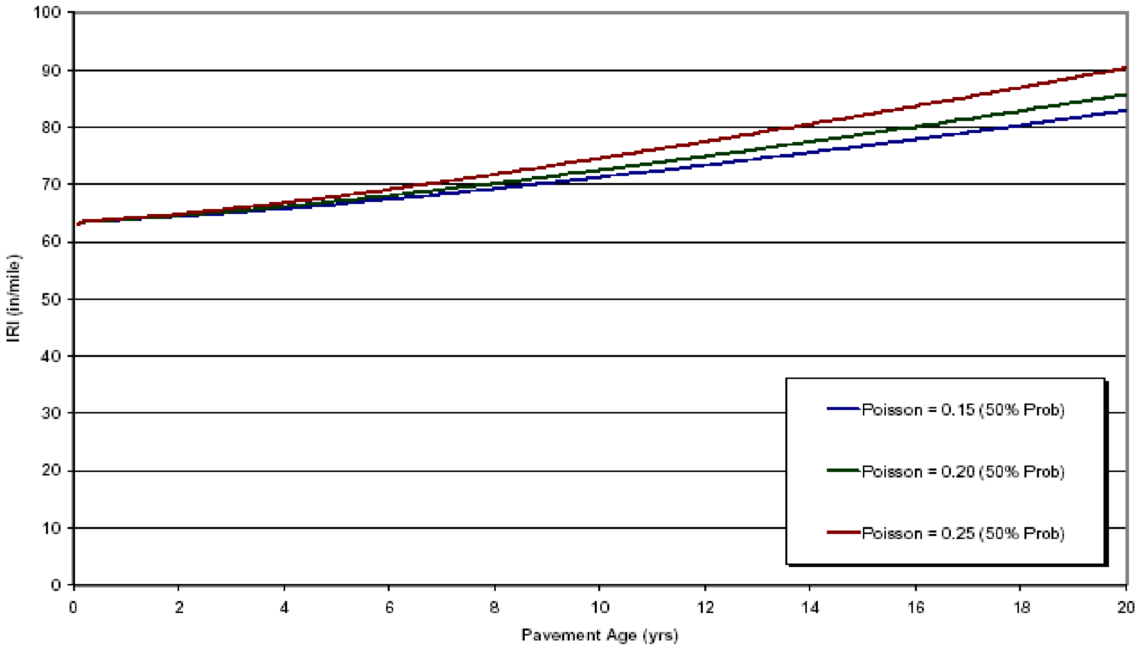


Figure 16 – Sensitivity of IRI to Poisson's Ratio (*1*)

2.4. CONCRETE PAVEMENT MIX DESIGN

The primary purpose of concrete mixture design is to obtain the desired characteristics for concrete for each different application. Concrete mixture design is the process of selecting the balanced proportion of concrete components including aggregates, Portland cement, water, some amount of entrapped air and other cementitious materials and/or chemical admixtures to obtain a concrete with desirable properties (*13)*. Admixtures capable of altering the concrete mixture properties typically include entraining admixtures that increase the air content of concrete and chemical admixtures that increase strength and workability, reduce mixing water requirements, accelerate or retard curing.

Improper mix proportioning can result in varying the input parameters of PCC pavement concrete which will affect economic and efficient mixture design when used in the MEPDG. Technically an irrational mixture proportion of concrete would produce less workable, segregated, inconsistent, less dense, low strength, and less durable concrete than what is suitable for construction (*13). Workability* is the concrete property that determines its capacity to be placed, consolidated and finished without harmful segregation whereas *Consistency* is the relative mobility of the concrete mixture. Both of these properties are measured in terms of the slump, a value that increases with the mobility of concrete. *Durability,* another property of concrete, is a measure of concrete resistance to severe weather conditions. The *Strength,* a measure of concrete durability, is measured as the capacity of the concrete to resist compression at the age of 28 days.

Another desirable concrete property, *Density* is used primarily for sound insulation and counterweights whereas the *Water-cement ratio* used in mix design is a control criterion of concrete strength. As has already been discussed, the variation in temperature of concrete has a significant effect on the pavement design, and the thermal gradient should be kept at an admissible level in order to avoid early age cracking.

2.5.1. General Mix Design

The basic method of PCC mix design generally accepted today is the mix design of American Concrete Institute (ACI). The two steps consist of mix proportioning and performance tests. The standard ACI method of mix design is divided into 8 steps consisting of slump selection, maximum aggregate size selection, mixing water and air content selection, water cement ratio, cement content, coarse aggregate content, fine aggregate content and adjustments for aggregate moisture (*13*).

2.5.1.1. Slump

Slump selection corresponds to the required workability which is the stiffest consistency that can be placed. Table 10 shows the general slump range specified by ACI for each application.

Table 10 ACI Specification of Slump for Different Applications. (*13*)

Type of Construction	Slump	
	(mm)	(inches)
Reinforced foundation walls and footings	25 - 75	1.0-3.0
Beams and reinforced walls & columns	25 - 100	1.0-4.0
Pavements and slabs	25 - 75	1.0-3.0
Mass concrete	25 - 50	1.0-2.0

2.5.1.2. Maximum size of Aggregate

PCC parameters such as workability, cement paste content and strength depend on the maximum size of aggregate and hence ACI specifies that it should be limited to 1/3 of the slab depth and ¾ of the minimum clear span between reinforcing bars. For pavements, the aggregate size specified is in the order of 1inch to 1.5 inch (*13*).

2.5.1.3. Amount of water and air content for mixing

Since the slump of the concrete is generally affected by other factors like aggregate size, particle shape, aggregate gradation, temperature, the amount of entrained air and admixtures, specified in Table 11 are the admissible slumps for the desired mixing water quantity (*13*). Air entrainment is particularly appropriate for pavement PCC in order to control the action of freeze and thaw.

Table 11 Water and Air Content Quantity Requirements for Different Slumps (*13*).

Slump	**Mixing Water Quantity in kg/m^3 (lb/yd^3) for the listed Nominal Maximum Aggregate Size in mm**							
	9.5	12.5	19	25	37.5	50	75	100
Air-Entrained PCC in mm								
25 - 50	181	175	168	160	148	142	122	107
75 - 100	202	193	184	175	165	157	133	119
150 - 175	216	205	197	184	174	166	154	-
Recommended Air Content (percent)								
Mild Exposure	4.5	4.0	3.5	3.0	2.5	2.0	1.5	1.0
Moderate Exposure	6.0	5.5	5.0	4.5	4.5	4.0	3.5	3.0
Severe Exposure	7.5	7.0	6.0	6.0	5.5	5.0	4.5	4.0

2.5.1.4. Water Cement Ratio

The properties of concrete like strength and durability are well correlated with the water cement ratio. The lower the water cement ratio, the higher the durability of the PCC. Compressive strength is the basis of selecting water cement ratio. Table 12 below shows the ACI specified requirements of compressive strength for water cement ratio (*13*).

Table 12 Relationship Between Water Cement Ratio and Compressive Strength (*13*).

28-Day Compressive Strength in MPa (psi)	Water-cement ratio by weight	
	Non-Air-Entrained	Air-Entrained
41.4 (6000)	0.41	-
34.5 (5000)	0.48	0.40
27.6 (4000)	0.57	0.48
20.7 (3000)	0.68	0.59
13.8 (2000)	0.82	0.74

2.5.1.4. Cement Content

Cement content is calculated from mixing water content and water – cement ratio. Most DOTs specifies the minimum cement content in the range of 300 -360 kg/ m^3 or 564 lbs/ ft^3 (*3*).

2.5.1.5. Coarse Aggregate Content

The workability of a mixture suitable for reinforced concrete construction decides the empirical selection of coarse aggregate. ACI recommends percentage by unit volume of coarse aggregate based on the nominal maximum aggregate size and fine aggregate fineness modulus. (*3*). Table 13 gives the specification requirements of ACI for the PCC pavement.

Table 13 Volume of Coarse Aggregate Per Unit Volume of PCC for Pavement (*13*)

Nominal Maximum Aggregate Size	Fine Aggregate Fineness Modulus			
	2.40	**2.60**	**2.80**	**3.00**
9.5 mm (0.375 inches)	0.50	0.48	0.46	0.44
12.5 mm (0.5 inches)	0.59	0.57	0.55	0.53
19 mm (0.75 inches)	0.66	0.64	0.62	0.60
25 mm (1 inches)	0.71	0.69	0.67	0.65
37.5 mm (1.5 inches)	0.75	0.73	0.71	0.69
50 mm (2 inches)	0.78	0.76	0.74	0.72

2.5.1.6. Fine Aggregate Content

The fine aggregate quantity is specified as the remaining quantity after specifying the quantities of water, cement, air and coarse aggregate.

2.5.1.7. Adjustments for the Aggregate Moisture Content

Aggregate moisture content is required to be adjusted since it affects other quantities like the aggregate weights and the amount of mixing water. For the purpose of mix design, the aggregates are calculated based on the dry oven unit weight, but in practice it is batched based on the actual weight which usually contains some moisture content (*13*). Also, if the aggregates are saturated surface dry, then they experience an increase in water content when in a wet condition. This causes net change in the amount of water required in the mix, thus making it necessary to take into account an adjustment for the aggregate moisture content.

5.2.2. Portland Cement Concrete Properties

The key factors that satisfactorily characterize key performance parameters of PCC are workability, strength, durability and early age behavior. It is difficult to draw a clean distinction between the characterization test and the performance test for PCC like HMA where the tests are often scale simulations of actual field conditions. PCC tests are directed more towards the physical properties of material (*13*). Table 14 shows the typical range of values for the various test methods used in testing the PCC.

Table 14 Test Performance Specification Limit for Each PCC Property Tested (*13*)

Property	Specification Limits
Slump (comparative tool)	Allowable variation is 50 mm (2 inches) ASTM C 143 and AASHTO T 119.
Compressive Strength Tensile Strength Flexural Strength	Range is from 3000 – 5000 Psi. ASTM C 39 and AASHTO T 22 ASTM C 496 and AASHTO T 198 ASTM C 78 and AASHTO T 97 also ASTM C 293 and AASHTO T 177
Freeze Thaw test	Typical value of DF between 40-60 ASTM C 666 and AASHTO T 161 also ASTM C 671
Air Content	3.0 - 7.0 percent as determined by statistical analysis ASTM C 231 and AASHTO T 152
Chemical Attack	Critical Cl^- content for steel corrosion is 0.6 – 1.2 kg Cl^- /m^3 of PCC. AASHTO T 259.
Early Age Behavior	HIPERPAV – assess the influence of mix design on the early age behavior of rigid pavement.

PCC tests are an integral part of mix design since all pavements can be described by their fundamental characteristics and performance. They can describe PCC characteristics and provide the means to relate mix design to intended performance. Typically, PCC performance tests concentrate on basic physical properties such as strength and durability. Early age behavior modeling can also be beneficial in predicting early strength gain, excessive plastic shrinkage, cracking and spalling (*13*). PCC performance modeling provides the crucial link between laboratory mix proportioning and field performance.

2.5.2. AHTD Specification For PCC Pavement Mix Design

2.5.2.1. Materials

The Arkansas State Highway and Transportation Department has provided a set of specifications for the materials or components of concrete suitable for the PCC pavement construction. Materials containing foreign matter, frost, or lumps or crusts of hardened substances should be avoided and the specification for each material is as detailed below.

