Final Report

Prepared for the Mississippi Department of Transportation

Guidelines for PCC Inputs to AASHTOWare Pavement ME

Report No. FHWA/MS-DOT-RD-14-260

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16. Abstract

The objective of this research study was to develop guidelines for portland cement concrete (PCC) material inputs to the AASHTOWare Pavement ME Design program. The AASHTOWare Pavement ME Design is the software program used by the Mississippi Department of Transportation (MDOT) to develop pavement design alternatives based on the mechanistic-empirical pavement design guide (MEPDG) procedure originally developed under National Cooperative Highway Research Program (NCHRP) Projects 1-37A, 1-40D, and 20-07/Task 288 & 327. MDOT has conducted several research projects to support the implementation of the MEPDG and for increasing the accuracy of the distress prediction models calibrated for local conditions and material sources. The current project focuses on PCC material inputs that represent the mix designs, cementitious materials, and the aggregate sources that will be used in future paving projects.

This report provides a summary of laboratory test results of 20 mix designs that include five different aggregate sources and four different options for supplementary cementitious materials (SCM) for partial cement replacement. The laboratory test results represent level 1 and 2 PCC material inputs and report the flexural strength, compressive strength, elastic modulus, poisson's ratio, coefficient of thermal expansion (CTE), and percent length change measurements. Strength and modulus data, are reported for 7, 14, 28, and 90 days as required by the MEPDG. The CTE measurements are reported at 28-days, while the shrinkage length change measurements are reported for ages of 7, 11,14, 21, 35, 63, 119, and 231 days. Level 2 correlation equations were developed based on compressive strength and other index properties to estimate flexural strength and elastic modulus. In general, these models demonstrate a slight deviation from the default level 2 models used in the global calibration of the MEPDG. Level 2 equations were also developed for each aggregate type and it is recommended that future efforts by MDOT for the recalibration of the rigid pavement distress prediction models should examine the sensitivity of these level 2 correlation equations and provide recommendations in the MDOT Design Manual.

17. Key Words Pavement ME Design, Mechanistic-Empirical, Rigid Pavement Design, PCC inputs, PCC Flexural Strength, PCC Compressive Strength, PCC Elastic Modulus, PCC CTE, PCC Shrinkage, Level 2 Correlations, Transverse Cracking, Joint Faulting, IRI, Smoothness.	**18. Distribution Statement** Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

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SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
In	Inches	25.4	Millimeters	mm
Ft	Feet	0.305	Meters	m
Yd	Yards	0.914	Meters	m
Mi	Miles	1.61	Kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
Ac	Acres	0.405	Hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	mL
Gal	Gallons	3.785	Liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
[NOTE: volumes greater than 1,000 shall be shown in m^3]				
		MASS		
Oz	Ounces	28.35	Grams	g
Lb	Pounds	0.454	Kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (metric tons)	Mg (or t)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9	Celsius	°C
	or (F-32)/1.8			
		ILLUMINATION		
Fc	foot-candles	10.76	Lux	lx
Fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
Lbf	Pounds	4.45	Newtons	N
lbf/in^2 (psi)	pounds per square inch	6.89	kiloPascals	kPa
k/in^2 (ksi)	kips per square inch	6.89	megaPascals	MPa
	DENSITY			
lb/ft^3 (pcf)	pounds per cubic foot	16.02	kilograms per cubic meter	kg/m^3
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
Mm	Millimeters	0.039	Inches	in
M	Meters	3.28	Feet	ft
M	Meters	1.090	Yards	yd
Km	Kilometers	0.621	Miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
Ha	Hectares	2.47	Acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	Milliliters	0.034	fluid ounces	fl oz
L	Liters	0.264	Gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
G	Grams	0.035	Ounces	oz
Kg	Kilograms	2.202	Pounds	lb
Mg (or t)	megagrams (metric tons)	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	Lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	Newtons	0.225	Pounds	Lbf
kPa	kiloPascals	0.145	pounds per square inch	lbf/in^2 (psi)
Mpa	MegaPascals	0.145	kips per square inch	k/in^2 (ksi)
		DENSITY		
kg/m^3	pounds per cubic foot	0.062	kilograms per cubic meter	lb/ft^3 (pcf)

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E 380. (Revised March 2003)

DISCLAIMER STATEMENT

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI	American Concrete Institute
AEA	Air entraining agent
CA_ID	Coarse aggregate identification
Cementitious_ID	Cementitious identification
CRCP	Continuously Reinforced Concrete Pavement
CTE	Coefficient of Thermal Expansion
FHWA	Federal Highway Administration
GGBFS	Ground granulated blast furnace slag
HMA	Hot Mix Asphalt
IRI	International Roughness Index
JPCP	Jointed Plain Concrete Pavement
LTPP	Long-term Pavement Performance
MDOT	Mississippi Department of Transportation
M-E	Mechanistic Empirical
MEPDG	Mechanistic Empirical Pavement Design Guide
MS-ATLAS	Mississippi – Advanced Traffic Loading Analysis System
NCHRP	National Cooperative Highway Research Program
PCA	Portland Cement Association
PCC	Portland cement concrete
PM	Pavement management
QA	Quality assurance
SCM	Supplementary cementitious material
TFHRC	Turner Fairbanks Highway Research Center
WR	Water reducer
w/c	Water to cementitious materials ratio

Executive Summary

The current project conducted by the Mississippi Department of Transportation (MDOT) is intended to support the implementation of the Mechanistic Empirical Pavement Design Guide (MEPDG) procedure. This study developed guidelines for providing portland cement concrete (PCC) inputs to the AASHTOWare Pavement ME program in the design of rigid pavements. The guidelines are based on laboratory results from tests performed on 20 PCC mix designs using material sources typical of paving mixes in Mississippi.

The 20 mix designs included in the test plan include five different aggregate sources and four different options for the use of supplementary cementitious materials (SCM) for partial cement replacement. The laboratory experimental plan comprised of standard tests to measure flexural strength, compressive strength, elastic modulus, poisson's ratio, coefficient of thermal expansion (CTE), and percent length change due to shrinkage. The laboratory test results represent level 1 and 2 PCC material inputs and they are reported at different test ages as required by the MEPDG procedure. Strength and modulus data are reported for 7, 14, 28, and 90 days as required by the MEPDG. The CTE measurements are reported at 28-days, while the shrinkage length change measurements are reported for ages of 1, 7, 14, 21, 35, 63, and 119 days. MDOT will collect future length change data for these samples up to the age of 455 days.

This report summarizes all test data and suggests level 1 input values for all PCC material properties. Level 2 correlation equations were developed based on compressive strength and other index properties to estimate flexural strength and elastic modulus. Also, the study examined strength gain trends in data for extrapolating long term strength and modulus values. In general, these models demonstrate a slight deviation from the default level 2 models used in the global calibration of the MEPDG. Level 2 equations were also developed for each aggregate type and examined for statistical significance. Further, a rigid pavement design example was analyzed using five of the 20 mix designs so as to include all aggregate sources and options for SCMs. The results of the analysis verified the benefit of using MDOT level 2 correlations over the default correlations to match performance predictions with analysis using level 1 inputs. The study recommended that future efforts by MDOT for the recalibration of the rigid pavement distress prediction models examine the sensitivity of these level 2 correlation equations to make final recommendations for inclusion in the MDOT Design Manual.

Chapter 1: Introduction

BACKGROUND

The Mechanistic Empirical Pavement Design Guide (MEPDG) procedure was originally developed under the National Cooperative Highway Research Program (NCHRP) Project 1-37A (ARA, 2004). For rigid pavement design, the distress prediction models were revised under continuing research projects NCHRP 1-40D (ARA, 2007) and NCHRP 20-07/Task 288 (ARA, 2011) and Task 327. The MEPDG procedure was eventually adopted by AASHTO as the standard for pavement design (AASHTO 2008) and AASHTO has made available standard guidelines for agencies to implement the procedure and perform local calibration of the distress models (2010). Pavement analysis and design can currently be performed using the software program managed and distributed as an AASHTOWare product, *Pavement ME* or commonly referred to as *AASHTOWare Pavement ME* and formerly also known as DARWin-ME. The Mississippi Department of Transportation (MDOT), like many other States, has been active with the implementation of the MEPDG procedure and adopting the Pavement ME program.

MDOT has conducted multiple research studies to assist with the implementation of the MEPDG. The two primary studies that have directly focused on the implementation of the pavement performance models are State Study (SS) 163 (Saeed and Hall, 2003), and SS 170 (Von Quintus and Rao, 2013a, 2013b). SS 163 developed a detailed implementation plan, and SS 170 provided the calibration and validation of the MEPDG distress transfer functions to Mississippi's conditions and construction specifications. SS 170 also included other technology transfer activities.

The local calibration of distress prediction and International Roughness Index (IRI) models under SS 170 utilized Long-Term Pavement Performance (LTPP) sections in Mississippi and a limited number of projects from MDOT's pavement management (PM) database. While, detailed data were available for the LTPP sections, the MDOT PM sections used as-built construction data, which were considered less reliable because the pavements were in service for an extended period. The MDOT calibrations under SS 170 reduced the bias introduced from the use of global calibration for the selected projects, but it was concluded that the availability of field data and information from forensic investigations can reduce the standard error in the predictions. It was also recommended that MDOT pursue a recalibration effort to improve the accuracy of the prediction models using an enhanced dataset to characterize the materials of the calibration sections. SS 170 suggested that the enhanced dataset used for future recalibration effort reflect field conditions of the calibration sections.

Alongside, and largely complementary to, SS 163 and SS 170, other studies were conducted to provide the tools necessary to improve the accuracy of inputs provided to the AASHTOWare Pavement ME program and MEPDG performance predictions. They have typically generated input data or developed procedures to determine various parameters necessary for design when the MEPDG procedure is fully implemented by MDOT. These studies are:

- Material characterization for hot mix asphalt (HMA) under SS 166(White et al., 2007), portland cement concrete (PCC) under Work Assignment No. BCD-MT 2013 entitled *Laboratory Data to Determine Impact of Coarse Aggregate Type and Cementitious Materials on Design Thickness of PCC Pavements* , and unbound materials under SS 170 (Von Quintus et al., 2013)
- Climate data input files under SS 232 (Traux et al., 2011)
- Traffic analysis consistent with MEPDG requirements under SS 165 and 188 (Buchanan, 2004; Jiang and Saeed, 2007).

Data generated from these studies serve as direct inputs to the AASHTOWare Pavement ME program and have been built-into the MDOT input libraries so that users can directly import inputs for the climate, material, and traffic categories applying to MDOT pavements.

MDOT recently funded an experimental program to test PCC mixtures that represent materials and mixture proportions likely to be used in concrete paving statewide. Twenty different mix designs using five different aggregate sources and four different options of supplementary cementitious materials (SCMs) for cement replacement were batched to determine various material properties needed as inputs to the MEPDG rigid pavement design procedure. These inputs, considered critical for performance prediction of jointed plain concrete pavements (JPCP), included both mechanical properties and properties that influence volumetric changes in the PCC slab. The material properties tested were the following:

- Unit weight
- Modulus of rupture or flexural strength
- Compressive strength
- Modulus of elasticity
- Poisson's ratio
- Coefficient of thermal expansion (CTE)
- Concrete shrinkage

These test data are a valuable resource for:

1. Use in MDOT's future routine pavement design by including them in the MDOT AASHTOWare input library. Because the test results are directly representative of the materials and mix designs that will be used in future pavement construction projects, these data will produce pavement designs that will closely simulate field performance. While it is highly recommended that a project should invest in level 1 testing, these data can serve as PCC material inputs for rigid pavement projects using the same material types, material sources and mix designs. This is analogous to the test data included in the input library for unbound materials and HMA materials.

2. Use in developing MDOT level 2 correlations and in establishing default values for MEPDG. These data provide a complete dataset of level 2 material properties with corresponding level 1 input values. The level 1 data essentially form the material property values that should be estimated by the correlations.
3. Verification of default values established in the global calibration of the distress models.
4. Use in future recalibration of the MDOT distress prediction models. The material test data may be used to verify the sensitivity of the models developed.

This report prepared under this study serves as a formal documentation of the test program, and the test results. This study also developed level 2 correlation equations to estimate key material properties for AASHTOWare Pavement ME design. The report discusses their significance in the mechanistic-empirical (M-E) design of pavements.

Research Objective

The objectives of this research project were the following:

- Review the PCC test data provided by MDOT. These data were generated from tests conducted by Burns Cooley and Dennis, Inc.
- Summarize test data and tabulate results that can be used as inputs to Pavement ME.
- Develop MEPDG level 2 correlations and default values using test data.
- Develop guidelines for selection of inputs for MEPDG analysis and design.

The study focused on one rigid pavement design type, the JPCP.

Organization of the Report

The report consists of five chapters, starting with the current chapter that provides an introduction to the study. Chapter 2 presents an introduction to PCC material inputs for rigid pavement design in the MEPDG and a discussion of material testing programs by other agencies. In addition, a review of level 2 models developed under other studies will be discussed. Chapter 3 describes the experimental program. Chapter 4 contains the test results, and includes a discussion of results and the development of level 2 correlations. Chapter 5 includes a summary of the study, its findings and recommendations. Technical references are provided at the end of Chapter 5. The report also includes two appendices. Appendix A includes the test results from testing all coarse and fine aggregates for certification. Appendix B tabulates all test data.

Chapter 2: Characterization of Portland Cement Concrete Materials for Rigid Pavement Design

Introduction to Rigid Pavement Design Using the MEPDG

All versions of the AASHTO Design Guide for Pavements starting from 1960's through 1993 were based on empirical models for serviceability based on the American Association of State Highway Officials (AASHO) Road test in the late 1950's. The rigid pavement design procedure incorporated limited M-E concepts in 1998 revisions, but the impact of the improvements were not fully demonstrated or appreciated. The need for, and benefits of, a mechanistic-based pavement design procedure were recognized at the time when the 1986 Design Guide was adopted (AASHTO 1986). The AASHTO Joint Task Force on Pavements supported the development of M-E based pavement design procedures leading to the NCHRP research studies 1-37A, 1-40D, 20-07/Task 288 and 327 (ARA, 2004; 2007; 2011). As discussed in the previous chapter, the rudimentary software program developed under 1-37A and 1-40D was replaced by an AASHTOWare product, Pavement ME. A complete description of the MEPDG procedures and the software program has been provided in the MDOT SS 170 products (Von Quintus, et al., 2013a, 2013b).

Hierarchical Inputs for MEPDG

The MEPDG procedure offers a hierarchical input level scheme to accommodate the designer's knowledge of the input parameter. Inputs can be provided at three different levels. Level 1 input represents highest level of knowledge of the parameter and includes project-specific data. Level 2 represents a moderate level of knowledge of the input parameter and often is calculated from correlations with other site-specific data or a less expensive measure. Level 3 represents the least knowledge of the input parameter and is based on "best-estimated" or default values. For example, Level 1 data for concrete flexural strength would involve a flexural beam test, Level 2 would be a flexural strength value estimated using a compressive strength test and correlation to flexural strength, and Level 3 would be a default value for concrete strength used by a particular highway agency.

Characterization of PCC Materials in the MEPDG

Different material properties are used to characterize PCC materials within the MEPDG framework for the design of jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP) types. Key parameters can be determined for each PCC mixture design through laboratory tests. These key parameters are used by the analytical model for critical response calculations, for damage calculations, and for performance predictions. The MEPDG procedure also identified additional parameters that will be used for modeling climatic effects through the PCC slab depth. Default values, analogous to constant values, were established for these parameters. Table 1 summarizes the various PCC inputs that are required for a rigid pavement analysis and categorizes them based on their role in the analysis process. Special notes provided in Table 1 identify the input level of these parameters. Chapter 3 of the report provides further discussion of standard test procedures required to determine these parameters, and their impact on design. This information was included in Chapter 3 because it is more appropriate with the contents of that chapter. Table 13 and Table 15 list the standard test procedures for fresh and hardened concrete properties. Table 14 summarizes the test ages, the input levels, and the impact of each parameter on the overall design.

Table 1. PCC material inputs considered by the MEPDG for JPCP and CRCP.

Materials category	Materials inputs required		
	Materials inputs required for critical response computations	Additional materials inputs required for distress/transfer functions	Additional material inputs required for climatic modeling
PCC materials (this covers surface layer only)	• Static modulus of elasticity over time[1] • Poisson's ratio[1] • Unit weight[1] • Coefficient of thermal expansion[1]	• Compressive strength over time[2] • Modulus of rupture over time[1] • Splitting tensile strength (CRCP only)[1] • Ultimate shrinkage[3] • Amount of reversible shrinkage[4] • Time to achieve 50 percent of ultimate shrinkage[4] • PCC zero-stress temperature[5]	• Surface shortwave absorptivity[4] • Thermal conductivity[4] • Heat capacity[4]

1 Standard test procedure is identified to determine this material property in the laboratory. When determined through laboratory testing, it represents a level 1 input.
2 Standard test procedure is identified to determine this material property in the laboratory. When value is determined through laboratory testing, this represents level 2 input because this parameter is used to calculate a level 1 input parameter. Level 3 inputs may be provided.
3 Level 2 value is estimated from compressive strength, cement type, curing type, cement content, and water-to-cementitious materials (w/c) ratio. Level 1 testing is not identified.
4 Default values established during global calibration. User-defined input may be provided if more accurate value is available. IF using a non-default value exercise caution by performing a thorough evaluation of the impact of this parameter.
5 Estimated from cement content and mean monthly temperatures at project location.

The MEPDG also requires the input of construction and field-specific parameters that are critical to performance. These construction or site features are not restrictive to a particular material, but they are associated with specific material index properties, climatic conditions, and construction practices.

Correlations Adopted for the MEPDG

The global calibration of the MEPDG distress models utilized several level 2 and level 3 inputs based on the best information available from literature and LTPP database. The following is a partial list of correlations used in the MEPDG for PCC material properties:

i. PCC flexural strength model is based on Portland Cement Association (PCA) and LTPP studies. The model uses the general model form used in literature for flexural strength estimation and the correlation can be expressed as:

$$MR = 9.5 * f'_c{}^{0.5} \qquad \text{Equation 1}$$

where:

MR is flexural strength in psi
f'_c is compressive strength in psi

ii. PCC elastic modulus correlations borrowed from American Concrete Institute (ACI) model. The model is:

$$E_c = \rho^{1.5} * 33 * f'_c{}^{0.5} \qquad \text{Equation 2}$$

where:

E_c modulus of elasticity in psi
ρ is the density in lb/ft^3
f'_c is compressive strength in psi

For unit weight of 145 lb/ft^3, this model will result in the equation:

$$E_c = 57{,}000 f'_c{}^{0.5} \qquad \text{Equation 3}$$

iii. Concrete strength gain models from long term test data collected by the PCA and by LTPP as part of Specific Pavement Studies (SPS)-2 time series data. The model is:

$$F\_STRRATIO = 1.0 + 0.12*\log_{10}(AGE/0.0767) - 0.01566*[\log_{10}(AGE/0.0767)]^2$$

Equation 4

where:

F_STRRATIO is ratio of the strength at any age normalized to the 28-day value
AGE is the age of the concrete from the day of casting in days

iv. Ultimate shrinkage calculation model, which is a function of compressive strength, cement type, curing type, cement content, and w/c ratio. This model was generated using historical shrinkage data (Bazant, 2000) and was subsequently adopted by the American Concrete Institute (ACI). The model is:

$$\varepsilon_{su} = C_1 \cdot C_2 \cdot \left\{ 26 w^{2.1} \left(f'_c \right)^{-0.28} + 270 \right\} \qquad \text{Equation 5}$$

where:

ε_{su} is the ultimate shrinkage strain, x 10^{-6}
C_1 is the cement type factor = 1.0, 0.8, and 1.1 for type I, II, III cements respectively
C_2 is the curing factor = 0.75, 1.0, and 1.2 for steam curing, wet curing and curing compound respectively.
w=water content, lb/ft^3 for the PCC mix

f'_c=28-day PCC compressive strength, psi

v. CTE defaults by coarse aggregate type, which were established based on testing and petrography performed under the LTPP program. Note that the CTE values that were originally generated using the AASHTO TP-60 (AASHTO, 2007) provisional test procedure were revised and made consistent with the AASHTO T 336 (AASHTO, 2011) procedure. Default values for CTE based on AASHTO T 336 were recommended under the NCHRP 20-07/Task 327 (ARA, 2011). The recommended CTE values for all aggregate types are summarized in Table 2 (ARA, 2011). Note that these values represent materials nationwide.

Table 2. National PCC CTE averages (ARA, 2011).

Primary aggregate origin	Primary aggregate class	PCC CTE, 10^{-6} / °F		Number of test sections
		Average	Standard deviation	
Igneous (Extrusive)	Andesite	NA	NA	NA
Igneous (Extrusive)	Basalt	4.4	0.5	18
Igneous (Plutonic)	Diabase	5.2	0.5	21
Igneous (Plutonic)	Granite	4.8	0.6	69
Metamorphic	Schist	4.4	0.4	17
Sedimentary	Chert	6.1	0.6	25
Sedimentary	Dolomite	5.0	0.7	30
Sedimentary	Limestone	4.4	0.7	160
Sedimentary	Quartzite	5.2	0.5	9
Sedimentary	Sandstone	5.8	0.5	7

The level 2 correlations and the level 3 default values listed above can clearly be revised as part of local calibration efforts should a valid test dataset be available. The level 2 correlations may also reduce the bias in the distress prediction models.

CORRELATIONS DEVELOPED FROM OTHER DATA SOURCES

Several previous research studies have attempted to develop correlations to predict PCC material properties based on index properties and mix proportioning factors. A very detailed review of existing literature and the models developed historically have been discussed in an LTPP research study (Rao, et al., 2012). However, the LTPP Data Analysis program conducted a study to utilize data collected from LTPP test sections to develop correlations to predict PCC material properties. A key benefit recognized from this effort was that the correlations developed represented paving mixes (rather than a larger dataset from ACI and PCA studies that included structural concrete as well) and that they also represented the sections used in the calibration. Several correlations were developed for compressive strength, flexural strength, elastic modulus, indirect tensile strength, CTE, and rigid pavement design features. The correlations developed are presented in Table 3 through Table 8 respectively (Rao et al., 2012). MDOT test data generated under this study offers a promising opportunity to develop such correlations that would support MEPDG implementation efforts.

Table 3. PCC compressive strength models developed from LTPP data. (Rao et al., 2012)

Model	Application
Compressive Strength Model 1—28-day Cylinder Strength Model: $f_{c,28d} = 4028.41841 - 3486.3501 * w/c + 4.02511 * CMC$	28-day strength for design, QA
Compressive Strength Model 2—Short-Term Cylinder Strength Model: $f_{c,t} = 6358.60655 + 3.53012 * CMC - 34.24312 * w/c * uw + 633.3489 * \ln(t)$	Design, QA, PM, opening strength for ages < 1 year
Compressive Strength Model 3—Short-Term Core Strength Model: $f_{c,t} = 98.92962 + 5.70412 * CMC + 28.48527 * \mathrm{uw} + 2570.13151 * \mathrm{MAS} * \mathrm{w/c}$ $-199.84664 * \mathrm{FM} + 611.30879 * \ln(t)$	Design, QA, PM, opening/ in-situ strength, for ages < 1 year
Compressive Strength Model 4—All Ages Core Strength Model: $f_{c,t} = -6022.44 - 854.46 * \mathrm{w/c} + 4.8656 * CMC + 68.5337 * uw + 533.15 * \ln(t)$	Design, QA, PM, in-situ strength, at any age
Compressive Strength Model 5—Long-Term Core Strength Model: $f_{c,LT} = -3467.3508 + 3.63452 * CMC + 0.42362 * uw^2$	Rehabilitation design and in-situ strength for ages > 5 years
where *w/c* = water to cementitious materials ratio *CMC* = cementitious material content, $\mathrm{lb/ft^3}$ *uw* = unit weight , $\mathrm{lb/ft^3}$ *t* = age, years *MAS* = maximum nominal aggregate size, inch *FM* = fineness modulus of fine aggregate	

Table 4. PCC flexural strength models developed from LTPP data. (Rao et al., 2012)

Model	Application
Flexural Strength Model 1—Flexural Strength Based on Compressive Strength: $MR = 22.7741 * f'_c{}^{0.4082}$	Design and PM when compressive strength at given age is available
Flexural Strength Model 2—Flexural Strength Based on Age, Unit Weight, and w/c Ratio: $MR_t = 676.0159 - 1120.31 * \mathrm{w/c} + 4.1304 * \mathrm{uw} + 35.74627 * \ln(\mathrm{t})$	Design and PM when index properties are available; predicts for any age.
Flexural Strength Model 3: Flexural Strength Based on Age, Unit Weight, and Cementitious Material Content $MR_t = 24.15063 + 0.55579 * \mathrm{CMC} + 2.96376 * \mathrm{uw} + 35.54463 * \ln(\mathrm{t})$	Design and PM when index properties are available; predicts for any age.
where *MR* = flexural strength, psi MR_t = flexural strength at age t years, psi f'_c = compressive strength determined at the same age, psi *w/c* = w/c ratio *CMC* = cementitious material content, lb/yd^3 *uw* = unit weight, lb/ft^3 *t* = pavement age, years	

Table 5. PCC elastic modulus models developed from LTPP data. (Rao et al., 2012)

Model	Application
Elastic Modulus Model 1—Model Based on Aggregate Type $E_c = (4.499*(UW)^{2.3481} * (f'c)^{0.2429})*D_{agg}$	Design and PM when compressive strength at given age and aggregate type are available
Elastic Modulus Model 2— Model Based on Age and Compressive Strength $E_{c,t} = 59.0287*(f'c_t)^{1.3}*(\ln(\frac{t}{0.03}))^{-0.2118}$	Design and PM when compressive strength at given age is available; predicts for any age.
Elastic Modulus Model 3—Model Based on Age and 28-day Compressive Strength: $E_{c,t} = 375.6*(f'c_{28-day})^{1..1}*(\ln(\frac{t}{0.03}))0.00524$	Design and PM when 28-day compressive strength is available; predicts for any age.
where E_c = PCC elastic modulus, psi E_t = elastic modulus at age t years *uw* = unit weight, pcf f'_c = compressive strength at same age, psi $f'_{c,\,28d}$ = 28-day compressive strength *t* = age at which modulus is determined, years Dagg = regressed constant depending on aggregate type: Andesite(1), Basalt(0.9286) Chert(1.0079), Diabase(0.9215), Dolomite(1.0254), Granite(0.8333), Limestone(1), Quartzite(0.9511), Sandstone(1)	

Table 6. PCC indirect tensile strength models developed from LTPP data. (Rao et al., 2012)

Model	Application
PCC Indirect Tensile Strength Model—Model Based on Compressive Strength: $f_t = 8.9068*(f'c)^{0.4785}$ where: f'_t = indirect tensile strength of the PCC material f'_c= compressive strength of the mix determined at the same age	Design when compressive strength is available

Table 7. PCC CTE models developed from LTPP data. (Rao et al., 2012)

Model	Application
CTE Model 1—CTE Based on Aggregate Type (Level 3 Equation for MEPDG): Basalt(4.86), Chert(6.9), Diabase(5.13), Dolomite(5.79), Gabbro(5.28), Granite(5.71), Limestone(5.25), Quartzite(6.18), Andesite(5.33), Sandstone(6.33)	Design, QC, PM when coarse aggregate rock type is available
CTE Model 2—CTE Based on Mix Volumetrics (Level 2 Equation for MEPDG): $CTE_{PCC} = CTE_{CA} * V_{CA} + 6.4514 * (1 - V_{CA})$ where CTE_{PCC} = CTE of the PCC material, x10^{-6} in/in/°F V_{CA} = volumetric proportion of the coarse aggregate (0 to 0.6) CTE_{CA} = Constant determined for each aggregate type – Basalt(3), Chert(6.4), Diabase(3.4835), Dolomite(5.1184), Gabbro(3.75), Granite(4.7423), Limestone(3.2886), Quartzite(6.1), Andesite(3.6243), Sandstone(4.5)	Design, QC, PM when coarse aggregate rock type and mix design proportioning are available

Table 8. Rigid pavement deltaT estimation model developed from LTPP data. (Rao et al., 2012)

Model	Application
deltaT – JPCP Design: $deltaT / inch = -5.27805 - 0.00794 * TR - 0.0826 * SW + 0.18632 * PCCTHK + 0.01677 * uw + 1.14008 * w/c + 0.01784 * latitide$ where *deltaT/inch* = predicted gradient in JPCP slab, °F/inch *TR* = difference between maximum and minimum temperature in construction month, °F *SW*= slab width, feet *PCCTHK*= JPCP slab thickness, inch *uw*= unit weight of PCC used in JPCP slab, lb/ft^3 *w/c*= w/c ratio *latitude* = latitude of the project location, degrees	Design, PM when mix design and construction weather information are available

Chapter 3: Experimental Program

INTRODUCTION

The experimental program included a comprehensive laboratory testing plan for 20 PCC mixture designs that MDOT considered to be representative of paving mixtures used in the State. The 20 PCC mixtures included five different coarse aggregate types and four different blends of cementitious materials, therefore creating a parametric study of two variables. The selected coarse aggregates used in the study cover the coarse aggregate material types and index properties representing potential major aggregate sources for use in construction of rigid pavements in the State. Likewise, the cementitious material blends cover the permitted supplementary cementitious materials and replacement levels specified in the Standard Specifications (MDOT 2004; MDOT 2014). Details of the materials and the mix proportioning are discussed in the future sections of this chapter.

The standard AASHTO or ASTM test procedures included in the experimental program were those specified by AASHTO (2008) to determine the material properties required as level 1 and level 2 inputs to the AASHTOWare Pavement ME program. As per the requirements of the MEPDG procedure, the material properties were reported at specified ages for characterizing changes in the concrete material properties during the design life. Details of the specific tests performed, and the test data collected are discussed in this chapter.

MATERIALS USED IN LABORATORY TEST PLAN

Cementitious Materials

MDOT Standard Specifications Section 701 permits the use of hydraulic cements as well as supplementary cementitious materials (SCMs), namely, fly ash and ground granulated blast furnace slag (GGBFS). Section 701 also states that the cement types shall be either Type I or Type II and classified as low-alkali cements conforming to AASHTO designation M85. Additionally, when SCMs are used, the maximum percentage cement replacement by weight is 25 percent for fly ash and 50% for GGBFS. Further, no restrictions are indicated about the type of fly ash, therefore permitting both Class C and Class F fly ashes.

Section 701 also permits the use of blended cements, i.e., Type IS—Portland blast-furnace slag cement, Type IP—Portland-pozzolan cement, and Type IL—Portland-limestone cement. However, no additional SCMs are permitted when cement blends of type IS and IP are used.

The test plan included PCC mixture designs with and without SCMs in accordance with Section 701, and covered the approved range of cementitious blends. The cementitious materials used in the test plan are as follows:

1. Cementitious 1 – 100 percent Type I/II cement.

2. Cementitious 2 – 75 percent Type I/II cement + 25 percent Class F fly ash.
3. Cementitious 3 – 75 percent Type I/II cement + 25 percent Class C fly ash.
4. Cementitious 4 – 50 percent Type I/II cement + 50 percent GGBFS.

Table 9 provides a summary of the cementitious blends and the relative proportioning of cementitious materials content in the mix designs.

Table 9. Cementitious materials used in the mix designs included in the test plan.

Cementitious ID	Cement (lb/yd^3)	Class F (lb/yd^3)	Class C (lb/yd^3)	Slag (lb/yd^3)	Total cementitious (lb/yd^3)
1	548	-	-	-	548
2	411	137	-	-	548
3	411	-	137	-	548
4	274	-	-	274	548

Coarse Aggregates

Section 703.03 of MDOT Standard Specifications, which provides the requirements for coarse aggregates used in PCC, approves the use of gravel or crushed limestone unless otherwise designated in the plans or special provisions. Further, aggregate soundness and abrasion requirements are specified. For soundness, the weighted percentage loss shall be no more than 15 percent when the sample is subjected to five cycles of soundness test with the use of magnesium sulfate under AASHTO T 104, and for abrasion resistance the percentage wear shall be no more than 40 under the AASHTO T96 (LA Abrasion) test procedure.

The coarse aggregate materials used in the test plan were chert gravels and crushed limestone from five different sources. The sources are denoted using a coarse aggregate identification (CA_ID) number, ranging from 1 through 5, as listed in Table 10. It also reports the aggregate size and the aggregate type, the bulk specific gravity (BSG) in dry and saturated surface dry (SSD) conditions, and percent absorption of the aggregate samples determined from the AASHTO T85 procedure.

Table 10. Coarse aggregate description, BSG, and absorption from AASHTO T85 testing.

CA_ID	Coarse aggregate description	Aggregate type/class	Size	BSG-dry	BSG-SSD	Absorption, %
1	High absorption gravel	Chert	No. 57	2.394	2.475	3.37
2	Crushed stone	Limestone	No. 57	2.597	2.636	1.49
3	Crushed stone	Limestone	No. 57	2.740	2.750	0.35
4	Low absorption gravel	Chert	No. 57	2.536	2.572	1.42
5	Small maximum size gravel	Chert	No. 67	2.453	2.513	2.45

Appendix A of the report contains other detailed test data for each source including gradation, unit weight, and void content.

In addition, the LA abrasion tests (AASHTO T 96) was performed for the two limestone sources, i.e. CA_ID 2 and 3, to measure toughness and indirectly examine causes for relative strength and modulus differences between the concrete mix designs batched using these two materials as will be discussed in the following chapters. The percentage loss was determined to be 24.9 and 21.9 for CA_IDs 2 and 3 respectively.

Fine Aggregates

MDOT specifications allow the use of natural sands for PCC in concrete pavements. The soundness requirements are same as that for coarse aggregates. All fine aggregate used in the experimental plan were sourced from Hammett with identification MDOT 3-26-2. The gradation and other properties are included in Appendix A. The BSG-dry, BSG-SSD, and the absorption of the fine aggregates used were 2.622, 2.636, and 0.52 respectively.

Admixtures

The mixture designs included in the experimental plan used air entraining agent (AEA) and Type-A water reducer. AIR-IN-XT was the AEA from Hunt Process and HPS-R the water reducer.

PCC Mix Designs

Mixture Proportioning

A total of 20 mix designs were used that consisted of 4 cementitious materials blends (listed in Table 9) and five different coarse aggregate types (listed in Table 10). For each of the 20 mix designs, the cementitious materials blends, the aggregate source, and the mix proportioning are summarized in Table 11. The 20 mix designs are identified with the reference MIX_ID in this table and throughout the rest of the report. Likewise the abbreviations CA_ID and Cementitious_ID used to identify the coarse aggregate source and the cementitious blend in the mix design will be used in the remainder of this report.

Also, testing protocol required approximately 12.5 cubic feet of concrete. This required multiple laboratory batches, which was typically 2 – 6.25 cubic feet batches. Test data provided in the tables are average data. For example, slump and unit weight data that will be reported in Chapter 4 represent the average from the two batches.

Table 11. Mixture proportioning for the 20 PCC mixes used in the experimental plan.

MIX _ID	Cast date in 2014	Cementitious _ID[1]	CA_ID[2]	Aggregate type	Total cementitious (lb/yd^3)	Coarse aggregate (lb/yd^3)	Fine aggregate (lb/yd^3)	Water (lb/yd^3)	AEA (fl Oz)	Type A-WR (fl Oz)	w/c
1	4/16	1	1	Chert	548	1929	1129.6	229.2	3.4	27.4	0.42
2	4/18	2	1	Chert	548	1929	1089.6	222.9	8.2	27.4	0.41
3	5/2	3	1	Chert	548	1929	1149.4	210.4	2.7	27.4	0.38
4	5/5	4	1	Chert	548	1929	1103.5	229.2	3.1	30.3	0.42
5	5/7	1	2	Limestone	548	1993	1180.1	231.3	2.7	27.4	0.42
6	5/9	2	2	Limestone	548	1993	1134.6	233.3	6.5	27.4	0.43
7	5/13	3	2	Limestone	548	1993	1183.3	225.0	3.0	29.6	0.41
8	5/15	4	2	Limestone	548	1993	1151.3	237.5	5.4	29.2	0.43
9	5/19	1	3	Limestone	548	2029	1228.2	231.3	2.1	27.4	0.42
10	5/21	2	3	Limestone	548	2029	1171.7	233.3	4.4	27.4	0.43
11	5/27	3	3	Limestone	548	2029	1231.5	220.8	3.7	27.4	0.40
12	6/2	4	3	Limestone	548	2029	1191.1	237.5	3.5	27.4	0.43
13	6/9	1	4	Chert	548	2031	1152.0	208.3	2.7	27.4	0.38
14	6/12	2	4	Chert	548	2031	1109.2	208.3	4.7	27.4	0.38
15	6/16	3	4	Chert	548	2031	1160.7	195.8	2.7	27.4	0.36
16	6/18	4	4	Chert	548	2031	1120.4	216.7	3.1	27.4	0.40
17	6/24	1	5	Chert	548	2012	1079.1	229.2	2.7	27.4	0.42
18	6/26	2	5	Chert	548	2012	1017.1	233.3	5.5	27.4	0.43
19	6/30	3	5	Chert	548	2012	1076.8	216.7	2.7	27.4	0.40
20	7/2	4	5	Chert	548	2012	1047.5	229.2	3.2	27.4	0.42

[1]Please see Table 9
[2]Please see **Error! Reference source not found.**

TEST PROGRAM

The test program included standard tests that are included in MDOT's standard specifications. Also included were specialized tests for other material properties that correspond to the level 1 and level 2 inputs defined in the MEPDG procedure. The tests are listed under the categories fresh concrete properties and hardened concrete properties. All samples were cast and cured in accordance with AASHTO R39.