2.5.2.1.1. Cement

Portland cement Type 1 such as Portland-Pozzolan Cement, AASHTO M 240, Type IP (20% maximum), Pozzolan-Modified Portland cement, AASHTO M 240, Type I (PM), Slag-Modified Portland cement, AASHTO M 240, Type I (SM) shall be used for PCC parameters in Arkansas (*14*). The limit for the allowable alkali content in the Portland cement is 0.60%. For cementitious material (Portland cement, fly ash or ground granulated blast-furnace slag), the alkali limit is 5 lbs /cu yd (*14*).

2.5.2.1.2. Fine Aggregate

The fine aggregate should be clean, hard, durable particles of natural sand or other approved inert material with similar characteristics. Aggregate maximum permissible percentages by weight obtained for different type of aggregate mineral are as follows. For AASHTO T 11 it is 2 Clay lumps, for AHTD Test Method 302 it is 0.5 Coal, for lignite by AASHTO T 113 method it is 0.25 and for Soft and flaky particles by AHTD Test Method 302 it is 2 clay lumps (*14*). Aggregates are subjected to testing according to AASHTO T 21 and the fine aggregate should comply with the grading requirements listed in Table 15 per method of AASHTO T 27 (*14*).

Table 15 Grading Requirements of Fine Aggregates (*14*)

Sieve, (mm)	Percent Passing
3/8"(9.5)	100
# 4 (4.75)	95-100
# 8 (2.36)	70-95
# 16 (1.18)	45-85
# 30 (0.600)	20-65
# 50 (0.300)	5-30
# 100 (0.150)	0-5

Fine aggregates used should be always free from injurious amount of organic impurities. From the established value of the fine aggregate used in the mix design, the fineness modulus of the fine aggregate should not vary more than 20 points and else would require redesigning of the mix (*14*).

2.5.2.1.3. Coarse Aggregate

Crushed stone or gravel consists of coarse aggregate which are clean, hard and durable fragments of rock of uniform quality. The percent of wear by the Los Angeles Test (AASHTO T 96) should not be greater than 40, and for the Soundness Test (Sodium Sulfate, AASHTO T 104), when subjected to 5 cycles, should not have a loss which exceed 12% (*14*). Gravel should have a percent of wear by the Los Angeles Test

(AASHTO T 96) not greater than 40. If required necessary by visual observation, the amount of deleterious substances are tested by laboratory methods for different types of aggregate materials which should be in the maximum permissible limits as shown in Table 16.

Table 16 Coarse Aggregate Test Specifications (*14*).

Test methods	Maximum Permissible Percentage by Weight
Removed by decantation (AASHTO T 11)	1
Coal and Lignite (AASHTO T 113)	0.25
Clay lumps (AHTD Test Method 302)	0.25
Soft fragments (AHTD Test Method 302)	5
Total Deleterious substances	5

If the percent loss from the fine aggregate does not exceed 0.5%, maximum percent by weight removed by decantation from crushed stone coarse aggregate may be increased to 1.8%. When the percent loss of fine aggregate is not more than 1 %, it can be increased to 1.5 % (*14*). Coarse aggregate should comply with the Table 17 grading requirements when tested according to AASHTO T 27: If the value of the fineness modulus exceeds the allowable limit of 20 points, then the mix need to be redesigned.

Table 17 Sieve Size and Gradation for Coarse Aggregates (*14*)

Sieve, (mm)	% Passing	
	Standard Gradation AHTD	**Alternative Gradation AASHTO M43 #57**
1½" (37.5)	100	100
1" (25.0)	60-100	95-100
3/4" (19.0)	35-75	-
1/2" (12.5)	-	25-60
3/8" (9.5)	10-30	-
#4 (4.75)	0-5	0-10
#8 (2.36)	-	0-5

2.5.2.1.4. Water

Water used in mixing or curing should be clean and free from injurious amounts of oil, salts, or other deleterious substances and should not contain more than 1000 ppm of chlorides, and the tests will be made according to AASHTO T 26 (*14*). Water from sources other than approved departments and that from shallow depth should be sampled and tested before use in concrete to exclude silt, mud, grass, or other foreign materials.

2.5.2.1.5. Admixtures

When specified on the plans or requested by the contractor, admixtures used will improve certain characteristics of the concrete. It also may be used when approved by the Engineer, supported with the manufacturer's certified formulation for the proposed admixture, and with sufficient evidence that the proposed admixture has given satisfactory results on other similar work (*14*). Chlorides should not be added during the manufacturing process. Dosage rate specified by the manufacturer has to be used and should be adjusted based on test results obtained by trial batches while using admixtures compatible with each other. A mechanical dispenser should be used for mixing admixture with water so as to accurately meter the additive throughout the mix water cycle (*14*).

Air Entraining Agent – Per the prescribed AASHTO M 154, the Air entraining agent is used to improve the required properties of concrete like plasticity, workability, etc (*14*). *Retarding Agent* – As per the AASHTO M 194, to modify the time of set of concrete, the retarding agent Type B or Type D admixture should be used. It is required that while specifying the air-entrained concrete, the air-entraining agent and the retarding agent should be added such that the air content of the concrete falls within the percentage range stipulated. Always make sure that the concrete to which the retarding agent is added has air content not greater than 3 percent (*14*). *Other Admixtures* - The use of other admixtures which help in improving the desirable properties of concrete will be decided by the Engineer depending on the specific project.

2.5.3. AHTD Pavement Mix Design

The Portland cement concrete pavement mix consists of Portland cement, water, admixtures, fine aggregate and coarse aggregate of the specified gradation and quality in specified proportions so that the resultant mix will produce a more desirable concrete of high durability.

The value of air content in fresh concrete determined by AASHTO T 152 shall be in the range of 6% ± 2%. Air entraining agent is added to the water to make a solution and then added to concrete while mixing to obtain uniform mixing of the admixture (*14*). The the minimum cement content specified is 564 pounds of cement per cubic yard of concrete. Including free moisture content of the aggregate, the water/cement ratio should be less than 0.45 pound per pound (*14*). Rate of substitution for fly ash, an allowed substitute in low early strength cements, is one pound of fly ash for each pound of replaced cement not exceeding 20 % by weight of cement (*14*). Ground granulated blast-furnace slag (GGBFS) as a partial replacement for Type I cement should not exceed 25% by weight, and the rate of substitution is one pound of GGBFS for each pound of cement replaced, which is not recommended in high early strength or blended cements (*14*). Listed are the concrete mixture properties specifications for AHTD in Table 18.

Table 18 AHTD Concrete Pavement Mixture Specifications

Property	**AHTD Specifications**
Slump	For comparison between mixes, the allowable variation to be acceptable is 2 inches.
Maximum Aggregate Size	Varies, but is often 1.5 inches
Water-Cement Ratio	shall not exceed 0.45
Cement Content	564 lb/yd^3 minimum cementitious material
Percent of Fly Ash & Slag	Fly ash 20% and Slag 25%

The minimum 28 day compressive strength determined by AASHTO T 22 is 4000 psi, and for mixed concrete the uniform consistency with a slump of not more than 2” is recommended as tested according to AASHTO T 119 (*14*). With the approval of the site engineer, a Type A water reducing concrete admixture or mid-range water reducing concrete admixture may be used. Fine and coarse aggregate proportion ensure satisfactory plasticity, workability, and consistency of the mix maintained with the further assuring that based on dry and rodded measure, the ratio of the fine aggregate to cement should be between 1.5 and 2.5 (*14*). Water/cement ratio, minimum cement content and a verification test result for the alkali reactivity tests (AASHTO T 303) should be in the specified limits.

CHAPTER 3. OBJECTIVES OF STUDY

The overall objective of this project is to characterize typical Arkansas pavement PCC mixtures in terms of the coefficient of thermal expansion (CTE), Poisson's ratio and modulus of elasticity in order to develop input values for the MEPDG. Specific objectives include:

- **Document Test Procedure of CTE, Poisson's Ratio and Modulus of Elasticity**

  Document the development and use of tests for determining CTE, Poisson's ratio, and modulus of elasticity for PCC. The University of Arkansas is currently evaluating equipment used for determining the CTE of Portland cement concrete and the obtained results are being studied for variability. Test specifications exist for determining the Poisson's ratio and modulus of elasticity of PCC. This first objective seeks to fully document and/or refine these testing protocols.

- **Determine the CTE and Poisson's Ratio of Concrete Pavement in Arkansas**

  Determine the value of CTE, Poisson's ratio and modulus of elasticity for PCC mixtures containing major aggregates and different cement proportions currently used in Arkansas for rigid pavement construction. The testing protocols developed in the first objective are used to test different batches of typical Arkansas PCC mixes for CTE and Poisson's ratio. A range of mixtures are identified that will allow the testing effort to "bracket" the expected range of results for Arkansas mixes.

- **Recommend MEPDG input values for CTE and Poisson's Ratio of PCC**

  The obtained values of CTE, Poisson's ratio and modulus of elasticity obtained from the testing program will provide guidance for pavement designers regarding the CTE and Poisson's ratio for the MEPDG. It may also provide designers data regarding variability of input values and associated impacts on design solutions.

- **Relate PCC mixture CTE and Poisson's Ratio to QA/QC properties.**

  Since the MEPDG predicts pavement performance, it is imperative that material properties used (assumed or otherwise) in the design process be verified during construction. It is not likely that either the CTE or the Poisson's ratio test will be conducted during construction; therefore this project will seek to establish relationship(s) between these properties and typical PCC tests conducted as part of the QA/QC process.

CHAPTER 4. EXPERIMENTAL PLAN

The experimental plan detailed here includes the testing matrix and tests conducted. The main objective of this study is to analyze the sensitivity of MEPDG input parameters CTE, Poisson's ratio and modulus of elasticity with the change in aggregate type, cement content and concrete age. Compressive strength, modulus of elasticity, modulus of rupture, indirect tensile strength, coefficient of thermal expansion, Poisson's ratio and shrinkage strain are the major material input values of MEPDG for Portland cement concrete pavement (PCCP).

4.1 DESIGN OF EXPERIMENTAL TEST CONCRETE MIX PROPORTION

In order to achieve the objective of developing state-specific PCC material input values for the new MEPDG, the above mentioned factors affecting the input values of CTE, Poisson's ratio and modulus of elasticity are considered while selecting the concrete mix proportions that brackets commonly used concrete mix designs for pavements in Arkansas.

The testing matrix considers variation of the following parameters:

1. Aggregate types (limestone, sandstone, syenite and gravel)
2. Neat cement and cement replacements (fly ash and ground granulated blast furnace slag)
3. Ages (7, 14, 28 and 90 days)

The experiment plan included 12 standard PCC mixtures, designed using four main aggregate types typically used for rigid pavement construction in Arkansas (limestone, sandstone, syenite and gravel) and three different proportions of cementitious materials (cement alone, cement and 20 percent fly ash, and cement and 25 percent ground granulated blast furnace slag). River sand from one source was used as fine aggregate in all mixtures. Also the PCC mixtures were designed in accordance with standard AHTD construction specifications. Mixture properties are presented in Table 19.

Table 19 Concrete Mix Proportion and Experimental Tests Description

Aggregate Type	**Cement Content**	**W/C Ratio**	**Air Content**	**Description**
Limestone	564	0.45	6 ± 2	For each test combination, (1) three replicates of cement paste are prepared for each of 7 and 28-day CTE tests; (2) three replicates of concrete mixture are prepared for each of 7 and 28-day CTE tests; (3) replicates of concrete mixture are prepared for each of 7,14,28, 90-day Ec and Poisson ratio; and (4) three replicates of concrete mixture are prepared for each of 7,14,28, 90-day Compressive Strength
	20 % Fly Ash	0.45	6 ± 2	
	25% Slag	0.45	6 ± 2	
Syenite	564	0.45	6 ± 2	
	20 % Fly Ash	0.45	6 ± 2	
	25% Slag	0.45	6 ± 2	
Sandstone	564	0.45	6 ± 2	
	20 % Fly Ash	0.45	6 ± 2	
	25% Slag	0.45	6 ± 2	
Gravel	564	0.45	6 ± 2	
	20 % Fly Ash	0.45	6 ± 2	
	25% Slag	0.45	6 ± 2	

In addition, cement paste was wet-sieved from the standard mixtures for additional CTE testing. For each PCC/cement paste mixture, three replicate specimens were prepared in accordance with ASTM C31/C192 and tested at 7 and 28 days in compliance with AASHTO TP 60. A total of 144 (24 PCC/cement paste mixtures × 3 replicates × 2 ages) CTE tests were performed.

Experimental Study includes four common aggregate types available in Arkansas. Neat cement content and water-cement ratio are selected based on the minimum requirements specified in the AHTD Specification. These minimum values are used to design almost all concrete mixtures, which meet AHTD requirements, for PCC pavements in Arkansas.

Experimental Study will provide typical coefficient of thermal expansion, modulus of elasticity, and Poisson's ratio values required for Level 1 inputs for each of the four aggregates with the tested cement proportion. The tests to be performed on fresh and hardened concrete to verify the characteristics of each batch are briefly discussed on the following sections. The exact proportion of mix obtained from the trial batch of concrete is shown in Table 20.

4.2 AHTD SPECIFICATIONS FOR THE AGGREGATES

Arkansas boasts rich resources of aggregates which are presently adequate to supply the needs of the state and the neighboring states that lack such resources. The major types of rocks present are limestone, sandstone, dolostone, novaculate, chert, syenite and gravel (*15*).

The specifications of AHTD to qualify as aggregate include the test requirements, grading and the proportion of aggregates used. The tests performed for the suitability of the aggregates used in pavements are the LA abrasion test, sodium sulfate soundness test and Alkali Sulfur Reactivity (ASR) test. The limit of percentage loss of aggregate for the LA abrasion test is 40% and for sodium sulfate test is 12% commonly followed throughout the country. For crushed stone the LA abrasion test loss is <45% and for Asphalt surface, it is <35% (*15*).

Table 20 Summary of 12 batch of concrete Mixture Properties

Concrete Mixture Proportion												
Materials	**Batch No.**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Cement (lb./yd^3)	564	451	423	564	451	423	564	451	423	564	451	423
Fly ash (lb./yd^3)	0	113	0	0	113	0	0	113	0	0	113	0
Slag (lb./yd^3)	0	0	141	0	0	141	0	0	141	0	0	141
Coarse Agg. (lb./yd^3)	1950	1950	1950	1950	1800	1800	1800	1800	1800	1800	1800	1800
Coarse Agg. Type*	LS	LS	LS	SS	SS	SS	SY	SY	SY	GR	GR	GR
Coarse Agg. Size (in.)	1	1	1	1	1	1	1	1	1	1	1	1
Fine Agg. (lb./yd^3)	1099	1093	1103	1106	1212	1222	1228	1224	1219	1228	1195	1190
Water (lb./yd^3)	254	254	254	254	254	254	254	248	254	243	248	254
Water / Cement	0.45	0.45	0.45	0.45	0.45	0.45	0.45	0.44	0.45	0.43	0.44	0.45
Daravair (fl oz./cwt)	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
Fresh Concrete Properties												
Temperature (^{o}F)	54	73	55	70	75	74	55	79	70	72	60	80
Slump (in.)	2.00	2.00	1.00	0.75	1.75	1.00	1.00	1.25	0.25	0.25	2.00	1.00
Air content (%)	5.8	5.5	5.5	4.0	4.3	4.0	5.0	5.3	4.0	4.0	4.0	4.0
Unit Weight (pcf)	141	144	143	143	141	140	141	140	145	143	141	143
Compressive Strength (psi)												
3-day strength	4320	3980	4830	4760	4140	3920	5640	4230	6200	4610	3240	4240
7-day strength	4980	4990	4990	4840	4240	4650	5920	5230	7180	5030	3860	4820
28-day strength	5330	5330	6040	5770	4900	5550	6710	6020	8170	5300	4450	5190

AHTD also specifies the dust-ratio, which is the proportion of fine particles in the aggregate material. The required specification for aggregates used in pavement construction is that no more than 2/3 of the material can pass through the # 200 sieve. Another requirement of AHTD for the road pavement aggregates is that no more than 60% of the course aggregates should be of limestone or dolostone and at least 40% must be siliceous aggregate such as sandstone, syenite, novaculite or chert (*15*). The reason for this specification that limestone and dolomite are carbonate rocks having low resistance to wear which over the years become smooth and make the road surface to slick. AHTD does not recognize ASR as a major issue in the rocks found in Arkansas and hence does not specify the test for alkali-silica reactivity.

4.2.1 Aggregates Used For AHTD Pavement Construction

Though abundantly available, not all rocks are suitable for aggregates to be used in road pavements. Limestone and dolostone are of carbonate origin and make very good aggregate. Limestone outperforms dolostone in soundness tests and hence proves a better aggregate material for road construction. Sandstone formations of some regions contain silica cement and produce highly durable aggregate.

Novaculate and chert make very good aggregates but require careful and selective quarrying since it is found mixed with shale. It also causes higher operating cost due to equipment wear. Syenite, a type of siliceous rock, is greatly available. It provides a high quality construction aggregate. Gravel satisfies the demand of crushed rocks recommended in highway construction. Hence the common aggregates used by AHTD for pavement construction satisfying the aggregate specifications are identified as limestone, sandstone, syenite and gravel.

4.3 TESTS ON FRESH CONCRETE

4.3.1 Slump Test

The slump test is a measure of consistency and workability of concrete, and is done according to the AASHTO T 119. Arkansas State Highway Transportation Department specifies a slump not less than 2 inches for PCC road pavements (*14*).

4.3.2 Air Content Test

Per the AHTD specification, the requirement of air content in concrete mix is 6+/- 2% and the standard test method suggested is AASHTO T 152-05 (ASTM C 231-04) a method to determine the *"Air Content of Freshly Mixed Concrete by the Pressure Method*" (*14*).

4.3.3 Unit Weight of Concrete Test

Though AHTD does not specify a method for the determination of unit weight of fresh concrete, the unit weight of fresh concrete can be obtained using the same test method for the determination of air content, AASHTO T 152. By determining the weight of the bowl of concrete and knowing the weight of the bowl, we can determine the unit weight of fresh concrete.

4.4 TESTING OF HARDENED CONCRETE SPECIMENS

Tests performed on hardened concrete cylindrical specimens include the compressive strength test, modulus of elasticity and the standard test of CTE as described in section 3.1.2 for 4" X 7" cylinders cured for 7 days and 28 days.

4.4.1 Compressive Strength Test

Tests for compressive strength are performed in accordance with the ASTM standard test method C 39- 83b for compressive strength of the cylindrical specimens. Three 4" X 8" cylindrical specimens were used for this test. The minimum strength requirement as per the specifications of AASHTO standard test T 22 is 4000 psi. This method consists of applying a compressive axial load to the molded cylinder at a prescribed rate until failure occurs. The compressive strength of the specimen is calculated by dividing the maximum load attained during the test by the cross sectional area of the specimen (*15*). The compressive *strength* is determined at 7 days, 14 days, 28 days and at 90 days.

The results of this test are used as the basis for quality control of concrete proportioning, mixing, and placing operations; determination of compliance with specifications; and control for evaluating effectiveness of admixtures and similar uses (*15*).

4.4.2 Modulus of Elasticity & Poisson's Ratio Test

ASTM 469, "*Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression",* was used to determine the values of modulus of elasticity and Poisson's ratio at 7 days, 14 days, 28 days and 90 days. A compressometer attached to the specimen measures the deformation of the cylindrical specimen as it is loaded in compression. The deformation at 40 % of average ultimate compressive strength of two concrete specimens was used to calculate the value of modulus of elasticity. Substantially, modulus of elasticity is the measure of resistance of the concrete specimen to deformation.

4.4.3. Coefficient of Thermal Expansion Test

AASHTO TP-60 is the standard test procedure for the measure of the concrete coefficient of thermal expansion. A concrete thermal expansion measuring device in compliance with AASHTO TP 60 was acquired for this project. User friendly software developed in compliance with the AASHTO TP 60 protocol monitors all test startup and run parameters automatically for this device. The system controls a uniform increase and decrease in temperature between 50F and 122F (10C and 50C) through the thermistor attached in the water bath and the temperature control of recirculation unit. Besides text, the software also displays graphically the temperature and length change information while running the test.

The software is programmed to repeat the test until two successive CTE measurements are within 0.15 microstrain/^{o}F (0.3 microstrain/^{o}C). Data is saved each 10 minute intervals, allowing for further data analysis. The system also includes an automated calibration procedure, using an A304 stainless steel standard sample and calibration software to insure accuracy in various ambient temperature environments. In this project, the CTE of the concrete was tested for 7 days and 28 days to study the dependency of CTE with time.

CHAPTER 5. RESULTS AND ANALYSIS

5.1 CTE TEST RESULTS

The 7day and 28 day CTE results of both PCC and cement paste observed for each of the 12 batches of concrete with 4 different aggregate types and 3 different cement proportion for PCC and cement paste are listed in Table 21.

Table 21 CTE of Concrete and Cement Paste Summary

Mixture Constituents		CTE (microstrain/^{o}F)			
		PCC Mixture		Cement Paste	
C. Agg.	Cementitious Mat.	7 days	28 days	7 days	28 days
Limestone	Cement Only	5.2	5.1	6.5	6.4
	Cement and 20% Fly Ash	5.0	5.0	6.6	6.5
	Cement and 25% Slag	5.3	5.2	6.6	6.8
Sandstone	Cement Only	6.4	6.4	6.6	6.5
	Cement and 20% Fly Ash	6.4	6.4	6.4	6.3
	Cement and 25% Slag	6.4	6.5	6.3	6.8
Syenite	Cement Only	5.0	5.2	6.6	6.4
	Cement and 20% Fly Ash	5.3	5.3	6.4	6.4
	Cement and 25% Slag	5.3	5.5	6.7	6.7
Gravel	Cement Only	6.9	6.9	6.6	6.6
	Cement and 20% Fly Ash	6.8	6.9	6.7	6.8
	Cement and 25% Slag	6.9	6.8	6.6	6.6

From the CTE test results of total 12 batches of concrete, it is noted that the average CTE of PCC mixture is 5.9 × 10-6 in./in./°F and cement paste is 6.55 in./in./oF. This range of average CTE values falls between the recommended ranges of CTE of 5 to 7 × 10-6 in./in./°F suggested by MEPDG per the FHWA study as part of the LTPP program. The range of CTE values for PCC mixtures determined in this study was approximately 5 to 7 × 10-6 in./in./ °F, which agrees with the range reported by the FHWA study as part of the LTPP program (17). Compared to the FHWA study, the variability of measured CTE in terms of standard deviation was much lower. The maximum standard deviation reported by the FHWA study was 0.8 × 10-6 in./in./°F for PCC mixtures using sandstone materials; for this study, the maximum value was 0.2 × 10-6 in./in./°F. This difference may be largely due to the method of preparing the test specimens and grouping the CTE results. In the FHWA study the field cores were from the LTPP program, and this study used the laboratory prepared samples.

The test follows the AASHTO recommended standard test method TP-60, where samples are tested at fully saturated condition to restrict the variability of CTE due to differential saturation condition. The 7 day and 28 day CTE test results for each of the 12 batches of concrete at the fully saturated condition did not show significant variation (Figure 17) in the mean CTE values, reinforcing the assumption that CTE is independent of concrete age.