Fresh Concrete Properties

Table 12 lists the fresh concrete properties that were measured for each batch. Figure 1 shows pictures of batching and testing fresh concrete properties listed in Table 12.

Table 12. Fresh concrete properties determined for each mix design.

Material property	Replicates	Standard	Specimen size	Test age (days)
Slump	1 per mix	AASHTO T119	NA	Fresh
Unit weight	1 per mix	AASHTO T121	NA	Fresh
Air content	1 per mix	AASHTO T152	NA	Fresh
Temperature	1 per mix	ASTM C1064	NA	Fresh

Loading the mixer

Slump test

Pressure for air content measurement

Roller meter for air content

Figure 1. Batching and testing fresh concrete properties.

Hardened Concrete Properties

Table 13 lists the material properties that were determined in the laboratory. Also listed in Table 13 are the test ages and the input level that corresponds to the test parameter. A short discussion is provided to describe how this input parameter is considered by the MEPDG procedure in performance prediction.

Table 13. Material properties determined in the laboratory test plan.

Material property	Ages (days)	AASHTO Pavement ME input levels	Comments on significance of this parameter in rigid pavement design
Mechanical Properties			
Flexural strength	7,14,28,90	• 1 • 3 needs 28-day value	Used to develop flexural strength gain model and to calculate fatigue damage.
Modulus of elasticity and Poisson's ratio	7,14,28,90	• 1 • 3 optional 28-day value	Used to develop modulus gain model and to calculate critical stresses for fatigue damage.
Compressive strength	7, 14, 28, 90	• 2 • 3 needs 28-day value	Used to calculate flexural strength, modulus of elasticity, and ultimate shrinkage using level 2 correlations. *Test program offers the opportunity to develop level 2 correlation equations for flexural strength and elastic modulus based on compressive strength data from the 20 mix designs.*
Splitting tensile strength	The laboratory plan did not include testing for this material property. This parameter is used only for CRCP design.		
Volume Change Properties – Thermal and Moisture Related			
Coefficient of thermal expansion	28 day	• 1 • 2 • 3	Used to calculate thermal stresses and strains in the slab that are a result of effective temperature gradients. CTE is required for all levels of input. Means to obtain the input value may vary. Level 1 input is obtained from laboratory test. Level 2 is typically based on aggregate type and level 3 represents a default value established by an agency. *Test data provide an opportunity to develop guidelines for level 2 and 3 inputs.*
Length change (from shrinkage)	7,11,14, 21,35, 63,119, 231,455	• 1 • 2 • 3	Ultimate shrinkage is the required input. Standard guidelines are unavailable to determine this value. MEPDG uses a level 2 correlation based on cement type, cement content, strength, and curing type.
Represent shrinkage ages of 0 (@7-day soak), 4,7,14,28,56,112,224,and 448 days			

Note the italicized content in Table 13, that point to the data sets in the test results that can be useful to develop level 2 correlations and level 3 default values specific to materials and mix designs satisfying MDOT standards.

Table 14 provides a summary of the standard test procedures adopted in the experimental program, the number of replicates used for each test as well as the size of the test specimens. Figure 2, Figure 3, and Figure 4 show pictures from the laboratory testing activities that were provided along with the test data for this report. Figure 2 shows the casting of the cylinders and beams for strength and modulus tests. Figure 3 shows the standard curing as well as the testing for strength, modulus, and CTE. Figure 4 shows the pictures from the curing and testing for length change measurements.

Table 14. List of tests performed, test ages, test specimen size and number of replicates.

Material property	Replicates	Test standard	Specimen size	Test age (days)
Mechanical Properties				
Compressive strength	4	AASHTO T22	6 X 12	7,14,28,90
Modulus of elasticity and poisson's ratio	3	ASTM C469	6 X 12	7,14,28,90
Flexural strength	3	AASHTO T97	6 X 6 X ±20	7,14,28,90
Volume Change Properties – Thermal and Moisture Related				
Coefficient of thermal expansion	2	AASHTO T336	4 X 8	28
Length change	4	AASHTO T160	4 X 4 X 11 ¼	4,7,14,28,35,56,112, 224,448

Casting 6"x 12"cylinders

Casting shrinkage test prisms

Figure 2. Casting test specimens for laboratory tests.

Standard curing of test specimens

Compressive strength testing

Flexural strength testing

Modulus of elasticity testing

CTE test set up

CTE testing and data collection

Figure 3. Pictures of strength, modulus and CTE testing.

Wet soaking of flexural strength samples

Shrinkage samples in drying room

Shrinkage test comparator readings

Figure 4. Pictures of shrinkage test curing and length change measurement.

Test Standards

The test standards that were used in the experimental plan, as identified in Table 12 and Table 14, are listed below for easy reference.

- AASHTO R39 "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory."
- AASHTO T119 "Standard Test Method for Slump of Hydraulic-Cement Concrete."
- AASHTO T121 "Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete."
- AASHTO T196 "Standard Method of Test for Air Content of Freshly Mixed Concrete by the Pressure Method."
- ASTM C1064 "Standard Test Method for Temperature of Freshly Mixed Hydraulic-Cement Concrete."
- AASHTO T22 "Standard Test Method for Compressive Strength of Cylindrical Specimens."
- ASTM C469 "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression."
- AASHTO T97 "Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading)."
- AASHTO T336 "Standard Test Method for Coefficient of Thermal Expansion of Hydraulic Cement Concrete."
- AASHTO T160 "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete."

Chapter 4: Test Results

INTRODUCTION

As stated in Chapter 1, the objectives of this project are to provide guidelines for PCC inputs to the AASHTOWare Pavement ME program. The guidelines developed are based on the analysis of test data generated from the experimental program described in Chapter 3. Test results from the experimental plan were provided by MDOT to the project team for developing the guidelines. All data provided, have been tabulated in Appendix B. The data are consistent with the test plan including the material properties reported, the standard test procedures adopted, and ages at which the tests were performed. The only exception is the shrinkage length change data. At this point data were only available for specimen ages of up to 119 days. Results from length change measurements at later ages will be added to the MDOT materials database as they become available.

This chapter presents an overview of the analysis of the test data provided by MDOT and a summary and discussion of the key test results for each of the 20 mix designs. The test result summaries include average and standard deviation values by age, material property, and mix design. Where appropriate, average values for each aggregate source or cementitious materials blend, are also provided. Individual test results are provided in Appendix B. Further, this chapter presents level 2 equations that were developed and level 3 default values that were established using the test results from the 20 mix designs for use with the AASHTOWare Pavement ME Design software.

TEST RESULTS

Fresh Concrete Properties

The fresh concrete properties determined at the time of batching—unit weight, slump, and air content—are reported for each mix design in Table 15. These results represent the average from all batches for each MIX_ID.

Table 15. Fresh concrete properties measured for all MIX_IDs.

MIX_ID	Cast date	CA_ID	Aggregate type	Cementitious ID	Slump (inch)	Air content (%)	Unit weight (lb/ft^3)
1	4/16/2014	1	Chert	1	1.375	5.25	142.2
2	4/18/2014	1	Chert	2	1.625	5.2	141.2
3	5/2/2014	1	Chert	3	2.375	4.65	143.8
4	5/5/2014	1	Chert	4	2.375	4.5	143.4

MIX_ID	Cast date	CA_ID	Aggregate type	Cementitious ID	Slump (inch)	Air content (%)	Unit weight (lb/ft^3)
5	5/7/2014	2	Limestone	1	2.625	5.8	144.4
6	5/9/2014	2	Limestone	2	2.375	5.5	144.5
7	5/13/2014	2	Limestone	3	2	5.15	145.7
8	5/15/2014	2	Limestone	4	1.75	4.55	146.1
9	5/19/2014	3	Limestone	1	2.5	5.15	149.3
10	5/21/2014	3	Limestone	2	2.75	4.65	148.6
11	5/27/2014	3	Limestone	3	2.75	5.4	147.7
12	6/2/2014	3	Limestone	4	2.5	5.3	147.04
13	6/9/2014	4	Chert	1	1.375	4.7	146.4
14	6/12/2014	4	Chert	2	2.75	4.5	144.3
15	6/16/2014	4	Chert	3	2.375	5.05	145.6
16	6/18/2014	4	Chert	4	2	4.5	145.66
17	6/24/2014	5	Chert	1	1.75	5.25	143
18	6/26/2014	5	Chert	2	2.625	4.95	141
19	6/30/2014	5	Chert	3	1.25	4.75	144.5
20	7/2/2014	5	Chert	4	1.25	4.4	144.4

Mechanical Properties

The average measured compressive strength, flexural strength, and modulus of elasticity, are tabulated by age in Table 16, Table 17, and Table 18, and respectively for all MIX_IDs. Table 19 provides a summary of the 28-day properties for the 20 MIX_IDs as well as the unit weights (from Table 15). These data are also plotted in Figure 5 through Figure 9 for mixes included in CA_IDs 1 through 5 respectively. Each figure includes three charts that plot the compressive strength, flexural strength, and modulus of elasticity respectively.

Table 16. Average compressive strength for each MIX_ID by test age.

MIX_ID	Age (days)	Average specimen length (inch)	Average specimen diameter (inch)	Average load at failure (lb)	Average compressive strength (psi)	Standard deviation of compressive strength (psi)	Ratio to 28-day compressive strength
1	7	12.00	5.98	157818	5616	229	0.84
1	14	12.08	6.02	176962	6219	143	0.94
1	28	12.11	6.01	188872	6648	287	1.00
1	90	12.07	6.02	210800	7408	188	1.11
2	7	12.02	5.97	123402	4414	141	0.77
2	14	12.00	5.97	133550	4772	112	0.83

MIX_ID	Age (days)	Average specimen length (inch)	Average specimen diameter (inch)	Average load at failure (lb)	Average compressive strength (psi)	Standard deviation of compressive strength (psi)	Ratio to 28-day compressive strength
2	28	12.04	5.97	161176	5756	130	1.00
2	90	12.02	5.96	196076	7028	190	1.22
3	7	12.06	5.96	154242	5538	295	0.78
3	14	12.00	5.99	180674	6420	127	0.90
3	28	12.00	5.97	199770	7133	283	1.00
3	90	12.00	5.97	221424	7910	323	1.11
4	7	12.02	5.96	123252	4413	277	0.63
4	14	12.01	5.99	178740	6345	192	0.90
4	28	12.00	5.94	194704	7020	492	1.00
4	90	12.04	5.98	220296	7846	235	1.12
5	7	12.05	5.99	153838	5455	102	0.86
5	14	12.02	5.98	167062	5942	197	0.93
5	28	12.05	6.01	180696	6365	259	1.00
5	90	12.05	6.00	198542	7036	214	1.11
6	7	12.08	6.01	123680	4367	222	0.73
6	14	12.06	6.01	140452	4955	182	0.83
6	28	12.10	6.02	169980	5968	170	1.00
6	90	12.06	6.01	209994	7414	297	1.24
7	7	12.05	6.02	174570	6136	317	0.77
7	14	12.08	6.00	209336	7404	167	0.93
7	28	12.05	6.03	227476	7973	160	1.00
7	90	12.07	6.02	264668	9295	376	1.17
8	7	12.01	5.94	157614	5680	198	0.71
8	14	12.04	5.96	210272	7528	258	0.94
8	28	12.04	5.98	225502	8041	212	1.00
8	90	12.03	5.99	234080	8313	545	1.03
9	7	12.04	5.95	170774	6140	225	0.84
9	14	12.02	5.96	195956	7022	140	0.96
9	28	12.03	5.99	206138	7316	158	1.00
9	91	12.00	5.97	222424	7952	215	1.09
10	7	12.12	6.03	152156	5324	112	0.78
10	14	12.02	5.98	170658	6076	322	0.89
10	28	12.04	6.00	192740	6812	182	1.00
10	90	12.03	5.98	248608	8841	290	1.30
11	7	12.14	6.02	159906	5620	320	0.77
11	14	12.08	6.02	188336	6617	150	0.91

MIX_ID	Age (days)	Average specimen length (inch)	Average specimen diameter (inch)	Average load at failure (lb)	Average compressive strength (psi)	Standard deviation of compressive strength (psi)	Ratio to 28-day compressive strength
11	28	12.06	6.03	208166	7296	119	1.00
11	90	12.13	6.02	245654	8644	534	1.18
12	7	12.07	6.02	147942	5195	203	0.71
12	14	12.10	6.02	189776	6659	389	0.92
12	28	12.11	6.04	207930	7268	314	1.00
12	92	12.12	6.02	242490	8534	159	1.17
13	7	12.05	6.00	163160	5777	250	0.84
13	14	12.06	6.00	173784	6151	163	0.89
13	28	12.03	5.98	193458	6878	174	1.00
13	90	12.00	5.99	198746	7045	222	1.02
14	7	12.05	6.03	137404	4818	118	0.72
14	14	12.07	6.03	162942	5709	150	0.85
14	28	12.07	6.02	190942	6715	131	1.00
14	90	12.07	6.02	232256	8154	203	1.21
15	7	12.10	6.04	171362	5991	152	0.79
15	14	12.07	6.02	192174	6755	357	0.89
15	28	12.03	6.00	215568	7617	425	1.00
15	90	12.09	6.02	242746	8531	236	1.12
16	7	12.09	6.03	151660	5314	211	0.73
16	14	12.07	6.02	185018	6506	207	0.89
16	28	12.10	6.01	206510	7270	144	1.00
16	90	12.04	6.02	211230	7419	550	1.02
17	7	12.02	5.99	171926	6102	173	0.85
17	14	12.03	5.98	195576	6962	612	0.96
17	28	12.00	5.96	201406	7217	345	1.00
17	90	12.02	5.98	227168	8092	274	1.12
18	7	12.00	5.98	135906	4840	124	0.73
18	14	12.02	5.99	159618	5663	199	0.85
18	28	12.00	5.98	185920	6631	27	1.00
18	90	12.06	5.99	225768	8002	269	1.21
19	7	12.05	5.99	192492	6822	363	0.83
19	14	12.07	5.98	223938	7980	251	0.97
19	28	12.04	6.00	232858	8237	393	1.00
19	90	12.03	5.96	265098	9498	169	1.15
20	7	12.10	6.04	163846	5724	138	0.72
20	14	12.18	6.02	208554	7320	140	0.93

MIX_ID	Age (days)	Average specimen length (inch)	Average specimen diameter (inch)	Average load at failure (lb)	Average compressive strength (psi)	Standard deviation of compressive strength (psi)	Ratio to 28-day compressive strength
20	28	12.15	6.03	225892	7908	116	1.00
20	90	12.13	6.04	245012	8563	375	1.08

Table 17. Average flexural strength for each MIX_ID by test age.

MIX_ID	Age (days)	Average specimen length (inch)	Average specimen width (inch)	Average specimen height (inch)	Average load at failure (lb)	Average flexural strength (psi)	Standard deviation of flexural strength (psi)	Ratio to 28-day flexural strength
1	7	21	6.04	6.07	8630.0	699.0	19.9	0.89
1	14	21	5.99	6.08	9283.3	755.0	27.6	0.96
1	28	21	6.01	6.04	9563.3	786.0	28.5	1.00
1	90	21	5.99	6.03	10613.3	877.0	48.5	1.12
2	7	21	6.02	6.08	7510.0	608.3	25.5	0.81
2	14	21	6.02	6.07	8610.0	699.0	14.7	0.93
2	28	21	6.03	6.07	9276.7	752.3	26.8	1.00
2	90	21	5.99	6.03	10703.3	885.3	40.7	1.18
3	7	21	6.07	6.04	8666.7	704.0	29.8	0.90
3	14	21	6.05	6.07	9270.0	748.0	38.2	0.96
3	28	21	6.02	6.06	9600.0	783.0	62.6	1.00
3	90	21	6.07	6.08	10896.7	874.7	37.5	1.12
4	7	21	6.01	6.06	8296.7	677.0	37.4	0.80
4	14	21	6.07	6.07	9846.7	793.7	21.1	0.94
4	28	21	6.01	6.10	10463.3	842.7	55.8	1.00
4	90	21	5.97	6.06	10300.0	847.0	24.8	1.01
5	7	21	6.01	6.06	8370.0	683.7	25.0	0.93
5	14	21	6.01	6.06	8966.7	730.0	35.5	0.99
5	28	21	6.01	6.08	9070.0	736.0	17.1	1.00
5	90	21	6.03	6.04	8896.7	727.7	11.8	0.99
6	7	21	6.02	6.06	7303.3	595.0	52.0	0.82
6	14	21	5.95	6.05	8223.3	680.3	4.6	0.94
6	28	21	6.00	6.08	8880.0	721.3	35.7	1.00
6	90	21	6.00	6.02	9753.3	807.0	6.1	1.12
7	7	21	6.04	6.09	9180.0	738.3	49.0	0.90
7	14	21	5.99	6.06	9780.0	801.3	15.6	0.98
7	28	21	5.99	6.09	10056.7	816.0	39.7	1.00

MIX_ID	Age (days)	Average specimen length (inch)	Average specimen width (inch)	Average specimen height (inch)	Average load at failure (lb)	Average flexural strength (psi)	Standard deviation of flexural strength (psi)	Ratio to 28-day flexural strength
7	90	21	5.97	6.05	10230.0	841.7	49.5	1.03
8	7	21	6.04	6.04	8820.0	719.7	32.0	0.79
8	14	21	6.05	6.07	10236.7	828.0	11.5	0.91
8	28	21	6.07	6.09	11406.7	913.0	59.0	1.00
8	90	21	5.98	6.04	11526.7	950.0	34.7	1.04
9	7	21	6.06	6.08	10796.7	866.7	19.4	0.93
9	14	21	6.06	6.03	11203.3	915.0	11.4	0.99
9	28	21	6.08	6.10	11663.3	927.7	12.7	1.00
9	91	21	6.11	6.08	11766.7	938.7	46.2	1.01
10	7	21	6.06	6.07	8963.3	722.7	9.3	0.77
10	14	21	6.07	6.09	10586.7	848.3	47.8	0.91
10	28	21	6.01	6.05	11410.0	932.7	33.6	1.00
10	90	21	6.00	6.07	12406.7	1009.3	35.2	1.08
11	7	21	6.05	6.06	9356.7	758.7	30.9	0.78
11	14	21	5.99	6.08	11023.3	895.3	19.6	0.92
11	28	21	5.96	6.04	11770.0	973.0	22.9	1.00
11	90	21	6.05	6.07	13036.7	1052.3	39.4	1.08
12	7	21	6.02	6.08	9176.7	741.0	44.2	0.71
12	14	21	6.06	6.08	11756.7	943.7	35.2	0.90
12	28	21	6.00	6.09	12940.0	1047.3	24.7	1.00
12	92	21	6.10	6.08	13400.0	1070.3	60.1	1.02
13	7	21	6.11	6.10	9766.7	774.3	56.1	0.90
13	14	21	6.02	6.08	10723.3	867.7	49.1	1.01
13	28	21	6.03	6.08	10610.0	858.3	37.9	1.00
13	90	21	5.98	6.08	11293.3	918.0	13.5	1.07
14	7	21	6.02	6.10	8583.3	690.0	14.0	0.81
14	14	21	6.00	6.08	10073.3	817.0	45.5	0.96
14	28	21	5.97	6.08	10406.7	850.3	32.7	1.00
14	90	21	6.01	6.04	11910.0	976.0	24.8	1.15
15	7	21	6.08	6.09	10073.3	804.7	49.0	0.89
15	14	21	6.02	6.07	10280.0	834.7	26.7	0.93
15	28	21	6.05	6.10	11276.7	901.0	3.5	1.00
15	90	21	6.03	6.05	12523.3	1021.0	49.4	1.13
16	7	21	6.00	6.08	8973.3	727.7	30.9	0.72
16	14	21	5.98	6.10	11253.3	911.0	39.1	0.91
16	28	21	5.96	6.08	12270.0	1004.3	11.0	1.00
16	90	21	5.95	6.08	13303.3	1088.7	57.6	1.08

MIX_ID	Age (days)	Average specimen length (inch)	Average specimen width (inch)	Average specimen height (inch)	Average load at failure (lb)	Average flexural strength (psi)	Standard deviation of flexural strength (psi)	Ratio to 28-day flexural strength
17	7	21	6.02	6.12	9123.3	729.3	11.5	0.90
17	14	21	5.98	6.07	9953.3	811.3	25.7	1.00
17	28	21	5.98	6.07	9933.3	810.7	28.7	1.00
17	90	21	5.97	6.05	10530.0	867.7	13.7	1.07
18	7	21	6.01	6.12	8360.0	668.7	21.5	0.88
18	14	21	5.97	6.08	8776.7	717.0	12.3	0.94
18	28	21	5.98	6.08	9393.3	763.7	46.6	1.00
18	90	21	5.99	6.07	11143.3	909.7	68.5	1.19
19	7	21	6.05	6.07	9810.0	793.0	15.6	0.94
19	14	21	6.04	6.08	10206.7	822.7	30.1	0.98
19	28	21	6.05	6.09	10526.7	843.7	4.9	1.00
19	90	21	6.07	6.07	11046.7	889.7	19.1	1.05
20	7	21	5.96	6.08	8880.0	726.3	42.1	0.78
20	14	21	6.02	6.09	10720.0	865.3	28.9	0.93
20	28	21	5.98	6.06	11296.7	927.7	41.0	1.00
20	90	21	5.96	6.08	11926.7	976.0	13.1	1.05

Table 18. Average modulus of elasticity for each MIX_ID by test age.

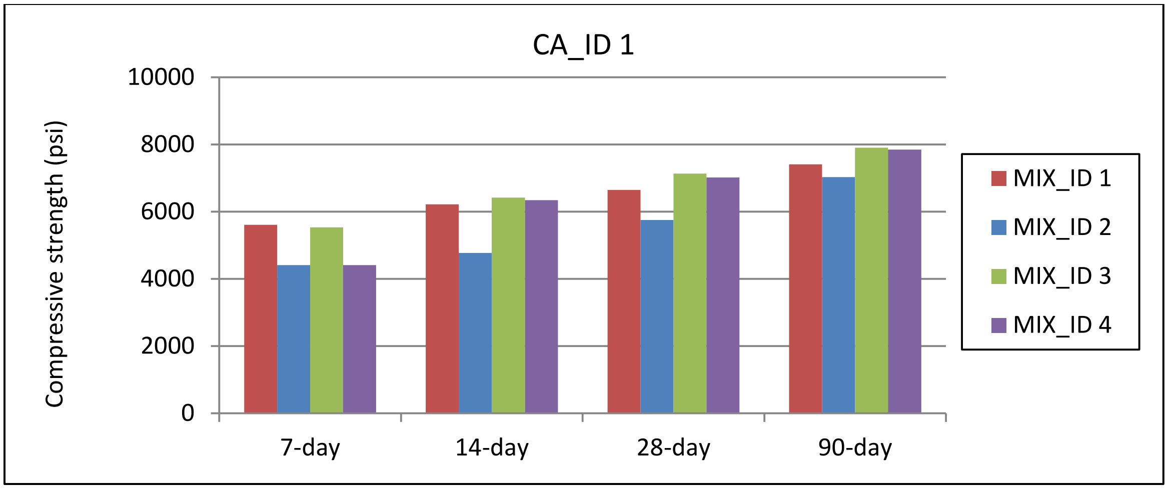
MIX_ID	Age (days)	Average specimen diameter (inch)	Average specimen height (inch)	Average modulus of elasticity (psi)	Standard deviation of modulus of elasticity (psi)	Average poisson's ratio	Standard deviation of poisson's ratio	Ratio to 28-day modulus value
1	7	5.99	12.19	5,250,000	132,288	0.16	0.00	0.89
1	14	6.02	0.00	5,450,000	350,000	0.15	0.04	0.93
1	28	6.02	12.32	5,883,333	256,580	0.17	0.01	1.00
1	90	6.00	12.25	6,033,333	548,483	0.19	0.04	1.03
2	7	5.96	12.25	4,950,000	50,000	0.14	0.00	0.95
2	14	5.97	12.22	4,933,333	76,376	0.15	0.01	0.94
2	28	5.98	12.21	5,233,333	230,940	0.16	0.00	1.00
2	90	5.98	12.36	5,700,000	312,250	0.16	0.02	1.09
3	7	5.96	12.30	5,116,667	104,083	0.15	0.01	0.81
3	14	5.98	12.19	5,816,667	354,730	0.15	0.02	0.92
3	28	5.97	12.20	6,333,333	354,730	0.14	0.01	1.00
3	90	5.96	12.22	5,683,333	378,594	0.13	0.01	0.90
4	7	5.96	12.24	5,216,667	175,594	0.15	0.01	0.88

MIX_ID	Age (days)	Average specimen diameter (inch)	Average specimen height (inch)	Average modulus of elasticity (psi)	Standard deviation of modulus of elasticity (psi)	Average poisson's ratio	Standard deviation of poisson's ratio	Ratio to 28-day modulus value
4	14	5.99	12.24	5,483,333	152,753	0.17	0.01	0.92
4	28	5.94	12.19	5,933,333	292,973	0.15	0.02	1.00
4	90	5.92	12.28	6,250,000	217,945	0.17	0.01	1.05
5	7	6.01	12.28	4,950,000	264,575	0.21	0.02	0.90
5	14	5.98	12.21	5,566,667	301,386	0.21	0.01	1.02
5	28	6.01	12.22	5,483,333	236,291	0.19	0.02	1.00
5	90	6.01	12.30	5,833,333	246,644	0.21	0.02	1.06
6	7	6.00	12.22	5,333,333	485,627	0.23	0.02	0.99
6	14	6.00	12.23	5,166,667	381,881	0.19	0.00	0.96
6	28	6.03	12.27	5,400,000	312,250	0.20	0.02	1.00
6	90	6.03	12.28	6,450,000	507,445	0.21	0.02	1.19
7	7	6.02	12.23	5,066,667	325,320	0.19	0.01	0.80
7	14	6.01	12.26	5,633,333	160,728	0.20	0.00	0.88
7	28	6.03	12.21	6,366,667	718,215	0.23	0.03	1.00
7	90	6.02	12.28	6,150,000	229,129	0.22	0.01	0.97
8	7	5.95	12.25	5,366,667	76,376	0.21	0.01	0.99
8	14	5.96	12.21	5,716,667	650,641	0.21	0.03	1.06
8	28	5.97	12.23	5,416,667	354,730	0.19	0.02	1.00
8	90	5.96	12.25	5,916,667	189,297	0.22	0.00	1.09
9	7	5.97	12.27	6,833,333	230,940	0.22	0.01	1.02
9	14	5.97	12.23	6,700,000	217,945	0.20	0.02	1.00
9	28	6.00	12.28	6,683,333	275,379	0.21	0.01	1.00
9	90	5.99	8.12	6,866,667	480,451	0.23	0.03	1.03
10	7	6.04	12.26	6,533,333	354,730	0.21	0.02	0.99
10	14	5.95	12.18	6,050,000	346,410	0.19	0.01	0.92
10	28	6.00	12.23	6,583,333	453,689	0.22	0.02	1.00
10	90	6.00	12.25	6,833,333	450,925	0.22	0.03	1.04
11	7	6.03	12.30	6,100,000	444,410	0.20	0.02	0.92
11	14	6.02	12.24	6,850,000	180,278	0.22	0.01	1.03
11	28	6.02	12.24	6,650,000	86,603	0.21	0.01	1.00
11	90	6.01	12.45	6,683,333	464,579	0.22	0.02	1.01
12	7	6.02	12.27	6,466,667	325,320	0.24	0.02	0.99
12	14	6.03	12.32	6,083,333	292,973	0.20	0.02	0.93
12	28	6.04	12.30	6,550,000	180,278	0.23	0.01	1.00
12	90	6.03	12.29	7,050,000	576,628	0.23	0.03	1.08
13	7	6.00	12.26	6,716,667	682,520	0.15	0.01	1.02
13	14	6.01	12.25	6,483,333	404,145	0.14	0.00	0.98
13	28	5.99	12.24	6,583,333	709,460	0.17	0.03	1.00

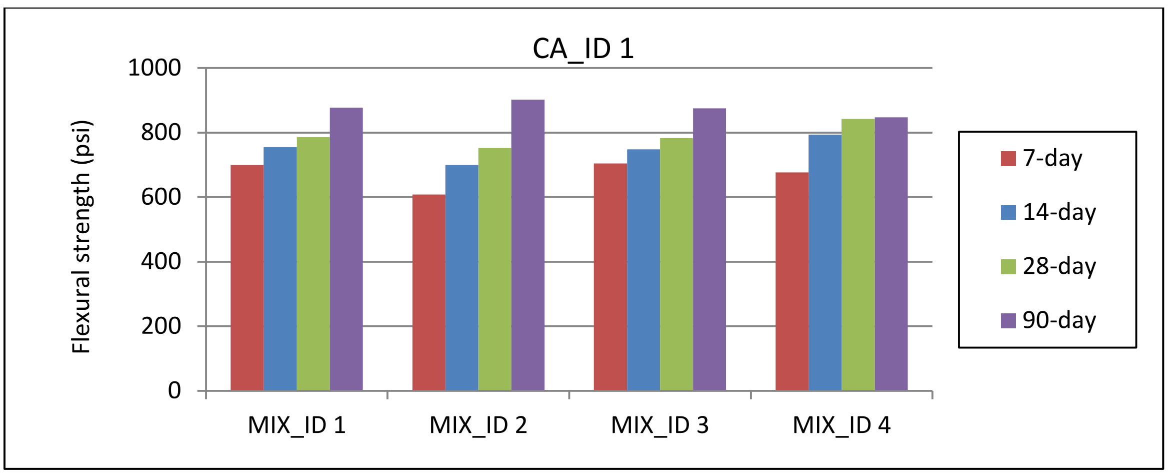
MIX_ID	Age (days)	Average specimen diameter (inch)	Average specimen height (inch)	Average modulus of elasticity (psi)	Standard deviation of modulus of elasticity (psi)	Average poisson's ratio	Standard deviation of poisson's ratio	Ratio to 28-day modulus value
13	90	5.98	12.20	6,616,667	256,580	0.14	0.01	1.01
14	7	6.03	12.23	6,000,000	427,200	0.15	0.02	0.91
14	14	6.03	12.25	5,616,667	57,735	0.13	0.02	0.86
14	28	6.01	12.24	6,566,667	152,753	0.14	0.01	1.00
14	90	6.01	12.29	6,850,000	350,000	0.14	0.00	1.04
15	7	6.04	12.28	6,800,000	888,819	0.13	0.03	1.02
15	14	6.03	12.24	6,566,667	317,543	0.11	0.01	0.99
15	28	6.01	12.19	6,666,667	332,916	0.18	0.02	1.00
15	90	6.01	12.24	7,000,000	217,945	0.15	0.01	1.05
16	7	6.03	12.44	6,350,000	556,776	0.15	0.02	0.84
16	14	6.01	12.27	6,683,333	152,753	0.17	0.01	0.89
16	28	6.01	12.33	7,533,333	76,376	0.15	0.01	1.00
16	90	6.00	12.26	6,600,000	312,250	0.14	0.01	0.88
17	7	5.98	12.20	5,333,333	202,073	0.15	0.00	0.91
17	14	5.99	0.00	5,900,000	300,000	0.16	0.02	1.01
17	28	5.96	12.21	5,833,333	175,594	0.14	0.01	1.00
17	90	5.95	12.20	6,150,000	390,512	0.15	0.01	1.05
18	7	5.97	12.18	4,933,333	175,594	0.15	0.01	0.87
18	14	6.00	12.17	5,333,333	76,376	0.16	0.01	0.94
18	28	5.98	12.23	5,700,000	312,250	0.15	0.01	1.00
18	90	5.99	12.24	5,733,333	305,505	0.14	0.01	1.01
19	7	6.00	12.29	5,766,667	76,376	0.15	0.00	0.92
19	14	5.97	12.23	5,816,667	340,343	0.17	0.02	0.93
19	28	6.00	12.27	6,250,000	278,388	0.15	0.01	1.00
19	90	6.00	12.23	6,450,000	576,628	0.12	0.02	1.03
20	7	6.02	12.34	5,350,000	444,410	0.16	0.01	0.92
20	14	6.03	12.44	5,700,000	50,000	0.15	0.02	0.98
20	28	6.04	12.28	5,816,667	775,134	0.15	0.01	1.00
20	90	6.04	12.31	6,366,667	682,520	0.16	0.03	1.09

Table 19. Average 28-day values for all mechanical properties for each MIX_ID.

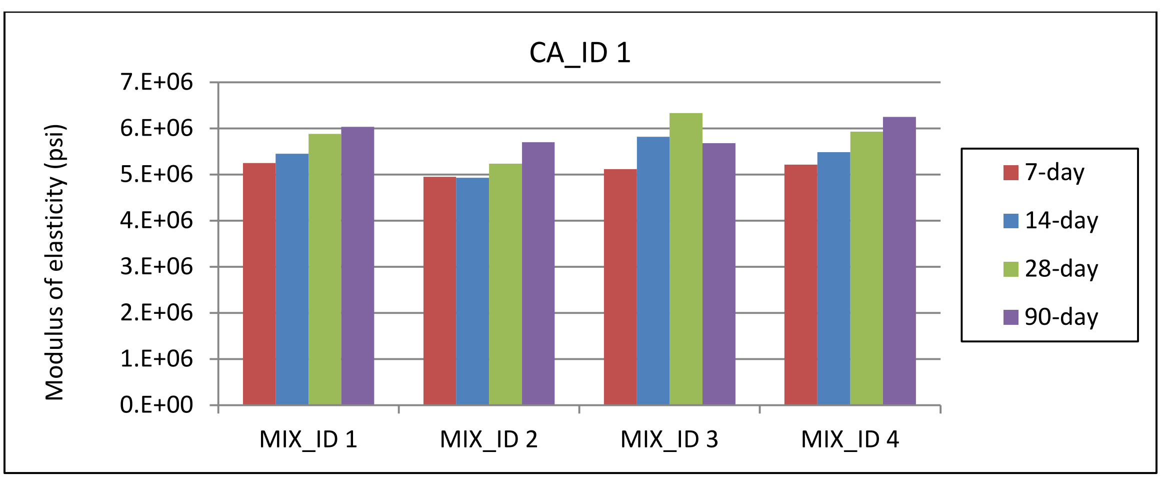
MIX_ID	Age, days	Compressive strength (psi)	Flexural strength (psi)	Modulus of elasticity (psi)	Poisson's ratio	Unit weight (lb/ft3)
1	28	6,648	786	5,883,333	0.17	142.2
2	28	5,756	752	5,233,333	0.16	141.2
3	28	7,133	783	6,333,333	0.14	143.8
4	28	7,020	843	5,933,333	0.15	143.4
5	28	6,365	736	5,483,333	0.19	144.4
6	28	5,968	721	5,400,000	0.20	144.5
7	28	7,973	816	6,366,667	0.23	145.7
8	28	8,041	913	5,416,667	0.19	146.1
9	28	7,316	928	6,683,333	0.21	149.3
10	28	6,812	933	6,583,333	0.22	148.6
11	28	7,296	973	6,650,000	0.21	147.7
12	28	7,268	1,047	6,550,000	0.23	147.04
13	28	6,878	858	6,583,333	0.17	146.4
14	28	6,715	850	6,566,667	0.14	144.3
15	28	7,617	901	6,666,667	0.18	145.6
16	28	7,270	1,004	7,533,333	0.15	145.66
17	28	7,217	811	5,833,333	0.14	143
18	28	6,631	764	5,700,000	0.15	141
19	28	8,237	844	6,250,000	0.15	144.5
20	28	7,908	928	5,816,667	0.15	144.4



a. Compressive strength for CA_ID 1.

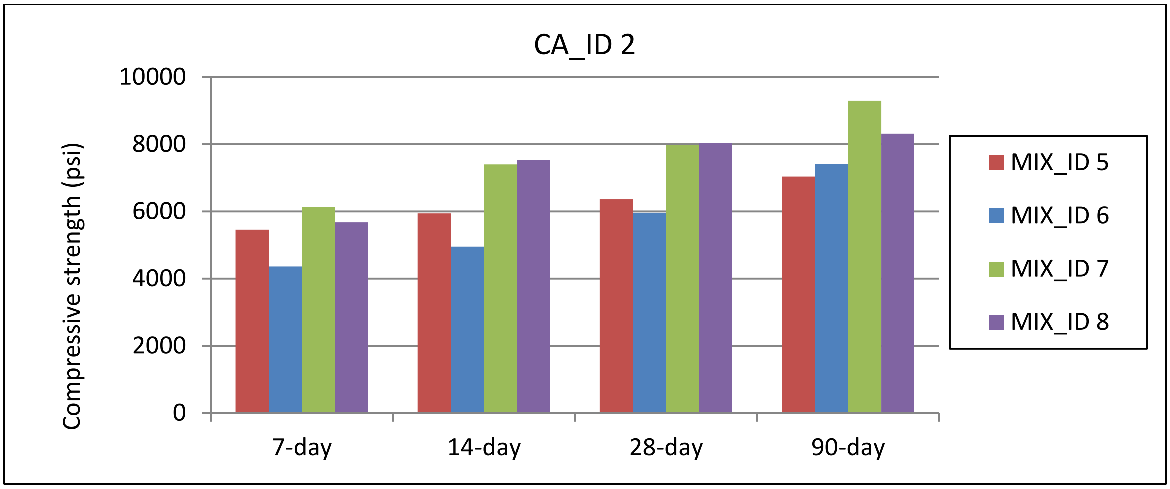


b. Flexural strength for CA_ID 1.

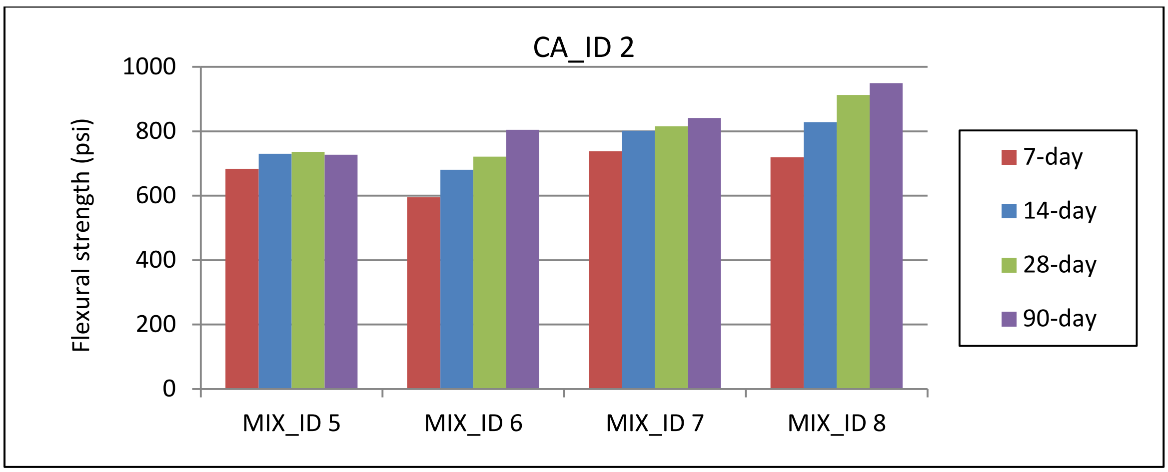


c. Modulus of elasticity for CA_ID 1

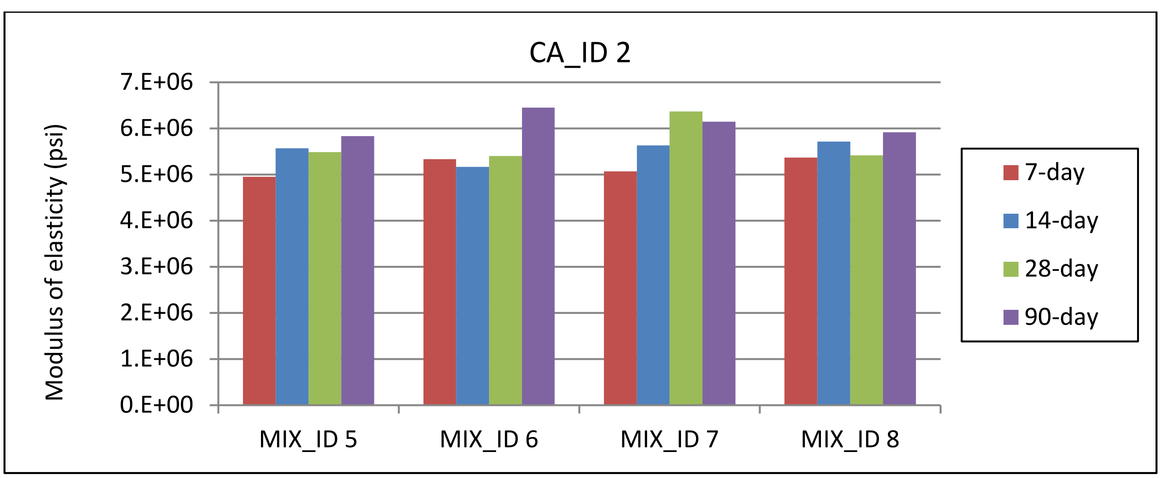
Figure 5. Strength and modulus results for MIX_IDs 1 through 4 with CA_ID 1.



a. Compressive strength for CA_ID 2.

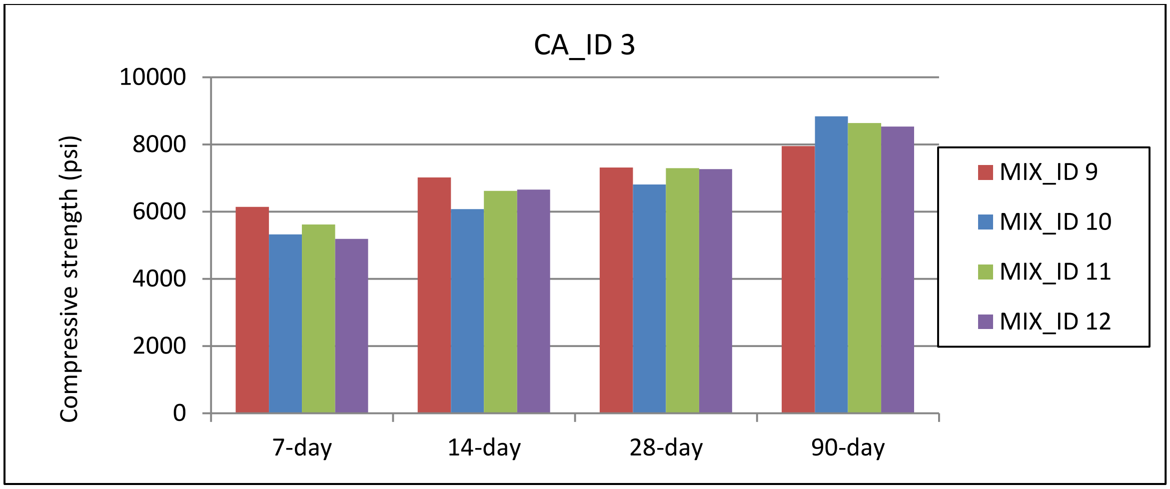


b. Flexural strength for CA_ID 2.

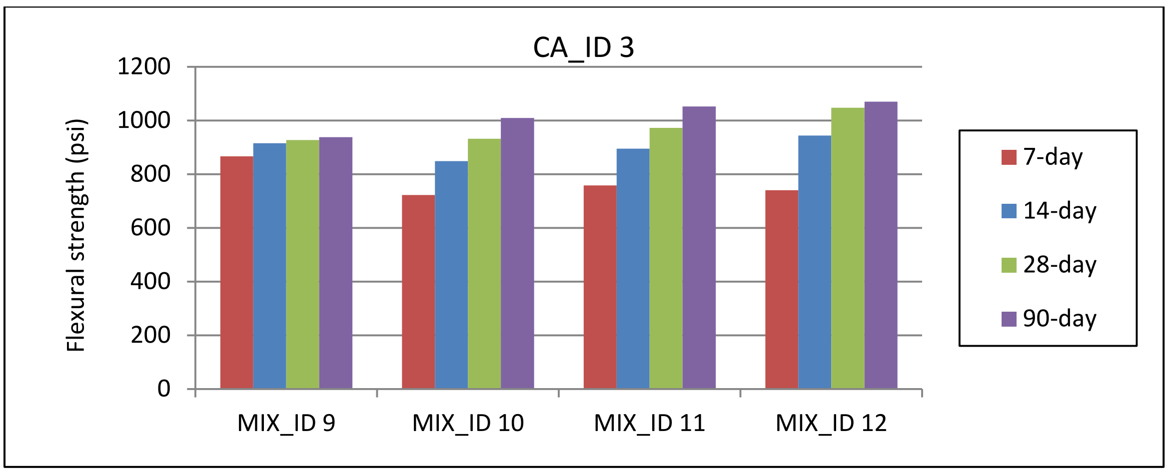


c. Modulus of elasticity for CA_ID 2

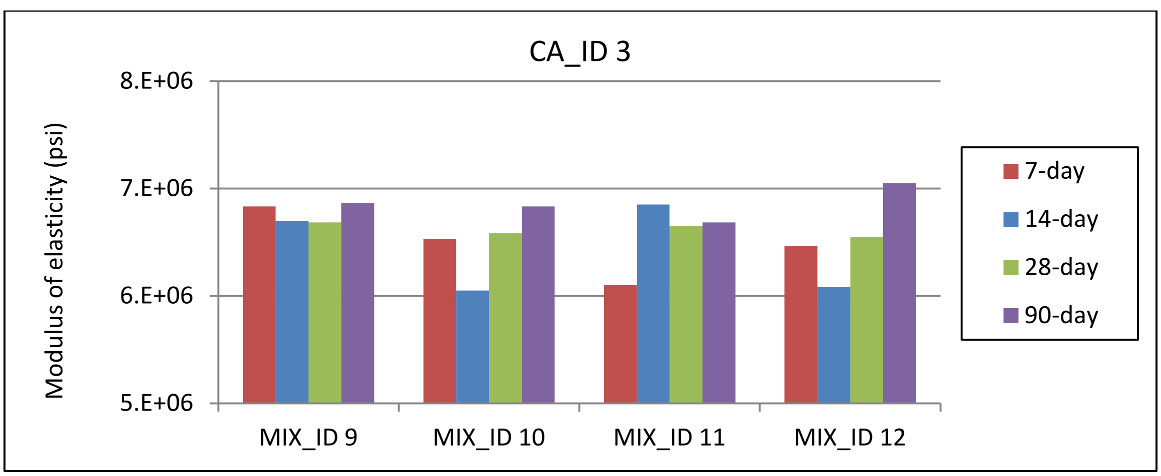
Figure 6. Strength and modulus results for MIX_IDs 5 through 8 with CA_ID 2.



a. Compressive strength for CA_ID 3.

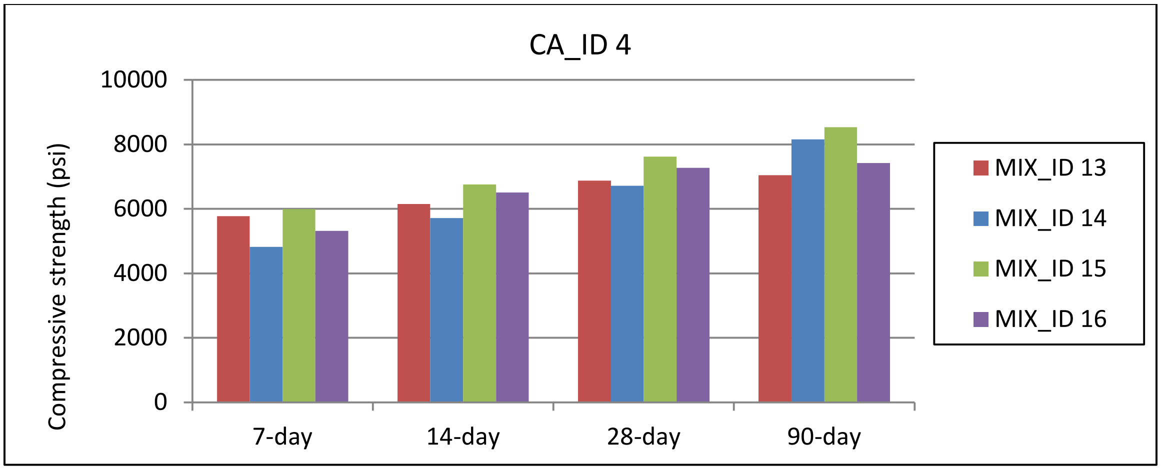


b. Flexural strength for CA_ID 3.

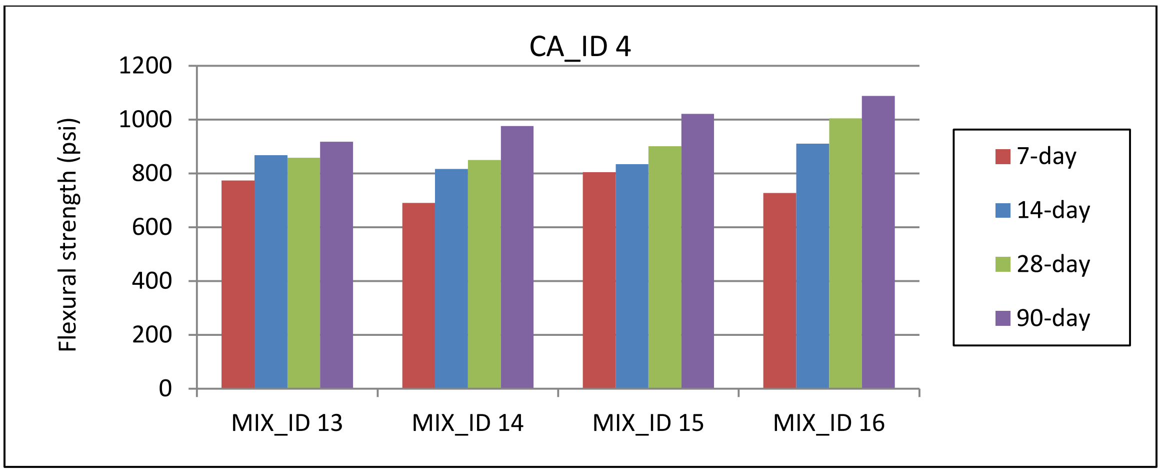


c. Modulus of elasticity for CA_ID 3.

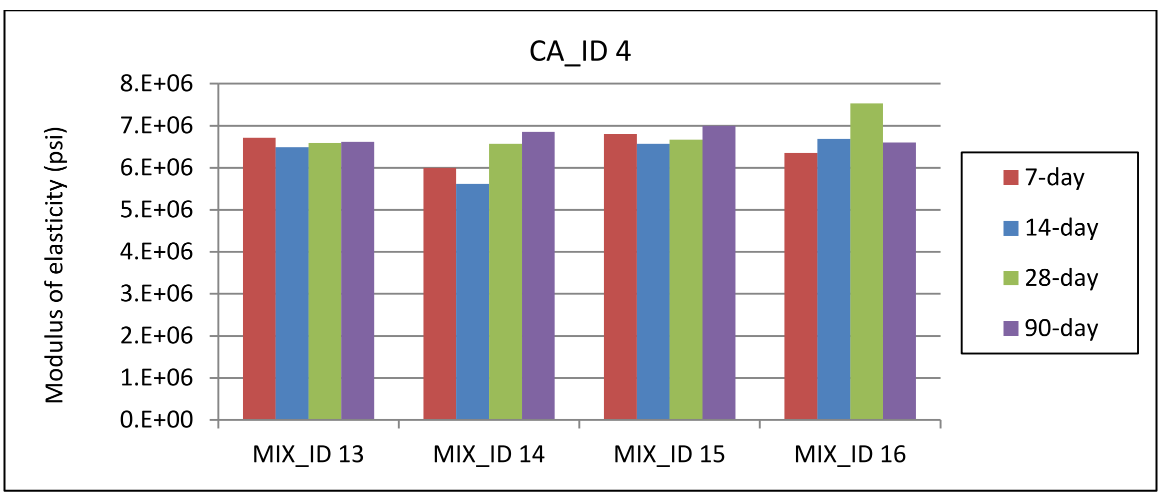
Figure 7. Strength and modulus results for MIX_IDs 9 through 12 with CA_ID 3.



Compressive strength for CA_ID 4.

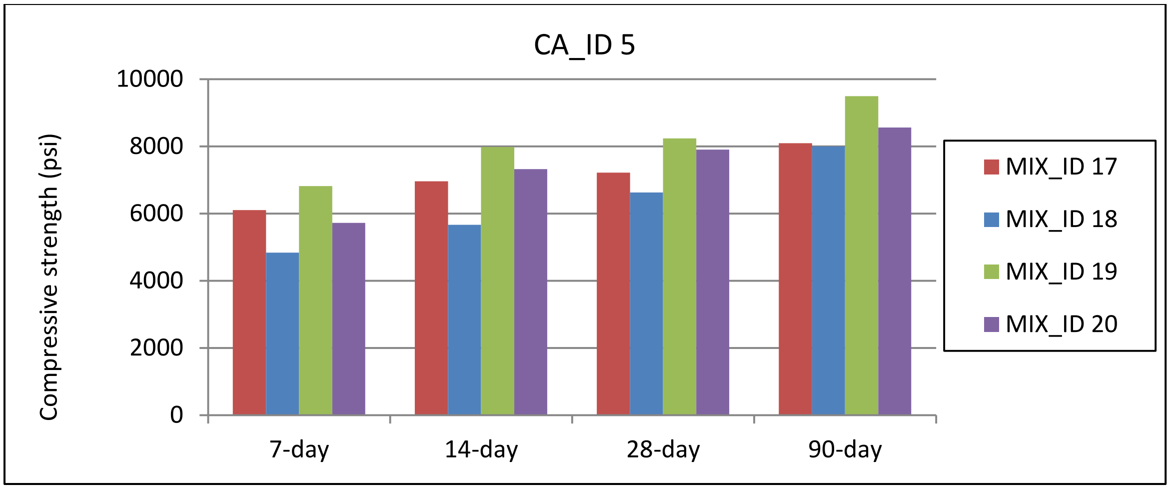


Flexural strength for CA_ID 4.

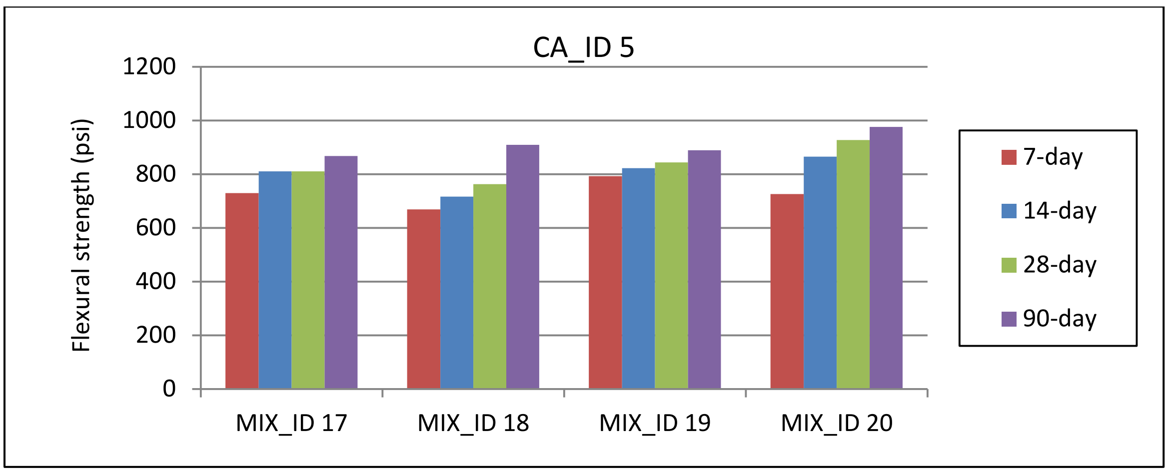


Modulus of elasticity for CA_ID 4.

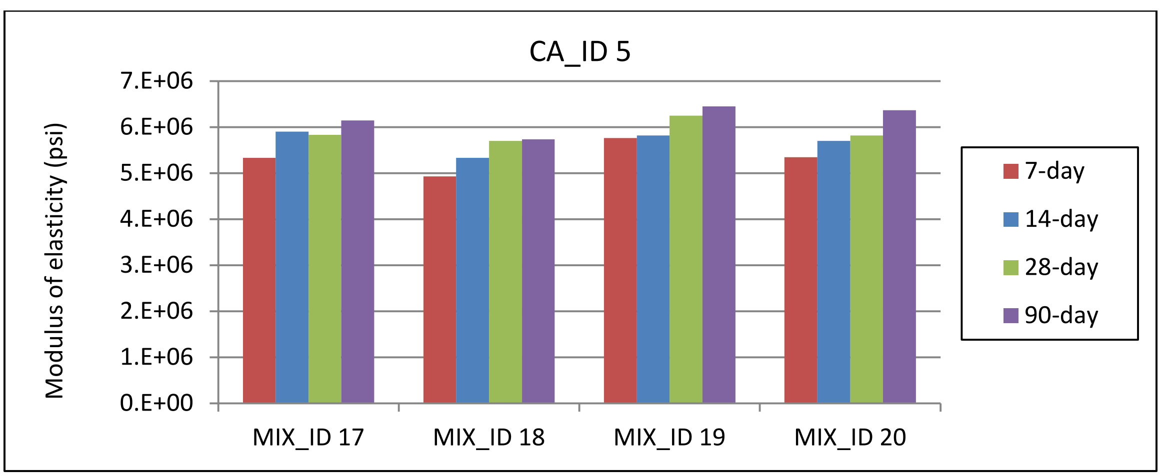
Figure 8. Strength and modulus results for MIX_IDs 13 through 16 with CA_ID 4.



a. Compressive strength for CA_ID 5.



b. Flexural strength for CA_ID 5.



c. Modulus of elasticity for CA_ID 5.

Figure 9. Strength and modulus results for MIX_IDs 17 through 20 with CA_ID 5.

Volume Change Properties

The primary volume change property used as a direct input to the MEPDG procedure is the PCC CTE. The CTE of the 20 MIX_IDs are presented in Table 20. The table also lists the aggregate description and the aggregate type. Further, the average CTE for each CA_ID (i.e. each of the five aggregate sources used in the test plan) is reported in Table 21. Table 22 lists the average CTE for each coarse aggregate type—limestone and chert gravels. This table also provides the average values for these aggregate types reported in the revised LTPP database (LTPP, SDR 24.0) after the correction to the CTE results were made. The LTPP values represent the national average for each aggregate type as well as the recommended level 3 input for the national calibration.

Table 20. 28-day coefficient of thermal expansion result for each MIX_ID.

MIX_ID	CA_ID	CA description	Aggregate	Average CTE, in/in/°F	Standard deviation of CTE, in/in/°F	Average CTE, in/in/°C
1	1	High Absorption Gravel	Gravel	6.58	0.01	11.84
2	1	High Absorption Gravel	Gravel	6.48	0.02	11.66
3	1	High Absorption Gravel	Gravel	6.94	0.20	12.49
4	1	High Absorption Gravel	Gravel	6.82	0.01	12.28
5	2	Crushed Limestone	Limestone	5.03	0.02	9.05
6	2	Crushed Limestone	Limestone	4.99	0.07	8.98
7	2	Crushed Limestone	Limestone	5.19	0.18	9.34
8	2	Crushed Limestone	Limestone	5.25	0.10	9.45
9	3	Crushed Limestone	Limestone	4.65	0.00	8.37
10	3	Crushed Limestone	Limestone	4.86	0.08	8.75
11	3	Crushed Limestone	Limestone	5.14	0.17	9.25
12	3	Crushed Limestone	Limestone	5.29	0.06	9.52
13	4	Low Absorption Gravel	Gravel	6.82	0.00	12.28
14	4	Low Absorption Gravel	Gravel	6.75	0.02	12.14
15	4	Low Absorption Gravel	Gravel	6.80	0.01	12.23
16	4	Low Absorption Gravel	Gravel	6.94	0.21	12.48
17	5	Small Maximum Size Gravel	Gravel	6.66	0.06	11.99
18	5	Small Maximum Size Gravel	Gravel	6.57	0.02	11.82
19	5	Small Maximum Size Gravel	Gravel	6.73	0.01	12.11
20	5	Small Maximum Size Gravel	Gravel	6.84	0.03	12.31

Table 21. 28-day coefficient of thermal expansion result for each aggregate source.

CA_ID	CA description	Aggregate type	Average CTE, in/in/°F
1	High Absorption Gravel	Chert	6.70
2	Crushed Limestone	Limestone	5.11
3	Crushed Limestone	Limestone	4.99
4	Low Absorption Gravel	Chert	6.82
5	Small Maximum Size Gravel	Chert	6.70

Table 22. 28-day coefficient of thermal expansion result for each aggregate type.

Aggregate type and class	Average CTE (in/in/°F)	Average CTE (in/in/°C)	Standard deviation of CTE (in/in/°F)	Average from LTPP testing (in/in/°F)*	Standard deviation from LTPP testing (in/in/°F)*
Chert gravel	6.7	12.14	0.16	6.1	0.6
Limestone	5.1	9.09	0.22	4.4	0.7
*The values reported include LTPP projects with a single aggregate type. The sample size is 25 for chert and 160 for limestone.					

The same data from Table 20 are plotted in Figure 10 for the 20 MIX_IDs. Further, the CTE values are also plotted grouped by the CA_ID and the Cementitious_ID in Figure 11 and Figure 12 respectively to highlight an impact of these two variables on the CTE value.

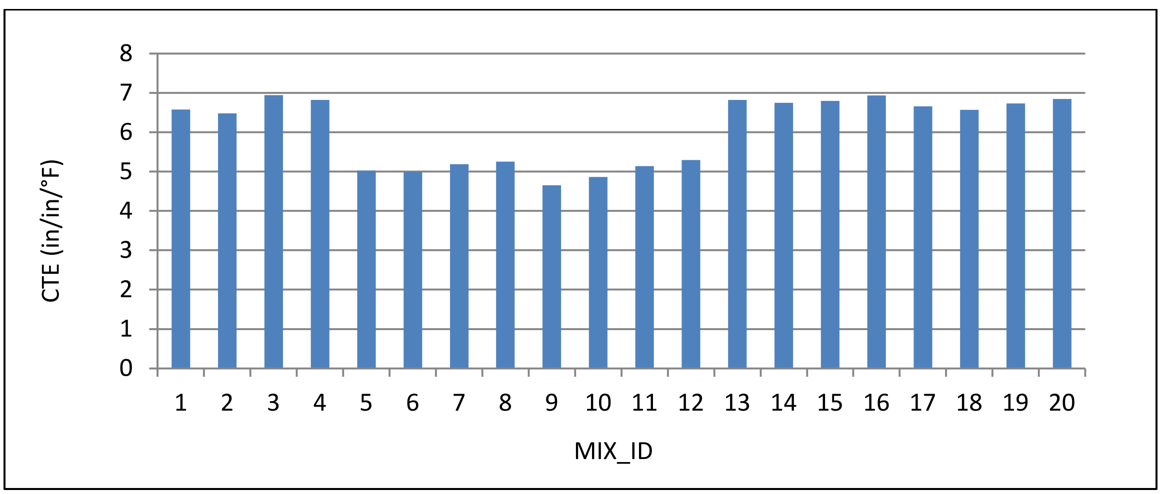


Figure 10. PCC CTE values measured for the 20 MIX_IDs.

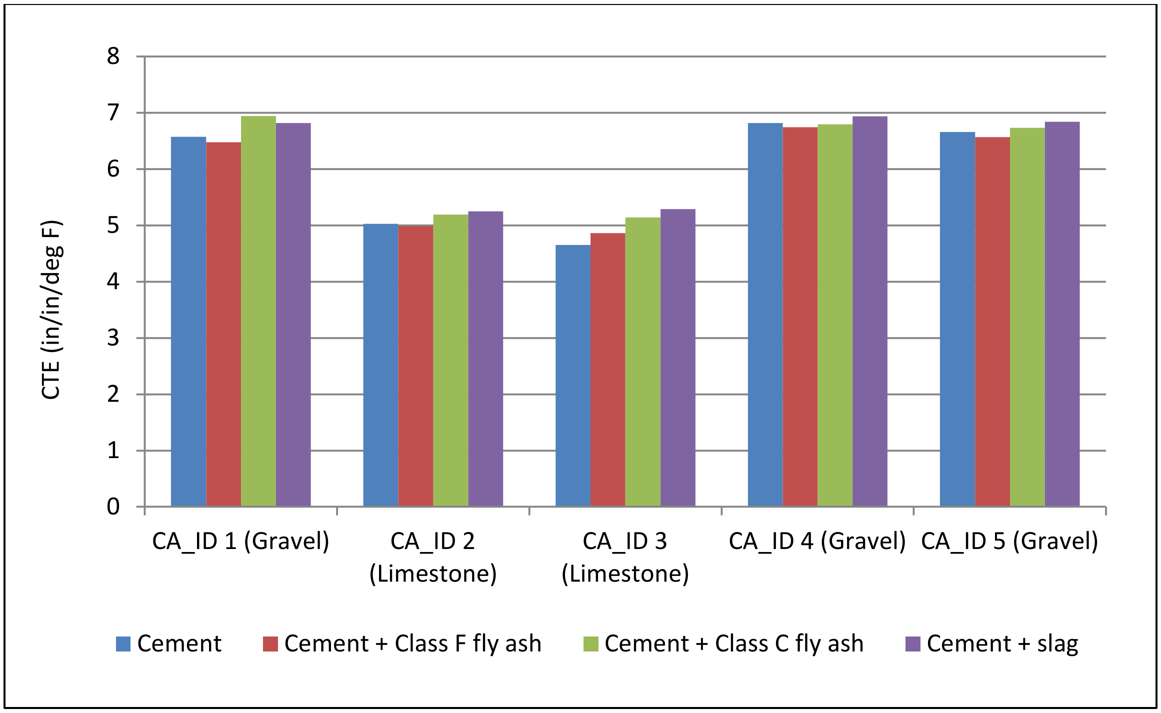


Figure 11. PCC CTE values for the 20 MIX_IDs grouped by the aggregate source.

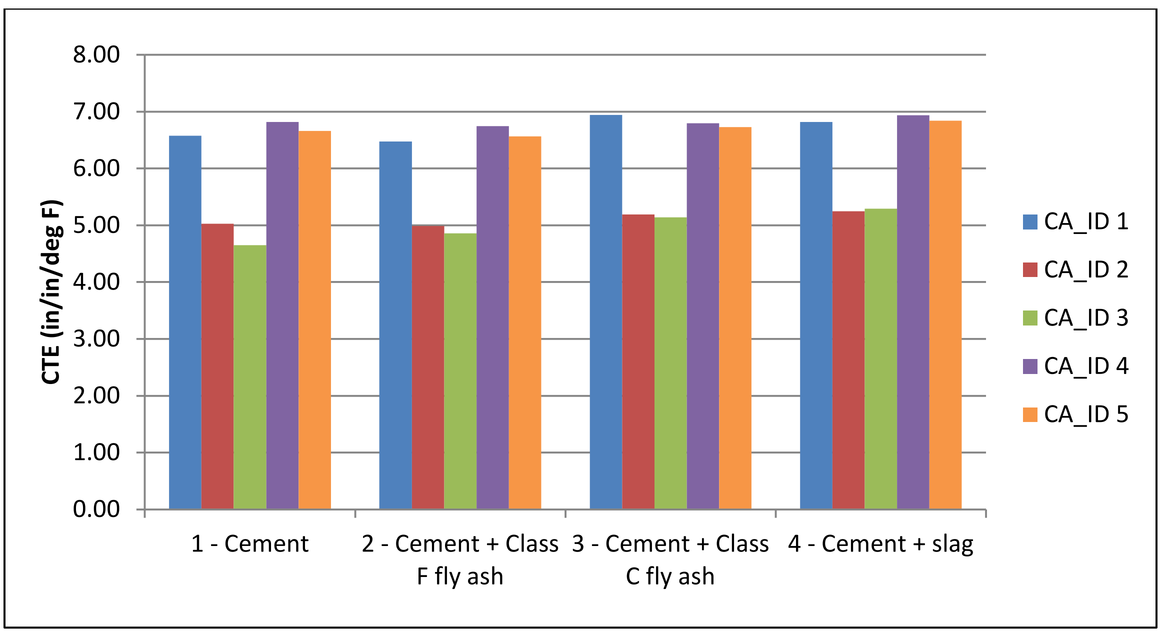


Figure 12. PCC CTE values for the 20 MIX_IDs grouped by the cementitious blend.

The second volume change parameter measured in the laboratory was related to shrinkage. Shrinkage related length change measurements (in inches) and the percentage shrinkage data are presented in Table 23. In this table, positive values denote shrinkage and negative values denote an expansion in length. Data for tests past 231 days, i.e. 224 days of drying, have not been collected yet. Also reported are the ultimate shrinkage values based on the MEPDG adopted default equation (presented as Equation 5) using *Cement Factor* of 1 for Type I cement, and *Curing Factor* of 1.2 for curing compound (MDOT Standard Specifications Section 501.03.20.1). The MEPDG model for ultimate shrinkage predicts values higher than those reported until 231 days, which is a favorable indication that the measured shrinkage does not exceed the ultimate shrinkage. The samples may be approaching the estimated ultimate shrinkage value over time. The ratios of 35-day shrinkage to 231 day shrinkage range from 26 to 68 percent with an average of 50 percent, suggesting 50% of the ultimate shrinkage may be occurring past 35 days for these mixes. The data is insufficient for further recommendations.

Table 23. Shrinkage based on length change measurements at 50% RH (initial comparator reading taken at a specimen age of 1 day).

MIX_ID	Specimen age at length change measurement (days)#									Ratio 35/231-day	Ultimate Shrinkage – MEPDG (x 10^{-6})###
	7 (0)	11## (4)	14 (7)	21 (14)	35 (28)	63 (56)	119 (112)	231 (224)	455 (448)		
1	-28	48	65	102	153	228	310	363	-	0.42	561
2	-40	47	70	113	185	265	318	368	-	0.50	557
3	-40	55	103	110	180	235	300	345	-	0.52	518
4	-65	3	18	25	60	88	158	233	-	0.26	557
5	-28	75	100	137	212	260	328	370	-	0.57	568
6	-20	65	90	157	227	270	338	383	-	0.59	577
7	-43	52	127	200	285	333	382	420	-	0.68	540
8	-53	32	57	95	132	180	235	305	-	0.43	566
9	-15	77	95	138	170	218	263	315	-	0.54	559
10	-30	45	93	130	175	228	263	308	-	0.57	568
11	-25	57	125	192	252	308	340	380	-	0.66	537
12	-47	38	52	73	113	155	205	258	-	0.44	573
13	2	77	95	120	173	253	303	363	-	0.48	516
14	-13	35	75	105	155	218	258	295	-	0.53	517
15	-8	85	110	153	205	258	295	338	-	0.61	488
16	-50	10	33	45	78	113	168	223	-	0.35	529
17	-20	25	53	98	155	220	295	360	-	0.43	555
18	-10	68	83	125	183	243	305	363	-	0.50	570
19	-27	45	80	123	180	258	323	365	-	0.49	522
20	-27	28	30	50	68	108	160	228	-	0.30	549

#Drying age reported in parenthesis.
##Varied from 10 to 12 days to avoid weekend measurements.
###Ultimate shrinkage value reduced by 20 percent for Type II cement.

Discussion of Test Results

Discussion of Test Results for Fresh Concrete Properties

The air content ranges from 4.4 to 5.8 percent, which is within the MDOT specification requirement of 3 to 6 percent. Slump values range from 1.25 to 2.75 inches, which are also within the maximum permitted value of 3 inches. The unit weight ranges from 141 to 149.3 lb/ft^3, which is very typical of paving mixes. Note that the LTPP database contains PCC unit weight values ranging from 136 to 156 lb/ft^3 with an average value of 147 lb/ft^3.

Discussion of Results for Mechanical Properties

The following can be inferred from the results presented in Table 17 through Table 19 and Figure 5 through Figure 9:

- The 28-day compressive strength values range from 5,756 to 8,237 psi with an average value of 7,104 psi. These values far exceed the minimum MDOT specification requirement of 3,500 psi. Further, these strengths are representative of typical values for paving mixes, although these values are characteristic of fairly good strength mixes. The average 28-day PCC compressive strength values in the LTPP database range from 3,034 to 7,611 psi with an average value of 5,239 psi. MDOT mixes have a higher than average compressive strength value compared to the mixes used in the sections included in the national calibration of the MEPDG models.
- The 7-day and 14-day compressive strength values were at least 4367 psi (MIX_ID 6) and 4772 psi (MIX_ID 2) respectively. Clearly, these mixes are capable of achieving the target strength of 3,500 psi well within the 28-day hydration period.
- The 28-day flexural strengths are in the range of 720 psi to 1047 psi with an average value of 860 psi. These values are again characteristic of high strength mixes. Note that a typical 28-day PCC flexural strength value used in rigid pavement design is 650 psi. The target flexural strength of the LTPP SPS-2 sections, which represent the newly constructed rigid pavement experiments nationwide, were 550 psi and 900 psi for the low strength and high strength PCC mixes respectively. The 28-day flexural strength values reported in the LTPP database range from 489 to 1006 psi with an average of 735 psi. Clearly, the MDOT mixes, show evidence of high 28-day flexural strengths.
- The flexural strengths in the time series data ranged from 595 psi (MIX_ID 6 @ 7 days) to 1089 psi (MIX_ID 16 @ 90 days) with an average of 830 psi. The lowest 14-day strength is 680 psi, which is above a typical flexural strength requirement of 650 psi for rigid pavement design. For a reference, LTPP sections used in the national calibration of the MEPDG models had flexural strength values of 467 to 1075 psi with an average value of 754 psi. These values represent flexural strength for ages up to 365 days.
- The 28-day elastic modulus values range from 5.2 to 7.5 x 10^6 psi, with an average of 6.2 x 10^6 psi. These values can be considered fairly high relative to the average value of 4.38 x 10^6 psi corresponding to LTPP sections used in the national calibration of rigid pavement models.