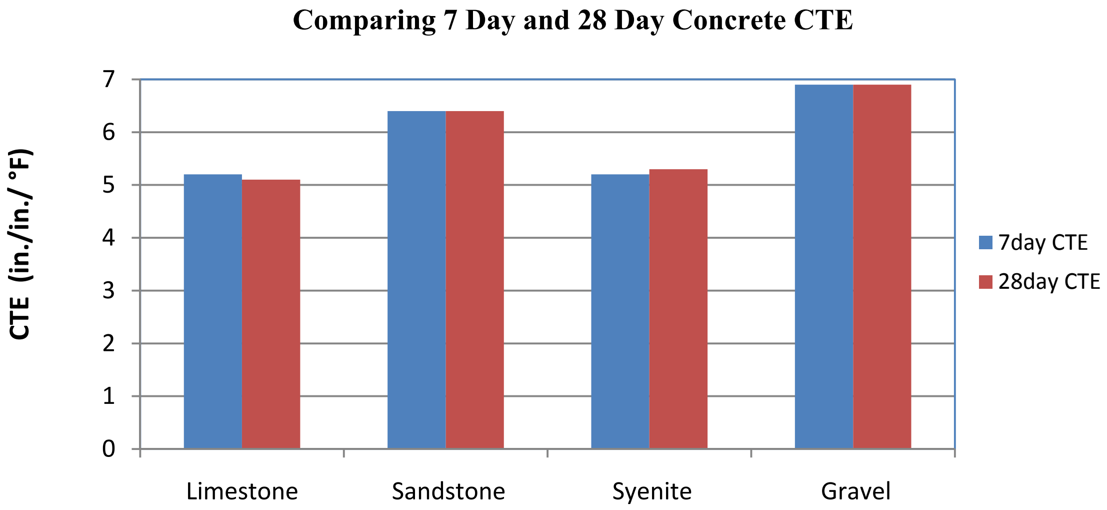


Figure 17 Graphical representation of comparing 7 day and 28 day CTE

However, these CTE values would be significantly different if the samples were not fully saturated, as reported by Sellevold and Bjontegaard (16). Along with the tested parameters of CTE such as aggregate type, cementitious content, are other factors that considerably affect the CTE such as relative humidity and degree of hydration. The MEPDG guide recommended CTE testing method of AASHTO TP-60, measuring the CTE at fully saturated condition ensuring the consistency of the humidity of the testing samples. Hence the effect of relative humidity and degree of hydration is not considered part of our investigative study.

5.1.1 Statistical Significance of Mixture Properties on CTE

A multi-factor Analysis of Variance (ANOVA) was performed on test results to evaluate the effect of the aggregate type and cementitious content on CTE with age both in PCC mixture and cement paste. The analysis results are shown in Table 22.

Table 22 ANOVA Results for Significance of Each Factor to CTE

Effect Source	Degree of Freedom (DF)	Sum of Square(SS)	Mean Square (MS)	F Ratio (F)	Prob>F (P)
Coarse Aggregates (Limestone,Sandstone,Syenite,Gravel)	3	69.255	23.085	43.4	0.000**
Cementitious Proportion (Cement only, Cement+20%Flyash, Cement+25% Blast Furnace slag)	2	1.467	0.733	1.38	0.255
Mixture Type (Standard Mixture, Cement Paste)	1	49.120	49.120	92.5	0.000**
Age (7 and 28 Day)	1	0.011	0.011	0.02	0.886
Sample No	2	0.200	0.100	0.19	0.828
** Significant Effect when P< 0.05					

The variability in the CTE test results of 3 samples measured using the CTE equipment-number of samples is also included as a factor in ANOVA to study the significance. It is noted that the 3 test samples of all concrete batches considered together does not give a P-factor greater than the 0.05, asserting the fact that the variation in samples is insignificant to cause an effect in the CTE value.

It is noted that aggregate type and the mixture type have a significant effect on the CTE of concrete with P-factor less than 0.05, whereas the change in cementitious content and age does not affect the CTE of concrete significantly. It is observed from the ANOVA interaction plot, the CTE of concrete varies considerably with aggregate type and mixture proportion. The cement paste wet-sieved from all PCC mixtures in this study had similar CTE results, and the average CTE value of cement paste was approximately 6.6 × 10-6 in./in./^{o}F. Figure 18 clearly shows that the CTE of cement paste is observed to be higher than concrete CTE supporting the fact that the thermal expansion of the cement matrix is higher than concrete.

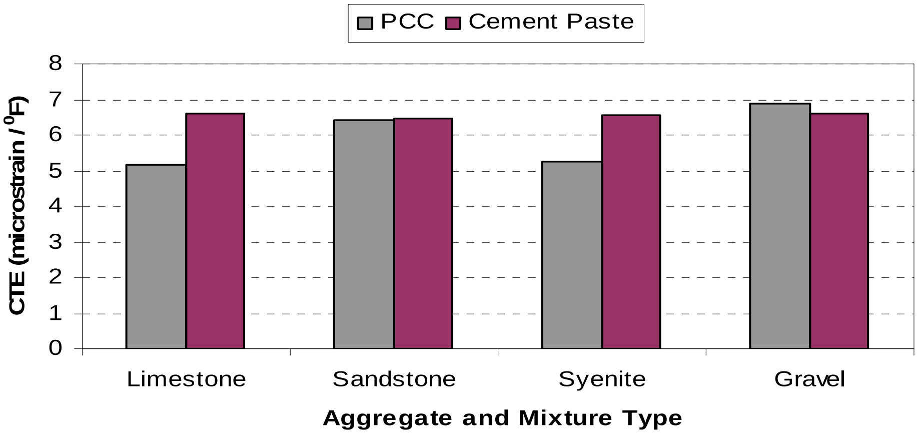


Figure 18 Coarse Aggregate and Mixture Type Vs CTE

From the observed results, it is noted that the CTE of sandstone matches with each of 12 batches of concrete wet sieved cement paste CTE. This may be due to the fine aggregate of the cement paste of all the 12 batches of concrete was identical (sand) – and the CTE of the cement paste represents the CTE of the sand. The use of siliceous sand as the fine aggregate in PCC is common practice, and is also consistent with FHWA recommendations; therefore the mixtures used in this study bracketed the most practical pavement mixture and their corresponding CTE properties. It is observed that when the fine aggregate and course aggregate are the same or have similar mineral composition, the CTE of concrete and cement paste matches. When the fine aggregate differs from the coarse aggregate in mineralogical composition, the CTE of concrete is influenced mainly by the coarse aggregate properties. Coarse aggregate with lower CTE restricts the thermal expansion of cement matrix which is naturally higher.

For PCC mixtures with the same type of aggregates, using different cementitious materials did not significantly affect the CTE. This implied that the use of fly ash or ground granulated blast furnace slag as a cementitious material in the PCC mixture did not influence the mixture's thermal expansion characteristics. The limestone and syenite aggregates behave similarly and have lower CTE values of approximately 5.2 × 10-6 in./in./^{o}F compared to sandstone and gravel. This may be attributed to the lower amount of quartz present in these stones. River gravel, with a higher percentage of quartz showed the highest average CTE value of about 6.9 × 10-6 in./in./ ^{o}F among the four aggregates tested.

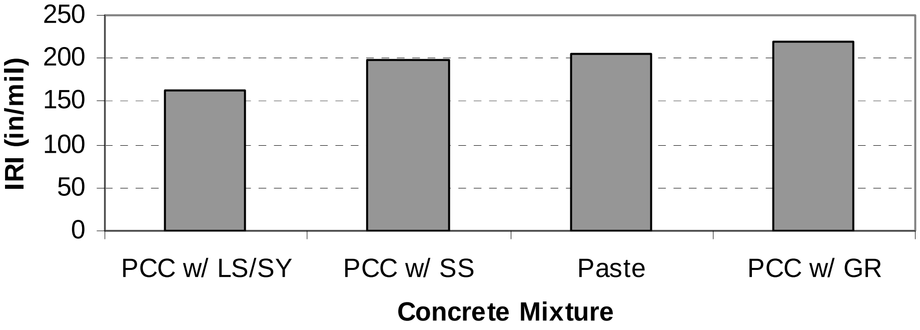
5.1.2 MEPDG Sensitivity of Mixture Properties to Measured CTE

In order to validate the engineering significance or the practical acceptance of statistical results, the sensitivity of the measured CTE is analyzed using the MEPDG software. Statistical ANOVA results showed that the coarse aggregate type and proportion significantly influence the CTE of a concrete mixture. However, 'statistical significance' does not necessarily warrant changes to engineering design. Thus the measured PCC material input values of CTE and corresponding strength properties of each concrete batch along with the default values recommended in MEPDG are input in the MEPDG software for sensitivity analysis. The varying input values for analysis other than the consistent default MEPDG values are as listed in Table 23.

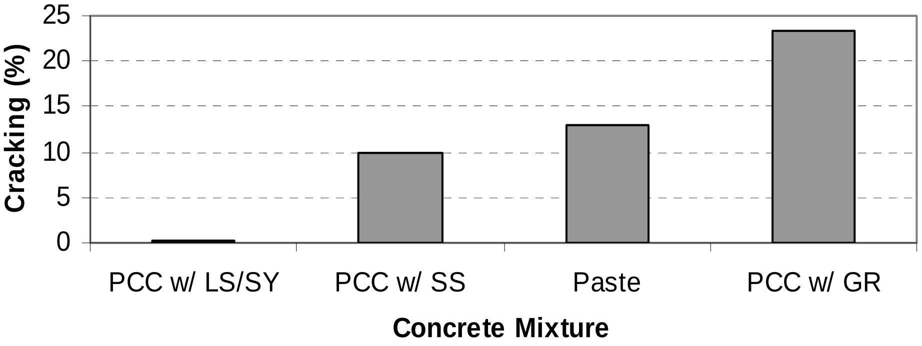
Table 23 Default MEPDG Input Value used in the Analysis of CTE

Description		MEPDG Input Value
General Information		
	Type of Design	Jointed Plain Concrete Pavement (JPCP)
	Reliability	50%
	Design Life	20 years
Traffic Volume		
	Two-way AADTT	10,000
	Lanes in Design Direction	2
Other Traffic Inputs		Default
Climate		Fayetteville, AR
Concrete Layer		
	Thickness	12 in.
	Coefficient of Thermal Expansion	5.2, 6.4, 6.6, 6.9 x 10^{-6}/°F
Granular Base		
	Thickness	8 in.
	Modulus	40,000 psi
Subgrade		
	Classification	A-7-6
	Modulus	7,000 psi

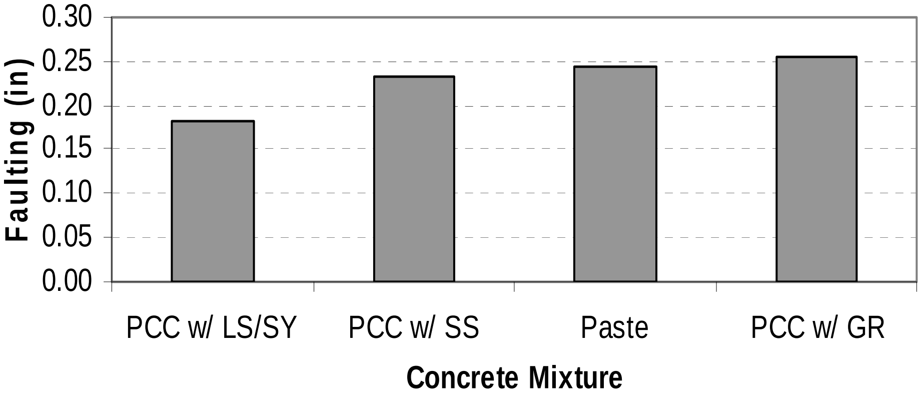
For this analysis the four average measured CTE values are 5.2 microstrain/°F for PCC mixtures with limestone/syenite aggregates, 6.4 microstrain/°F for PCC mixtures with sandstones, 6.6 microstrain/°F for cement paste and 6.9 microstrain/°F for PCC mixtures with gravels. Figure 19 presents three plots of pavement distresses, including the International Roughness Index (IRI), cracking, and faulting, predicted by the MEPDG software (version 1.0). From the analysis results as represented in Figure 19, the following observations are offered.