- The time series data for elastic modulus shows that the values range between 4.9 and 7.5 x 10^6 psi with an average of 6.0 x 10^6 psi. As a reference, the LTPP database contains an average elastic modulus value of 4.8 x 10^6 psi for PCC tested between 7 and 365 days after casting and an average value of 4.6 x 10^6 psi for long term values up to 45 years.
- Strength gain and modulus gain over the test period, i.e. from casting to the 90-day period, follow consistent trends. Relative to the 28-day value, the increase in compressive strength is between 2 to 30 percent with an average of 14 percent. The increase in flexural strength is up to 20 percent, with an average of eight percent. Finally the increase in elastic modulus is up to 19 percent with an average of five percent.

Discussion of Results for Volumetric Change Properties

Coefficient of Thermal Expansion

The following are observations related to PCC CTE properties based on data reported in Table 20 through Table 22, and Figure 10 through Figure 12:

- The CTE property in MDOT mixes vary over a fairly large range. They range from 4.65 to 6.94 x 10^{-6} in/in/°F.
- The CTE of mixes with chert gravels (MIX_IDs 1 through 4 and 13 through 20) are consistently higher than that of limestone mixes (MIX_IDs 5 through 12) as is evident in Figure 10. Chert gravels refer to CA_IDs 1, 4, and 5, while the limestone sources refer to CA_IDs 2 and 3.
- The impact of coarse aggregate on the CTE values is evident as seen in Figure 11. Figure 12 on the other hand shows that the cementitious blend, i.e. the use of a straight cement mix vs the use of SCMs, does not have an impact on the CTE values.
- The average CTE values for each aggregate class (limestone and chert) are slightly higher than the average values determined from LTPP sections. The average values are 5.1 and 6.7 x 10^{-6} in/in/°F for limestone and gravels respectively, compared to corresponding LTPP values of 4.4 and 6.1 x 10^{-6} in/in/°F. Therefore the values are higher by 0.6 to 0.7 x 10^{-6} in/in/°F.
- For the 20 MIX_IDs, the standard deviation values (same lab, same mix design) are within 0.2x10^{-6} in/in/degF and these values are on an average within 0.05x10^{-6}in/in/°F. For a given aggregate source (different mix designs, i.e. different cementitious blends) the standard deviation is less than 0.3x10^{-6} in/in/degF. These show excellent repeatability. However, note that these values are based on two sample replicates. The AASHTO T 336 precision and bias statement is being developed using CTE data determined from three sample replicates (Rao, C., Personal Communication with FHWA, 2014).

Length Change and Shrinkage

The discussion of results in this section is related to PCC shrinkage characteristics based on data reported in Table 23. Prior to the discussion of the data, this section provides fundamental details about shrinkage inputs to the MEPDG procedure.

In the testing performed, shrinkage samples were soaked for a period of 7 days and then subjected to 50 percent relative humidity. Length change values were measured at different ages as per the AASHTO standard. It is important to recognize that the test standard adopted and the data collected do not provide the direct inputs required by the AASHTOWare program. The inputs required for design are the ultimate shrinkage, and the days to 50 percent shrinkage, which enable the program to estimate PCC shrinkage at different ages. Ultimate shrinkage can be either estimated using the default MEPDG/ACI model available in the program or estimated based on agency procedures. The time to achieve 50 percent of the shrinkage was assumed to be 35 days for the national calibration of the rigid pavement distress prediction models.

The following can be noted from the data presented in Table 23:

- PCC shrinkage shows a minor expansion at 7 days, which is expected because the sample was soaked continually during this period.
- Shrinkage values continually increase over the drying period from 7 days to 231 days as expected. Shrinkage in the slag mixes, i.e. Cementitious_ID 4, is lower than in the other Cementitious_ID.
- PCC shrinkage values at 35 days are, on an average, 59, 49, and 30 percent of the 119-day, 231-day and ultimate shrinkage values respectively. . This implies that the time required to achieve 50% of the ultimate shrinkage could be longer than 35 days. For example, for Mix_ID 2, the 35, 119 and 231 day shrinkage values are 185, 318, and 368 $\mu\varepsilon$ respectively, relating to 35/119-day and 35/231-day ratios of 58 and 50 percent respectively. Therefore, the ultimate shrinkage of 557 $\mu\varepsilon$ is closer to 60 days.
- Ultimate shrinkage values are higher than measured shrinkage to 231 days. Additional test data (455 day value) will be necessary to compare if the values are approaching the ultimate shrinkage value. The ratios of the 119-day and 231-day shrinkage to the ultimate shrinkage are on an average 50 and 60 percent respectively. Additional data will be necessary to make decisive conclusions whether this data can be used to determine the time needed for achieving 50 percent of ultimate shrinkage.
- The data suggests that the SCMs used as cement replacement may have an impact on shrinkage values. Mixes with slag, i.e. MIX_IDs 4, 8, 12, 16, and 20, generally show much lower shrinkage values.

Impact on AASHTOWare Rigid Pavement Design

PCC properties reported in this experimental plan, when compared to national average values, may have varying impacts on rigid pavement designs developed using the MEPDG procedure. For a given design, i.e. for a given layer structure, design features, traffic, and climate, designs developed with MDOT PCC properties may result in:

- Higher values of critical stresses calculated because of higher elastic modulus values.
- Higher curling stresses for a given temperature differential because of higher PCC CTE.
- Higher transverse joint opening values for JPCP and transverse crack opening for CRCP because of the higher CTE values.
- Lower accumulated damage values for the calculated stresses because of higher flexural strength values.

However, because of the interaction effects of the different PCC inputs, it is also possible that these effects may offset each other and the overall impact on design may be minimal. The overall design including the selection of base layer and the selection of design features will also determine the extent to which the PCC material properties will influence the overall design. In addition, it is important to note that PCC properties are used in several other empirical models (such as ultimate shrinkage or zero stress temperature calculation, for example) that are integral to the pavement response models of the MEPDG.

VERIFICATION OF TEST DATA

MDOT test samples were sent to an external laboratory for verification of the modulus of elasticity and the CTE test results that were obtained from the ASTM C469 and AASHTO T336 tests. The external test location selected was the PCC lab at the Federal Highway Turner Fairbanks Highway Research Center in McLean, VA. Table 24 and Table 25 provide a summary of the results generated by FHWA in comparison to the results from MDOT's testing for CTE and modulus of elasticity respectively.

Table 24. Comparison of AASHTO T336 CTE values determined by MDOT and FHWA.

MIX_ID	MDOT CTE values (ε/°C)*		FHWA CTE values (ε/°C)*		Inter lab	
	CTE 1	CTE 2	CTE 1	CTE 2	% Difference	Average difference (ε/°C)
3	12.74 (7.1)	12.24 (6.8)	12.00 (6.7)	11.80 (6.6)	4.96	0.59
4	12.26 (6.8)	12.29 (6.8)	12.00 (6.7)	12.20 (6.8)	1.45	0.17
7	9.57 (5.3)	9.11 (5.1)	9.10 (5.1)	8.80 (4.9)	4.36	0.39
15	12.22 (6.8)	12.24 (6.8)	12.20 (6.8)	12.20 (6.8)	0.25	0.03
*Values in parenthesis are reported in (ε/°F)						

The CTE values from the two laboratories for the selected MIX_IDs are within 5 percent of each other. These estimates are in agreement with the results observed from the inter-laboratory study performed by FHWA, in which the tolerable inter-laboratory difference in CTE values using three specimens was established as 0.78 ε/°C (Personal Communication with FHWA TFHRC staff in December, 2014).

Table 25. Comparison of ASTM C 469 results from testing by MDOT and FHWA.

MIX_ ID	Test age	MDOT		FHWA		% higher than FHWA	
		Modulus of elasticity	Poisson's ratio	Modulus of elasticity	Poisson's ratio	Modulus of elasticity	Poisson's ratio
3	7	5,126,402	0.15	4,978,787	0.17	2.96	-11.76
3	14	5,827,669	0.15	6,488,719	0.20	-10.19	-25.00
3	28	6,323,253	0.14	5,389,562	0.20	17.32	-30.00
3	90	5,690,728	0.13	5,797,517	0.16	-1.84	-18.75
4	7	5,211,921	0.15	4,905,416	0.17	6.25	-11.76
4	14	5,480,335	0.17	5,349,037	0.17	2.45	0.00
4	28	5,947,406	0.15	5,893,692	0.18	0.91	-16.67
4	90	6,241,745	0.17	6,436,866	0.18	-3.03	-5.56
7	7	5,064,281	0.19	No data	No data	No data	No data
7	14	5,629,090	0.20	5,641,115	0.21	-0.21	-4.76
7	28	6,365,021	0.23	6,174,560	0.24	3.08	-6.12
7	90	6,136,248	0.22	6,533,117	0.22	-6.07	0.00
15	7	6,792,086	0.13	7,993,991	0.16	-15.04	-18.75
15	14	6,573,852	0.11	7,066,125	0.18	-6.97	-38.89
15	28	6,665,799	0.18	7,150,504	0.15	-6.78	20.00
15	90	7,008,619	0.15	7,294,556	0.15	-3.92	0.00
19	7	5,757,931	0.15	5,796,786	0.17	-0.67	-11.76
19	14	5,816,558	0.17	6,065,259	0.17	-4.10	0.00
19	28	6,249,697	0.15	6,505,345	0.16	-3.93	-6.25
19	90	6,442,009	0.12	6,040,015	0.17	6.66	-29.41

Data in Table 25 , which presents the comparison of moduli of elasticity for five mixes at all ages, suggests that the values reported by the two laboratories are within 2 percent on an average. However, direct comparisons of individual sets of data suggest that the MDOT results were overestimated by as much as 17.3 percent and underestimated by as much as 15 percent. While this disparity does initially appear to be significant, a closer examination of data also indicates that the results are within 7 percent for most cases. Mix_IDs 4, 7, and 19 show results within 7 percent for all days of testing. Mix_IDs 3 and 15 show results above 7 percent only for 2 test ages (14 and 28) and 1 test age (7 day) respectively. In fact, the 90 day result is within 4 percent for 4 of the 5 mixes, and within 7 percent for all mixes.

DEVELOPMENT OF LEVEL 2 CORRELATIONS AND OTHER DEFAULT VALUES

The data set available from this test program lends itself to the development of level 2 correlations for flexural strength and modulus of elasticity, as well as other default strength gain and modulus gain factors. The level 2 equations and time-dependent mix property factors developed with the MDOT data set will be representative of the mix designs used in rigid pavement projects within the state and more likely to yield performance predictions closer to those from using level 1 factors.

As with any dataset, there were multiple alternatives for each level 2 correlation developed in this project. For each level 2 equation, the project team presents the models developed using accepted model forms, discusses the strengths and limitations of the models, and recommends feasible alternatives that exhibit comparable statistical validations. A future effort for the recalibration of the rigid pavement distress models for MDOT will have to involve a thorough examination of the presented models and recommend the most appropriate

Flexural Strength Correlations

In the absence of level 1 flexural strength inputs, the current AASHTO default equation to estimate flexural strength is a function of the level 2 compressive strength as discussed in Chapter 2. A comparison of the measured flexural strength and the predicted flexural strength based on the AASHTO equation from the 20 mixes is shown in Figure 13. The figure suggests that the model has a bias and a questionable predictive ability. The errors are higher at higher strength levels and the flexural strength is generally under predicted.

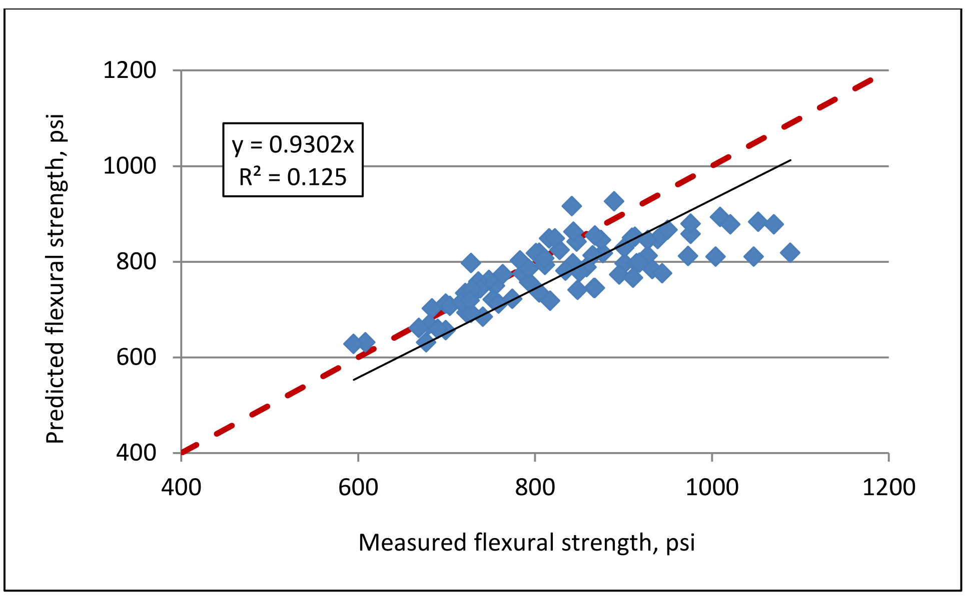


Figure 13. AASHTO default- Predicted vs measured flexural strength.

A paired t-test comparison of the dataset is presented in Table 26. The statistical verification performed at a 95 percent confidence level indicates that the data sets do not have equal population means (P-value <0.05). Based on the data collected from the MDOT experiments, the default level 2 equation may not provide flexural strength estimates that correspond to the level 1 values.

Table 26. Paired t-test for comparison of measured and AASHTO predicted flexural strength.

Parameter	Measured	Predicted
Mean	830.6	778.8
Variance	12032.9	4801.2
Observations	80	80
Pearson Correlation	0.781537	
Hypothesized Mean Difference	0	
df	79	
t Stat	6.574013	
P(T<=t) one-tail	2.41E-09	
t Critical one-tail	1.664371	
P(T<=t) two-tail	**4.82E-09**	
t Critical two-tail	1.99045	

Models Using Data for 20 Mixes

The project team developed level 2 correlations for flexural strength based on the most common model forms as a function of the level 2 parameter, compressive strength. These model forms were:

$MR = a * f'_c{}^{0.5}$, which is referred to as the 0.5 power model in this report.

$MR = a * f'_c{}^{b}$, which is referred to as the power model in this report.

The models established using data from all data representing the 20 mix designs are:

$MR = 10.144 * f'_c{}^{0.5}$ MDOT Model 1

$MR = 4.5912 * f'_c{}^{0.5894}$ MDOT Model 2

Where
MR = modulus of rupture or flexural strength, psi, and
f’c = compressive strength, psi

Figure 14 and Figure 15 show the correlation between the dependent and independent variables using the model forms for the 0.5 power model and the power model respectively. The regression coefficients developed and the model statistics are presented in Table 27.

Table 27. Regression coefficients and statistics for flexural strength models.

MDOT Model	Model form	Regression Coefficients	Regression statistics (N=80)	Data range
1	0.5 power model	a = 10.144	R^2 = 59.9% Standard error = 69 psi	Compressive strength: 4367 to 9497 psi, and Flexural strength: 595 to 1088 psi
2	Power model	a = 4.5912 b = 0.5894	R^2 = 65.1% Standard error = 69 psi	

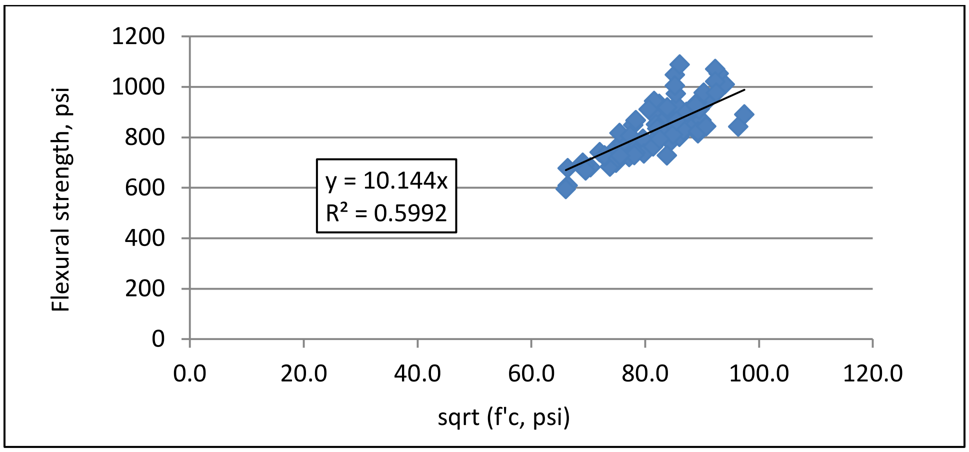


Figure 14. Correlation between compressive strength and flexural strength – MDOT Model 1.

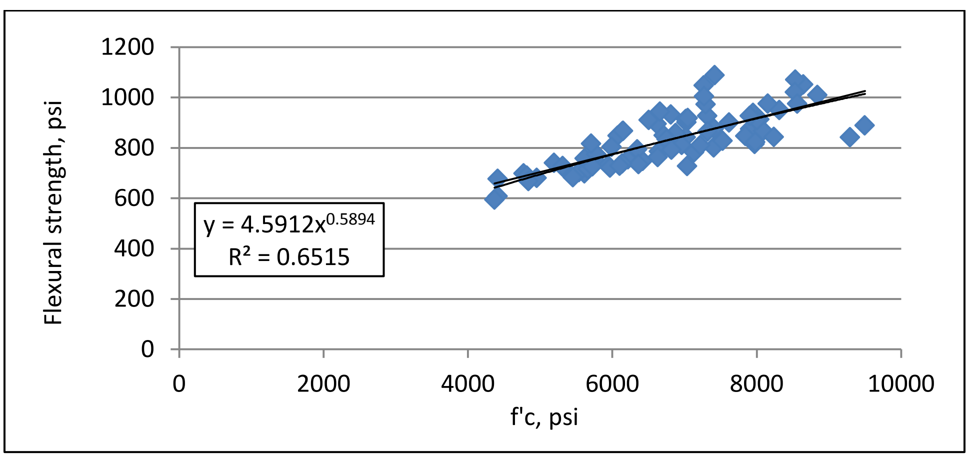


Figure 15. Correlation between compressive strength and flexural strength – MDOT Model 2.

Figure 16 and Figure 17 show the predicted vs measured flexural strength plots for the 0.5 power model and the power model respectively. These plots suggest that MDOT models 1 and 2 have reduced bias across the flexural strength values range. They offset the under prediction at the higher flexural strength levels seen in the AASHTO default model by a marginal over prediction at lower flexural strength values. The predictive ability is however improved as evidenced by the paired t-test results presented in Table 28 (P value >0.05) and the slope of approximately 1.0 for the fit in Figure 16 and Figure 17.

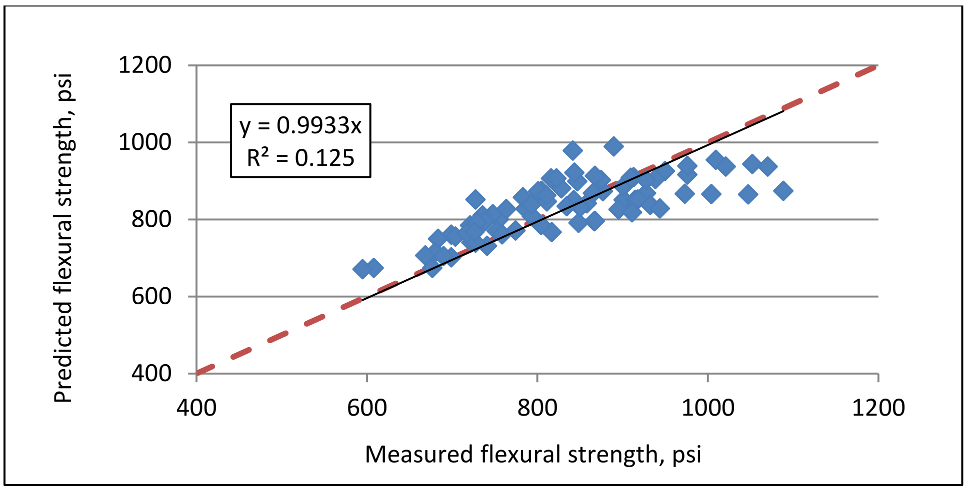


Figure 16. Predicted vs measured flexural strength for MDOT Model 1 (0.5 power model using MDOT test data for all mixes).

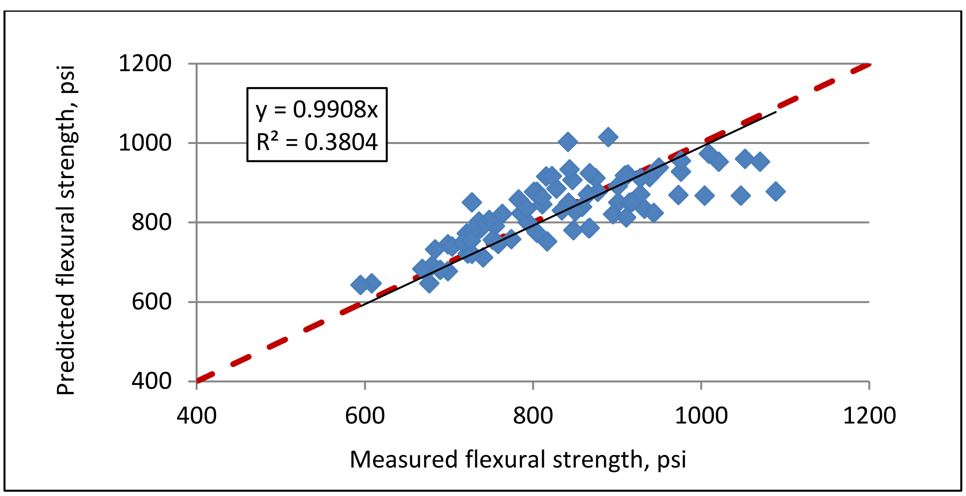


Figure 17. Predicted vs measured flexural strength for MDOT Model 2 (power model using MDOT test data for all mixes).

Table 28. Paired t-test for MDOT Models 1 and 2.

Parameter	MDOT Model 1		MDT Model 2	
	Measured	Predicted	Measured	Predicted
Mean	830.56	831.59	830.56	828.28
Variance	12032.93	5473.81	12032.93	7503.66
Observations	80.00	80.00	80.00	80.00
Pearson Correlation	0.78		0.78	
Hypothesized Mean Difference	0.00		0.00	
Df	79.00		79.00	
t Stat	-0.13		0.30	
P(T<=t) one-tail	0.45		0.38	
t Critical one-tail	1.66		1.66	
P(T<=t) two-tail	0.89		0.77	
t Critical two-tail	1.99		1.99	

Further, a comparison of the predicted values based on MDOT Models 1, 2, and the MEPDG default are superimposed on a single chart in Figure 18 and the error values are plotted in Figure 19. These figures highlight the improved prediction from Models 1 and 2 relative to the default equation in the AASHTOWare Pavement ME Design software.

The predictive ability of the model and the model bias were further examined to assess the effect of other dominating variables—the CA_ID and the Cementitious_ID. It was found that the error trends were strongly governed by aggregate type or CA_ID. Figure 20 and Figure 21 show, for MDOT Models 1 and 2 respectively, the predicted versus measured flexural strengths in data subgroups for each CA_ID. The errors can be therefore vastly reduced if the CA_ID factor can be incorporated into the models.

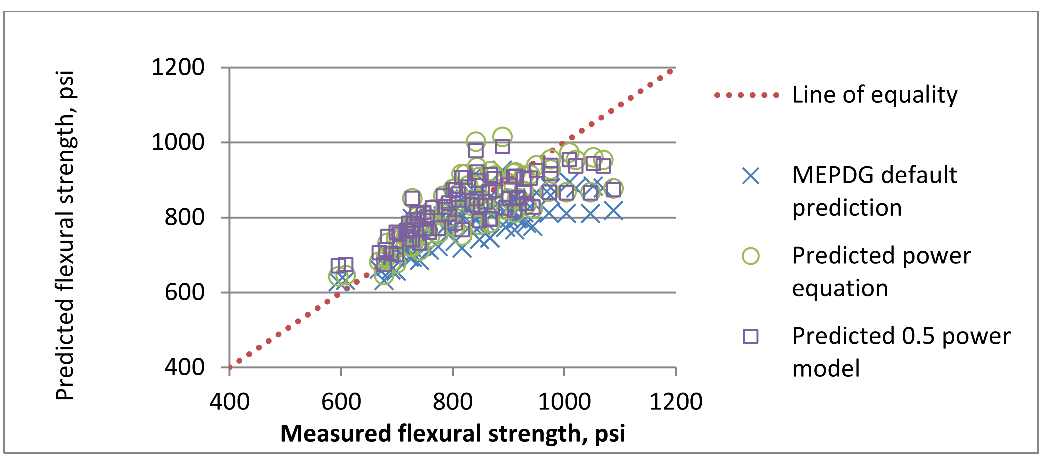


Figure 18. Predicted vs measured flexural strength for MDOT Models 1 and 2.

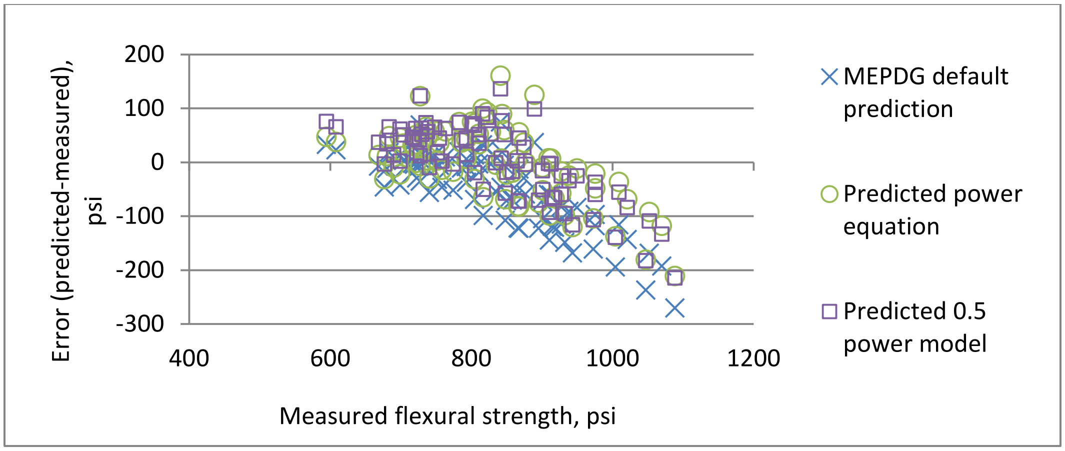


Figure 19. Prediction error vs measured flexural strength for MDOT Models 1 and 2.

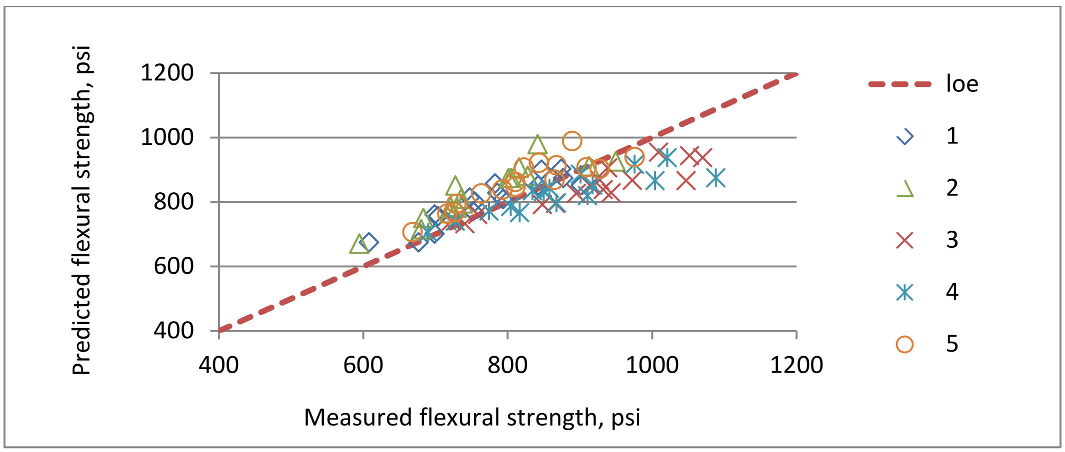


Figure 20. Prediction error vs measured flexural strength for MDOT Model 1 by CA_ID.

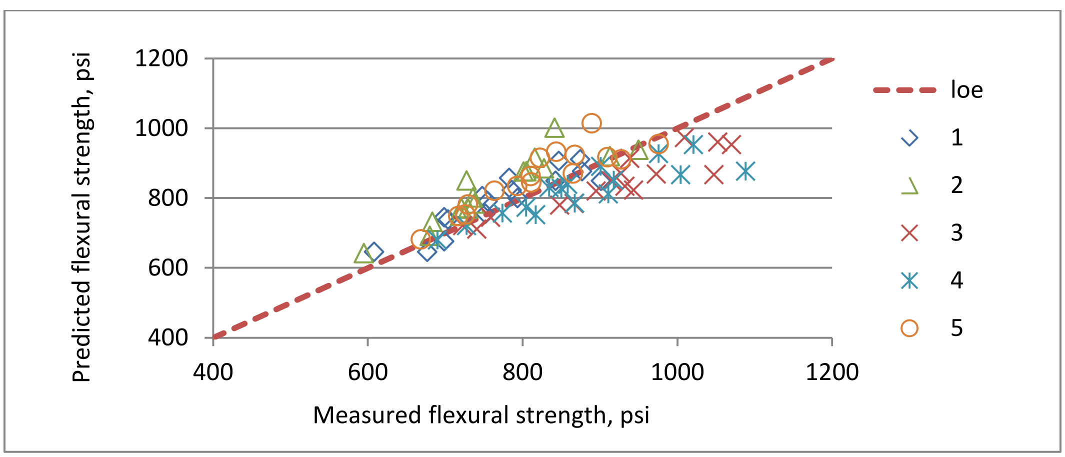


Figure 21. Prediction error vs measured flexural strength for MDOT Model 2 by CA_ID.

Enhanced Models

The 0.5 power model and the power model forms were further examined to incorporate the effect of the CA_ID factor. Based on statistical regression, the model coefficients were specific to each aggregate source or CA_ID. The models were therefore established as:

$$MR = a * f'^{\,0.5}_{c} \qquad \text{MDOT Model 3}$$

$$MR = a * f'^{\,b}_{c} \qquad \text{MDOT Model 4}$$

The model coefficients and the model statistics for MDOT Models 3 and 4 are reported in Table 29. Note that the model coefficients vary by CA_ID. These models based on aggregate type regress better than MDOT Models 1 and 2 with higher R^2 values and lower standard errors. The range of data for the overall models is same as that reported for Models 1 and 2 in Table 27. It is cautioned that the range is different for each CA_ID, which must be verified from data in Appendix B. The fit obtained within each data subgroup is also reported in Table 29.

Table 29. Regression coefficients and statistics for flexural strength models by CA_ID.

MDOT Model	Model form	Regression coefficients and statistics					
		CA_ID	a	b	R^2 (%)	Standard error (psi)	All data (N=80)
3	0.5 power model	1	9.7816	-	83	34	R^2 = 84.8% fit for predicted vs measured. Standard error = 44 psi.
		2	9.4012	-	80	40	
		3	11.0280	-	79	52	
		4	10.805	-	70	61	
		5	9.6891	-	79	38	
4	Power model	1	7.5366	0.5297	84	35	R^2 = 86.0% fit for predicted vs. measured. Standard error = 41 psi.
		2	7.6295	0.5235	84	43	
		3	2.2333	0.6801	85	46	
		4	1.7049	0.7090	80	56	
		5	6.9302	0.5376	83	40	

The predicted vs measured plots for MDOT Models 3 and 4 are presented in Figure 22 and Figure 23. These figures demonstrate the improvement in the predictive ability of MDOT Model 3 and 4 over Models 1 and 2 respectively. Paired t-test results presented in Table 30 suggest that the two samples have the same population means at 95 percent confidence level ($P>0.05$).

The analysis process also verified the impact of Cementitious_ID. Data was grouped by Cementitious_ID for developing predictive correlations with the 0.5 power model and the power model. The results, presented in Table 31, suggest a very poor fit compared to the quality of fit from Models 3 and 4 in Table 29. It is clear that the CA_ID influences the flexural strength to compressive strength relationship; however, the same cannot be stated for changes in Cementitious_ID.

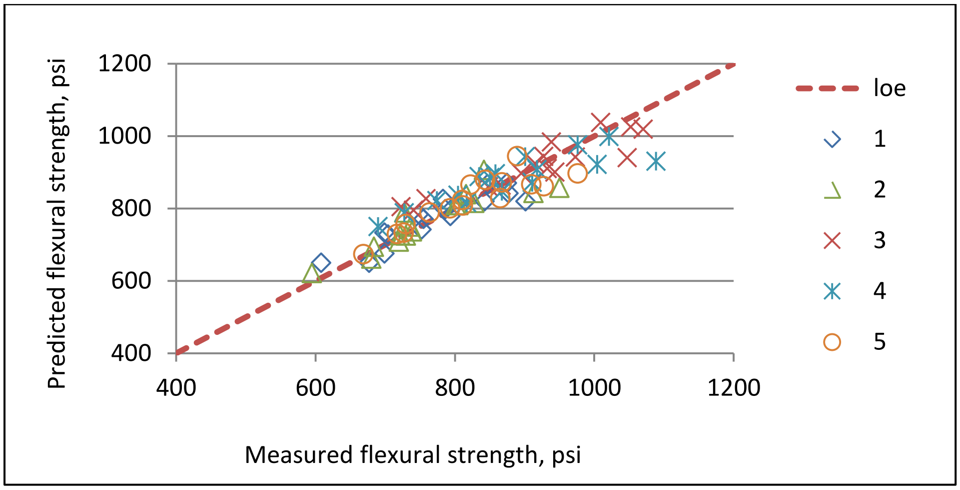


Figure 22. Predicted vs measured flexural strength values for MDOT Model 3 (0.5 power model by CA_ID).

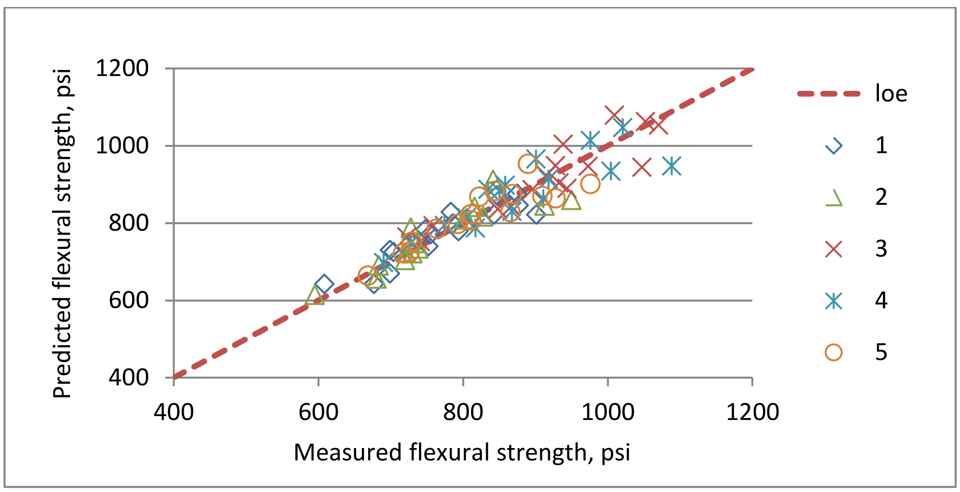


Figure 23. Predicted vs measured flexural strength values for MDOT Model 4 (power model by CA_ID).

Table 30. Paired t-test for MDOT Models 3 and 4.

Parameter	MDOT Model 3		MDT Model 4	
	Measured	Predicted	Measured	Predicted
Mean	830.56	831.53	830.56	829.68
Variance	12032.93	8506.42	12032.93	10500.94
Observations	80.00	80.00	80.00	80.00
Pearson Correlation	0.92		0.93	
Hypothesized Mean Difference	0.00		0.00	
df	79.00		79.00	
t Stat	-0.20		0.19	
P(T<=t) one-tail	0.42		0.42	
t Critical one-tail	1.66		1.66	
P(T<=t) two-tail	0.84		0.85	
t Critical two-tail	1.99		1.99	

Table 31. Models statistics for correlations by Cementitious_ID show poor fit.

Cementitious_ID	0.5 power model		Power model	
	Coefficient, a	R^2	Coefficients a, b	R^2
1	9.99	49%	2.5643, 0.6541	52%
2	10.10	80%	2.2721, 0.6706	86%
3	9.86	40%	16.868, 0.439	43%
4	10.62	60%	3.2854, 0.632	66%

Recommendation for Level 2 Equation to Estimate Flexural Strength

Models 3 and 4 provide the closest match between level 1 data and level 2 estimates for flexural strength. It is recommended that these models be adopted by MDOT in the implementation of the AASHTOWare software for rigid pavement design. In the absence of information about the aggregate type of the PCC mix, it is recommended that MDOT Model 2 be adopted. Future recalibration efforts by MDOT should examine the sensitivity of MDOT Models 2, 3 and 4 for performance prediction and select the optimum level 2 correlation equation. If MDOT Models 3 and 4 are preferred, then it may be necessary to have information about the aggregate source prior to design. Information about aggregate source will be necessary for CTE estimation as well.

Modulus of Elasticity Correlations

The statistical procedures used to develop the modulus of elasticity correlations are similar to those used for the development of the flexural strength correlations. The discussions are brief for modulus of elasticity models to avoid repetition of technical information.

The default correlation in the MEPDG program for level 2 modulus of elasticity estimation is based on compressive strength as discussed previously. The results from a paired t-test using the MDOT data from the 20 mix designs, shown in Table 32, is indicative of poor predictive ability of the default model. The data available also provides a great resource to develop level 2 correlations that will be representative of MDOT mixes.

Table 32. Paired t-test for measured and predicted modulus of elasticity values using the AASHTO default level 2 correlation.

Parameter	Measured	Predicted
Mean	6033333	4672984
Variance	3.74E+11	1.73E+11
Observations	80	80
Pearson Correlation	0.52	
Hypothesized Mean Difference	0.00	
df	79.00	
t Stat	22.86	
P(T<=t) one-tail	0.00	
t Critical one-tail	1.66	
P(T<=t) two-tail	1.43E-36	
t Critical two-tail	1.99	

Models Using Data for 20 Mixes

The data from the 20 mix designs were used to develop a relationship between modulus of elasticity and compressive strength using the model forms typically used by other researchers. In addition, a third model for elastic modulus as a function of unit weight, and compressive strength was developed. The models established are:

$$E = 73360 * f'_c{}^{0.5}$$ MDOT Model 5

$$E = 409110 * f'_c{}^{0.305}$$ MDOT Model 6

$$E = 4.91 * w^{2.41} * f'_c{}^{0.23}$$ MDOT Model 7

where:

E = elastic modulus, psi
f'c = compressive strength, psi
w = unit weight, lb/ft^3

The predicted vs. measured plots are presented in, Figure 24, Figure 25, and Figure 26 for MDOT Models 5, 6, and 7 respectively. These plots also show the estimates from the current MEPDG level 2 equation to demonstrate that the bias from the AASHTO default equation is eliminated (slope =~1) and the prediction error is reduced. The errors in prediction are plotted in Figure 27. The models statistics are presented in Table 33 and the paired t-test results in Table 34. The paired t-test show that there are no significant differences between the measured and predicted values for all three models at a confidence level of 95 percent.

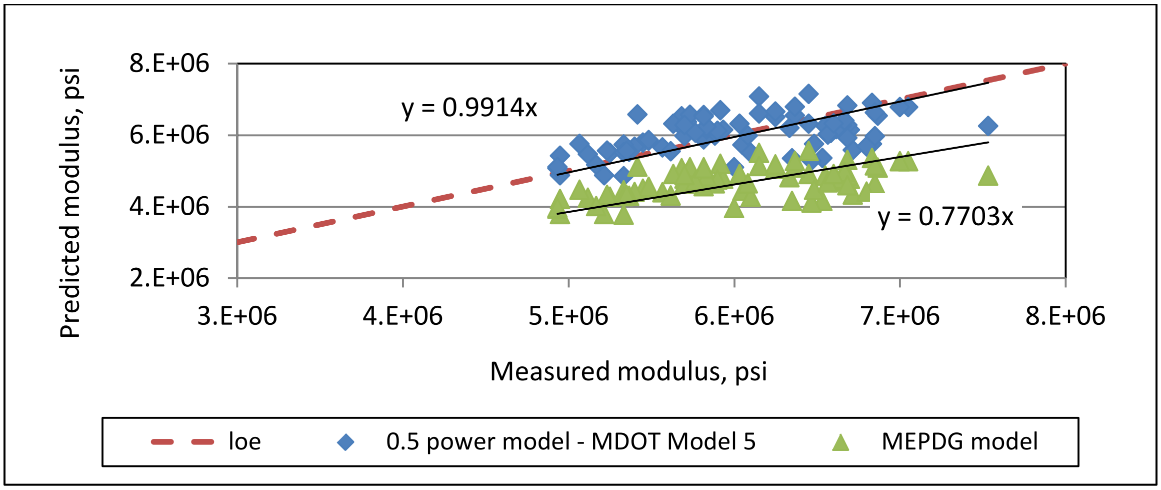


Figure 24. Predicted vs measured elastic modulus from MDOT Model 5.

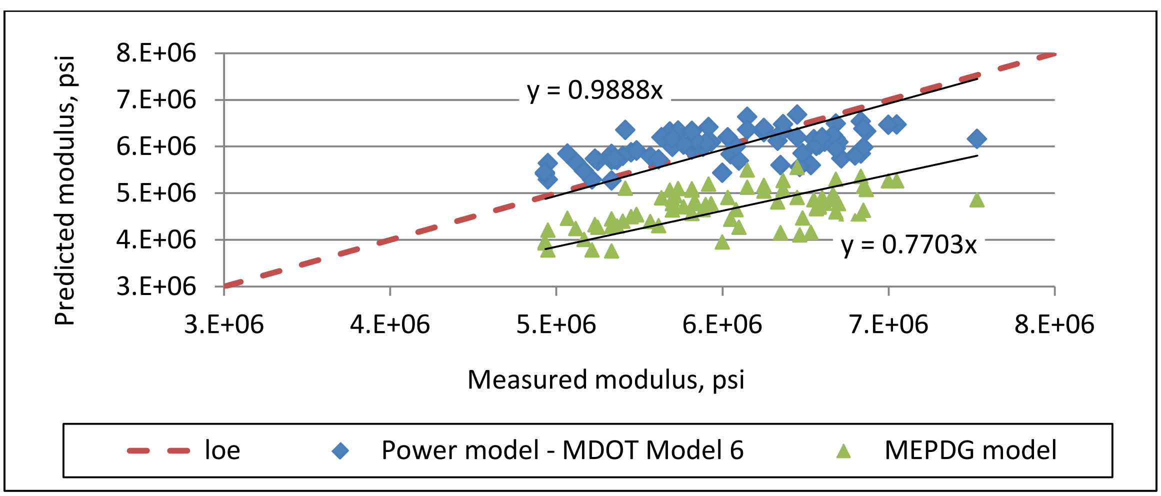


Figure 25. Predicted vs measured elastic modulus from MDOT Model 6.

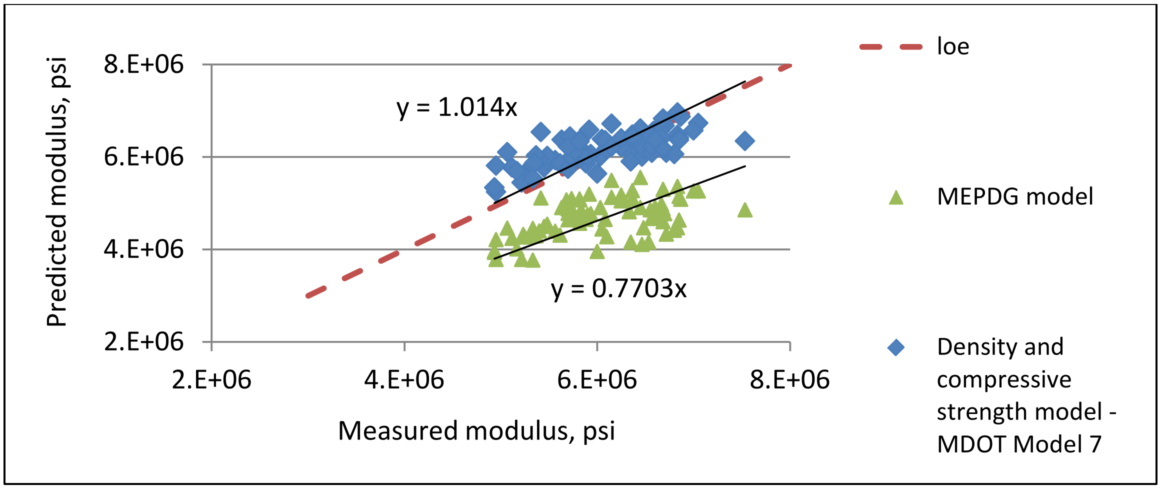


Figure 26. Predicted vs measured elastic modulus from MDOT Model 7.

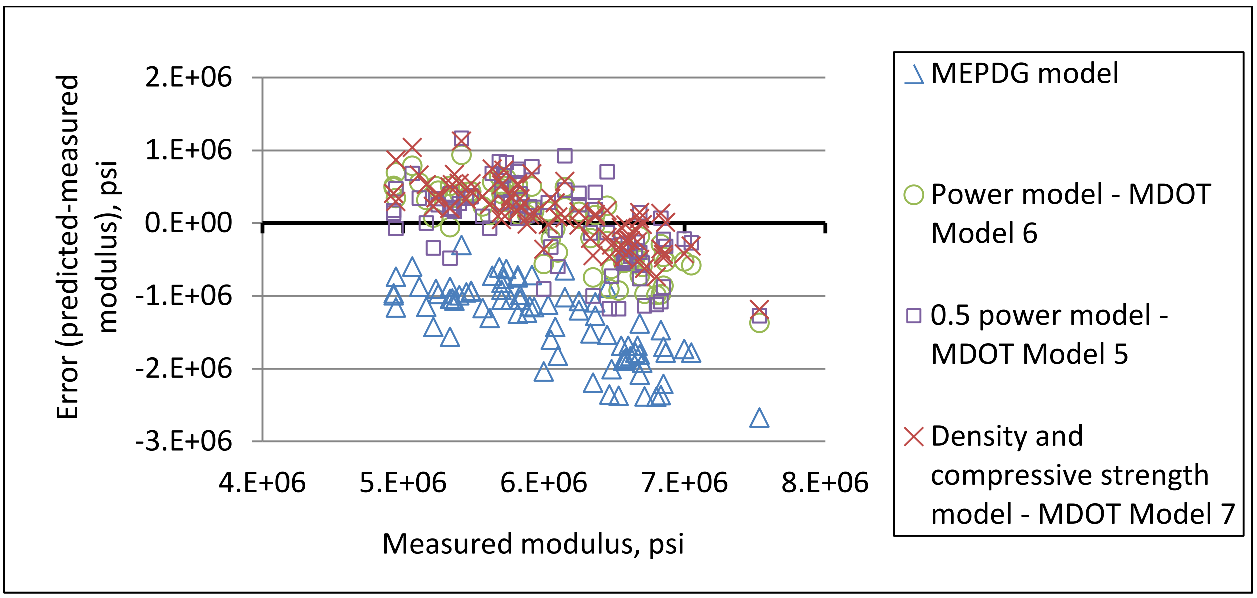


Figure 27. Error in prediction vs measured elastic modulus from MDOT Models 5, 6, and 7.

Table 33. Modulus of elasticity model statistics.

MDOT Model	Model form	R^2 (%)	Standard error (psi)
5	0.5 power model	26.9	566,513
6	Power model	29.1	522,273
7	Compressive strength and unit weight model	51.9	423,135

Table 34. Paired t-test results for MDOT Models 5, 6, and 7.

Parameter	*Measured*	*Predicted - MDOT Model 5*	*Predicted - MDOT Model 6*	*Predicted - MDOT Model 7*
Mean	6033333	6014213	6008963	6034874
Variance	3.74E+11	2.86E+11	1.08E+11	2.22E+11
Observations	80	80	80	80
Pearson Correlation		0.52	0.52	0.80
Hypothesized Mean Difference		0	0	0
df		79	79	79
t Stat		0.30	0.42	-0.04
P(T<=t) one-tail		0.38	0.34	0.49
t Critical one-tail		1.66	1.66	1.66
P(T<=t) two-tail		0.76	0.68	0.97
t Critical two-tail		1.99	1.99	1.99

Overall, MDOT models 5, 6, and 7 are closer to estimating the level 1 modulus values compared to the default MEPDG equation, but they tend to under predict at higher modulus values and marginally over predict at lower values. Furthermore, MDOT model 7 shows a better fit than models 5 and 6.

A closer examination of the prediction results from MDOT Model 5 and 6 reveals a bias by aggregate type or CA_ID. Similar to the aggregate-specific models developed for flexural strength prediction (MDOT Models 3, and 4), aggregate specific models were also considered for elastic modulus properties as discussed next.

Enhanced Models

MDOT Models 5 and 6 were revised to incorporate the effect of CA_ID in the regression. The revised models can be expressed as:

$$E = a * f'_c{}^{0.5} \qquad \text{MDOT Model 8}$$

$$E = \mathrm{a} * f'_c{}^{b} \qquad \text{MDOT Model 9}$$

where:
E= modulus of elasticity, psi.
f'c = compressive strength, psi.
a, *b* = regression coefficients specific to CA_ID as listed in Table 35.

Table 35 also summarizes the model statistics. MDOT Model 8 provides a good fit for CA_IDs 1 and 5, while the model shows very poor correlation for CA_IDs 2, 3, and 4. Clearly, the model is inconclusive for the current data available and cannot be recommended for implementation. MDOT Model 9, however, shows good correlation and can be evaluated further for its predictive ability.

Table 35. Regression coefficients and statistics for MDOT 8 and 9 to estimate modulus of elasticity.

MDOT Model	CA_ID	a	b	R^2 (%)	Standard error	All data fit
8	1	70537		65.9	257985	Standard error = 340,971 psi. R^2=75.7% fit for the predicted vs. measured.
	2	68403		18.9	394248	
	3	78974		-120.5*	438799	
	4	80871		4.98	402641	
	5	68102		78.5	188113	
9	1	229467	0.3652	75.2	224338	Standard error = 662,778 psi. R^2=58.7% fit for predicted vs. measured.
	2	523594	0.2693	51.5	306215	
	3	2000000	0.1585	32.9	244424	
	4	654322	0.2627	40.9	319584	
	5	203805	0.3768	88.1	144652	

*Implies data has very poor fit and the model is not acceptable.

The paired t-test for MDOT models 8 and 9 are presented in Table 36. The results show that MDOT Model 9 does not satisfy the paired t-test check and therefore cannot be recommended for use. The predicted vs measured plots for MDOT Model 8 and 9 by CA_ID are presented in Figure 28 and Figure 29.

Table 36. Paired t-test results for MDOT Models 8 and 9 to predict modulus by CA_ID.

Parameter	*MDOT Model 8*		*MDOT Model 9*	
	Measured	*Predicted*	*Measured*	*Predicted*
Mean	6,033,333	6,015,238	6,033,333	6,333,552
Variance	3.74E+11	4.78E+11	3.74E+11	1.04E+12
Observations	80	80	80	80
Pearson Correlation	0.87		0.78	
Hypothesized Mean Difference	0		0	
df	79		79	
t Stat	0.47		-4.05	
P(T<=t) one-tail	0.32		5.91E-05	
t Critical one-tail	1.67		1.66	
P(T<=t) two-tail	0.64		0.000118	
t Critical two-tail	1.99		1.99	

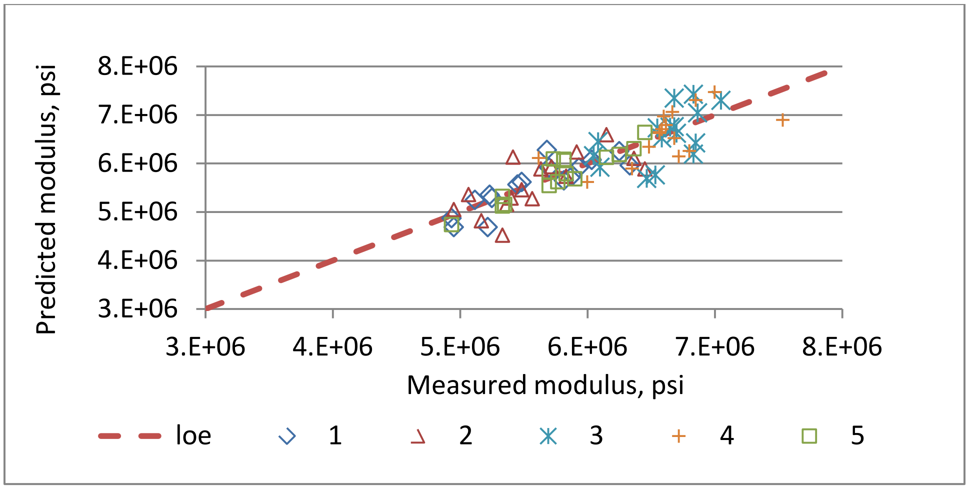


Figure 28. Predicted vs measured modulus values for MDOT Model 8.

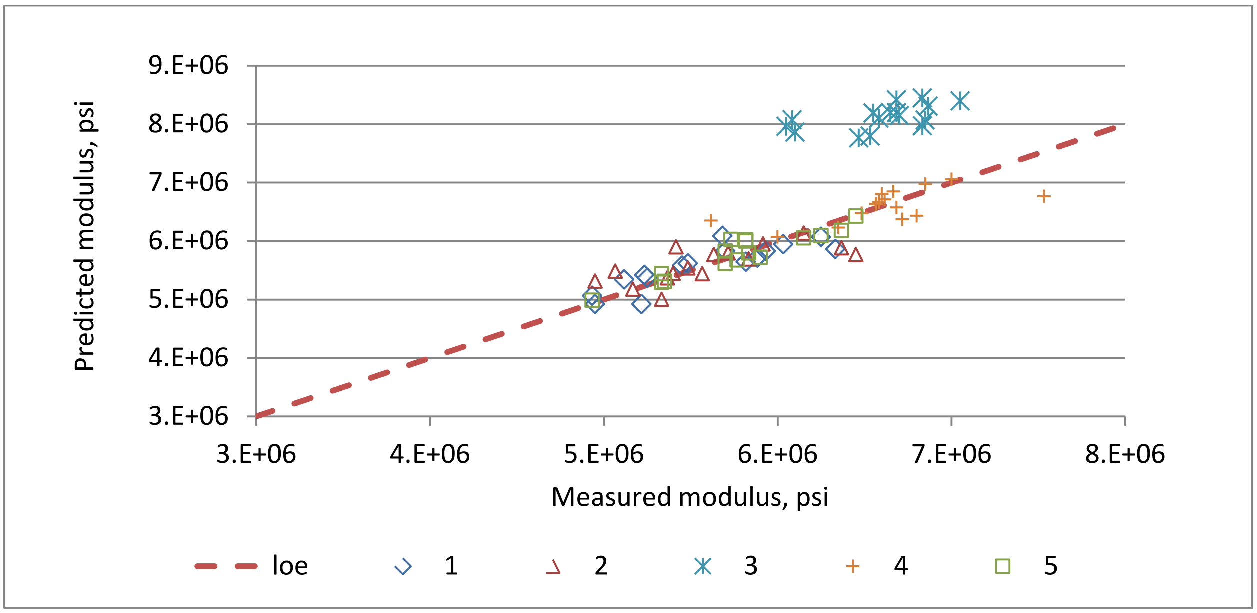


Figure 29. Predicted vs measured modulus values for MDOT Model 9.

In Figure 29 the lack of fit for data representing CA_ID 3 is evident for MDOT Model 9. Eliminating CA_ID 3 from the dataset passes MDOT Model 9 statistical checks. Clearly with the available data, it is not possible to explain the cause for this disparity or to refine the model. A closer examination of the aggregate properties showed that this aggregate source has a higher dust content, lower weight, and higher percent loss from abrasion testing, which are indicative of a weaker aggregate. The amount of dust may also have a negative impact on the paste / aggregate bond resulting in different modulus-strength behavior. It may be possible to use MDOT Model 9 for other aggregate types.

Recommendation for Level 2 Equation to Estimate Modulus of Elasticity

Model 5, 6, and 7 provide the closest match between level 1 data and level 2 estimates for modulus of elasticity. It is recommended that these models be considered by MDOT in the implementation of the AASHTOWare Pavement ME Design for rigid pavement design. Future recalibration efforts by MDOT should examine the sensitivity of these models for performance prediction and select the optimum level 2 correlation equation. If MDOT Model 9 is recommended for specific aggregate types, then it may be necessary to have information about the aggregate source prior to design. Information about aggregate source will be necessary for CTE estimation as well.

Strength Gain Models

The strength gain and modulus gain trends were evaluated by normalizing them to the 28-day values. The MEPDG procedure requires an input for the 20 year strength and modulus ratios, which has been fixed and capped at 1.2, 1.2, and 1.44 for flexural strength, elastic modulus, and compressive strength respectively. Table 37 reports the strength gain factors from the default model. These factors were established based on long term strength data from experimental studies.

Table 37. Strength and modulus gain factors from default equation.

age, days	age, years	log(age, years)	Ratio for flexural strength and modulus of elasticity	Ratio for compressive strength
7	0.0192	-0.60	0.92	0.85
14	0.0384	-0.30	0.96	0.93
28	0.0767	0	1.00	1.00
90	0.2466	0.51	1.06	1.12
7300	20	2.42	1.20	1.44

The test data suggests that the Cementitious_ID has an effect on the strength gain trends, which is likely because of different rates of cementitious material hydration. The average flexural strength gain factors by Cementitious_ID are reported in Table 38. The data were fit to polynomial models and the predicted flexural strength factor at 20 years was calculated from regressed equation.

The 20-year strength ratio predictions for each Cementitious_ID are reported in Table 38. The ratios are significantly higher than the default value, i.e., the default value is conservative.

The 20-year modulus ratio projections are in the range of 1.0 to 1.11 for Cementitious_ID 1, 3, and 4, and it is 1.53 for Cementitious_ID 2. Again, the default value of 1.2 is more conservative. Also, an evaluation of compressive strength ratios provided poor ability to project strength gain over 20 years using polynomial function form based on 7 to 90 day strength values.

Table 38. Summary of strength gain ratios based on Cementitious_ID.

Cementitious_ID	Age (days)	Average flexural strength (psi)		Strength ratio normalized to 28-day value			
			N	Min	Max	Average	20-year estimate
1	7	750.6	5	0.89	0.93	0.91	
1	14	815.8	5	0.96	1.01	0.99	
1	28	823.7333	5	1.00	1.00	1.00	
1	90	865.8	4	0.99	1.12	1.05	
1	20-year ratio based on model extrapolation						1.63
2	7	656.9333	5	0.77	0.88	0.82	
2	14	752.3333	5	0.91	0.96	0.94	
2	28	804.0667	5	1.00	1.00	1.00	
2	90	920.3	5	1.08	1.20	1.15	
2	20-year ratio based on model extrapolation						1.66
3	7	759.7333	5	0.78	0.94	0.88	
3	14	820.4	5	0.92	0.98	0.95	
3	28	863.3333	5	1.00	1.00	1.00	
3	90	935.8667	5	1.03	1.13	1.08	
3	20-year ratio based on model extrapolation						1.28
4	7	718.3333	5	0.71	0.80	0.76	
4	14	868.3333	5	0.90	0.94	0.92	
4	28	947	5	1.00	1.00	1.00	
4	90	986.4	4	1.01	1.08	1.04	
4	20-year ratio based on model extrapolation						1.37

Recommendation for Strength Gain Ratio Factors

The project team does not recommend the use of strength gain factors based on the available test data. The projected ratios are less conservative and based on the fact that the default factors were derived from long term laboratory data, it is advisable to use the default values.

Impact on Design

The objective of developing level 2 correlations is to use them in AASHTOWare Pavement ME Design software. A design project analysis was performed to compare the performance prediction and the optimum design thickness for three input sets:

- Level 1 inputs – flexural strength, modulus, CTE inputs from test data
- AASHTOWare Pavement ME Design default level 2 inputs – compressive strength from test data (implying use of default level 2 correlations), CTE defaults

- MDOT level 2 inputs - flexural strength and modulus from MDOT level 2 correlations, and CTE inputs from MDOT defaults for aggregate type. This was input as a pseudo level 1 input.

Five MIX_IDs were randomly selected for use in this comparative study but consisted of all CA_IDs and Cementitious_ID. The MIX_IDs that were selected were:

- Mix_ID 1 – Mix with CA_ID 1 and Cementitious_ID 1
- Mix_ID 6 – Mix with CA_ID 2 and Cementitious_ID 2
- Mix_ID 11 – Mix with CA_ID 3 and Cementitious_ID 3
- Mix_ID 16 – Mix with CA_ID 4 and Cementitious_ID 4
- Mix_ID 17 – Mix with CA_ID 5 and Cementitious_ID 1

The design project used in the analysis was borrowed from an ongoing MDOT design project on interstate I-269. Key design inputs and considerations are tabulated in Table 39.

Table 39. Design inputs and design considerations for the comparative analysis.

Input Category	Inputs
Project details	Design life = 35 years. Pavement type = Jointed plain concrete pavement (JPCP).
Design criteria (provided by MDOT)	Transverse cracking = 4%. Joint faulting = 0.19 inch. IRI = 250 in/mile. Design reliability = 95% for interstates and highways.
Climate	Location latitude, longitude, elevation = 34.77, -89.497, 613 ft Climate file = Marshall, MS
Traffic	Load spectra generated using WIM data and MS-Atlas Initial traffic in 2017 = 4,680 heavy trucks Cumulative traffic in 2034 (17 years) = 20,684,200 trucks. Cumulative traffic 2052 (35 years) = 52,848,900 trucks.
Structure	Layer 1 – JPCP. Layer 2 – 4-inch flexible concrete base. Layer 3 – 6-inch cement base soil cement. Subgrade – AASHTO A-6 material (semi-infinite).
Design features	Doweled joints, 1.5” diameter spaced 12 inches. Widened slab. Joint spacing = 16 feet and reduced to 15 feet to meet performance criteria if needed. Shoulder type – Tied shoulders. (Note that tied shoulder is not typically used by MDOT) Permanent curl/warp effective temperature difference = -10°F.

The results of the three levels of analysis are presented in Table 40. The table presents, for each level of input considered and for each mix design, the results of the optimized design and the age at which the performance criteria are met. The table also lists whether the considered default level 2 inputs and the MDOT level 2 inputs match the results of the level 1 analysis.

Table 40. Summary of designs with level 1, default level 2, and MDOT level 2 inputs.

Input level	Mix_ID	Thickness, in	Joint spacing, ft	Pass/Fail	Age at 4% cracking	Age at 0.19 in faulting	Age at IRI of 250in/mile	Match Level 1?
Level 1[1]	1	10	16	Fail	20 years	≥35 years	≥35 years	-
Level 1	1	10	15	Pass	≥35 years	≥35 years	≥35 years	-
Default Level 2	1	10	16	Pass	≥35 years	≥35 years	≥35 years	No
MDOT Level 2[2]	1	10	15	Pass	≥35 years	≥35 years	≥35 years	Yes*
Level 1	6	10	16	Pass	≥35 years	≥35 years	≥35 years	-
Default Level 2	6	10	16	Pass	≥35 years	≥35 years	≥35 years	Yes
MDOT Level 2	6	10	16	Pass	≥35 years	≥35 years	≥35 years	Yes
Level 1	11	10	16	Pass	≥35 years	≥35 years	≥35 years	-
Default Level 2	11	10	16	Pass	≥35 years	≥35 years	≥35 years	Yes
MDOT Level 2	11	10	16	Pass	≥35 years	≥35 years	≥35 years	Yes
Level 1[3]	16	10	16	Fail	≥35 years	22 years	≥35 years	-
Level 1	16	10	15	Fail	≥35 years	27 years	≥35 years	-
Default Level 2	16	10	16	Pass	≥35 years	≥35 years	≥35 years	No
MDOT Level 2[4]	16	10	15	Fail	≥35 years	29 years	≥35 years	Yes*
Level 1[5]	17	10	16	Fail	32 years	≥35 years	≥35 years	-
Level 1	17	10	15	Pass	≥35 years	≥35 years	≥35 years	-
Default Level 2	17	10	16	Pass	≥35 years	≥35 years	≥35 years	No
MDOT Level 2[6]	17	10	15	Pass	≥35 years	≥35 years	≥35 years	Yes*

[1] 11" slab fails in faulting at 18 years
[2] 16' joint spacing fails in faulting
[3] 11" fails in faulting at 15 years
[4] Design does not pass at 15' joint spacing
[5] 11" slab fails in faulting at 19 years
[6] Design fails at 16' joint spacing
*This case shows that the results from using MDOT level 2 estimates are similar to those from level 1 inputs, while default level 2 estimates produce different designs.

Note that the results presented in Table 40 are based on the distress models developed by MDOT's local calibration under State Study 170 (Von Quintus, et al., 2013). The performance criteria were also provided by MDOT. Therefore, these results do not represent the outcome of rigid pavement analysis that may be performed using JPCP distress models from global calibration or local calibration coefficients from other agencies. Also, note that the local calibration of the MDOT models was performed using AASHTOWare Pavement ME Version 1.3.

The results in Table 40 were intended to provide a preliminary evaluation of the benefit of using MDOT level 2 correlations developed under this study in lieu of the AASHTOWare default correlations. The results show that in 3 of the 5 cases analyzed, i.e. MIX IDs 1, 16, and 17, the default level 2 estimates produce different designs compared to the designs developed from level 1 testing. In contrast, the MDOT level 2 correlations produce designs similar to those developed from level 1 inputs. The performance predictions from MDOT level 2 correlations are closer to the predictions from level 1 inputs. These results demonstrate the value of using the MDOT level 2 correlations over the default correlations.

Recommendations for use of MDOT Level 2 Estimates

While these results are valid within the realm of the analysis performed, it is to be recognized that the limited number of cases analyzed were randomly selected from the mix designs tested. Again, the outcome of the analyses might have led to different conclusions if a different set of cases were to be used for the analyses or if the calibration coefficients of the distress models were to be revised. Also, the dataset used in the comparison are somewhat manufactured data, because the level 2 correlations were developed using the very same dataset that will produce level 2 estimates very close to the level 1 test data. The correlations have not been evaluated or utilized for an independent dataset. This study strongly recommends a closer evaluation of the sensitivity of these models under future recalibration efforts.

Chapter 5: Summary and Recommendations

Summary of Project Scope

MDOT has been actively engaged in the implementation of the MEPDG procedure and the AASHTOWare Pavement ME Design software for the design of pavements based on the MEPDG. Several research projects have been conducted under these efforts, which have included projects to develop accurate inputs to the program and the local calibration of the distress models. Under a future effort MDOT plans to make improvements to the performance prediction models using field materials data and forensic investigations data. This study provides recommendations for the selection of PCC material properties as inputs to the AASHTOWare Pavement ME Design software for the design of rigid pavements using the MEPDG procedure.

Summary of Project Findings

MDOT funded laboratory tests of 20 PCC mixture designs that included materials and mixture proportioning representative of paving mixes in Mississippi. The mix designs included four different options for the use of SCMs and five different coarse aggregate sources as listed below:

- Cementitious materials identified using the abbreviation Cementitious_ID:
  1. Cementitious_ID 1 – 100 percent Type I/II cement.
  2. Cementitious_ID 2 – 75 percent Type I/II cement + 25 percent Class F fly ash.
  3. Cementitious_ID 3 – 75 percent Type I/II cement + 25 percent Class C fly ash.
  4. Cementitious_ID 4 – 50 percent Type I/II cement + 50 percent GGBFS.
- Coarse aggregate sources identified using the abbreviation CA_ID:
  1. CA_ID 1 — High absorption gravel, a chert gravel source
  2. CA_ID 2 — Crushed limestone
  3. CA_ID 3 — Crushed limestone
  4. CA_ID 4 — Low absorption gravel, a chert gravel source
  5. CA_ID 5 — Small maximum size gravel, a chert gravel source

The mix designs are summarized in Table 12. The laboratory experiments were designed to generate test results for material properties required as inputs to the MEPDG analysis under both level 1 and level 2 categories as summarized in Table 14. The standard tests performed and the test ages are summarized in Table 13 and Table 15, respectively. Laboratory measured values were reported for flexural strength, compressive strength, modulus of elasticity, poisson's ratio, CTE and shrinkage related length change. Strength and modulus values were reported for 7, 14, 28, and 90 days as required by the MEPDG. CTE measurements are reported at 28-days, while the shrinkage length change measurements are reported for ages of 7, 11,14, 21, 35, 63, 119, and 231 days. MDOT will collect future length change data for these samples to include measurements at 455 days.

Test Results

Results from this study will serve as level 1 input values for all PCC material properties and may be used for future rigid pavement designs when appropriate. A summary of all 28-day values for the 20 MIX_IDs are presented in Table 20, while compressive strength, flexural strength, modulus & poisson's ratio, and shrinkage values for all test ages are tabulated in Table 17, Table 18, Table 19, and Table 24 respectively. CTE values by MIX_ID, by aggregate source (CA_ID) and by aggregate type are summarized in Table 21, Table 22, and Table 23, respectively

The following general conclusions are drawn from the concrete mixture test results with regard to their use in MEPDG analysis and design:

- The test results are generally within the range of values observed in the LTPP data used for the global calibration of the distress models. However, the strength and modulus values were generally higher than the national average values.
- Strength and modulus results displayed consistent strength gain and modulus gain trends but due to inadequate data from long term values, it was not possible to project long-term (20-yr to 28-day) strength ratios for MEPDG analysis.
- The CTE data showed that there was a distinct difference in the value depending on the aggregate type, similar to national findings. The chert gravels showed higher values than crushed limestone sources. However, the average CTE values for each aggregate type—6.7 and 5.1 x $^{10-6}$ in/in/°F for chert gravels and crushed limestone—were higher than the national averages by 0.6 to 0.7 x $^{10-6}$ in/in/°F.
- The test results were generally within tolerable accuracy levels and demonstrated repeatability within allowable limits.
- Companion CTE and modulus test results generated at an independent laboratory, the FHWA TFHRC labs, provided reasonable comparisons.

Development of Level 2 Correlations

Level 2 correlation equations were developed based on compressive strength and other index properties to estimate flexural strength and elastic modulus. In general, these models demonstrate a slight deviation from the default level 2 models used in the global calibration of the MEPDG. Additionally, because of the controlled nature of the experimental program, it was possible to improve the level 2 correlations to account for the aggregate type. Also, the study examined strength gain trends in data for extrapolating long term strength and modulus values. The strength gain patterns were influenced by the cementitious materials blend, i.e. the type of SCM used. All level 2 equations were thoroughly examined for statistical significance prior to establishing the correlation for use in design. A summary of the alternatives developed for level 2 correlations are presented in Table 41. It is however recommended that future calibration effort evaluate the sensitivity of these correlations to final design before recommending the appropriate model for use in routine design.

Table 41. Alternatives for level 2 correlations based on MDOT PCC test data.

<table>
<tr><td>Knowledge of aggregate</td><td>Flexural strength</td><td>Elastic modulus</td></tr>
<tr><td>No</td><td>MDOT Model 2:
$$MR = 4.5912 * f'_c{}^{0.5894}$$</td><td>MDOT Model 5:
$$E = 73360 * f'_c{}^{0.5}$$
MDOT Model 6:
$$E = 409110 * f'_c{}^{0.305}$$
MDOT Model 7:
$$E = 4.91 * w^{2.41} * f'_c{}^{0.23}$$</td></tr>
<tr><td>Yes</td><td>MDOT Model 3:
$$MR = a * f'_c{}^{0.5}$$
where a has the values:
<table>
<tr><td>CA_ID</td><td>a</td></tr>
<tr><td>1</td><td>9.7816</td></tr>
<tr><td>2</td><td>9.4012</td></tr>
<tr><td>3</td><td>11.0280</td></tr>
<tr><td>4</td><td>10.805</td></tr>
<tr><td>5</td><td>9.6891</td></tr>
</table>
MDOT Model 4:
$$MR = a * f'_c{}^{b}$$
where a and b have the values:
<table>
<tr><td>CA_ID</td><td>a</td><td>b</td></tr>
<tr><td>1</td><td>7.5366</td><td>0.5297</td></tr>
<tr><td>2</td><td>7.6295</td><td>0.5235</td></tr>
<tr><td>3</td><td>2.2333</td><td>0.6801</td></tr>
<tr><td>4</td><td>1.7049</td><td>0.7090</td></tr>
<tr><td>5</td><td>6.9302</td><td>0.5376</td></tr>
</table></td><td>MDOT Model 9:
$$E = \mathrm{a} * f'_c{}^{b}$$
where a and b have the values:
<table>
<tr><td>CA_ID</td><td>a</td><td>b</td></tr>
<tr><td>1</td><td>229467</td><td>0.3652</td></tr>
<tr><td>2</td><td>523594</td><td>0.2693</td></tr>
<tr><td>3</td><td>2000000</td><td>0.1585</td></tr>
<tr><td>4</td><td>654322</td><td>0.2627</td></tr>
<tr><td>5</td><td>203805</td><td>0.3768</td></tr>
</table></td></tr>
<tr><td colspan="3">In all equations above
MR is the flexural strength in psi
f’c is the compressive strength in psi
E is the modulus of elasticity in psi, and
w is the unit weight of concrete in lb/ft^3</td></tr>
</table>

Verification of Level 2 Correlations

A rigid pavement design example was analyzed using five of the 20 mix designs so as to include all aggregate sources and options for SCMs. The results of the analysis verified the benefit of using MDOT level 2 correlations over the default correlations to match performance predictions with analysis using level 1 inputs. The study recommended that future efforts by MDOT for the recalibration of the rigid pavement distress prediction models examine the sensitivity of these level 2 correlation equations to make final recommendations for inclusion in the MDOT Design Manual.