(a) International Roughness Index versus coefficient of thermal expansion



(b) Cracking versus coefficient of thermal expansion



(c) Faulting versus coefficient of thermal expansion

Figure 19 Effect of consistent CTE property on pavement performance.

The roughness coefficient is predicted to have the least value for the concrete mixture with the aggregates of lowest CTE value (limestone and syenite). The predicted IRI values corresponding to other PCC mixtures and cement paste were higher, and they were similar to each other. Similarly, for the cracking distress predicted it is clear that the percent of slab cracking is comparatively higher for the concrete mixture with aggregates of higher CTE. It is interesting to note that the increase in slab cracking for concrete with sandstone is approximately 50 times more than what is predicted for the concrete with limestone. If PCC mixtures with gravels were used, the percent of slabs cracked increased by a factor of two for a difference in measured CTE results of 0.5 microstrain/°F between PCC mixtures using sandstones and gravels. This indicated that the type of aggregates significantly influenced the predicted percent of slabs cracked. The predicted faulting also follows a similar pattern as the plot of predicted IRI.

The observed results of the sensitivity of cement paste to the MEPDG distress models of roughness, cracking and faulting indicate that significant factors that influence the response is the aggregate type and proportion present in the cement matrix. Although it is obvious from the results that coarse aggregates with lower CTE influence the CTE of the corresponding PCC mixture, the proportion and type of fine aggregate in the cement paste also affects the CTE of the PCC.

Considering the statistical analysis results and the sensitivity analysis it could be concluded that the type and proportion of coarse aggregate used in PCC mixture significantly influenced the mixture CTE and its corresponding pavement response, from both statistical and practical perspectives.

5.2 POISSON’S RATIO TEST RESULTS

For each of the 12 batches of PCC with 4 different aggregate types and 3 different cement proportion, MEPDG recommended the test method of ASTM C 469 to obtain the Level 1

MEPDG input value of Poisson's ratio at 7, 14, 28 and 90 days. The observed results are listed in Table 24.

Table 24 Summary of Test results of Poisson's Ratio

Mixture Constituents		Poisson's Ratio			
Coarse Agg.	Cementitious	7 days	14 days	28 days	90 days
Limestone	Cement Only	0.24	0.22	0.23	0.25
	Cement and 20% Fly Ash	0.23	0.23	0.23	0.24
	Cement and 25% Slag	0.21	0.22	0.23	0.22
Sandstone	Cement Only	0.15	0.17	0.17	0.17
	Cement and 20% Fly Ash	0.17	0.17	0.17	0.18
	Cement and 25% Slag	0.16	0.17	0.16	0.18
Syenite	Cement Only	0.23	0.25	0.25	0.25
	Cement and 20% Fly Ash	0.24	0.25	0.26	0.25
	Cement and 25% Slag	0.24	0.23	0.27	0.28
Gravel	Cement Only	0.18	0.18	0.18	0.18
	Cement and 20% Fly Ash	0.18	0.19	0.18	0.18
	Cement and 25% Slag	0.18	0.20	0.19	0.19

5.2.1 Statistical Significance of Mixture Properties on Poisson's Ratio

The effect of the aggregate type, cementitious content and age on PR is analyzed using ANOVA. The analysis results are shown in Table 25. From the ANOVA test results it is noted that the Poisson's ratio is significantly affected by the type of coarse aggregate used. This could be explained by the fact that Poisson's ratio, a measure of lateral and longitudinal strain, will be mainly influenced by the coarse aggregate which constitutes 70% of the concrete. Among the type of aggregates, syenite has the highest value of

Poisson’s ratio with limestone closely following. Sandstone and gravel showed comparatively lower values of Poisson’s ratio. Figure 20 shows a comparative chart of values of Poisson’s ratio for each aggregate. Varying the cementitious content did not affect the Poisson’s ratio of the concrete. Also the age of concrete is not significant statistically to validate a change in Poisson’s ratio of concrete.

Table 25 ANOVA Results for Significance of Each Factor to PR

Effect Source	Degree of Freedom (DF)	Sum of Square(SS)	Mean Square (MS)	F Ratio (F)	Prob>F (P)
Coarse Aggregates (Limestone,Sandstone, Syenite,Gravel)	3	0.153	0.05088	92.28	0.000**
Cementitious Proportion (Cement only, Cement+20%Flyash, Cement+25% BFslag)	2	0.0008	0.00042	0.76	0.469
Age (7, 14,28 and 90 Day)	3	0.0024	0.00081	1.47	0.226
Sample No	2	0.0003	0.00018	0.34	0.714
** Significant Effect when P< 0.05					

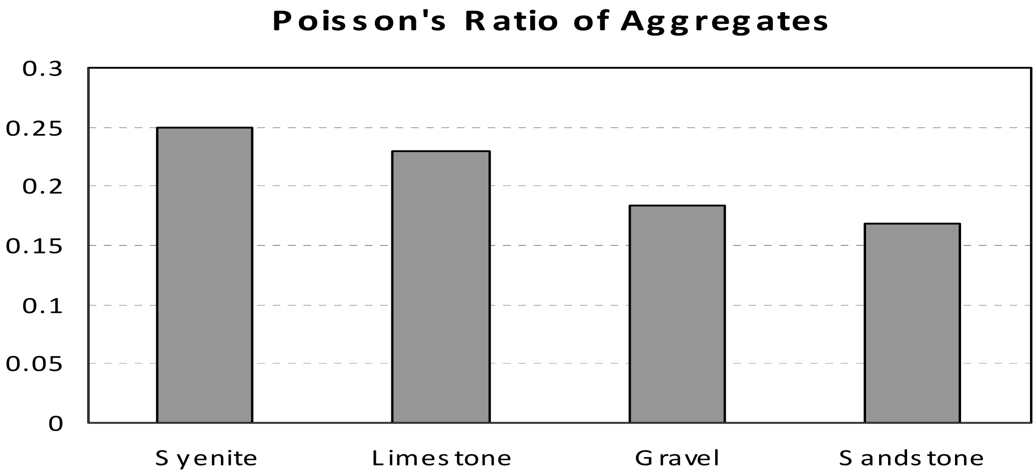


Figure 20 Effect of Aggregate Type on Poisson’s Ratio

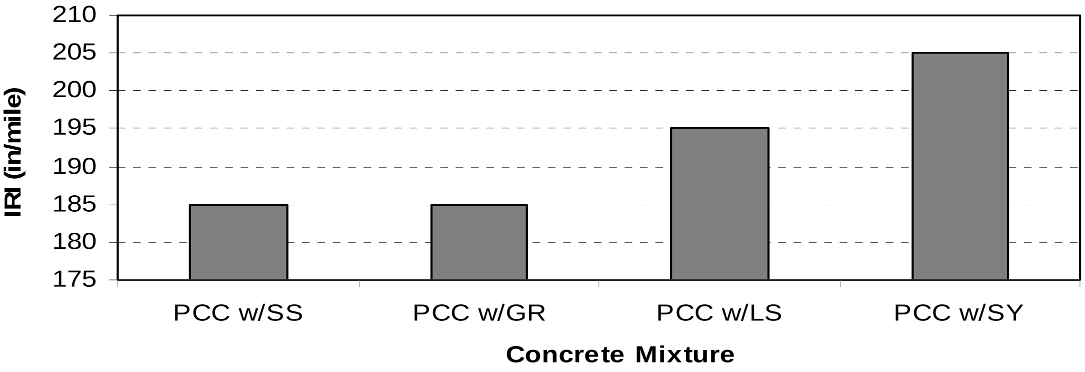
5.2.2 MEPDG Sensitivity of Mixture Properties to Poisson’s Ratio

The engineering significance of the varying aggregate type on Poisson’s ratio is analyzed by varying the Poisson’s ratio in MEPDG to obtain the response of cracking, faulting and roughness of cracking. The input values used in analysis other than the default values of MEPDG are listed in Table 26.

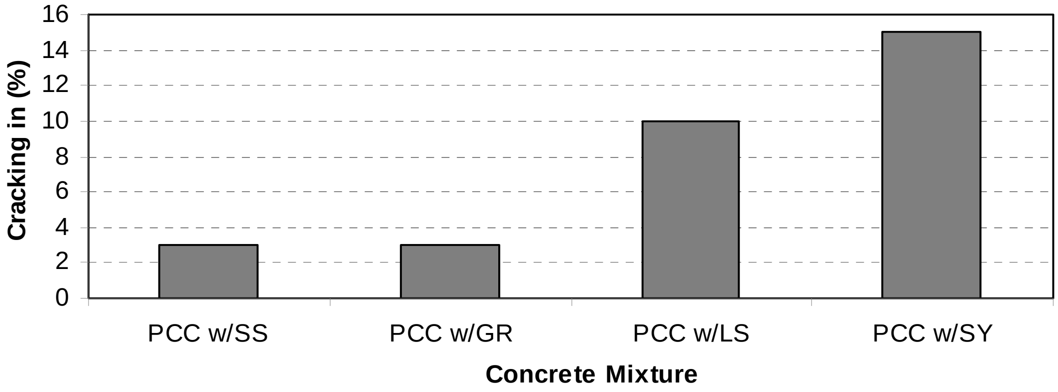
Table 26 Default MEPDG input values used in the analysis for Poisson’s Ratio

Description		**MEPDG Input Value**
General Information		
	Type of Design	Jointed Plain Concrete Pavement (JPCP)
	Reliability	50%
	Design Life	20 years
Traffic Volume		
	Two-way AADTT	10,000
	Lanes in Design Direction	2
Other Traffic Inputs		Default
Climate		Fayetteville, AR
Concrete Layer		
	Thickness	12 in.
	Coefficient of Thermal Expansion	6.2 x 10^{-6}/^{o}F
	Poisson's Ratio	0.23, 0.17. 0.25, 0.18
Granular Base		
	Thickness	8 in.
	Modulus	40,000 psi
Subgrade		
	Classification	A-7-6
	Modulus	7,000 psi

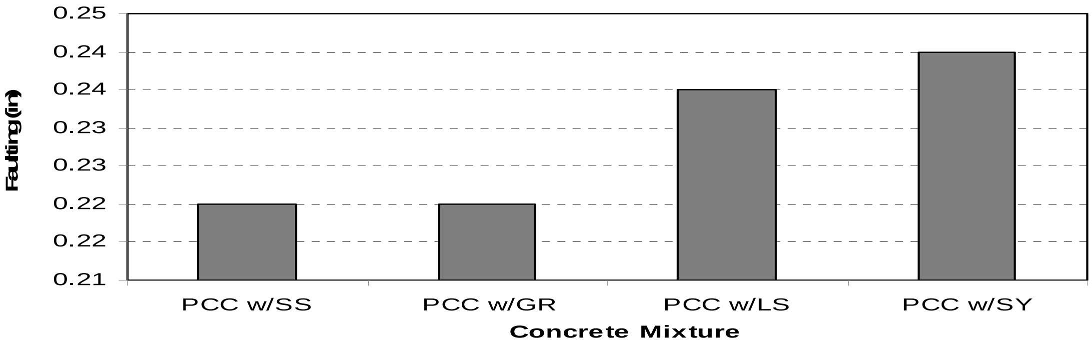
Figure 21 presents three plots of pavement distresses, including the International Roughness Index (IRI), cracking, and faulting, predicted by the MEPDG software (version 1.0) for different Poisson’s ratio.