RECOMMENDATIONS FOR SELECTION OF INPUTS TO AASHTOWARE PAVEMENT ME

Recommendations provided in this section are based on the test results evaluated under this study and level 2 correlations summarized in Table 42. The expected impact on pavement performance for these level 2 correlations was also assessed based on current local calibration models (Von Quintus, et al., 2013). These recommendations have to be verified under future MDOT recalibration efforts before they may be extended to designs based on recalibrated distress prediction models. The following guidelines may be adopted when rigid pavement designs are considered using materials and mix designs meeting MDOT specifications (MDOT, 2014). The recommendations are presented in order of preferred process of assembling input data, and illustrated in Figure 30.

Level 1 Inputs

If adequate resources can be made available for level 1 laboratory testing, results from flexural strength, modulus of elasticity, poisson's ratio, and CTE should be utilized as inputs to the AASHTOWare Pavement ME software. In addition, unit weight, cementitious materials content, w/c ratio, cement type and curing type may also be specified. Level 1 inputs will essentially override all other default values suggested for design.

Level 2 Inputs

Aggregate Information is Available

- For CTE:
  - If the aggregate source and type are known, i.e. the coarse aggregate is identical to a CA_ID in this study, use CTE information from Table 22.
  - If only aggregate type is known, use CTE values from Table 23.
- For flexural strength use MDOT Model 3 or 4.
- For modulus of elasticity use MDOT Model 9.
- For poisson's ratio, use 0.18.

Aggregate information is NOT Available

- For CTE, perform laboratory test.
- For flexural strength use MDOT Model 2.

- For modulus of elasticity use MDOT Model 5, 6, or 7.
- For poisson's ratio, use 0.18.

Recommendations under level 2 inputs are applicable only if:

i. The cementitious materials content is ~550 lb/yd^3, and it includes either no SCM or Class F fly ash, Class C fly ash, or GGBFS. SCM replacement should be no more than 25, 25, and 50 percent for class F fly ash, class C fly ash, and slag respectively.
ii. The cement type is a Type I/II cement. These recommendations certainly will not apply to Type III cement mixes or mixes used for fast track construction.
iii. The coarse aggregate type is either a chert gravel source or a crushed limestone source.
iv. The w/c ratio is 0.40 to 0.43, except it may be lower if the aggregate used has a low absorption.
v. Aggregate proportioning is in accordance with MDOT at S-501 specification.

Level 3 Inputs

For level 3 inputs, it is recommended that material properties in the materials library be utilized. For this,

- Compare material source information with that of the 20 mix designs from the experimental program. Identify the mix design, or the MIX_ID, that aligns with the materials selected. The combination of CA_ID and Cementitious_ID results in a unique MIX_ID as identified in Table 16. In addition, for this:
    - Cement shall be type I/II cement, and cementitious materials may include no SCM, or 25% class F fly ash, 25 percent class C fly ash, or 50 percent slag.
    - Coarse aggregate types shall be limited to crushed limestone or chert gravels.
    - Aggregate sources and properties should align with information reported in Table 10 and Table 11.
    - Fine aggregate shall be sand.
- Adopt the material proportioning used in the mix design
- Use level 1 PCC materials data from the MDOT Materials library for AASHTOWare Pavement ME Design software.

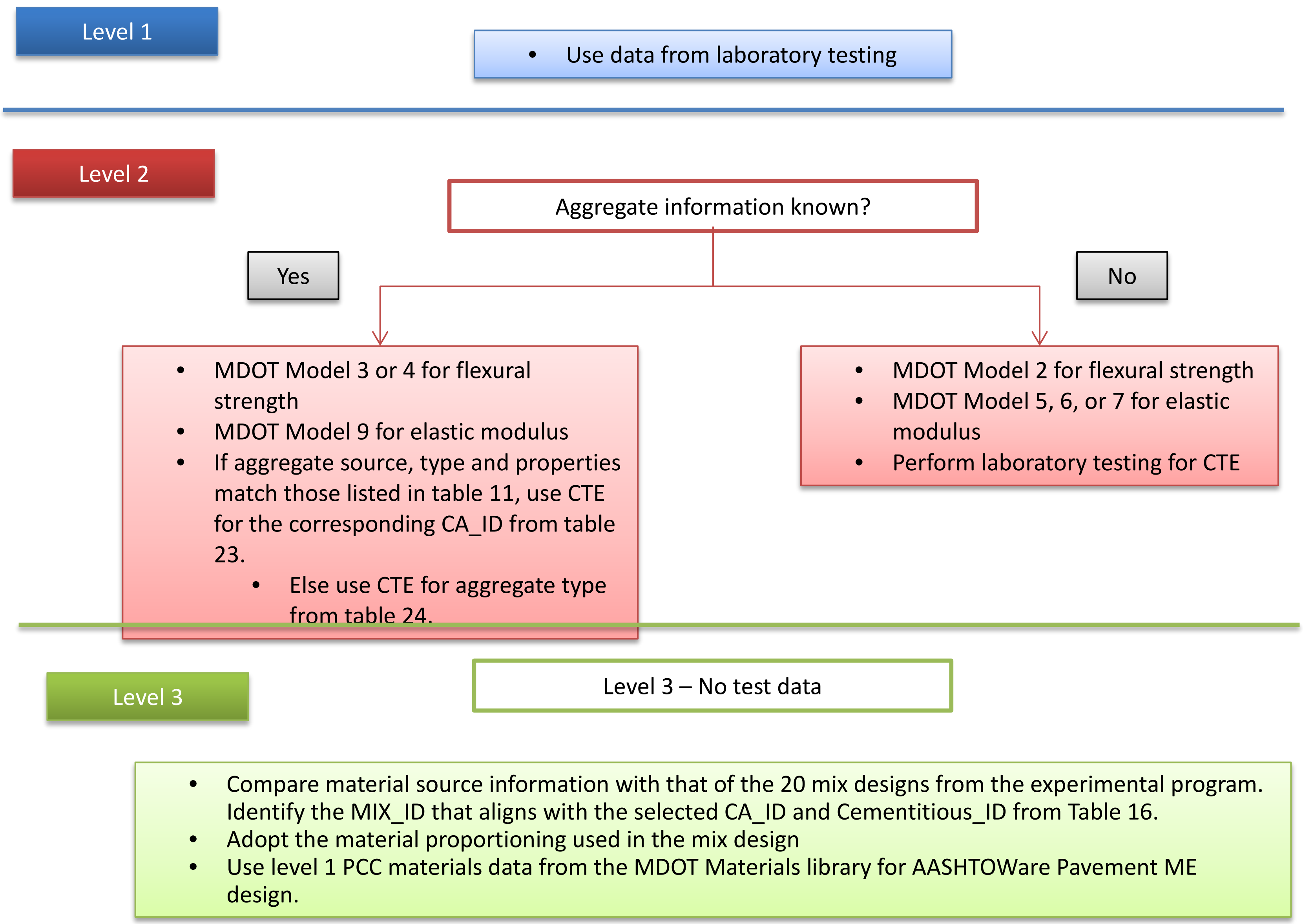


Figure 30. Recommendations for selection of inputs for AASHTOWare Pavement ME.

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Appendix A – Aggregate Test Results

BURNS COOLEY DENNIS, INC.
CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

278 COMMERCE PARK DRIVE
RIDGELAND, MISSISSIPPI 39157

Phone: (601) 856-2332
Fax: (601) 856-3552

To: MDOT
PO Box 1850
Jackson, MS 39215-1850

Attn: Project Manager

Report Date: 4/15/2014

BCD Project No.: 120420

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 1

Aggregate Size: No 57

Sampling Location: Plant Stockpile

CA_ID 1

Sampled By: Scott B

Gradation ID No: **2**

Date Sampled: 4/11/2014 Time Sampled: 9:00:00 AM

Tested By: Jimmy S

Date Tested: 4/14/2014

AGGREGATE GRADATION - AASHTO T11 and AASHTO T27

Initial Dry Weight (g): 11861.2 Sieve Sizes: Coarse 16 x 24 Fine 0.0

Sieve Size	Cumulative Weight Retained (g)	Individual Weight Retained (g)	Individual % Retained	Total % Retained	Total % Passing	Specification Min.	Specification Max.
2	0.0	0.0	0.0	0	100	100	100
1 1/2"	0.0	0.0	0.0	0	100	100	100
1	183.0	183.0	1.5	2	98	95	100
3/4"	1904.3	1721.3	14.5	16	84		
1/2"	7189.1	5284.8	44.6	61	39	25	60
3/8"	10405.6	3216.5	27.1	88	12		
No. 4	11633.4	1227.8	10.4	98	2	0	10
No. 8	11721.5	88.1	0.7	99	1	0	5
No. 16	11751.6	30.1	0.3	99	1		
No. 30	11766.6	15.0	0.1	99	1		
No. 50	11781.9	15.3	0.1	99	1		
No. 100	11798.4	16.5	0.1	99	1		
Pan	11842.1	43.7	0.4				

Dry Weight After Washing (g): 11848.5

FM: 6.98

Material Finer Than No. 200 (%): 0.1

REPORTED BY: Aggregate Testing Technician

REVIEWED BY: Engineer

BURNS COOLEY DENNIS, INC.
CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

278 COMMERCE PARK DRIVE
RIDGELAND, MISSISSIPPI 39157

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To: MDOT
PO Box 1850
Jackson, MS 39215-1850

Attn: Project Manager

Report Date: 4/15/2014

BCD Project No.: 140241

Project: SP-9999-09(110)/106812-101000

SOURCE AND SAMPLING INFORMATION

Aggregate Source:	CA_ID 1	Aggregate Size:	No 57
Sampling Location:	Stockpile		
Sampled By:	Scott B		
Date Received:	4/11/2014	Tested By:	Larry M
BCD Lab No:		Date Tested:	4/15/2014

SPECIFIC GRAVITY AND ABSORPTION OF COARSE AGGREGATE (AASHTO T85)

	Sample 1	Sample 2	Average
A = mass of oven-dry test sample in air (0.1 g)	**5756.4**	**5889.1**	
B = mass of saturated-surface-dry sample in air (0.1 g)	**5947.8**	**6090.0**	
C = mass of saturated test sample in water (0.1 g)	**3546.5**	**3627.7**	
Bulk Specific Gravity (Dry) **Bulk sp gr = A / (B-C)**	**2.397**	**2.392**	**2.394**
Bulk Specific Gravity (Saturated-Surface-Dry) **Bulk sp gr (saturated-surface-dry) = B / (B-C)**	**2.477**	**2.473**	**2.475**
Absorption, percent **= [(B-A) / A] X 100**	**3.32**	**3.41**	**3.37**

REPORTED BY: ______________________ CMT Manager ______________________ Engineer

BURNS COOLEY DENNIS, INC.

CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

Determining Unit Weight and Voids in Aggregate (AASHTO T19)

278 COMMERCE PARK DRIVE
RIDGELAND, MISSISSIPPI 39157

Phone: (601) 856-2332
Fax: (601) 856-3552

To: MDOT
PO Box 1850
Jackson, MS 39215-1850

Report Date: 4/17/2014

Attn: Project Manager

BCD Project No.: 140241

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 1

Aggregate Size: No 57

Sampled By: Scott B

Tested By: Jimmy S

Date Received: 4/11/2014

Date Tested: 4/16/2014

Unit Weight		
Sample Number:	1	2
Calibrated volume of measure, V (ft^{3})	0.500	0 500
Tare weight of measure, T (lb)	16.30	16.40
Mass of aggregate plus measure, G (lb)	63 90	64.58
Unit weight of aggregate, M (lb/ft^3) M=(G-T)/V	95 20	96.36
Void Content		
Average unit weight, M_{avg} (lb/ft^3)	96	
Bulk Dry Specific Gravity of Aggregate, S	2.394	
Density of Water, (62 3 lb/ft^3)	62 3	
Void Content, % = 100[(S*W)-M]/(S*W)	35.8	

REPORTED BY: CMT Manager

Engineer

BURNS COOLEY DENNIS, INC.
CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

278 COMMERCE PARK DRIVE
RIDGELAND, MISSISSIPPI 39157

Phone: (601) 856-2332
Fax: (601) 856-3552

To: MDOT
PO Box 1850
Jackson, MS 39215-1850

Attn: Project Manager

Report Date: 5/7/2014

BCD Project No.: 120420

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 2

Aggregate Size: No 57

CA_ID 2

Sampling Location: Plant Stockpile

Sampled By: Scott B

Gradation ID No: **3**

Date Sampled: 4/18/2014 Time Sampled: 9:00:00 AM

Tested By: Jimmy S

Date Tested: 4/23/2014

AGGREGATE GRADATION - AASHTO T11 and AASHTO T27

Initial Dry Weight (g): 13465.1 Sieve Sizes: Coarse 16 x 24 Fine 0.0

Sieve Size	Cumulative Weight Retained (g)	Individual Weight Retained (g)	Individual % Retained	Total % Retained	Total % Passing	Specification Min.	Specification Max.
2	0.0	0.0	0.0	0	100	100	100
1 1/2"	0.0	0.0	0.0	0	100	100	100
1	210.5	210.5	1.6	2	98	95	100
3/4"	1913.3	1702.8	12.6	14	86		
1/2"	7074.2	5160.9	38.3	53	47	25	60
3/8"	10388.1	3313.9	24.6	77	23		
No. 4	12604.9	2216.8	16.5	94	6	0	10
No. 8	12950.3	345.4	2.6	96	4	0	5
No. 16	13035.9	85.6	0.6	97	3		
No. 30	13087.0	51.1	0.4	97	3		
No. 50	13128.4	41.4	0.3	97	3		
No. 100	13158.2	29.8	0.2	98	2		
Pan	13483.9	325.7	2.4				

Dry Weight After Washing (g): 13186.3

FM: 6.70

Material Finer Than No. 200 (%): 2.1

REPORTED BY: Aggregate Testing Technician

REVIEWED BY: Engineer

BURNS COOLEY DENNIS, INC.
CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

278 COMMERCE PARK DRIVE
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BCD Project No.: 140241

Project: SP-9999-09(110)/106812-101000

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 2

Aggregate Size: No 57

Sampling Location: Stockpile

Sampled By: Scott B

Date Received: 4/18/2014

Tested By: Jimmy S

BCD Lab No:

Date Tested: 4/23/2014

SPECIFIC GRAVITY AND ABSORPTION OF COARSE AGGREGATE (AASHTO T85)

	Sample 1	Sample 2	Average
A = mass of oven-dry test sample in air (0.1 g)	**4726.1**	**4415.7**	
B = mass of saturated-surface-dry sample in air (0.1 g)	**4798.8**	**4479.2**	
C = mass of saturated test sample in water (0.1 g)	**2974.0**	**2783.4**	
Bulk Specific Gravity (Dry) **Bulk sp gr = A / (B-C)**	**2.590**	**2.604**	**2.597**
Bulk Specific Gravity (Saturated-Surface-Dry) **Bulk sp gr (saturated-surface-dry) = B / (B-C)**	**2.630**	**2.641**	**2.636**
Absorption, percent **= [(B-A) / A] X 100**	**1.54**	**1.44**	**1.49**

REPORTED BY: CMT Manager Engineer

BURNS COOLEY DENNIS, INC.

CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

Determining Unit Weight and Voids in Aggregate (AASHTO T19)

278 COMMERCE PARK DRIVE
RIDGELAND, MISSISSIPPI 39157

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To: MDOT
PO Box 1850
Jackson, MS 39215-1850

Report Date: 5/6/2014

Attn: Project Manager

BCD Project No.: 140241

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 2

Aggregate Size: No 57

Sampled By: Scott B

Tested By: Jimmy S

Date Received: 4/18/2024

Date Tested: 4/23/2014

Unit Weight		
Sample Number:	1	2
Calibrated volume of measure, V (ft^{3})	0.500	0.500
Tare weight of measure, T (lb)	16.40	16.40
Mass of aggregate plus measure, G (lb)	66.80	66.50
Unit weight of aggregate, M (lb/ft^3) M=(G-T)/V	100.80	100.20
Void Content		
Average unit weight, M_{avg} (lb/ft^3)	101	
Bulk Dry Specific Gravity of Aggregate, S	2.597	
Density of Water, (62.3 lb/ft^3)	62.3	
Void Content, % = 100[(S*W)-M]/(S*W)	37.9	

REPORTED BY: _______ CMT Manager

_______ Engineer

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PO Box 1850
Jackson, MS 39215-1850

Attn: Project Manager

Report Date: 5/19/2014

BCD Project No.: 120420

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 3

Aggregate Size: No 57

Sampling Location: Pit Stockpile

CA_ID 3

Sampled By: Scott B

Gradation ID No: 4

Date Sampled: 5/14/2014 Time Sampled: 9:00:00 AM

Tested By: Jimmy S

Date Tested: 5/16/2014

AGGREGATE GRADATION - AASHTO T11 and AASHTO T27

Initial Dry Weight (g): 10263.0 Sieve Sizes: Coarse 16 x 24 Fine 0.0

Sieve Size	Cumulative Weight Retained (g)	Individual Weight Retained (g)	Individual % Retained	Total % Retained	Total % Passing	Specification	
						Min.	Max.
2	0.0	0.0	0.0	0	100	100	100
1 1/2"	0.0	0.0	0.0	0	100	100	100
1	276.0	276.0	2.7	3	97	95	100
3/4"	2738.3	2462.3	24.0	27	73		
1/2"	6585.2	3846.9	37.5	64	36	25	60
3/8"	8455.9	1870.7	18.2	82	18		
No. 4	9999.2	1543.3	15.0	97	3	0	10
No. 8	10095.0	95.8	0.9	98	2	0	5
No. 16	10123.5	28.5	0.3	99	1		
No. 30	10136.4	12.9	0.1	99	1		
No. 50	10144.4	8.0	0.1	99	1		
No. 100	10151.7	7.3	0.1	99	1		
Pan	10259.7	108.0	1.1				

Dry Weight After Washing (g): 10168.7

FM: 7.00

Material Finer Than No. 200 (%) 0.9

REPORTED BY: Aggregate Testing Technician

REVIEWED BY: Engineer

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CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

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Attn: Project Manager

Report Date: 4/15/2014

BCD Project No.: 140241

Project: SP-9999-09(110)/106812-101000

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 3

Aggregate Size: No 57

Sampling Location: Stockpile

Sampled By: Scott B

Date Received: 5/14/2014

Tested By: Kevin W

BCD Lab No:

Date Tested: 5/16/2014

SPECIFIC GRAVITY AND ABSORPTION OF COARSE AGGREGATE (AASHTO T85)

	Sample 1	Sample 2	Average
A = mass of oven-dry test sample in air (0.1 g)	**5026.9**	**4985.8**	
B = mass of saturated-surface-dry sample in air (0.1 g)	**5045.3**	**5002.5**	
C = mass of saturated test sample in water (0.1 g)	**3207.7**	**3185.9**	
Bulk Specific Gravity (Dry) **Bulk sp gr = A / (B-C)**	**2.736**	**2.745**	**2.740**
Bulk Specific Gravity (Saturated-Surface-Dry) **Bulk sp gr (saturated-surface-dry) = B / (B-C)**	**2.746**	**2.754**	**2.750**
Absorption, percent **= [(B-A) / A] X 100**	**0.37**	**0.33**	**0.35**

REPORTED BY: ______________________ CMT Manager

______________________ Engineer

BURNS COOLEY DENNIS, INC.

CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

Determining Unit Weight and Voids in Aggregate (AASHTO T19)

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Report Date: 4/17/2014

Attn: Project Manager

BCD Project No.: 140241

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 3

Aggregate Size: No 57

Sampled By: Scott B

Tested By: Jimmy S

Date Received: 5/14/2014

Date Tested: 5/6/2014

Unit Weight		
Sample Number:	1	2
Calibrated volume of measure, V (ft^{3})	0.500	0.500
Tare weight of measure, T (lb)	16.40	16.40
Mass of aggregate plus measure, G (lb)	68.50	68.70
Unit weight of aggregate, M (lb/ft^3) M=(G-T)/V	104.20	104.60
Void Content		
Average unit weight, M_{avg} (lb/ft^3)	104	
Bulk Dry Specific Gravity of Aggregate, S	2.740	
Density of Water, (62.3 lb/ft^3)	62.3	
Void Content, % = 100[(S*W)-M]/(S*W)	38.8	

REPORTED BY: CMT Manager

Engineer

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CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

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PO Box 1850
Jackson, MS 39215-1850

Attn: Project Manager

Report Date: 6/6/2014

BCD Project No.: 120420

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 4

Aggregate Size: No 57

CA_ID 4

Sampling Location: Pit Stockpile

Sampled By: Scott B

Gradation ID No: **5**

Date Sampled: 6/4/2014 Time Sampled: 9:00:00 AM

Tested By: Jimmy S

Date Tested: 6/5/2014

AGGREGATE GRADATION - AASHTO T11 and AASHTO T27

Initial Dry Weight (g): 11470.9 Sieve Sizes: Coarse 16 x 24 Fine 0.0

Sieve Size	Cumulative Weight Retained (g)	Individual Weight Retained (g)	Individual % Retained	Total % Retained	Total % Passing	Specification Min.	Specification Max.
2	0.0	0.0	0.0	0	100	100	100
1 1/2"	0.0	0.0	0.0	0	100	100	100
1	2268.7	2268.7	19.8	20	80	95	100
3/4"	5112.0	2843.3	24.8	45	55		
1/2"	8471.8	3359.8	29.3	74	26	25	60
3/8"	10105.7	1633.9	14.2	88	12		
No. 4	11255.8	1150.1	10.0	98	2	0	10
No. 8	11425.4	169.6	1.5	100	0	0	5
No. 16	11440.9	15.5	0.1	100	0		
No. 30	11446.1	5.2	0.0	100	0		
No. 50	11455.3	9.2	0.1	100	0		
No. 100	11461.0	5.7	0.0	100	0		
Pan	11477.7	16.7	0.1				

Dry Weight After Washing (g): 11469.4

FM: 7.30

Material Finer Than No. 200 (%): 0.0

REPORTED BY: [signature]
Aggregate Testing Technician

REVIEWED BY: [signature]
Engineer

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CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

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To: MDOT
PO Box 1850
Jackson, MS 39215-1850

Report Date: 6/9/2014

BCD Project No.: 140241

Attn: Project Manager

Project: SP-9999-09(110)/106812-101000

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 4

Aggregate Size: No 57

Sampling Location: Stockpile

Sampled By: Scott B

Date Received: 5/30/2014

Tested By: Jimmy S.

BCD Lab No:

Date Tested: 6/7/2014

SPECIFIC GRAVITY AND ABSORPTION OF COARSE AGGREGATE (AASHTO T85)

	Sample 1	Sample 2	Average
A = mass of oven-dry test sample in air (0.1 g)	**5119.9**	**5145.6**	
B = mass of saturated-surface-dry sample in air (0.1 g)	**5195.7**	**5215.5**	
C = mass of saturated test sample in water (0.1 g)	**3174.9**	**3188.2**	
Bulk Specific Gravity (Dry) **Bulk sp gr = A / (B-C)**	**2.534**	**2.538**	**2.536**
Bulk Specific Gravity (Saturated-Surface-Dry) **Bulk sp gr (saturated-surface-dry) = B / (B-C)**	**2.571**	**2.573**	**2.572**
Absorption, percent **= [(B-A) / A] X 100**	**1.48**	**1.36**	**1.42**

REPORTED BY: CMT Manager Engineer

BURNS COOLEY DENNIS, INC.

CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

Determining Unit Weight and Voids in Aggregate (AASHTO T19)

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PO Box 1850
Jackson, MS 39215-1850

Report Date: 6/9/2014

Attn: Project Manager

BCD Project No.: 140241

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 4

Aggregate Size: No 57

Sampled By: Scott B.

Tested By: Jimmy S

Date Received: 6/4/2014

Date Tested: 6/5/2014

Unit Weight		
Sample Number:	1	2
Calibrated volume of measure, V (ft^{3})	0.500	0.500
Tare weight of measure, T (lb)	16.40	16.40
Mass of aggregate plus measure, G (lb)	68.10	67.90
Unit weight of aggregate, M (lb/ft^3) M=(G-T)/V	103.40	103.00
Void Content		
Average unit weight, M_{avg} (lb/ft^3)	103	
Bulk Dry Specific Gravity of Aggregate, S	2.536	
Density of Water, (62.3 lb/ft^3)	62.3	
Void Content, % = 100[(S*W)-M]/(S*W)	34.7	

REPORTED BY: ______________
CMT Manager

____
Engineer

BURNS COOLEY DENNIS, INC.
CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

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To: MDOT
PO Box 1850
Jackson, MS 39215-1850

Attn: Project Manager

Report Date: 6/19/2014

BCD Project No.: 140241

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 5

Aggregate Size: No 67

Sampling Location: Pit Stockpile

CA_ID 5

Sampled By: Scott B

Gradation ID No: 6

Date Sampled: 6/13/2014 Time Sampled: 9:00:00 AM

Tested By: Jimmy S

Date Tested: 6/16/2014

AGGREGATE GRADATION - AASHTO T11 and AASHTO T27

Initial Dry Weight (g): 5233.4 Sieve Sizes: Coarse 16 x 24 Fine 0.0

Sieve Size	Cumulative Weight Retained (g)	Individual Weight Retained (g)	Individual % Retained	Total % Retained	Total % Passing	Specification	
						Min.	Max.
2	0.0	0.0	0.0	0	100	100	100
1 1/2"	0.0	0.0	0.0	0	100	100	100
1	0.0	0.0	0.0	0	100	100	100
3/4"	113.8	113.8	2.2	2	98	80	100
1/2"	1819.5	1705.7	32.6	35	65		
3/8"	3029.1	1209.6	23.1	58	42	20	55
No. 4	4983.5	1954.4	37.3	95	5	0	10
No. 8	5215.4	231.9	4.4	100	0	0	5
No. 16	5224.9	9.5	0.2	100	0		
No. 30	5225.2	0.3	0.0	100	0		
No. 50	5225.8	0.6	0.0	100	0		
No. 100	5226.8	1.0	0.0	100	0		
Pan	5232.6	5.8	0.1				

Dry Weight After Washing (g): 5228.8

FM: 6.54

Material Finer Than No. 200 (%): 0.1

REPORTED BY: Aggregate Testing Technician

REVIEWED BY: Engineer

BURNS COOLEY DENNIS, INC.
CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

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Attn: Project Manager

Report Date: 6/9/2014

BCD Project No.: 140241

Project: SP-9999-09(110)/106812-101000

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 5

Aggregate Size: No 67

Sampling Location: Stockpile

Sampled By: Scott B

Date Received: 6/13/2014

Tested By: Jimmy S.

BCD Lab No:

Date Tested: 6/17/2014

SPECIFIC GRAVITY AND ABSORPTION OF COARSE AGGREGATE (AASHTO T85)

	Sample 1	Sample 2	Average
A = mass of oven-dry test sample in air (0.1 g)	**4085.0**	**5177.3**	
B = mass of saturated-surface-dry sample in air (0.1 g)	**4182.5**	**5307.0**	
C = mass of saturated test sample in water (0.1 g)	**2520.9**	**3191.7**	
Bulk Specific Gravity (Dry) **Bulk sp gr = A / (B-C)**	**2.458**	**2.448**	**2.453**
Bulk Specific Gravity (Saturated-Surface-Dry) **Bulk sp gr (saturated-surface-dry) = B / (B-C)**	**2.517**	**2.509**	**2.513**
Absorption, percent **= [(B-A) / A] X 100**	**2.39**	**2.51**	**2.45**

REPORTED BY: CMT Manager ... Engineer

BURNS COOLEY DENNIS, INC.

CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

Determining Unit Weight and Voids in Aggregate (AASHTO T19)

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To: MDOT
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Jackson, MS 39215-1850

Report Date: 6/9/2014

Attn: Project Manager

BCD Project No.: 140241

SOURCE AND SAMPLING INFORMATION

Aggregate Source: CA_ID 5

Aggregate Size: No 57

Sampled By: Scott B.

Tested By: Jimmy S

Date Received: 6/13/2014

Date Tested: 6/16/2014

Unit Weight		
Sample Number:	1	2
Calibrated volume of measure, V ($ft^{3)}$)	0.500	0.500
Tare weight of measure, T (lb)	16.40	16.40
Mass of aggregate plus measure, G (lb)	66.90	66.90
Unit weight of aggregate, M (lb/ft^3) M=(G-T)/V	101.00	101.00
Void Content		
Average unit weight, M_{avg} (lb/ft^3)	101	
Bulk Dry Specific Gravity of Aggregate, S	2.453	
Density of Water, (62.3 lb/ft^3)	62.3	
Void Content, % = 100[(S*W)-M]/(S*W)	33.9	

REPORTED BY: CMT Manager

Engineer

BURNS COOLEY DENNIS, INC.
CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

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To: MDOT
PO Box 1850
Jackson, MS 39215-1850

Attn: Project Manager

Report Date: 4/15/2014

BCD Project No.: 120420

SOURCE AND SAMPLING INFORMATION

Aggregate Source: Sand – Fine Aggregate

Aggregate Size: Fine

Sampling Location: Plant Stockpile

Sand – Fine Aggregate

Sampled By: Scott B

Gradation ID No: 1

Date Sampled: 4/11/2014 Time Sampled: 9:00:00 AM

Tested By: Jimmy S

Date Tested: 4/14/2014

AGGREGATE GRADATION - AASHTO T11 and AASHTO T27

Initial Dry Weight (g): 532.1 Sieve Sizes: Coarse 0.0 Fine 12 in. dia.

Sieve Size	Cumulative Weight Retained (g)	Individual Weight Retained (g)	Individual % Retained	Total % Retained	Total % Passing	Specification	
						Min.	Max.
2	0.0	0.0	0.0	0	100	100	100
1 1/2"	0.0	0.0	0.0	0	100	100	100
1	0.0	0.0	0.0	0	100	100	100
3/4"	0.0	0.0	0.0	0	100	100	100
1/2"	0.0	0.0	0.0	0	100	100	100
3/8"	0.0	0.0	0.0	0	100	100	100
No. 4	1.9	1.9	0.4	0	100	95	100
No. 8	25.8	23.9	4.5	5	95	80	100
No. 16	70.5	44.7	8.4	13	87	50	90
No. 30	160.7	90.2	17.0	30	70	0	60
No. 50	468.2	307.5	57.8	88	12	5	30
No. 100	528.5	60.3	11.3	99	1	0	10
Pan	529.4	0.9	0.2				

Dry Weight After Washing (g): 529.5

FM: 2.36

Material Finer Than No. 200 (%) 0.5

REPORTED BY: Aggregate Testing Technician

REVIEWED BY: Engineer

BURNS COOLEY DENNIS, INC.
CONSTRUCTION MATERIALS AND ENGINEERING TESTING SERVICES

278 COMMERCE PARK DRIVE
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PO Box 1850
Jackson, MS 39215-1850

Attn: Project Manager

Report Date: 4/15/2014

BCD Project No.: 140241

Project: SP-9999-09(110)/106812-101000

SOURCE AND SAMPLING INFORMATION

Aggregate Source: Sand – Fine Aggregate

Aggregate Size: Sand

Sampling Location: Stockpile

Sampled By: Scott B

Date Received: 4/11/2014

Tested By: Larry M

BCD Lab No:

Date Tested: 4/15/2014

SPECIFIC GRAVITY AND ABSORPTION OF FINE AGGREGATE (AASHTO T84)

	Sample 1	Sample 2	Average
A = mass of oven-dry test sample in air (0.1 g)	**497.7**	**500.5**	
B = mass of pycnometer filled with water (0.1 g)	**658.2**	**656.9**	
S = mass of saturated-surface-dry specimen (0.1 g)	**500.5**	**502.9**	
C = mass of pycnometer with SSD specimen and water to calibration mark (0.1 g)	**968.7**	**969.1**	
Bulk Specific Gravity (Dry) **Bulk sp gr = A / (B+S-C)**	**2.619**	**2.625**	**2.622**
Bulk Specific Gravity (Saturated-Surface-Dry) **Bulk sp gr (saturated-surface-dry) = S / (B=S-C)**	**2.634**	**2.637**	**2.636**
Absorption, percent **= [(S-A) / A] X 100**	**0.56**	**0.48**	**0.52**

REPORTED BY: CMT Manager

Engineer

Appendix B – Laboratory Test Data

Table A- 1. Mixture proportioning for the mix designs used in the experimental plan

MIX_ID	Cast date	Batch#	Cement (lb/yd^3)	Class F (lb/ydY^3)	Class C (lb/yd^3)	Slag (lb/yd^3)	Total cementitious (lb/yd^3)	Coarse aggregate (lb/yd^3)	Fine aggregate (lb/yd^3)	Water (lb/yd^3)	Admixture 1 (fl. Oz)	Admixture 2 (fl. Oz)	Slump (inch)	Air content (percent)	Unit weight (lb/ft^3)
1	4/16/2014	1	548				548	1929	1135	229.2	4.11	27.40	1.25	5.8	142.6
1	4/16/2014	2	548				548	1929	1124	229.2	2.74	27.40	1.5	4.7	141.8
2	4/18/2014	1	411	137			548	1929	1090	222.9	8.22	27.40	1.5	4.9	142.6
2	4/18/2014	2	411	137			548	1929	1090	222.9	8.22	27.40	1.75	5.5	139.8
3	5/2/2014	1	411		137		548	1929	1149	210.4	2.74	27.40	2.75	4.7	143.2
3	5/2/2014	2	411		137		548	1929	1149	210.4	2.74	27.40	2	4.6	144.4
4	5/5/2014	1	274			274	548	1929	1103	229.2	3.12	27.40	2.5	4.5	143.8
4	5/5/2014	2	274			274	548	1929	1103	229.2	3.12	33.25	2.25	4.5	143
5	5/7/2014	1	548				548	1993	1180	231.3	2.74	27.40	2.5	5.3	145.4
5	5/7/2014	2	548				548	1993	1180	231.3	2.74	27.40	2.75	6.3	143.4
6	5/9/2014	1	411	137			548	1993	1146	233.3	6.85	27.40	2.25	6	143.4
6	5/9/2014	2	411	137			548	1993	1124	233.3	6.25	27.40	2.5	5	145.6
7	5/13/2014	1	411		137		548	1993	1194	225.0	3.01	27.40	2	4.9	145.8
7	5/13/2014	2	411		137		548	1993	1172	225.0	3.01	31.78	2	5.4	145.6
8	5/15/2014	1	274			274	548	1993	1160	237.5	4.27	27.40	1.5	4.6	146
8	5/15/2014	2	274			274	548	1993	1143	237.5	6.47	31.07	2	4.5	146.2
9	5/19/2014	1	548				548	2029	1228	231.3	2.19	27.40	2.25	5.5	149
9	5/19/2014	2	548				548	2029	1228	231.3	2.05	27.40	2.75	4.8	149.6
10	5/21/2014	1	411	137			548	2029	1172	233.3	4.38	27.40	2.75	4.8	148.6
10	5/21/2014	2	411	137			548	2029	1172	233.3	4.38	27.40	2.75	4.5	148.6
11	5/27/2014	1	411		137		548	2029	1231	220.8	4.30	27.40	2.75	5.2	147.8

MIX_ID	Cast date	Batch#	Cement (lb/yd^3)	Class F (lb/ydY^3)	Class C (lb/yd^3)	Slag (lb/yd^3)	Total cementitious (lb/yd^3)	Coarse aggregate (lb/yd^3)	Fine aggregate (lb/yd^3)	Water (lb/yd^3)	Admixture 1 (fl. Oz)	Admixture 2 (fl. Oz)	Slump (inch)	Air content (percent)	Unit weight (lb/ft^3)
11	5/27/2014	2	411		137		548	2029	1231	220.8	3.01	27.40	2.75	5.6	147.6
12	6/2/2014	1	274			274	548	2029	1191	237.5	3.51	27.40	2.25	5.2	147.4
12	6/2/2014	2	274			274	548	2029	1191	237.5	3.51	27.40	2.75	5.4	146.68
13	6/9/2014	1	548				548	2031	1152	208.3	2.74	27.40	1.5	4.9	146.2
13	6/9/2014	2	548				548	2031	1152	208.3	2.74	27.40	1.25	4.5	146.6
14	6/12/2014	1	411	137			548	2031	1117	208.3	4.93	27.40	2.75	4.5	145
14	6/12/2014	2	411	137			548	2031	1101	208.3	4.38	27.40	2.75	4.5	143.6
15	6/16/2014	1	411		137		548	2031	1161	195.8	2.74	27.40	2.25	5.1	145.4
15	6/16/2014	2	411		137		548	2031	1161	195.8	2.74	27.40	2.5	5	145.8
16	6/18/2014	1	274			274	548	2031	1131	216.7	3.07	27.40	2	4.6	145
16	6/18/2014	2	274			274	548	2031	1109	216.7	3.07	27.40	2	4.4	146.32
17	6/24/2014	1	548				548	2012	1090	229.2	2.74	27.40	1.25	5	143.8
17	6/24/2014	2	548				548	2012	1068	229.2	2.74	27.40	2.25	5.5	142.2
18	6/26/2014	1	411	137			548	2012	1028	233.3	5.48	27.40	2.5	5	141.4
18	6/26/2014	2	411	137			548	2012	1006	233.3	5.48	27.40	2.75	4.9	140.6
19	6/30/2014	1	411		137		548	2012	1077	216.7	2.74	27.40	1.25	4.5	145
19	6/30/2014	2	411		137		548	2012	1077	216.7	2.74	27.40	1.25	5	144
20	7/2/2014	1	274			274	548	2012	1048	229.2	3.07	27.40	1.25	4.4	144
20	7/2/2014	2	274			274	548	2012	1048	229.2	3.36	27.40	1.25	4.4	144.8