(a) International Roughness Index versus Poisson's Ratio



(b) Cracking versus Poisson's Ratio



(c) Faulting versus Poisson's Ratio

Figure 21 Effect of consistent PR property on pavement performance.

The average measured Poisson's ratio of each aggregate are 0.23 for PCC mixtures with limestone, 0.17 for PCC mixtures with sandstones, 0.25 for syenite and 0.18 for PCC mixtures with gravels. For testing the sensitivity of Poisson's ratio, the CTE of the aggregate is kept constant at 6.2 microstrain/oF, which is the average CTE of all the four aggregate types considered for study. From Figure 21, it is noted that for sandstone and gravel with similar Poisson's ratio of 0.17, the predicted distresses are lower compared to limestone and syenite. Syenite, with a higher Poisson's ratio of 0.25, displayed higher distresses of cracking, roughness and faulting. Comparatively, cracking distress showed more sensitivity to varying Poisson's ratio than faulting and IRI. Cracking of syenite and limestone was found to be 3-5 times higher than sandstone and gravel when CTE is kept constant at 6.2 microstrain/°F.

Comparing the distress prediction shown in Figure 22, for CTE of each aggregate with a constant Poisson's Ratio of 0.20 (series 1) and with CTE and Poisson's ratio of each aggregate (Series 2), it is noted that Poisson's ratio influences the cracking distress significantly. It can be noted that a lower value of Poisson's ratio of sand and gravel helps reduce 10-50% cracking compared to Series 1. Syenite and limestone – with higher Poisson's ratio values – induced more cracking, compared to the negligible cracking of Series 1 with constant Poisson's ratio of 0.02. It is noted that faulting and IRI were found to be not significantly influenced by Poisson's ratio.

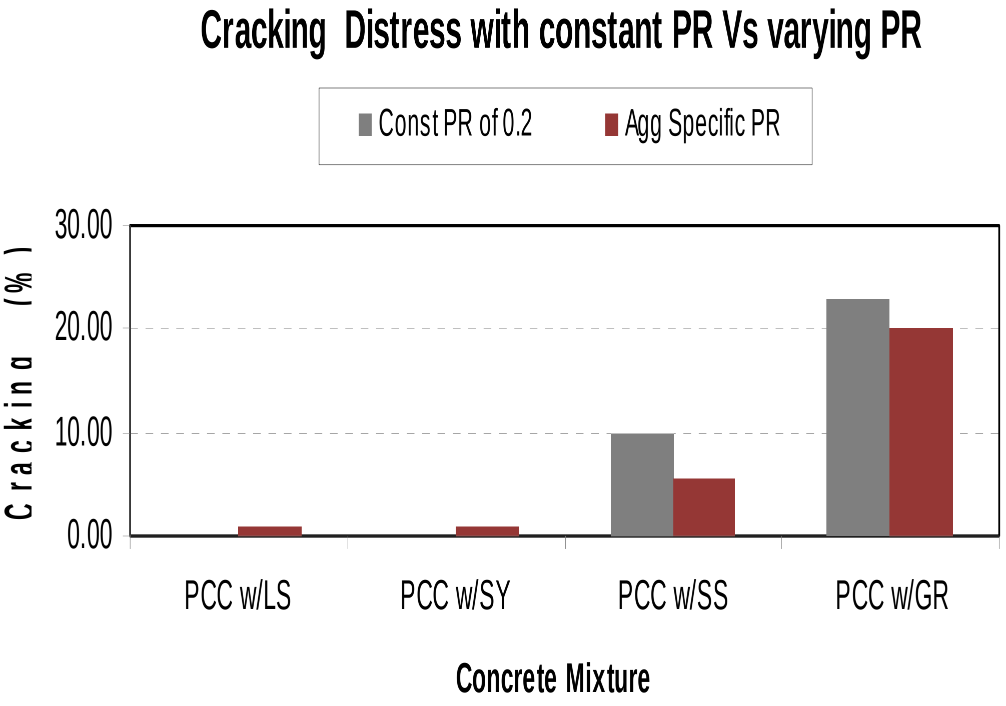


Figure 22 Comparing the Effect of Poisson's ratio on pavement performance.

Hence from the sensitivity analysis of Poisson's ratio with varying aggregate types and cementitious proportion, it is observed that varying aggregate type significantly influences the Poisson's ratio. The influence of Poisson's ratio in pavement cracking distress prediction is also seen to be prominent. A lower value of Poisson's ratio of sandstone and gravel helps reduce the cracking compared to limestone and syenite aggregate.

5.3 MODULUS OF ELASTICITY TEST RESULTS

Results of 12 batches of concrete, for the MEPDG recommended test method of ASTM C 469 tested for modulus of elasticity at 7, 14, 28 and 90 days are listed in Table 27. The average 28 day modulus of elasticity of concrete for limestone aggregate, sandstone, syenite and gravel are 5.82, 3.35, 5.43, 5.92 MPsi respectively.

Table 27 Summary of Modulus of Elasticity Results

Mixture Constituents		Modulus of Elasticity Test Results			
Coarse Agg.	**Cementitious**	**7 days**	**14 days**	**28 days**	**90 days**
Limestone	Cement Only	5.52	5.61	5.99	6.18
	Cement and 20% Fly Ash	5.47	5.54	5.67	6.11
	Cement and 25% Slag	4.99	5.50	5.80	6.03
	Average	**5.33**	**5.55**	**5.82**	**6.11**
Sandstone	Cement Only	2.94	3.18	3.51	3.59
	Cement and 20% Fly Ash	2.84	3.04	3.20	3.41
	Cement and 25% Slag	2.78	3.05	3.35	3.60
	Average	**2.85**	**3.09**	**3.35**	**3.53**
Syenite	Cement Only	5.32	5.39	5.53	5.93
	Cement and 20% Fly Ash	5.01	5.17	5.45	5.68
	Cement and 25% Slag	4.53	4.86	5.30	6.63
	Average	**4.95**	**5.14**	**5.43**	**6.08**
Gravel	Cement Only	5.80	5.98	6.22	6.50
	Cement and 20% Fly Ash	4.78	5.04	5.33	5.79
	Cement and 25% Slag	5.46	5.80	6.21	6.66
	Average	**5.35**	**5.61**	**5.92**	**6.32**

For a Level 1 input of modulus of elasticity, the MEPDG requires the construction of a modulus gain curve to predict the modulus of elasticity at any age of concrete based on the regression model form. The regression model equation represented in Equation 10 has three regression coefficients α_1, α_2, α_3 which are optimized using regression analysis.

MODRATIO = $\alpha_1 + \alpha_2 \log_{10}(\text{AGE}) + \alpha_3 [\log_{10}(\text{AGE})]^2$ ……………………….(Eq-10)

Where, MOD RATIO = ratio of Ec at a given age to Ec at 28 days

AGE = Specimen age in years

$\alpha_1, \alpha_2, \alpha_3$ = Regression Coefficients

The regression coefficients obtained for the average modulus of elasticity of each of the four different aggregates measured at 7, 14, 28, 90 are as listed in Table 28.

Table 28 Optimized Regression Coefficients for Modulus of Elasticity

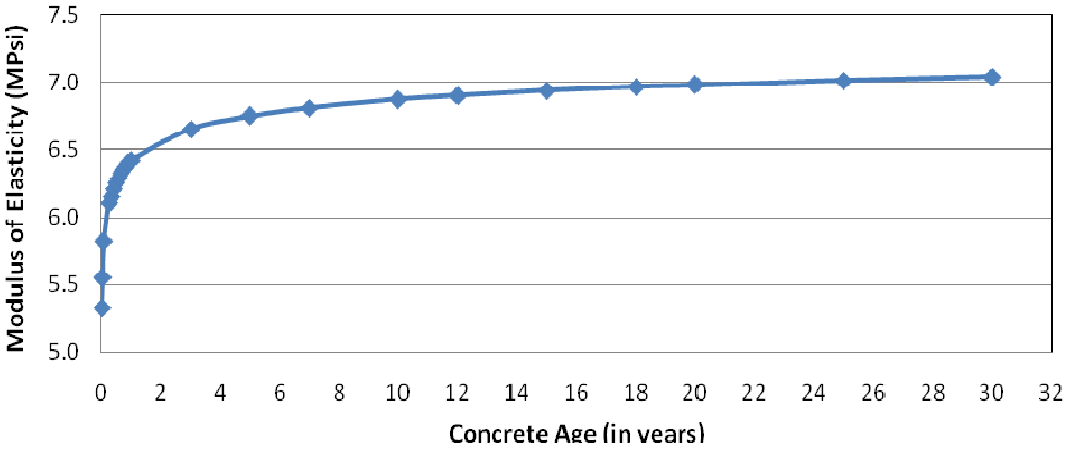
Age (Yr)	ME (MPa)	(20yr ME/ 28day ME)	MOD Ratio	Optimized values of $\alpha_1, \alpha_2, \alpha_3$
0.01918	4.62000	0.90058	0.88427	1.14492
0.03836	4.85000	0.94542	0.94542	0.08952
0.07671	5.13000	1.00000	1.00000	-0.03626
0.24658	5.53000	1.07797	1.07708	
20.00000	6.15600	1.20000	1.20000	

The regression coefficients calculated separately for each type of aggregate is given in Table 29. It is noted that the regression coefficients do not vary much from the values obtained for the average modulus of elasticity of the four aggregates.

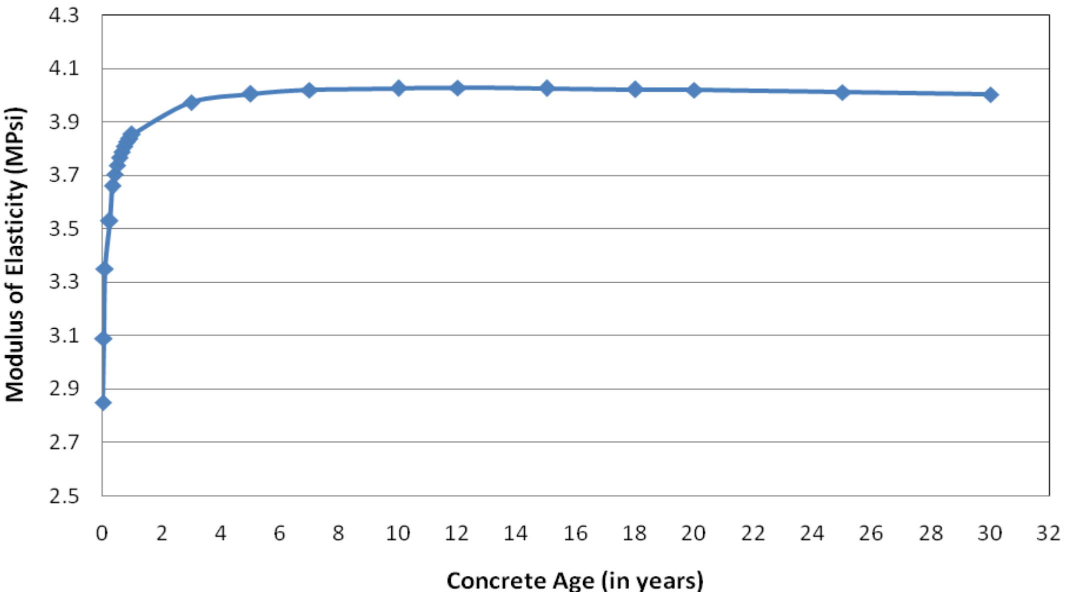
Table 29 Regression Coefficients Optimized for Each Aggregate Type

Regression Coefficients	Limestone	Sandstone	Syenite	Gravel	Average
α_1	1.10332	1.14999	1.14284	1.14099	1.13428
α_2	0.08935	0.09699	0.08925	0.08901	0.09115
α_3	-0.01156	-0.04500	-0.03483	-0.03356	-0.03124

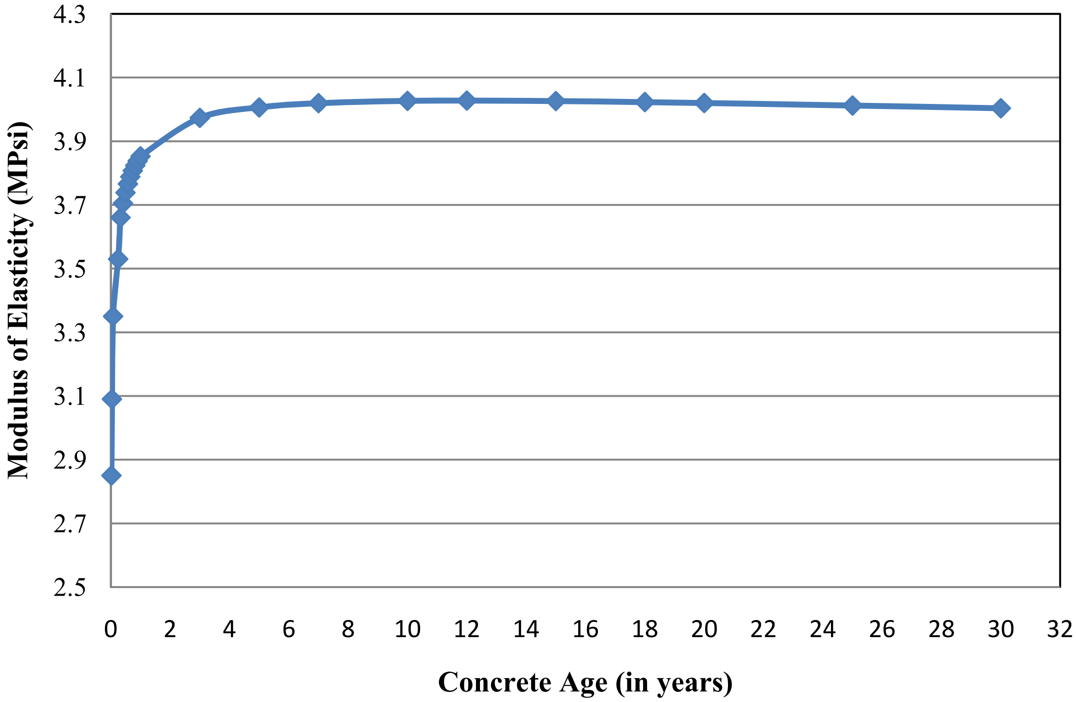
The graph obtained for predicting the modulus at any age of the concrete using the regression equation for each aggregate and for the average of each of the 4 aggregates is shown in Figure 23. The modulus curve plotted shows that modulus of elasticity increases with age more rapidly up to 90 days and then increases at a lower rate.



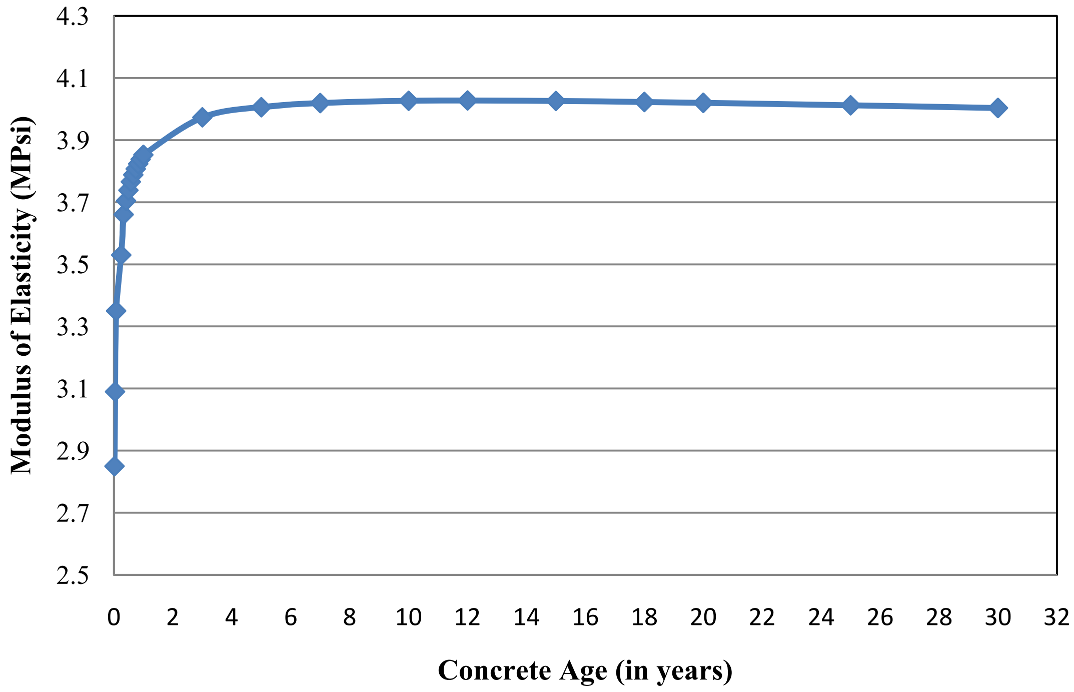
a) Modulus Data required for MEPDG (Limestone)



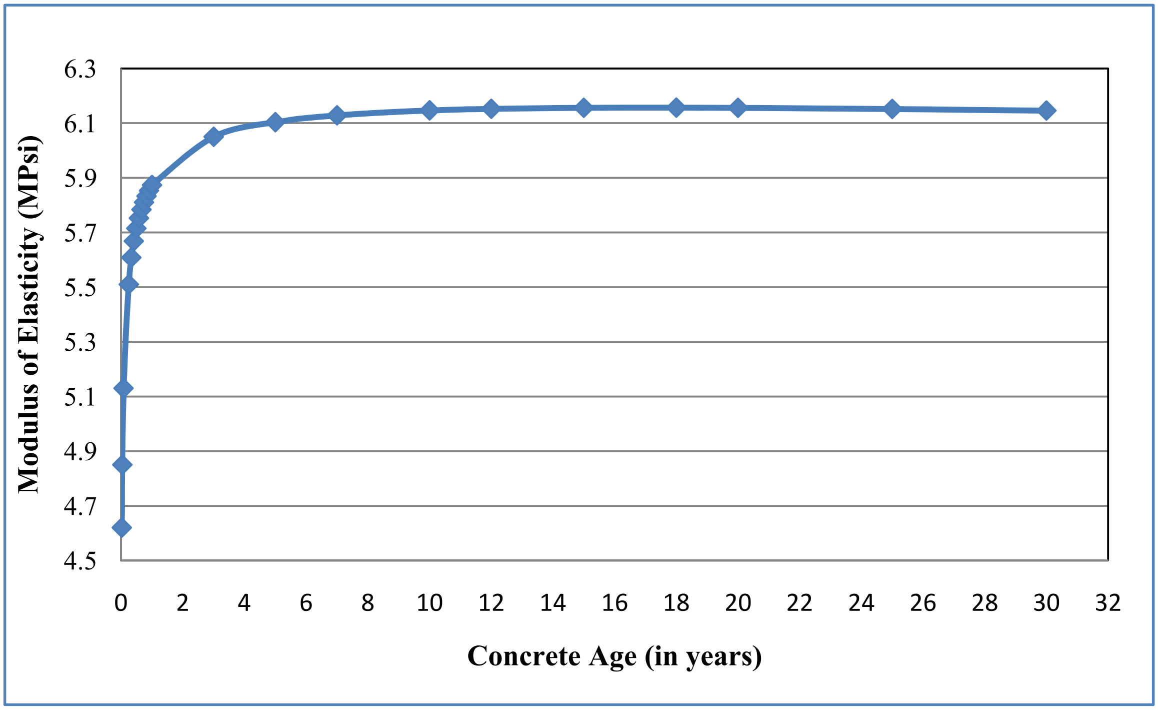
b) Modulus Data required for MEPDG (Sandstone)



c) Modulus Data required for MEPDG (Syenite)



d) Modulus Data required for MEPDG (Gravel)



e) Modulus Data required for MEPDG (Average of 4 aggregates)

Figure 23 Modulus Data required for MEPDG

Using this curve plotted using the regression equation with optimized regression coefficients, the modulus of elasticity of concrete at any age can be predicted, which could be used in the MEPDG design guide as a Level 1 input value. For a Level 2 input value, the MEPDG recommends to calculate static modulus of elasticity from the compressive strength test and unit weight of PCC using American Concrete Institute (ACI) equation 8.2, shown here as Equation 11:

$$Ec = 33 \times \rho^{3/2} \times (f'_c)^{½} \quad \text{.......................................(Eq. 11)}$$

Where: Ec = PCC Elastic Modulus (psi)

P = unit weight concrete (lb/ft^3)

f'_c = Compressive strength of PCC (psi)

It is noted that the estimated value of static modulus of elasticity at Level 2 PCC input value in the MEPDG using Equation 11 shown in Table 30 is found to be less than the measured average modulus of elasticity listed in Table 25. This may be due to the fact that the modulus measured in Level 1 input is the ASTM C 469 method which calculates the chord modulus which is approximately higher than the secant or static modulus calculated using the Equation 11 for Level 2 inputs. Also the MEPDG states that the strain level encountered in pavement is typically minimal compared to major differences in value of chord modulus and secant modulus.

Table 30 Modulus of Elasticity Estimated for Level 2 PCC input value in MEPDG

Mixture Constituents	Modulus of Elasticity (Mpa)			
Cementitious	**7 days**	**14 days**	**28 days**	**90 days**
Limestone	3.812	4.069	4.300	4.349
Sandstone	3.767	3.898	4.236	4.501
Syenite	4.217	4.504	4.798	4.919
Gravel	3.658	3.909	4.039	4.450

In the MEPDG, the Level 3 input value for the elastic modulus is obtained from a single point (28 day modulus of rupture (MR) or compressive strength (F'c) using the strength ratio equation (Equation 12) based on single point MR estimate).

$$F\_STRRATIO\_3=1.0+0.12*\log_{10}(AGE/0.0767)-0.01566*[\log_{10}(AGE/0.0767)^{2} \ldots \text{(Eq. 12)}$$

Where, F_STRRATIO _3 = Ratio of MR at a given age to MR at 28 days

AGE = Specimen age in years

Using the predicted strength ratio at any age multiplied to the 28 day MR give the MR value at any age which helps predict the elastic modulus at that age.

Another approach is to convert the measured compressive strength into MR values using the Equation 13 and subsequently develop the strength modulus gain over time.

$$MR = 9.5 *(f'_{c})^{1/2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\text{(Eq. 12)}$$

Since the testing of modulus of rupture is not included in our scope of research, the modulus of elasticity based on MR is not tabulated.