Table A- 2. Flexural strength test results

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen length (inch)	Specimen width (inch)	Specimen height (inch)	Load at failure (lb)	Flexural strength (psi)
1	4/23/2014	7	1	21	6.00	6.03	8620	711
1	4/23/2014	7	2	21	6.07	6.12	8540	676
1	4/23/2014	7	3	21	6.05	6.05	8730	710
1	4/30/2014	14	1	21	6.00	6.07	9310	758
1	4/30/2014	14	2	21	6.00	6.08	8950	726
1	4/30/2014	14	3	21	5.98	6.08	9590	781
1	5/14/2014	28	1	21	6.00	6.03	9170	757
1	5/14/2014	28	2	21	6.05	6.03	9620	787
1	5/14/2014	28	3	21	5.98	6.05	9900	814
1	7/15/2014	90	1	21	5.95	6	10120	850
1	7/15/2014	90	2	21	6.03	6.03	11370	933
1	7/15/2014	90	3	21	6.00	6.05	10350	848
2	4/25/2014	7	1	21	5.95	6.1	7790	633
2	4/25/2014	7	2	21	6.02	6.05	7470	610
2	4/25/2014	7	3	21	6.08	6.08	7270	582
2	5/2/2014	14	1	21	6.00	6.1	8780	708
2	5/2/2014	14	2	21	6.03	6.08	8450	682
2	5/2/2014	14	3	21	6.02	6.03	8600	707
2	5/16/2014	28	1	21	6.08	6.05	9020	730
2	5/16/2014	28	2	21	6.00	6.08	9180	745
2	5/16/2014	28	3	21	6.00	6.08	9630	782
2	5/27/2014	90	1	21	5.98	6	10200	853
2	7/17/2014	90	2	21	6.02	6.05	10680	872
2	7/17/2014	90	3	21	5.97	6.03	11230	931
3	5/9/2014	7	1	21	6.10	6.05	8830	712
3	5/9/2014	7	2	21	6.05	6.03	8910	729
3	5/9/2014	7	3	21	6.05	6.05	8260	671
3	5/16/2014	14	1	21	6.08	6.07	9840	791
3	5/16/2014	14	2	21	6.08	6.07	9150	735
3	5/16/2014	14	3	21	6.00	6.07	8820	718
3	5/30/2014	28	1	21	6.03	6.03	10420	855
3	5/30/2014	28	2	21	6.05	6.07	9190	742
3	5/30/2014	28	3	21	5.97	6.07	9190	752
3	7/31/2014	90	1	21	6.07	6.07	10400	837
3	7/31/2014	90	2	21	6.08	6.08	10920	875
3	7/31/2014	90	3	21	6.07	6.08	11370	912

Table A- 2. Flexural strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen length (inch)	Specimen width (inch)	Specimen height (inch)	Load at failure (lb)	Flexural strength (psi)
4	5/12/2014	7	1	21	5.95	6.05	8600	711
4	5/12/2014	7	2	21	6.05	6.05	7840	637
4	5/12/2014	7	3	21	6.02	6.08	8450	683
4	5/19/2014	14	1	21	6.05	6.03	9630	788
4	5/19/2014	14	2	21	6.05	6.07	10120	817
4	5/19/2014	14	3	21	6.10	6.1	9790	776
4	6/2/2014	28	1	21	5.92	6.12	10210	829
4	6/2/2014	28	2	21	6.08	6.1	9990	795
4	6/2/2014	28	3	21	6.03	6.08	11190	904
4	8/3/2014	90	1	21	5.95	6.05	10360	856
4	8/3/2014	90	2	21	6.00	6.07	10630	866
4	8/3/2014	90	3	21	5.95	6.05	9910	819
5	5/14/2014	7	1	21	5.95	6.03	8210	683
5	5/14/2014	7	2	21	6.10	6.07	8850	709
5	5/14/2014	7	3	21	5.97	6.07	8050	659
5	5/21/2014	14	1	21	6.10	6.1	9470	751
5	5/21/2014	14	2	21	5.95	6.07	8390	689
5	5/21/2014	14	3	21	5.99	6.02	9040	750
5	6/4/2014	28	1	21	6.08	6.1	9230	734
5	6/4/2014	28	2	21	5.97	6.08	9240	754
5	6/4/2014	28	3	21	5.97	6.05	8740	720
5	8/5/2014	90	1	21	6.08	6.05	8830	714
5	8/5/2014	90	2	21	6.05	6.02	8940	734
5	8/5/2014	90	3	21	5.97	6.05	8920	735
6	5/16/2014	7	1	21	6.03	6.05	7670	626
6	5/16/2014	7	2	21	6.02	6.07	7690	624
6	5/16/2014	7	3	21	6.02	6.05	6550	535
6	5/23/2014	14	1	21	5.95	6.05	8260	683
6	5/23/2014	14	2	21	5.95	6.02	8090	675
6	5/23/2014	14	3	21	5.95	6.07	8320	683
6	6/6/2014	28	1	21	6.02	6.03	8600	707
6	6/6/2014	28	2	21	5.98	6.1	9420	762
6	6/6/2014	28	3	21	6.00	6.1	8620	695
6	6/17/2014	90	1	21	5.97	5.97	9590	811
6	8/7/2014	90	2	21	6.02	6.05	9910	810
6	8/7/2014	90	3	21	6.00	6.05	9760	800
7	5/20/2014	7	1	21	5.98	6.07	9260	756
7	5/20/2014	7	2	21	6.08	6.12	8640	683
7	5/20/2014	7	3	21	6.05	6.08	9640	776
7	5/27/2014	14	1	21	6.02	6.02	9540	787
7	5/27/2014	14	2	21	6.00	6.08	9840	799
7	5/27/2014	14	3	21	5.95	6.07	9960	818
7	6/10/2014	28	1	21	6.00	6.08	9690	786
7	6/10/2014	28	2	21	6.00	6.05	10500	861
7	6/10/2014	28	3	21	5.97	6.13	9980	801
7	8/11/2014	90	1	21	6.00	6.08	9840	799

Table A- 2. Flexural strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen length (inch)	Specimen width (inch)	Specimen height (inch)	Load at failure (lb)	Flexural strength (psi)
7	8/11/2014	90	2	21	5.95	6.05	10040	830
7	8/11/2014	90	3	21	5.97	6.03	10810	896
8	5/22/2014	7	1	21	6.02	6.05	8800	719
8	5/22/2014	7	2	21	6.08	6.03	9240	752
8	5/22/2014	7	3	21	6.02	6.05	8420	688
8	5/29/2014	14	1	21	6.13	6.1	10540	832
8	5/29/2014	14	2	21	6.03	6.05	10260	837
8	5/29/2014	14	3	21	5.98	6.05	9910	815
8	6/12/2014	28	1	21	6.12	6.1	11580	915
8	6/12/2014	28	2	21	6.12	6.08	10720	853
8	6/12/2014	28	3	21	5.98	6.08	11920	971
8	8/13/2014	90	1	21	5.98	6.05	11770	968
8	8/13/2014	90	2	21	5.98	6.05	11070	910
8	8/13/2014	90	3	21	5.98	6.03	11740	972
9	5/26/2014	7	1	21	6.08	6.1	10680	850
9	5/26/2014	7	2	21	6.02	6.07	10620	862
9	5/26/2014	7	3	21	6.08	6.08	11090	888
9	6/2/2014	14	1	21	6.05	6.05	11190	910
9	6/2/2014	14	2	21	6.05	6.02	11300	928
9	6/2/2014	14	3	21	6.07	6.03	11120	907
9	6/16/2014	28	1	21	6.05	6.1	11750	939
9	6/16/2014	28	2	21	6.15	6.12	11690	914
9	6/16/2014	28	3	21	6.05	6.08	11550	930
9	8/18/2014	91	1	21	6.13	6.08	11270	895
9	8/18/2014	91	2	21	6.13	6.08	12430	987
9	8/18/2014	91	3	21	6.07	6.07	11600	934
10	5/28/2014	7	1	21	6.05	6.05	8800	715
10	5/28/2014	7	2	21	6.07	6.1	9200	733
10	5/28/2014	7	3	21	6.07	6.05	8890	720
10	6/4/2014	14	1	21	6.10	6.08	10070	804
10	6/4/2014	14	2	21	5.95	6.08	10980	899
10	6/4/2014	14	3	21	6.15	6.1	10710	842
10	6/18/2014	28	1	21	5.97	6.05	11680	962
10	6/18/2014	28	2	21	6.08	6.08	11740	940
10	6/18/2014	28	3	21	5.97	6.03	10810	896
10	8/19/2014	90	1	21	5.95	6.1	12080	982
10	8/19/2014	90	2	21	6.02	6.05	12840	1049
10	8/19/2014	90	3	21	6.03	6.07	12300	997
11	6/3/2014	7	1	21	6.05	6.05	9260	753
11	6/3/2014	7	2	21	6.07	6.05	9020	731
11	6/3/2014	7	3	21	6.02	6.08	9790	792
11	6/10/2014	14	1	21	5.98	6.08	10930	890
11	6/10/2014	14	2	21	6.03	6.08	11360	917
11	6/10/2014	14	3	21	5.97	6.08	10780	879
11	6/24/2014	28	1	21	5.92	6.08	12070	993
11	6/24/2014	28	2	21	6.00	6	11730	978

Table A- 2. Flexural strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen length (inch)	Specimen width (inch)	Specimen height (inch)	Load at failure (lb)	Flexural strength (psi)
11	6/24/2014	28	3	21	5.97	6.05	11510	948
11	8/25/2014	90	1	21	5.95	6.05	12810	1059
11	8/25/2014	90	2	21	6.13	6.08	12710	1010
11	8/25/2014	90	3	21	6.08	6.08	13590	1088
12	6/9/2014	7	1	21	6.10	6.1	9190	729
12	6/9/2014	7	2	21	5.97	6.07	8600	704
12	6/9/2014	7	3	21	6.00	6.08	9740	790
12	6/16/2014	14	1	21	5.98	6.05	11960	984
12	6/16/2014	14	2	21	6.08	6.1	11660	928
12	6/16/2014	14	3	21	6.13	6.1	11650	919
12	6/30/2014	28	1	21	6.02	6.07	12560	1019
12	6/30/2014	28	2	21	6.00	6.1	13130	1059
12	6/30/2014	28	3	21	5.97	6.1	13130	1064
12	9/2/2014	92	1	21	6.10	6.1	14280	1132
12	9/2/2014	92	2	21	6.08	6.08	13320	1067
12	9/2/2014	92	3	21	6.12	6.05	12600	1012
13	6/16/2014	7	1	21	6.12	6.07	9170	732
13	6/16/2014	7	2	21	6.07	6.12	10590	838
13	6/16/2014	7	3	21	6.13	6.1	9540	753
13	6/23/2014	14	1	21	5.97	6.07	10970	898
13	6/23/2014	14	2	21	6.02	6.07	11020	894
13	6/23/2014	14	3	21	6.07	6.1	10180	811
13	7/7/2014	28	1	21	6.02	6.1	10250	824
13	7/7/2014	28	2	21	6.03	6.05	10450	852
13	7/7/2014	28	3	21	6.03	6.08	11130	899
13	9/7/2014	90	1	21	6.00	6.07	11110	905
13	9/7/2014	90	2	21	6.00	6.08	11490	932
13	9/7/2014	90	3	21	5.95	6.1	11280	917
14	6/19/2014	7	1	21	6.05	6.12	8860	704
14	6/19/2014	7	2	21	5.98	6.08	8300	676
14	6/19/2014	7	3	21	6.02	6.1	8590	690
14	6/26/2014	14	1	21	5.95	6.05	10480	866
14	6/26/2014	14	2	21	6.10	6.08	9720	776
14	6/26/2014	14	3	21	5.95	6.12	10020	809
14	7/10/2014	28	1	21	5.95	6.05	10240	846
14	7/10/2014	28	2	21	6.02	6.1	10200	820
14	7/10/2014	28	3	21	5.93	6.08	10780	885
14	9/10/2014	90	1	21	6.00	6.03	11720	967
14	9/10/2014	90	2	21	6.02	6.05	12290	1004
14	9/10/2014	90	3	21	6.02	6.05	11720	957
15	6/23/2014	7	1	21	6.08	6.1	10130	806
15	6/23/2014	7	2	21	6.10	6.05	10580	853
15	6/23/2014	7	3	21	6.05	6.12	9510	755
15	6/30/2014	14	1	21	6.07	6.08	10100	810
15	6/30/2014	14	2	21	6.00	6.05	10530	863
15	6/30/2014	14	3	21	5.98	6.08	10210	831

Table A- 2. Flexural strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen length (inch)	Specimen width (inch)	Specimen height (inch)	Load at failure (lb)	Flexural strength (psi)
15	7/14/2014	28	1	21	6.07	6.1	11360	905
15	7/14/2014	28	2	21	6.07	6.08	11210	899
15	7/14/2014	28	3	21	6.02	6.12	11260	899
15	9/14/2014	90	1	21	6.08	6.08	12070	967
15	9/14/2014	90	2	21	5.93	6.03	12740	1064
15	9/14/2014	90	3	21	6.08	6.05	12760	1032
16	6/25/2014	7	1	21	5.98	6.1	9220	746
16	6/25/2014	7	2	21	5.98	6.1	9210	745
16	6/25/2014	7	3	21	6.03	6.05	8490	692
16	7/2/2014	14	1	21	5.98	6.1	11580	937
16	7/2/2014	14	2	21	5.97	6.07	11370	930
16	7/2/2014	14	3	21	5.98	6.13	10810	866
16	7/16/2014	28	1	21	5.92	6.08	12250	1008
16	7/16/2014	28	2	21	6.02	6.05	12140	992
16	7/16/2014	28	3	21	5.93	6.1	12420	1013
16	9/16/2014	90	1	21	5.97	6.08	12620	1029
16	9/16/2014	90	2	21	5.95	6.08	13980	1144
16	9/16/2014	90	3	21	5.93	6.08	13310	1093
17	7/1/2014	7	1	21	6.00	6.1	8910	718
17	7/1/2014	7	2	21	6.03	6.13	9180	729
17	7/1/2014	7	3	21	6.02	6.12	9280	741
17	7/8/2014	14	1	21	6.00	6.1	10430	841
17	7/8/2014	14	2	21	6.00	6.05	9730	797
17	7/8/2014	14	3	21	5.95	6.07	9700	796
17	7/22/2014	28	1	21	6.00	6.08	10250	832
17	7/22/2014	28	2	21	5.97	6.1	10150	822
17	7/22/2014	28	3	21	5.98	6.03	9400	778
17	9/22/2014	90	1	21	5.97	6.05	10650	877
17	9/22/2014	90	2	21	5.95	6.05	10580	874
17	9/22/2014	90	3	21	5.98	6.05	10360	852
18	7/3/2014	7	1	21	6.02	6.12	8660	691
18	7/3/2014	7	2	21	6.00	6.12	8090	648
18	7/3/2014	7	3	21	6.00	6.12	8330	667
18	7/10/2014	14	1	21	6.00	6.1	8960	722
18	7/10/2014	14	2	21	5.95	6.05	8780	726
18	7/10/2014	14	3	21	5.95	6.08	8590	703
18	7/24/2014	28	1	21	6.00	6.05	9690	794
18	7/24/2014	28	2	21	5.97	6.08	9650	787
18	7/24/2014	28	3	21	5.98	6.12	8840	710
18	9/24/2014	90	1	21	5.97	6.07	11510	942
18	9/24/2014	90	2	21	5.98	6.05	11630	956
18	9/24/2014	90	3	21	6.03	6.08	10290	831
19	7/7/2014	7	1	21	6.10	6.05	9740	785
19	7/7/2014	7	2	21	6.07	6.05	9670	783
19	7/7/2014	7	3	21	5.98	6.1	10020	811
19	7/14/2014	14	1	21	6.00	6.07	10340	842

Table A- 2. Flexural strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen length (inch)	Specimen width (inch)	Specimen height (inch)	Load at failure (lb)	Flexural strength (psi)
19	7/14/2014	14	2	21	6.05	6.07	9760	788
19	7/14/2014	14	3	21	6.07	6.1	10520	838
19	7/28/2014	28	1	21	6.07	6.08	10550	846
19	7/28/2014	28	2	21	6.00	6.12	10580	847
19	7/28/2014	28	3	21	6.07	6.08	10450	838
19	9/28/2014	90	1	21	6.05	6.05	10750	874
19	9/28/2014	90	2	21	6.10	6.08	11070	884
19	9/28/2014	90	3	21	6.05	6.08	11320	911
20	7/9/2014	7	1	21	5.98	6.05	9180	755
20	7/9/2014	7	2	21	5.95	6.08	8280	678
20	7/9/2014	7	3	21	5.95	6.1	9180	746
20	7/16/2014	14	1	21	6.07	6.08	10860	871
20	7/16/2014	14	2	21	6.02	6.08	10310	834
20	7/16/2014	14	3	21	5.97	6.1	10990	891
20	7/30/2014	28	1	21	5.95	6.07	10850	891
20	7/30/2014	28	2	21	6.00	6.05	11220	920
20	7/30/2014	28	3	21	5.98	6.05	11820	972
20	9/30/2014	90	1	21	5.95	6.08	11740	961
20	9/30/2014	90	2	21	5.95	6.1	12080	982
20	9/30/2014	90	3	21	5.97	6.05	11960	985

Table A- 3. Compressive strength test results

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength (psi)
1	4/23/2014	7	1	5.99	12.02	149630	5310
1	4/23/2014	7	2	5.99	12.03	156440	5561
1	4/23/2014	7	3	5.97	11.98	154870	5533
1	4/23/2014	7	4	5.98	11.97	161870	5773
1	4/23/2014	7	5	5.99	12.00	166280	5901
1	4/30/2014	14	1	6.03	12.12	175260	6137
1	4/30/2014	14	2	6.02	12.10	171570	6028
1	4/30/2014	14	3	6.02	12.12	177490	6245
1	4/30/2014	14	4	6.03	12.07	179200	6286
1	4/30/2014	14	5	6.01	12.00	181290	6401
1	5/14/2014	28	1	6.02	12.08	176480	6210
1	5/14/2014	28	2	6.02	12.07	196900	6928
1	5/14/2014	28	3	6.02	12.10	195780	6879
1	5/14/2014	28	4	6.02	12.13	186950	6578
1	5/14/2014	28	5	6.01	12.15	188250	6647
1	7/15/2014	90	1	6.04	12.05	218940	7653
1	7/15/2014	90	2	6.03	12.07	205590	7199

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
1	7/15/2014	90	3	6.02	12.12	206210	7256
1	7/15/2014	90	4	6.01	12.08	213590	7529
1	7/15/2014	90	5	6.01	12.03	209670	7404
2	4/25/2014	7	1	5.99	12.08	129250	4587
2	4/25/2014	7	2	5.96	12.02	126050	4518
2	4/25/2014	7	3	5.98	12.00	118800	4229
2	4/25/2014	7	4	5.96	12.00	122000	4381
2	4/25/2014	7	5	5.95	12.02	120910	4356
2	5/2/2014	14	1	5.97	12.02	131830	4710
2	5/2/2014	14	2	5.97	11.98	135620	4852
2	5/2/2014	14	3	5.97	12.05	132900	4748
2	5/2/2014	14	4	5.97	12.02	129590	4636
2	5/2/2014	14	5	5.98	11.95	137810	4915
2	5/16/2014	28	1	5.97	12.08	160910	5757
2	5/16/2014	28	2	5.96	12.00	155650	5589
2	5/16/2014	28	3	5.98	12.02	159280	5670
2	5/16/2014	28	4	5.97	12.00	163980	5859
2	5/16/2014	28	5	5.99	12.08	166060	5903
2	7/17/2014	90	1	5.97	12.03	196110	7016
2	7/17/2014	90	2	5.96	12.03	192730	6920
2	7/17/2014	90	3	5.96	12.00	194990	7001
2	7/17/2014	90	4	5.98	12.00	192560	6855
2	7/17/2014	90	5	5.95	12.05	203990	7348
3	5/9/2014	7	1	5.96	12.08	143770	5153
3	5/9/2014	7	2	5.95	12.07	150350	5406
3	5/9/2014	7	3	5.95	12.03	165450	5960
3	5/9/2014	7	4	5.96	12.10	154980	5565
3	5/9/2014	7	5	5.97	12.00	156660	5605
3	5/16/2014	14	1	6.00	11.98	175810	6228
3	5/16/2014	14	2	5.99	12.08	179110	6367
3	5/16/2014	14	3	5.97	12.00	183420	6553
3	5/16/2014	14	4	6.01	11.95	184440	6501
3	5/16/2014	14	5	5.97	11.98	180590	6452
3	5/30/2014	28	1	5.99	11.95	202330	7193
3	5/30/2014	28	2	5.97	12.02	202380	7241
3	5/30/2014	28	3	5.97	12.03	206170	7376
3	5/30/2014	28	4	5.98	12.02	202260	7213
3	5/30/2014	28	5	5.97	11.98	185710	6644
3	7/31/2014	90	1	5.95	12.00	213010	7659
3	7/31/2014	90	2	5.99	11.97	223460	7944
3	7/31/2014	90	3	5.97	12.00	236200	8439
3	7/31/2014	90	4	5.96	12.00	219480	7867
3	7/31/2014	90	5	5.99	12.02	214970	7642
4	5/12/2014	7	1	5.96	12.05	124710	4470
4	5/12/2014	7	2	6.00	12.05	111840	3962

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
4	5/12/2014	7	3	5.97	12.00	123970	4429
4	5/12/2014	7	4	5.95	12.02	131090	4722
4	5/12/2014	7	5	5.95	11.97	124650	4482
4	5/19/2014	14	1	6.00	12.00	173070	6131
4	5/19/2014	14	2	6.00	12.02	180060	6378
4	5/19/2014	14	3	5.99	12.02	176640	6268
4	5/19/2014	14	4	5.97	12.00	185830	6649
4	5/19/2014	14	5	6.00	12.03	178100	6298
4	6/2/2014	28	1	5.97	11.98	201510	7199
4	6/2/2014	28	2	5.93	12.02	190180	6886
4	6/2/2014	28	3	5.96	12.00	174600	6258
4	6/2/2014	28	4	5.92	12.00	208260	7579
4	6/2/2014	28	5	5.94	12.00	198970	7180
4	8/3/2014	90	1	5.99	12.02	227230	8064
4	8/3/2014	90	2	5.97	12.05	211700	7563
4	8/3/2014	90	3	5.97	12.03	213300	7631
4	8/3/2014	90	4	5.99	11.98	226380	8048
4	8/3/2014	90	5	5.99	12.12	222870	7923
5	5/14/2014	7	1	6.00	12.03	157780	5589
5	5/14/2014	7	2	5.95	11.97	149860	5389
5	5/14/2014	7	3	6.01	12.10	150840	5326
5	5/14/2014	7	4	6.00	12.08	154260	5464
5	5/14/2014	7	5	6.02	12.07	156450	5505
5	5/21/2014	14	1	6.00	12.05	160970	5702
5	5/21/2014	14	2	6.00	12.03	172500	6111
5	5/21/2014	14	3	6.02	12.05	166610	5862
5	5/21/2014	14	4	5.96	11.97	172080	6179
5	5/21/2014	14	5	5.96	12.00	163150	5858
5	6/4/2014	28	1	6.02	12.08	181070	6362
5	6/4/2014	28	2	6.03	12.03	170380	5966
5	6/4/2014	28	3	6.02	12.05	188340	6627
5	6/4/2014	28	4	6.00	12.07	185200	6560
5	6/4/2014	28	5	6.00	12.03	178490	6312
5	8/5/2014	90	1	6.01	12.05	194050	6852
5	8/5/2014	90	2	6.01	12.05	201240	7106
5	8/5/2014	90	3	5.92	12.07	203040	7375
5	8/5/2014	90	4	6.02	12.05	195730	6877
5	8/5/2014	90	5	6.03	12.05	198650	6968
6	5/16/2014	7	1	6.00	12.08	116200	4109
6	5/16/2014	7	2	6.03	12.12	118130	4143
6	5/16/2014	7	3	6.02	12.10	129860	4563
6	5/16/2014	7	4	6.01	12.08	128740	4538
6	5/16/2014	7	5	5.97	12.03	125470	4483
6	5/23/2014	14	1	6.03	12.10	141350	4949
6	5/23/2014	14	2	6.03	12.05	134990	4735

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
6	5/23/2014	14	3	5.94	12.02	145230	5241
6	5/23/2014	14	4	6.03	12.07	140700	4926
6	5/23/2014	14	5	6.02	12.07	139990	4926
6	6/6/2014	28	1	6.00	12.08	169230	5995
6	6/6/2014	28	2	6.04	12.12	174400	6096
6	6/6/2014	28	3	6.03	12.13	163490	5724
6	6/6/2014	28	4	6.03	12.07	167590	5878
6	6/6/2014	28	5	6.03	12.08	175190	6145
6	8/7/2014	90	1	6.01	12.07	219920	7752
6	8/7/2014	90	2	6.01	12.05	206310	7285
6	8/7/2014	90	3	6.01	12.05	197970	6990
6	8/7/2014	90	4	6.02	12.10	216590	7621
6	8/7/2014	90	5	5.99	12.05	209180	7423
7	5/20/2014	7	1	5.98	11.98	168840	6011
7	5/20/2014	7	2	6.05	12.10	179840	6266
7	5/20/2014	7	3	6.04	12.08	164480	5749
7	5/20/2014	7	4	6.00	12.02	171260	6056
7	5/20/2014	7	5	6.03	12.05	188430	6598
7	5/27/2014	14	1	6.02	12.10	216540	7609
7	5/27/2014	14	2	5.95	12.02	204860	7380
7	5/27/2014	14	3	6.00	12.13	208580	7389
7	5/27/2014	14	4	6.03	12.10	204360	7155
7	5/27/2014	14	5	6.01	12.07	212340	7485
7	6/10/2014	28	1	6.02	12.07	226040	7954
7	6/10/2014	28	2	6.03	12.05	220470	7720
7	6/10/2014	28	3	6.04	12.03	233390	8146
7	6/10/2014	28	4	6.01	12.07	228730	8062
7	6/10/2014	28	5	6.04	12.03	228750	7984
7	8/11/2014	90	1	6.03	12.05	256110	8967
7	8/11/2014	90	2	6.02	12.05	281660	9911
7	8/11/2014	90	3	6.02	12.10	257670	9067
7	8/11/2014	90	4	6.04	12.10	261960	9156
7	8/11/2014	90	5	6.01	12.07	265940	9374
8	5/22/2014	7	1	5.96	12.03	159300	5710
8	5/22/2014	7	2	5.93	12.03	161000	5829
8	5/22/2014	7	3	5.96	12.00	162880	5848
8	5/22/2014	7	4	5.93	12.03	155950	5657
8	5/22/2014	7	5	5.95	11.95	148940	5356
8	5/29/2014	14	1	5.97	12.08	206820	7389
8	5/29/2014	14	2	5.97	12.08	207200	7403
8	5/29/2014	14	3	6.00	11.98	204810	7255
8	5/29/2014	14	4	5.92	12.02	212170	7721
8	5/29/2014	14	5	5.97	12.02	220360	7873
8	6/12/2014	28	1	6.00	12.08	227780	8069
8	6/12/2014	28	2	5.98	12.05	223110	7957

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
8	6/12/2014	28	3	5.97	12.05	219500	7853
8	6/12/2014	28	4	5.99	12.05	236570	8395
8	6/12/2014	28	5	5.95	11.98	220550	7931
8	8/13/2014	90	1	6.00	12.05	227710	8066
8	8/13/2014	90	2	5.98	12.03	251540	8971
8	8/13/2014	90	3	5.99	12.07	231590	8218
8	8/13/2014	90	4	5.98	12.02	244880	8718
8	8/13/2014	90	5	6.00	12.00	214680	7591
9	5/26/2014	7	1	5.95	12.05	162320	5837
9	5/26/2014	7	2	5.90	12.00	176750	6465
9	5/26/2014	7	3	5.98	12.02	172430	6138
9	5/26/2014	7	4	5.98	12.03	170390	6077
9	5/26/2014	7	5	5.95	12.10	171980	6184
9	6/2/2014	14	1	5.94	11.98	196520	7102
9	6/2/2014	14	2	5.96	12.05	191580	6867
9	6/2/2014	14	3	5.99	12.03	193730	6875
9	6/2/2014	14	4	5.95	12.03	199340	7168
9	6/2/2014	14	5	5.97	12.03	198610	7096
9	6/16/2014	28	1	6.00	12.02	203400	7205
9	6/16/2014	28	2	5.95	12.00	206970	7442
9	6/16/2014	28	3	6.04	12.10	209900	7326
9	6/16/2014	28	4	6.02	12.00	202460	7114
9	6/16/2014	28	5	5.95	12.03	207960	7491
9	8/18/2014	91	1	5.95	11.98	223570	8039
9	8/18/2014	91	2	6.00	12.02	217850	7717
9	8/18/2014	91	3	6.00	11.98	218100	7726
9	8/18/2014	91	4	5.93	11.98	224210	8118
9	8/18/2014	91	5	5.97	12.02	228390	8160
10	5/28/2014	7	1	6.03	12.17	155810	5456
10	5/28/2014	7	2	6.04	12.10	150280	5253
10	5/28/2014	7	3	6.04	12.13	155550	5437
10	5/28/2014	7	4	6.03	12.13	149420	5241
10	5/28/2014	7	5	6.04	12.08	149720	5233
10	6/4/2014	14	1	6.03	12.07	164360	5755
10	6/4/2014	14	2	6.01	12.05	172870	6093
10	6/4/2014	14	3	5.95	12.03	178880	6432
10	6/4/2014	14	4	5.93	11.98	175460	6353
10	6/4/2014	14	5	5.99	11.98	161720	5749
10	6/18/2014	28	1	6.00	11.98	185660	6577
10	6/18/2014	28	2	6.04	12.10	196250	6859
10	6/18/2014	28	3	5.96	12.00	197000	7074
10	6/18/2014	28	4	6.01	12.07	193550	6822
10	6/18/2014	28	5	6.02	12.07	191240	6729
10	8/19/2014	90	1	5.97	11.97	252290	9014
10	8/19/2014	90	2	5.95	11.98	233710	8419

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
10	8/19/2014	90	3	6.01	12.10	258360	9107
10	8/19/2014	90	4	5.97	12.00	242480	8663
10	8/19/2014	90	5	6.02	12.10	256200	9002
11	6/3/2014	7	1	6.01	12.12	159480	5631
11	6/3/2014	7	2	6.00	12.22	144530	5111
11	6/3/2014	7	3	6.02	12.10	164090	5766
11	6/3/2014	7	4	6.04	12.17	171080	5980
11	6/3/2014	7	5	6.03	12.10	160350	5614
11	6/10/2014	14	1	6.03	12.08	185000	6489
11	6/10/2014	14	2	6.03	12.07	183510	6437
11	6/10/2014	14	3	5.99	12.02	188030	6672
11	6/10/2014	14	4	6.02	12.10	193530	6800
11	6/10/2014	14	5	6.04	12.12	191610	6688
11	6/24/2014	28	1	6.04	12.13	209520	7313
11	6/24/2014	28	2	6.04	12.07	213580	7465
11	6/24/2014	28	3	6.05	12.05	205480	7160
11	6/24/2014	28	4	6.03	12.08	205570	7210
11	6/24/2014	28	5	5.99	11.97	206680	7334
11	8/25/2014	90	1	6.02	12.08	251340	8844
11	8/25/2014	90	2	6.01	12.15	219970	7754
11	8/25/2014	90	3	6.02	12.23	243290	8561
11	8/25/2014	90	4	6.02	12.08	257880	9074
11	8/25/2014	90	5	6.02	12.10	255790	8988
12	6/9/2014	7	1	6.03	12.05	143920	5048
12	6/9/2014	7	2	6.02	12.05	152450	5364
12	6/9/2014	7	3	6.02	12.08	154050	5413
12	6/9/2014	7	4	6.04	12.07	141390	4935
12	6/9/2014	7	5	6.01	12.08	147900	5213
12	6/16/2014	14	1	6.02	12.05	189630	6663
12	6/16/2014	14	2	6.03	12.10	191940	6721
12	6/16/2014	14	3	6.02	12.10	203860	7163
12	6/16/2014	14	4	6.03	12.15	190410	6679
12	6/16/2014	14	5	6.03	12.08	173040	6069
12	6/30/2014	28	1	6.03	12.05	215280	7538
12	6/30/2014	28	2	6.04	12.07	203160	7101
12	6/30/2014	28	3	6.05	12.10	218490	7613
12	6/30/2014	28	4	6.05	12.17	207780	7240
12	6/30/2014	28	5	6.02	12.18	194940	6850
12	9/2/2014	92	1	6.02	12.22	244080	8588
12	9/2/2014	92	2	6.03	12.05	235240	8251
12	9/2/2014	92	3	6.01	12.17	243980	8600
12	9/2/2014	92	4	6.02	12.05	244570	8593
12	9/2/2014	92	5	6.01	12.12	244580	8636
13	6/16/2014	7	1	5.98	12.02	158340	5647
13	6/16/2014	7	2	6.03	12.08	160260	5621

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
13	6/16/2014	7	3	6.03	12.10	158010	5542
13	6/16/2014	7	4	5.99	12.05	167240	5945
13	6/16/2014	7	5	5.98	11.98	171950	6132
13	6/23/2014	14	1	5.97	12.02	175500	6279
13	6/23/2014	14	2	6.01	12.07	177480	6267
13	6/23/2014	14	3	5.98	12.00	174920	6238
13	6/23/2014	14	4	6.01	12.12	167450	5902
13	6/23/2014	14	5	6.04	12.07	173570	6067
13	7/7/2014	28	1	5.98	12.05	196610	6999
13	7/7/2014	28	2	5.98	12.00	197580	7046
13	7/7/2014	28	3	5.93	12.02	191540	6935
13	7/7/2014	28	4	6.04	12.05	194390	6794
13	7/7/2014	28	5	6.00	12.03	187170	6618
13	9/7/2014	90	1	6.01	12.02	204170	7209
13	9/7/2014	90	2	6.01	11.98	206790	7289
13	9/7/2014	90	3	5.99	12.05	189490	6736
13	9/7/2014	90	4	6.01	12.00	196500	6926
13	9/7/2014	90	5	5.96	11.97	196780	7066
14	6/19/2014	7	1	6.04	12.03	135590	4739
14	6/19/2014	7	2	6.01	12.07	134480	4740
14	6/19/2014	7	3	6.04	12.03	138720	4842
14	6/19/2014	7	4	6.03	12.05	135510	4753
14	6/19/2014	7	5	6.02	12.07	142720	5015
14	6/26/2014	14	1	6.03	12.07	160830	5631
14	6/26/2014	14	2	6.02	12.08	161670	5689
14	6/26/2014	14	3	6.05	12.05	161080	5613
14	6/26/2014	14	4	6.03	12.05	170580	5973
14	6/26/2014	14	5	6.02	12.08	160550	5641
14	7/10/2014	28	1	6.03	12.03	194380	6818
14	7/10/2014	28	2	6.03	12.05	193360	6782
14	7/10/2014	28	3	6.02	12.08	192570	6776
14	7/10/2014	28	4	6.02	12.10	184750	6492
14	7/10/2014	28	5	6.00	12.08	189650	6706
14	9/10/2014	90	1	6.01	12.07	229800	8100
14	9/10/2014	90	2	6.05	12.07	235180	8180
14	9/10/2014	90	3	6.02	12.10	241100	8472
14	9/10/2014	90	4	6.02	12.05	225200	7913
14	9/10/2014	90	5	6.01	12.08	230000	8107
15	6/23/2014	7	1	6.03	12.07	166440	5828
15	6/23/2014	7	2	6.04	12.07	174480	6099
15	6/23/2014	7	3	6.06	12.10	167880	5821
15	6/23/2014	7	4	6.05	12.15	175350	6110
15	6/23/2014	7	5	6.01	12.10	172660	6097
15	6/30/2014	14	1	6.03	12.13	182270	6393
15	6/30/2014	14	2	5.98	12.02	205380	7311