5.4 COMPRESSIVE STRENGTH TEST RESULTS

In MEPDG compressive strength is required to calculate the elastic modulus, flexural strength and indirect tensile strength at hierarchical input level 2 and level 3. The obtained results of the test for the 12 batches of concrete are listed in Table 31. As noted, the strength of concrete increases with age and approximately 30 to 40 % increase in strength is obtained within 90 days. MEPDG does not provide a strength gain equation for compressive strength. It is noted that syenite showed highest compressive strength at each 7, 14, 28 and 90 days and gravel exhibiting comparatively lower strength. The lower strength of natural sand gravel may be due to less bonding of aggregate with the cement matrix. But all the 12 batch of concrete mixture satisfied the AHTD compressive strength specifications of having minimum 4000 Psi at 28 days.

Table 31 Summary of Compressive Strength Test Results

PCC Mixture		Compressive Strength			
Coarse Agg.	**Cementitious**	**7 days**	**14 days**	**28 days**	**90 days**
Limestone	Cement Only	4320	4980	5340	5540
	Cement and 20% Fly Ash	3980	4990	5330	6170
	Cement and 25% Slag	4830	4990	6040	7050
Sandstone	Cement Only	4760	4840	5770	6080
	Cement and 20% Fly Ash	4140	4240	4900	5480
	Cement and 25% Slag	3920	4650	5540	6750
Syenite	Cement Only	5640	5920	6620	6830
	Cement and 20% Fly Ash	4230	5230	6010	6720
	Cement and 25% Slag	6200	7180	8170	8320
Gravel	Cement Only	4610	5130	5100	6590
	Cement and 20% Fly Ash	3240	3860	4450	4940
	Cement and 25% Slag	4240	4820	5190	6370

5.5 CORRELATION OF CTE AND PR TO QA/QC PROPERTIES

It is noted from the data analysis that the parameters discussed including coefficient of thermal expansion, Poisson’s ratio and strength, and stiffness parameters (elastic modulus and compressive strength) are important in pavement design. A study done at Democritus University of Thrace, estimating the elastic modulus and Poisson’s ratio using ASTM C-94 on sandstone aggregate, found elastic modulus and Poisson’s ratio to be linearly related to compressive strength (*18*). It would be of interest to know if these parameters are related based on the results of this study.

The relationship between the tested variables of CTE, Poisson's ratio, modulus of elasticity and compressive strength, was evaluated using a Pearson correlation test. The Pearson product moment correlation coefficient gives the linear relationship between variables. For CTE and Poisson's ratio, as listed in Table 32, the coefficient is -0.828, which shows that Poisson's ratio is inversely related to CTE. When CTE is correlated to Modulus of Elasticity and compressive strength it is noted that the Pearson coefficient is negative, which again shows that modulus decrease with increase in CTE value. For higher values of CTE, the value of Poisson's ratio, elastic modulus and compressive strength are lower. In studying the correlation with other parameters, it is noted that Poisson's ratio and elastic modulus show positive correlation with each other and compressive strength, but negative correlation with CTE.

Table 32 Correlation between Tested Concrete Properties

Concrete Properties	**Pearson Coefficient of Correlation**			
	CTE	**PR**	**ME**	**CS**
CTE	1.00	-0.83	-0.28	-0.48
PR	-0.83	1.00	0.48	0.66
ME	-0.28	0.48	1.00	0.04
CS	-0.48	0.66	0.04	1.00

Table 33 illustrates the relationship between these properties.

Table 33 Regression and ANOVA Results of Relating Concrete Properties

Limestone							
Properties	**Equation**	**S**	**R-Sq (%)**	**SS**	**MS**	**F**	**P**
CTE- PR	CET = 8.844 - 13.06 PR	0.041	92.8	0.022	0.220	12.940	0.173
CTE- ME	CET = 9.849 - 0.7014 ME	0.095	62.2	0.015	0.015	1.650	0.422
CTE- CS	CET = 4.997 + 0.000165 CS	0.084	70.2	0.017	0.017	2.350	0.368
PR- ME	PR = - 0.1165 + 0.06064 ME	0.004	85.5	0.000	0.000	5.890	0.249
PR- CS	PR = 0.3007 - 0.000014 CS	0.003	90.9	0.000	0.000	9.970	0.195
ME- CS	ME = 6.841 - 0.000221 CS	0.015	99.3	0.030	0.030	140.28	0.054
Sandstone							
CTE- PR	CET = 8.975 - 15.00 PR	0.047	75	0.007	0.007	3.000	0.330
CTE- ME	CET = 4.895 + 0.4848 ME	0.069	45.4	0.004	0.004	0.830	0.530
CTE- CS	CET = 5.573 + 0.000172 CS	0.036	84.8	0.007	0.007	5.570	0.255
PR- ME	PR = 0.2954 - 0.03960 ME	0.002	90.8	0.000	0.000	9.870	0.196
PR- CS	PR = 0.2229 - 0.000011 CS	0.001	98.5	0.000	0.000	65.640	0.078
ME- CS	ME = 2.005 + 0.000236 CS	0.054	82.5	0.014	0.014	4.730	0.274
Syenite							
CTE- PR	CET = - 0.350 + 25.00 PR	0.061	89.3	0.031	0.031	8.330	0.212
CTE- ME	CET = 9.645 - 0.6935 ME	0.143	41.9	0.015	0.015	0.720	0.552
CTE- CS	CET = 5.159 + 0.000115 CS	0.100	71.7	0.025	0.025	2.530	0.357
PR- ME	PR = 0.4383 - 0.03488 ME	0.004	74.1	0.000	0.000	2.860	0.340
PR- CS	PR = 0.2293 + 0.000003 CS	0.006	39.2	0.000	0.000	0.640	0.570
ME- CS	ME = 1.324 + 0.000702 CS	0.212	95.4	0.930	0.930	20.690	0.139
Gravel							
CTE- PR	CET = 7.537 - 4.231 PR	0.044	33.2	0.001	0.001	0.500	0.609
CTE- ME	CET = 7.170 - 0.07100 ME	0.022	82.8	0.002	0.002	4.800	0.273
CTE- CS	CET = 7.008 - 0.000051 CS	0.025	78.2	0.002	0.002	3.590	0.309
PR- ME	PR = 0.1374 + 0.008066 ME	0.005	57.5	0.000	0.000	1.350	0.452
PR- CS	PR = 0.1536 + 0.000006 CS	0.004	63.2	0.000	0.000	1.710	0.415
ME- CS	ME = 2.190 + 0.000739 CS	0.040	99.7	0.477	0.477	299.92	0.037

Analyzing the relationship of CTE with Poisson’s ratio, it is noted that except gravel, all aggregates showed a comparably higher R-Sq value, indicating a good fit of the predicted regression model. The regression equation with the best ‘fit’ corresponds to limestone aggregates. The regression fit obtained by relating the CTE with ME is comparably poor, except for gravel aggregate. However, it is noted that the CTE and compressive strength relationship has a convincingly good fit for the regression plot predicted for all of the four aggregates. The Poisson’s ratio relationship with elastic modulus, for aggregates except gravel, shows a comparably good fit of the regression equation. For the compressive strength relationship with Poisson’s ratio, only syenite showed a relatively lower value of R-Sq for the regression model predicted. All four aggregates showed excellent fit for the linear relationship predicted for elastic modulus and compressive strength.

From this analysis, it could be concluded that there is linear relationship between the concrete properties of CTE, Poisson’s ratio, elastic modulus and compressive strength, when analyzed for each type of aggregate individually. When the analysis is done for the 12 batches of concrete together, none of the properties showed good fit to the prediction model of the regression plot. This again emphasizes the importance that most of the concrete properties are dependent on coarse aggregate whose properties vary significantly.

CHAPTER 9. CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS

In this research of characterizing material input values for MEPDG, the obtained test results analysis has lead to the following conclusions.

1. CTE value of PCC mixtures can be determined satisfactorily using automated CTE measuring equipment as per the AASHTO recommended CTE test method TP 60. The variability of CTE values determined in this project using the automated CTE measuring equipment favorably compared to that reported in other studies.
2. The type of coarse aggregates in the PCC mixture significantly influenced the CTE and pavement performance predictions. Other parameters including cementitious content and concrete age does not have considerable effect on concrete CTE. But there is appreciable difference in CTE of Coarse aggregate and cement paste. Thus, the proportion and type of coarse aggregates used for a PCC mixture may significantly affect the CTE and subsequent pavement performance predictions.
3. In this study of cement paste with fine aggregate sand, a common fine aggregate used in pavement construction, the difference in CTE with the cement paste was significant for all other coarse aggregate except sandstone having similar mineralogical composition. This reinstates the need for standardizing the minimum amount and type of coarse aggregate needed to compensate high CTE of cement matrix and obtain the desired CTE in PCC pavement mixture that helps reduce early pavement distresses.

4. The effect of using Level 1 and 3 CTE inputs for PCC mixtures with limestone and sandstone was not significant to validate a change in the aggregate CTE in MEPDG specific to the state of Arkansas. CTE recommendations for PCC mixtures with gravels were not available in the MEPDG for comparisons.
5. Poisson's ratio of concrete is found to be sensitive to the type of coarse aggregate used but not affected by varying cementitious proportion and age of concrete. The sensitivity analysis showed that pavement distress increases with increase in Poisson's ratio, especially the cracking distress. Lower value of Poisson's ratio help reduce cracking distress even when the CTE of PCC mixture is high.
6. Elastic modulus of concrete at level 1 design input for each 12 batch of concrete are measured using MEPDG recommended ASTM C 469 test method. The coefficients $\alpha_{1,}$ $\alpha_{2,}$ $\alpha_{3,}$ of regression model equation used in predicting the modulus of elasticity of concrete at any age are optimized for concrete with each four type of aggregate.
7. Compressive strength measured for the 12 batches of concrete at each 7,14,28 and 90 day could be used to obtain the level 2 and level 3 design inputs of elastic modulus, flexural strength and indirect tensile strength in the absence of level 1 design input.
8. It is interesting to note that though sandstone exhibited a higher compressive strength comparable to other aggregates, the elastic modulus was considerably less. This may be due to the different mineralogical composition of the sandstone used in this study, which emphasize the importance of knowing the mineralogical properties of coarse aggregate that influence most pavement PCC properties.
9. Pearson correlation coefficient shows that Poisson's ratio, elastic modulus and compressive strength exhibit positive correlation with each other except CTE, which

has negative correlation. CTE is found to be lower when the value of Poisson's ratio, elastic modulus and compressive strength are higher.

10. CTE measured at saturated condition does not vary with concrete age and hence compressive strength. But Poisson's ratio, elastic modulus and compressive strength is found to have linear relationship with compressive strength and concrete age.

9.2 RECOMMENDATIONS

The following recommendations are made based on the findings in this study:

1. It is recommended that a future testing plan for developing typical PCC inputs especially CTE inputs for implementation of the MEPDG in a state or region include all aggregate types used for concrete materials in rigid pavement construction.
2. CTE recommendations for Level 3 input in the MEPDG should be updated to include more aggregate types, especially gravels, which had higher CTE values than other types of aggregate in this study.
3. It is also advisable to standardize the minimum proportion of coarse aggregate required to be used in pavement PCC to reduce early distresses based on the available aggregate CTE and other PCC input parameter test results specific to each state or region.
4. Due to the sensitivity of cracking distress to Poisson's ratio, it is recommended that always a level 1 input of laboratory measured value of Poisson's ratio be used in MEPDG.

5. The regression equation for elastic modulus of concrete with coefficients optimized for each 4 types of aggregates used in the study could be used to predict their concrete elastic modulus at any age.
6. Since the CTE and other properties including Poisson's ratio, elastic modulus and compressive strength are mainly influenced by the mineralogical composition of the coarse aggregate, it is recommended that for aggregates used in pavement PCC, the mineral composition and properties are known.

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