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
15	6/30/2014	14	3	6.01	12.03	194460	6854
15	6/30/2014	14	4	6.02	12.08	185420	6515
15	6/30/2014	14	5	6.06	12.10	193340	6704
15	7/14/2014	28	1	5.98	11.98	221260	7877
15	7/14/2014	28	2	6.02	12.08	195270	6871
15	7/14/2014	28	3	5.97	11.95	218040	7790
15	7/14/2014	28	4	6.02	12.05	218380	7673
15	7/14/2014	28	5	6.03	12.10	224890	7874
15	9/14/2014	90	1	6.02	12.05	249420	8776
15	9/14/2014	90	2	6.03	12.15	243260	8532
15	9/14/2014	90	3	6.03	12.10	239970	8402
15	9/14/2014	90	4	6.01	12.05	247450	8738
15	9/14/2014	90	5	6.02	12.08	233630	8209
16	6/25/2014	7	1	6.04	12.10	146970	5137
16	6/25/2014	7	2	6.03	12.08	144010	5051
16	6/25/2014	7	3	6.03	12.10	154440	5417
16	6/25/2014	7	4	6.03	12.10	158340	5554
16	6/25/2014	7	5	6.03	12.08	154540	5411
16	7/2/2014	14	1	6.04	12.12	193020	6747
16	7/2/2014	14	2	6.02	12.05	187770	6598
16	7/2/2014	14	3	6.01	12.13	175520	6187
16	7/2/2014	14	4	6.05	12.05	187560	6535
16	7/2/2014	14	5	5.98	12.00	181220	6463
16	7/16/2014	28	1	6.03	12.15	204450	7159
16	7/16/2014	28	2	6.03	12.12	201890	7081
16	7/16/2014	28	3	6.02	12.10	208820	7337
16	7/16/2014	28	4	6.03	12.15	209500	7348
16	7/16/2014	28	5	5.97	12.00	207890	7427
16	9/16/2014	90	1	6.02	12.00	200580	7058
16	9/16/2014	90	2	6.03	12.05	216930	7609
16	9/16/2014	90	3	6.04	12.03	201060	7028
16	9/16/2014	90	4	6.02	12.05	201940	7096
16	9/16/2014	90	5	6.01	12.08	235640	8306
17	7/1/2014	7	1	5.99	12.02	173560	6159
17	7/1/2014	7	2	6.02	12.02	167790	5904
17	7/1/2014	7	3	5.96	11.97	169710	6083
17	7/1/2014	7	4	6.03	12.10	171430	6002
17	7/1/2014	7	5	5.96	12.00	177140	6361
17	7/8/2014	14	1	5.98	12.00	195520	6973
17	7/8/2014	14	2	5.97	11.98	166680	5964
17	7/8/2014	14	3	5.97	12.03	210150	7519
17	7/8/2014	14	4	6.02	12.08	210540	7398
17	7/8/2014	14	5	5.98	12.05	194990	6954
17	7/22/2014	28	1	5.98	12.00	186180	6628
17	7/22/2014	28	2	5.96	12.00	201900	7250

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
17	7/22/2014	28	3	5.97	12.02	206490	7388
17	7/22/2014	28	4	5.95	11.98	202590	7298
17	7/22/2014	28	5	5.96	11.98	209870	7522
17	9/22/2014	90	1	6.00	12.07	233290	8249
17	9/22/2014	90	2	5.97	11.95	219760	7851
17	9/22/2014	90	3	6.00	12.05	229850	8142
17	9/22/2014	90	4	5.96	12.02	235420	8438
17	9/22/2014	90	5	5.97	12.00	217520	7782
18	7/3/2014	7	1	6.00	11.95	139840	4954
18	7/3/2014	7	2	5.98	12.00	133680	4759
18	7/3/2014	7	3	5.96	12.03	138410	4961
18	7/3/2014	7	4	5.98	12.03	131300	4674
18	7/3/2014	7	5	5.98	11.97	136300	4852
18	7/10/2014	14	1	6.00	12.02	157540	5581
18	7/10/2014	14	2	5.96	11.97	156340	5604
18	7/10/2014	14	3	6.01	12.00	164030	5782
18	7/10/2014	14	4	6.01	12.07	168020	5933
18	7/10/2014	14	5	5.98	12.03	152160	5417
18	7/24/2014	28	1	5.97	12.02	185650	6633
18	7/24/2014	28	2	5.97	12.02	186230	6663
18	7/24/2014	28	3	5.99	11.98	185520	6595
18	7/24/2014	28	4	5.98	11.98	185820	6615
18	7/24/2014	28	5	5.98	12.00	186380	6647
18	9/24/2014	90	1	6.03	12.10	232710	8148
18	9/24/2014	90	2	5.97	12.05	223670	7991
18	9/24/2014	90	3	5.98	12.02	220910	7878
18	9/24/2014	90	4	5.96	12.05	232630	8353
18	9/24/2014	90	5	6.04	12.07	218920	7641
19	7/7/2014	7	1	5.98	11.98	189270	6750
19	7/7/2014	7	2	6.00	12.07	179700	6366
19	7/7/2014	7	3	6.02	12.12	197600	6943
19	7/7/2014	7	4	5.98	12.05	206220	7354
19	7/7/2014	7	5	6.01	12.05	189670	6697
19	7/14/2014	14	1	6.02	12.10	217700	7660
19	7/14/2014	14	2	5.98	12.02	225190	8031
19	7/14/2014	14	3	5.92	12.02	229330	8330
19	7/14/2014	14	4	6.03	12.15	223790	7836
19	7/14/2014	14	5	5.95	12.05	223680	8043
19	7/28/2014	28	1	5.99	12.00	237520	8444
19	7/28/2014	28	2	6.01	12.07	216800	7642
19	7/28/2014	28	3	6.03	11.97	229260	8027
19	7/28/2014	28	4	5.94	12.05	236760	8544
19	7/28/2014	28	5	6.04	12.12	243950	8527
19	9/28/2014	90	1	5.96	12.00	263090	9430
19	9/28/2014	90	2	5.95	12.05	259820	9343

Table A- 3. Compressive strength test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Load at failure (lb)	Compressive strength, psi
19	9/28/2014	90	3	5.94	12.05	260260	9406
19	9/28/2014	90	4	5.99	12.03	275410	9773
19	9/28/2014	90	5	5.97	12.02	266910	9536
20	7/9/2014	7	1	6.04	12.05	163020	5690
20	7/9/2014	7	2	6.09	12.10	169210	5819
20	7/9/2014	7	3	6.02	12.08	159300	5597
20	7/9/2014	7	4	6.04	12.13	160300	5603
20	7/9/2014	7	5	6.01	12.15	167400	5911
20	7/16/2014	14	1	6.02	12.13	203230	7141
20	7/16/2014	14	2	6.02	12.18	211640	7447
20	7/16/2014	14	3	6.03	12.22	209670	7341
20	7/16/2014	14	4	6.02	12.17	212150	7457
20	7/16/2014	14	5	6.03	12.20	206080	7216
20	7/30/2014	28	1	6.03	12.13	228810	8026
20	7/30/2014	28	2	6.03	12.25	228340	8009
20	7/30/2014	28	3	6.06	12.10	228280	7915
20	7/30/2014	28	4	6.03	12.13	223460	7838
20	7/30/2014	28	5	6.02	12.15	220570	7750
20	9/30/2014	90	1	6.05	12.13	247160	8597
20	9/30/2014	90	2	6.04	12.15	227180	7941
20	9/30/2014	90	3	6.05	12.13	247010	8607
20	9/30/2014	90	4	6.03	12.13	249110	8722
20	9/30/2014	90	5	6.02	12.10	254600	8946

Table A- 4. Elastic modulus and poisson's ratio test results

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Modulus of elasticity (psi)	Poisson's ratio
1	4/23/2014	7	7	6.01	12.16	5150000	0.16
1	4/23/2014	7	8	5.98	12.18	5200000	0.15
1	4/23/2014	7	9	5.99	12.23	5400000	0.16
1	4/30/2014	14	13	6.02	0.00	5450000	0.18
1	4/30/2014	14	14	6.03	0.00	5100000	0.10
1	4/30/2014	14	15	6.01	0.00	5800000	0.16
1	5/14/2014	28	19	6.02	12.27	6100000	0.16
1	5/14/2014	28	20	6.02	12.32	5600000	0.17
1	5/14/2014	28	21	6.01	12.36	5950000	0.18
1	7/15/2014	90	25	6.00	12.27	5600000	0.15
1	7/15/2014	90	26	6.02	12.27	5850000	0.18
1	7/15/2014	90	27	5.99	12.22	6650000	0.24

Table A- 4. Elastic modulus and poisson's ratio test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Modulus of elasticity (psi)	Poisson's ratio
2	4/25/2014	7	7	5.98	12.27	5000000	0.14
2	4/25/2014	7	8	5.96	12.22	4950000	0.14
2	4/25/2014	7	9	5.95	12.27	4900000	0.14
2	5/2/2014	14	13	5.97	12.25	4950000	0.14
2	5/2/2014	14	14	5.97	12.24	4850000	0.16
2	5/2/2014	14	15	5.98	12.17	5000000	0.14
2	5/16/2014	28	19	5.98	12.17	5100000	0.16
2	5/16/2014	28	20	5.97	12.21	5500000	0.16
2	5/16/2014	28	21	5.99	12.24	5100000	0.16
2	7/17/2014	90	25	5.98	12.34	5450000	0.14
2	7/17/2014	90	26	5.97	12.38	6050000	0.17
2	7/17/2014	90	27	5.98	12.37	5600000	0.16
3	5/9/2014	7	7	5.95	12.24	5150000	0.15
3	5/9/2014	7	8	5.96	12.33	5200000	0.15
3	5/9/2014	7	9	5.97	12.34	5000000	0.16
3	5/16/2014	14	13	5.97	12.21	6200000	0.14
3	5/16/2014	14	14	6.01	12.17	5750000	0.18
3	5/16/2014	14	15	5.97	12.20	5500000	0.14
3	5/30/2014	28	19	5.97	12.19	6400000	0.15
3	5/30/2014	28	20	5.98	12.18	6650000	0.14
3	5/30/2014	28	21	5.97	12.24	5950000	0.14
3	7/31/2014	90	25	5.96	12.19	5950000	0.13
3	7/31/2014	90	26	5.96	12.21	5250000	0.14
3	7/31/2014	90	27	5.97	12.25	5850000	0.12
4	5/12/2014	7	7	5.97	12.26	5200000	0.14
4	5/12/2014	7	8	5.95	12.27	5400000	0.16
4	5/12/2014	7	9	5.95	12.19	5050000	0.16
4	5/19/2014	14	13	5.99	12.27	5450000	0.17
4	5/19/2014	14	14	5.97	12.20	5650000	0.16
4	5/19/2014	14	15	6.00	12.26	5350000	0.18
4	6/2/2014	28	19	5.96	12.18	5600000	0.13
4	6/2/2014	28	20	5.92	12.20	6150000	0.16
4	6/2/2014	28	21	5.94	12.18	6050000	0.17
4	8/3/2014	90	25	5.93	12.24	6350000	0.17
4	8/3/2014	90	26	5.92	12.24	6000000	0.18
4	8/3/2014	90	27	5.92	12.35	6400000	0.16
5	5/14/2014	7	7	6.01	12.27	4650000	0.19
5	5/14/2014	7	8	6.00	12.24	5050000	0.21
5	5/14/2014	7	9	6.02	12.33	5150000	0.22
5	5/21/2014	14	13	6.02	12.25	5250000	0.20
5	5/21/2014	14	14	5.96	12.17	5600000	0.22
5	5/21/2014	14	15	5.96	12.21	5850000	0.21
5	6/4/2014	28	19	6.02	12.19	5750000	0.21
5	6/4/2014	28	20	6.00	12.22	5300000	0.17
5	6/4/2014	28	21	6.00	12.24	5400000	0.19
5	8/5/2014	90	25	6.02	12.35	5550000	0.20
5	8/5/2014	90	26	6.00	12.26	5950000	0.23

Table A- 4. Elastic modulus and poisson's ratio test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Modulus of elasticity (psi)	Poisson's ratio
5	8/5/2014	90	27	6.00	12.29	6000000	0.22
6	5/16/2014	7	7	6.02	12.26	5750000	0.23
6	5/16/2014	7	8	6.01	12.22	5450000	0.24
6	5/16/2014	7	9	5.97	12.17	4800000	0.21
6	5/23/2014	14	13	5.94	12.16	5250000	0.19
6	5/23/2014	14	14	6.03	12.22	5500000	0.19
6	5/23/2014	14	15	6.02	12.30	4750000	0.19
6	6/6/2014	28	19	6.03	12.29	5050000	0.19
6	6/6/2014	28	20	6.03	12.24	5650000	0.22
6	6/6/2014	28	21	6.03	12.28	5500000	0.19
6	8/7/2014	90	25	6.02	12.29	7000000	0.22
6	8/7/2014	90	26	6.02	12.29	6350000	0.21
6	8/7/2014	90	27	6.04	12.25	6000000	0.19
7	5/20/2014	7	7	6.04	12.26	4750000	0.18
7	5/20/2014	7	8	6.00	12.24	5050000	0.18
7	5/20/2014	7	9	6.03	12.20	5400000	0.20
7	5/27/2014	14	13	6.00	12.30	5750000	0.19
7	5/27/2014	14	14	6.03	12.27	5450000	0.20
7	5/27/2014	14	15	6.01	12.20	5700000	0.20
7	6/10/2014	28	19	6.04	12.24	5550000	0.20
7	6/10/2014	28	20	6.01	12.20	6650000	0.24
7	6/10/2014	28	21	6.04	12.18	6900000	0.24
7	8/11/2014	90	25	6.02	12.27	6100000	0.22
7	8/11/2014	90	26	6.02	12.30	5950000	0.21
7	8/11/2014	90	27	6.03	12.27	6400000	0.22
8	5/22/2014	7	7	5.96	12.26	5350000	0.20
8	5/22/2014	7	8	5.93	12.28	5450000	0.21
8	5/22/2014	7	9	5.95	12.22	5300000	0.22
8	5/29/2014	14	13	6.00	12.21	5050000	0.19
8	5/29/2014	14	14	5.92	12.19	5750000	0.19
8	5/29/2014	14	15	5.97	12.23	6350000	0.23
8	6/12/2014	28	19	5.97	12.21	5800000	0.21
8	6/12/2014	28	20	5.99	12.24	5100000	0.19
8	6/12/2014	28	21	5.95	12.25	5350000	0.17
8	8/13/2014	90	25	5.98	12.27	6000000	0.22
8	8/13/2014	90	26	5.98	12.23	5700000	0.23
8	8/13/2014	90	27	5.93	12.24	6050000	0.22
9	5/26/2014	7	7	5.98	12.24	7100000	0.22
9	5/26/2014	7	8	5.98	12.25	6700000	0.21
9	5/26/2014	7	9	5.95	12.33	6700000	0.24
9	6/2/2014	14	13	5.99	12.26	6450000	0.17
9	6/2/2014	14	14	5.95	12.19	6850000	0.22
9	6/2/2014	14	15	5.97	12.23	6800000	0.21
9	6/16/2014	28	19	6.04	12.38	6500000	0.21
9	6/16/2014	28	20	6.02	12.23	6550000	0.20
9	6/16/2014	28	21	5.95	12.22	7000000	0.22
9	8/17/2014	90	25	6.03	12.20	7300000	0.25

Table A- 4. Elastic modulus and poisson's ratio test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Modulus of elasticity (psi)	Poisson's ratio
9	8/17/2014	90	26	6.01	12.17	6350000	0.20
9	8/17/2014	90	27	5.94	0.00	6950000	0.23
10	5/28/2014	7	7	6.04	12.29	6600000	0.21
10	5/28/2014	7	8	6.03	12.25	6150000	0.20
10	5/28/2014	7	9	6.04	12.23	6850000	0.23
10	6/4/2014	14	13	5.95	12.21	5850000	0.18
10	6/4/2014	14	14	5.93	12.16	5850000	0.19
10	6/4/2014	14	15	5.98	12.17	6450000	0.20
10	6/18/2014	28	19	5.96	12.19	6100000	0.20
10	6/18/2014	28	20	6.01	12.24	6650000	0.22
10	6/18/2014	28	21	6.02	12.25	7000000	0.24
10	8/19/2014	90	25	5.96	12.27	6800000	0.22
10	8/19/2014	90	26	6.01	12.21	6400000	0.19
10	8/19/2014	90	27	6.02	12.28	7300000	0.24
11	6/3/2014	7	7	6.02	12.27	5750000	0.19
11	6/3/2014	7	8	6.04	12.37	6600000	0.22
11	6/3/2014	7	9	6.03	12.25	5950000	0.18
11	6/10/2014	14	13	5.99	12.20	7000000	0.21
11	6/10/2014	14	14	6.02	12.26	6900000	0.24
11	6/10/2014	14	15	6.04	12.26	6650000	0.22
11	6/24/2014	28	19	6.05	12.24	6750000	0.20
11	6/24/2014	28	20	6.03	12.28	6600000	0.21
11	6/24/2014	28	21	5.99	12.21	6600000	0.22
11	8/25/2014	90	25	6.03	12.55	6550000	0.21
11	8/25/2014	90	26	6.02	12.40	6300000	0.21
11	8/25/2014	90	27	5.99	12.39	7200000	0.24
12	6/9/2014	7	7	6.02	12.25	6150000	0.21
12	6/9/2014	7	8	6.04	12.29	6450000	0.25
12	6/9/2014	7	9	6.01	12.28	6800000	0.25
12	6/16/2014	14	13	6.02	12.28	5750000	0.19
12	6/16/2014	14	14	6.03	12.42	6300000	0.20
12	6/16/2014	14	15	6.03	12.25	6200000	0.22
12	6/30/2014	28	19	6.05	12.24	6600000	0.24
12	6/30/2014	28	20	6.05	12.31	6700000	0.23
12	6/30/2014	28	21	6.02	12.36	6350000	0.22
12	8/31/2014	90	25	6.04	12.37	6500000	0.21
12	8/31/2014	90	26	6.04	12.22	7650000	0.26
12	8/31/2014	90	27	6.01	12.28	7000000	0.23
13	6/16/2014	7	7	6.03	12.29	6600000	0.16
13	6/16/2014	7	8	5.98	12.25	7450000	0.15
13	6/16/2014	7	9	5.98	12.23	6100000	0.14
13	6/23/2014	14	13	5.98	12.16	6050000	0.15
13	6/23/2014	14	14	6.01	12.33	6550000	0.14
13	6/23/2014	14	15	6.04	12.26	6850000	0.15
13	7/7/2014	28	19	5.93	12.25	6450000	0.14
13	7/7/2014	28	20	6.04	12.24	5950000	0.21
13	7/7/2014	28	21	6.00	12.24	7350000	0.15

Table A- 4. Elastic modulus and poisson's ratio test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Modulus of elasticity (psi)	Poisson's ratio
13	9/7/2014	90	25	5.93	12.22	6900000	0.15
13	9/7/2014	90	26	6.02	12.21	6550000	0.13
13	9/7/2014	90	27	6.00	12.17	6400000	0.14
14	6/19/2014	7	7	6.04	12.23	5550000	0.13
14	6/19/2014	7	8	6.03	12.23	6400000	0.14
14	6/19/2014	7	9	6.02	12.24	6050000	0.17
14	6/26/2014	14	13	6.05	12.24	5550000	0.11
14	6/26/2014	14	14	6.03	12.25	5650000	0.12
14	6/26/2014	14	15	6.02	12.27	5650000	0.14
14	7/10/2014	28	19	6.02	12.23	6600000	0.13
14	7/10/2014	28	20	6.02	12.24	6700000	0.15
14	7/10/2014	28	21	6.00	12.25	6400000	0.15
14	9/10/2014	90	25	6.02	12.30	7250000	0.14
14	9/10/2014	90	26	6.01	12.34	6700000	0.14
14	9/10/2014	90	27	6.00	12.24	6600000	0.14
15	6/23/2014	7	7	6.06	12.28	6100000	0.11
15	6/23/2014	7	8	6.05	12.29	6500000	0.13
15	6/23/2014	7	9	6.01	12.28	7800000	0.16
15	6/30/2014	14	13	6.01	12.21	6750000	0.11
15	6/30/2014	14	14	6.02	12.25	6200000	0.13
15	6/30/2014	14	15	6.06	12.27	6750000	0.11
15	7/14/2014	28	19	5.97	12.13	6450000	0.16
15	7/14/2014	28	20	6.02	12.24	6500000	0.18
15	7/14/2014	28	21	6.03	12.21	7050000	0.21
15	9/14/2014	90	25	5.98	12.29	7100000	0.16
15	9/14/2014	90	26	6.02	12.20	7150000	0.14
15	9/14/2014	90	27	6.03	12.24	6750000	0.14
16	6/25/2014	7	7	6.03	12.42	6850000	0.16
16	6/25/2014	7	8	6.03	12.48	6450000	0.15
16	6/25/2014	7	9	6.03	12.43	5750000	0.12
16	7/2/2014	14	13	6.01	12.34	6550000	0.16
16	7/2/2014	14	14	6.05	12.22	6650000	0.16
16	7/2/2014	14	15	5.98	12.25	6850000	0.18
16	7/16/2014	28	19	6.02	12.35	7450000	0.14
16	7/16/2014	28	20	6.03	12.36	7550000	0.14
16	7/16/2014	28	21	5.97	12.28	7600000	0.16
16	9/16/2014	90	25	6.02	12.28	6250000	0.14
16	9/16/2014	90	26	6.01	12.25	6700000	0.13
16	9/16/2014	90	27	5.96	12.25	6850000	0.14
17	7/1/2014	7	7	5.96	12.19	5450000	0.15
17	7/1/2014	7	8	6.03	12.26	5450000	0.15
17	7/1/2014	7	9	5.96	12.15	5100000	0.15
17	7/8/2014	14	13	5.97	0.00	5900000	0.16
17	7/8/2014	14	14	6.02	0.00	6200000	0.18
17	7/8/2014	14	15	5.98	0.00	5600000	0.14
17	7/22/2014	28	19	5.97	12.20	5650000	0.13
17	7/22/2014	28	20	5.95	12.21	6000000	0.14

Table A- 4. Elastic modulus and poisson's ratio test results, Cont.

MIX_ID	Test date	Age (days)	Sample replicate number	Specimen diameter (inch)	Specimen height (inch)	Modulus of elasticity (psi)	Poisson's ratio
17	7/22/2014	28	21	5.96	12.21	5850000	0.16
17	9/22/2014	90	25	5.97	12.21	6600000	0.17
17	9/22/2014	90	26	5.95	12.19	5950000	0.14
17	9/22/2014	90	27	5.93	12.19	5900000	0.15
18	7/3/2014	7	7	5.96	12.16	4950000	0.16
18	7/3/2014	7	8	5.98	12.16	5100000	0.14
18	7/3/2014	7	9	5.98	12.22	4750000	0.16
18	7/10/2014	14	13	6.01	12.17	5400000	0.17
18	7/10/2014	14	14	6.01	12.20	5350000	0.16
18	7/10/2014	14	15	5.98	12.14	5250000	0.15
18	7/24/2014	28	19	5.98	12.18	5450000	0.14
18	7/24/2014	28	20	5.98	12.30	6050000	0.16
18	7/24/2014	28	21	5.98	12.21	5600000	0.16
18	9/24/2014	90	25	6.00	12.19	6000000	0.15
18	9/24/2014	90	26	6.00	12.25	5800000	0.14
18	9/24/2014	90	27	5.98	12.27	5400000	0.13
19	7/7/2014	7	7	6.02	12.38	5750000	0.15
19	7/7/2014	7	8	5.98	12.29	5850000	0.15
19	7/7/2014	7	9	6.01	12.21	5700000	0.15
19	7/14/2014	14	13	5.92	12.14	5550000	0.15
19	7/14/2014	14	14	6.03	12.27	5700000	0.17
19	7/14/2014	14	15	5.95	12.29	6200000	0.20
19	7/28/2014	28	19	6.03	12.22	6000000	0.14
19	7/28/2014	28	20	5.94	12.29	6200000	0.15
19	7/28/2014	28	21	6.04	12.29	6550000	0.15
19	9/28/2014	90	25	6.02	12.22	7100000	0.15
19	9/28/2014	90	26	5.93	12.23	6000000	0.12
19	9/28/2014	90	27	6.04	12.24	6250000	0.10
20	7/9/2014	7	7	6.02	12.34	4850000	0.17
20	7/9/2014	7	8	6.04	12.34	5500000	0.16
20	7/9/2014	7	9	6.01	12.33	5700000	0.15
20	7/16/2014	14	13	6.03	12.45	5650000	0.16
20	7/16/2014	14	14	6.02	12.43	5700000	0.13
20	7/16/2014	14	15	6.03	12.45	5750000	0.17
20	7/30/2014	28	19	6.06	12.27	5800000	0.15
20	7/30/2014	28	20	6.03	12.28	6600000	0.16
20	7/30/2014	28	21	6.02	12.30	5050000	0.14
20	9/30/2014	90	25	6.05	12.33	7150000	0.19
20	9/30/2014	90	26	6.03	12.35	6050000	0.16
20	9/30/2014	90	27	6.03	12.26	5900000	0.12

Table A- 5. Length change at different ages, psi

MIX_ID	Sample ID	1 day	7 days	10 days	11 days	12 days	14 days	21 days	35 days	@63 days	119 days
1	A	0.0072	0.003			-0.005	-0.006	-0.01	-0.015	-0.023	-0.03
1	B	0.004	0.003			-0.004	-0.006	-0.009	-0.014	-0.022	-0.031
1	C	0.0869	0.002			-0.006	-0.008	-0.012	-0.017	-0.025	-0.034
1	D	-0.0063	0.003			-0.004	-0.006	-0.01	-0.015	-0.021	-0.029
2	A	-0.0379	0.003		-0.005		-0.008	-0.012	-0.019	-0.027	-0.031
2	B	0.0003	0.004		-0.005		-0.006	-0.01	-0.018	-0.025	-0.032
2	C	-0.0024	0.004		-0.005		-0.007	-0.013	-0.019	-0.028	-0.033
2	D	-0.0381	0.005		-0.004		-0.007	-0.01	-0.018	-0.026	-0.031
3	A	-0.0353	0.002		-0.006		-0.011	-0.011	-0.018	-0.024	-0.03
3	B	-0.0162	0.005		-0.004		-0.01	-0.01	-0.018	-0.023	-0.03
3	C	-0.0215	0.005		-0.005		-0.009	-0.011	-0.017	-0.023	-0.029
3	D	-0.0145	0.004		-0.007		-0.011	-0.012	-0.019	-0.024	-0.031
4	A	-0.0421	0.006		-6.9E-17		-0.003	-0.004	-0.007	-0.01	-0.018
4	B	-0.0098	0.005		-0.001		-0.003	-0.004	-0.007	-0.01	-0.017
4	C	-0.0171	0.006		-0.001		-0.002	-0.002	-0.005	-0.007	-0.014
4	D	0.0057	0.009		0.001		0.001	-1.4E-16	-0.005	-0.008	-0.014
5	A	0.001	0.003			-0.007	-0.009	-0.013	-0.02	-0.025	-0.031
5	B	0.0055	0.002			-0.008	-0.011	-0.014	-0.022	-0.028	-0.034
5	C	0.0038	0.004			-0.007	-0.009	-0.013	-0.021	-0.025	-0.033
5	D	-0.0135	0.002			-0.008	-0.011	-0.015	-0.022	-0.026	-0.033
6	A	-0.0445	0.001		-0.008		-0.01	-0.016	-0.023	-0.027	-0.034
6	B	-0.0569	0.005		-0.004		-0.006	-0.013	-0.02	-0.024	-0.031
6	C	-0.011	0.001		-0.007		-0.01	-0.017	-0.024	-0.029	-0.035
6	D	-0.0391	0.001		-0.007		-0.01	-0.017	-0.024	-0.028	-0.035
7	A	0.0119	0.009	0			-0.008	-0.016	-0.024	-0.029	-0.034
7	B	-0.0524	0.003	-0.007			-0.014	-0.021	-0.03	-0.034	-0.039
7	C	-0.0297	0.003	-0.007			-0.015	-0.022	-0.031	-0.036	-0.041
7	D	-0.0242	0.002	-0.007			-0.014	-0.021	-0.029	-0.034	-0.039
8	A	-0.0299	0.005		-0.004		-0.006	-0.01	-0.014	-0.019	-0.024
8	B	-0.0365	0.004		-0.004		-0.007	-0.01	-0.014	-0.019	-0.025
8	C	-0.0499	0.006		-0.002		-0.004	-0.009	-0.012	-0.016	-0.021
8	D	-0.0308	0.006		-0.003		-0.006	-0.009	-0.013	-0.018	-0.024

Table A- 5. Length change at different ages, Cont.

MIX_ID	Sample ID	1 day	7 days	10 days	11 days	12 days	14 days	21 days	35 days	@63 days	119 days
9	A	-0.0215	0.001		-0.009		-0.011	-0.015	-0.019	-0.024	-0.028
9	B	-0.0191	0.003		-0.005		-0.007	-0.012	-0.014	-0.018	-0.023
9	C	-0.0233	0.001		-0.008		-0.01	-0.014	-0.017	-0.022	-0.026
9	D	-0.033	0.001		-0.009		-0.01	-0.014	-0.018	-0.023	-0.028
10	A	-0.0628	0.004	-0.004			-0.009	-0.013	-0.018	-0.023	-0.027
10	B	-0.0069	0.001	-0.006			-0.011	-0.014	-0.019	-0.024	-0.027
10	C	-0.0208	0.004	-0.004			-0.008	-0.012	-0.016	-0.021	-0.024
10	D	-0.0437	0.003	-0.004			-0.009	-0.013	-0.017	-0.023	-0.027
11	A	-0.008	0.003	-0.006			-0.012	-0.019	-0.024	-0.029	-0.032
11	B	-0.008	0.003	-0.004			-0.012	-0.018	-0.025	-0.031	-0.034
11	C	-0.0412	0.001	-0.007			-0.014	-0.021	-0.027	-0.032	-0.036
11	D	-0.0218	0.003	-0.006			-0.012	-0.019	-0.025	-0.031	-0.034
12	A	-0.0277	0.003		-0.006		-0.007	-0.009	-0.013	-0.017	-0.022
12	B	-0.0077	0.007		-0.002		-0.004	-0.005	-0.01	-0.014	-0.019
12	C	-0.0302	0.005		-0.004		-0.005	-0.008	-0.011	-0.016	-0.022
12	D	-0.0213	0.004		-0.003		-0.005	-0.007	-0.011	-0.015	-0.019
13	A	-0.044	-0.001		-0.008		-0.01	-0.012	-0.018	-0.027	-0.032
13	B	-0.0206	1.39E-16		-0.007		-0.009	-0.011	-0.016	-0.023	-0.028
13	C	0.0044	0		-0.008		-0.01	-0.013	-0.018	-0.026	-0.031
13	D	-0.0541	6.94E-17		-0.008		-0.009	-0.012	-0.017	-0.025	-0.03
14	A	-0.0462	0.001		-0.004		-0.008	-0.011	-0.016	-0.023	
14	B	-0.0215	0.002		-0.002		-0.007	-0.01	-0.015	-0.02	
14	C	-0.0182	0.001		-0.004		-0.007	-0.01	-0.014	-0.02	
14	D	-0.028	0.001		-0.004		-0.008	-0.011	-0.017	-0.024	
15	A	-0.03	0.001		-0.009		-0.012	-0.016	-0.021	-0.026	
15	B	-0.0187	0.001		-0.008		-0.011	-0.015	-0.021	-0.027	
15	C	-0.0193	0.001		-0.008		-0.01	-0.015	-0.02	-0.026	
15	D	-0.0581	6.94E-17		-0.009		-0.011	-0.015	-0.02	-0.024	
16	A	-0.0041	0.006	0			-0.002	-0.004	-0.007	-0.01	
16	B	-0.0205	0.004	-0.002			-0.005	-0.006	-0.009	-0.013	
16	C	-0.0413	0.005	-0.001			-0.004	-0.004	-0.007	-0.011	
16	D	-0.0241	0.005	-0.001			-0.002	-0.004	-0.008	-0.011	
17	A	-0.0095	0.002	-0.003			-0.006	-0.01	-0.017	-0.023	

Table A- 5. Length change at different ages, Cont.

MIX_ID	Sample ID	1 day	7 days	10 days	11 days	12 days	14 days	21 days	35 days	@63 days	119 days
17	B	-0.047	0.002	-0.002			-0.005	-0.01	-0.014	-0.021	
17	C	-0.0394	0.002	-0.003			-0.006	-0.01	-0.016	-0.023	
17	D	-0.0196	0.002	-0.002			-0.004	-0.009	-0.015	-0.021	
18	A	-0.0082	0.001		-0.007		-0.008	-0.012	-0.019	-0.025	
18	B	-0.0273	0.001		-0.007		-0.008	-0.012	-0.018	-0.023	
18	C	-0.0242	0.001		-0.007		-0.009	-0.014	-0.019	-0.026	
18	D	-0.017	0.001		-0.006		-0.008	-0.012	-0.017	-0.023	
19	A	-0.0239	0.003		-0.004		-0.007	-0.011	-0.017	-0.025	
19	B	-0.0223	0.003		-0.004		-0.008	-0.012	-0.017	-0.025	
19	C	-0.0218	0.002		-0.006		-0.009	-0.014	-0.02	-0.027	
19	D	-0.0342	0.003		-0.004		-0.008	-0.012	-0.018	-0.026	
20	A	-0.0298	0.002			-0.003	-0.003	-0.005	-0.007	-0.011	
20	B	-0.0323	0.004			-0.002	-0.002	-0.004	-0.006	-0.01	
20	C	-0.0126	0.002			-0.003	-0.004	-0.006	-0.008	-0.011	
20	D	-0.0122	0.003			-0.003	-0.003	-0.005	-0.006	-0.011	

Table A- 6. Coefficient of thermal expansion measurements

MIX_ID	Sample _ID	Length (mm)	Weight (grams)			CTE (in/in/°C)	CTE (in/in/°F)
			Initial	2nd day	3rd day		
1	1-41	177.6	3340.5	3340.8	3340.9	11.83	6.57
1	1-42	180.3	3385.5	3385.3	3385.7	11.85	6.58
2	2-41	178.8	3278.3	3278.6	3278.7	11.63	6.46
2	2-42	179.6	3312.3	3312.6	3312.8	11.69	6.49
3	3-41	177.9	3357.5	3361.8	3362.6	12.74	7.08
3	3-42	177.0	3295.8	3299.1	3300.0	12.24	6.80
4	4-41	177.8	3360.7	3363.6	3364.0	12.26	6.81
4	4-42	178.8	3380.2	3382.2	3382.9	12.29	6.83
5	5-41	179.8	3489.4	3489.8	3490.3	9.07	5.04
5	5-42	177.9	3473.9	3474.5	3475.0	9.01	5.01
6	6-41	178.8	3464.6	3464.8	3464.9	8.90	4.94
6	6-42	177.8	3442.1	3442.6	3442.8	9.06	5.04
7	7-41	179.1	3456.8	3461.0	3461.2	9.57	5.32
7	7-42	179.2	3477.5	3481.9	3482.5	9.11	5.06
8	8-41	177.7	3434.5	3434.8	3435.0	9.33	5.18
8	8-42	177.4	3429.3	3429.8	3429.7	9.58	5.32
9	9-41	177.1	3560.8	3561.5		8.38	4.65
9	9-42	178.0	3560.0	3561.0		8.38	4.65
10	10-41	176.1	3501.4	3501.5	350.6	8.86	4.92
10	10-42	176.0	3499.3	3499.7	3500.0	8.64	4.80
11	11-41	178.1	3561.5	3565.0	3565.7	9.47	5.26
11	11-42	178.3	3543.3	3546.9	3547.5	9.03	5.02
12	12-41	178.2	3524.3	3524.1	3524.7	9.45	5.25
12	12-42	178.2	3525.0	3525.1	3525.6	9.60	5.33
13	13-41	179.0	3454.7	3455.5	3456.2	12.28	6.82
13	13-42	180.1	3491.1	3491.9	3492.5	12.28	6.82
14	14-41	177.4	3432.8	3434.3	3434.7	12.17	6.76
14	14-42	177.6	3452.2	3453.4	3453.9	12.12	6.73
15	15-41	177.3	3452.8	3453.1		12.22	6.79
15	15-42	177.7	3456.0	3456.3		12.24	6.80
16	16-41	177.6	3440.1	3440.1		12.75	7.08
16	16-42	177.5	2450.9	3451.1		12.22	6.79
17	17-41	177.2	3378.3	3381.1	3381.0	12.06	6.70
17	17-42	176.8	3355.8	3358.2	3358.4	11.91	6.62
18	18-41	177.0	3385.8	3386.3	3386.4	11.85	6.58
18	18-42	177.5	3370.7	3371.3	3371.6	11.79	6.55
19	19-41	177.7	3389.9	3391.2	3392.1	12.10	6.72
19	19-42	177.8	3404.3	3405.7	3406.4	12.14	6.74
20	20-41	177.4	3417.2	3418.6	3418.9	12.35	6.86
20	20-42	178.1	3427.7	3429.1	3429.1	12.28	6.82