Task 4: Testing Iowa Portland Cement Concrete Mixtures for the AASHTO Mechanistic-Empirical Pavement Design Procedure

National Concrete Pavement Technology Center

CP Tech Center

Final Report
May 2008

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16. Abstract

The present research project was designed to identify the typical Iowa material input values that are required by the Mechanistic-Empirical Pavement Design Guide (MEPDG) for the Level 3 concrete pavement design. It was also designed to investigate the existing equations that might be used to predict Iowa pavement concrete for the Level 2 pavement design.

In this project, over 20,000 data were collected from the Iowa Department of Transportation (DOT) and other sources. These data, most of which were concrete compressive strength, slump, air content, and unit weight data, were synthesized and their statistical parameters (such as the mean values and standard variations) were analyzed. Based on the analyses, the typical input values of Iowa pavement concrete, such as 28-day compressive strength (f'_c), splitting tensile strength (f_{sp}), elastic modulus (E_c), and modulus of rupture (MOR), were evaluated. The study indicates that the 28-day MOR of Iowa concrete is 646 ± 51 psi, very close to the MEPDG default value (650 psi). The 28-day E_c of Iowa concrete (based only on two available data of the Iowa Curling and Warping project) is $4.82 \pm 0.28 \times 10^6$ psi, which is quite different from the MEPDG default value (3.93×10^6 psi); therefore, the researchers recommend re-evaluating after more Iowa test data become available. The drying shrinkage (ε_c) of a typical Iowa concrete (C-3WR-C20 mix) was tested at Concrete Technology Laboratory (CTL). The test results show that the ultimate shrinkage of the concrete is about 454 microstrain and the time for the concrete to reach 50% of ultimate shrinkage is at 32 days; both of these values are very close to the MEPDG default values. The comparison of the Iowa test data and the MEPDG default values, as well as the recommendations on the input values to be used in MEPDG for Iowa PCC pavement design, are summarized in Table 20 of this report.

The available equations for predicting the above-mentioned concrete properties were also assembled. The validity of these equations for Iowa concrete materials was examined. Multiple-parameters nonlinear regression analyses, along with the artificial neural network (ANN) method, were employed to investigate the relationships among Iowa concrete material properties and to modify the existing equations so as to be suitable for Iowa concrete materials. However, due to lack of necessary data sets, the relationships between Iowa concrete properties were established based on the limited data from CP Tech Center's projects and ISU classes only. The researchers suggest that the resulting relationships be used by Iowa pavement design engineers as references only.

The present study furthermore indicates that appropriately documenting concrete properties, including flexural strength, elastic modulus, and information on concrete mix design, is essential for updating the typical Iowa material input values and providing rational prediction equations for concrete pavement design in the future.

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TASK 4: TESTING IOWA PORTLAND CEMENT CONCRETE MIXTURES FOR THE AASHTO MECHANISTIC-EMPIRICAL PAVEMENT DESIGN PROCEDURE

Final Report
May 2008

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EXECUTIVE SUMMARY

In this project, over 20,000 sets of Iowa portland cement concrete (PCC) test data were collected and compiled to be used as the PCC material inputs in the Mechanistic-Empirical Pavement Design Guide (MEPDG). These data were from the Iowa Department of Transportation (Iowa DOT), ten different projects conducted by the National Concrete Pavement Technology Center (CP Tech Center), the Long-Term Pavement Performance (LTPP) database, and the concrete mixes cast and tested in the classes of Iowa State University (ISU). The statistical parameters of these data, such as the mean values and standard variations, were then analyzed and compared with the MEPDG default values. Based on the results of the studies, the recommendations for the Iowa PCC material input values were suggested. In addition, the existing predictive equations that describe the relationships between concrete properties were examined. Modified equations are proposed for their potential uses in the MEPDG Level 2 design of Iowa pavement.

Based on the statistical analyses of the available data, the Iowa typical concrete properties required by MEPDG as the PCC material inputs can be described as follows:

- Unit weight (uw) = 142.7 ± 2.1 pcf
  (330 data from Iowa DOT 15 QMC projects)
- 28-day compressive strength $(f'_c)_{28} = 4397 \pm 638$ psi
  (Data of 1596 samples from Iowa DOT CWRC/QMC mixes after 2000)
- 28-day modulus of rupture $(MOR)_{28}=646 \pm 51$ psi
  (Data of 243 samples from Iowa DOT QMC projects after 2000)
- 28-day elastic modulus $(E_c)_{28} = 4.82 \pm 0.28\text{x}10^6$ psi
  (Only two data available from Iowa curling and warping project)
- 20-year compressive strength (maybe used for overlay design) $(f'_c)_{20y} \approx 7630 \pm 810$ psi
  (22 data from LTPP database and "PVT30", "HSCPP" and "FEBCO" projects)
- 20-year elastic modulus (maybe used for overlay design) $(E_c)_{20y} \approx 4.48 \pm 0.56\text{x}10^6$ psi
  (11 data from LTPP data base and "HSCPP" project)

Due to lack of necessary data sets, the relationships between Iowa concrete properties were established based on the limited data from CP Tech Center's projects and ISU classes only. Based on the linear regression analyses of these data, the following equations are recommended for predicting Iowa concrete properties:

- $f'_{c,t}$ (psi) = -134,119 + 10,300(w/b) + 978(uw) + 125(CMF) + 30.6[log(t)] – 752 (w/b*uw) - 0.865(uw)*(CMF) $(R^2=0.76)$
- $E_c=80{,}811 \bullet f'^{\,0.4659}_c$ $(R^2=0.80)$
- $MOR=12.93 \bullet f'^{\,0.4543}_c$ $(R^2=0.54)$
- $f'_{sp}=1.019 \bullet f'^{\,0.7068}_c$ $(R^2=0.73)$

These relationships can be used by Iowa pavement design engineers as references for Level 2 pavement design.

The typical drying shrinkage value (ε_c) of Iowa concrete was obtained from the samples made with the Iowa C-3WR-C20 mix and tested at Concrete Technology Laboratory (CTL). The test results show that the ultimate shrinkage of the concrete is about 454 microstrain and the time for the concrete to reach 50% of ultimate shrinkage is at 32 days; both of these values are very close to the MEPDG default values.

Table 20, as presented inside the report and also shown below, summarizes the comparison of the default PCC input values from MEPDG and the values from the analyses of Iowa test data. The table also includes recommendations for the Iowa PCC input values to be used in the MEPDG.

It can be noted that the MEPDG default values are frequently recommended for Iowa pavement design. It is because either the differences between the Iowa test values and the MEPDG default values are small or there are no sufficient and completed Iowa test data available to achieve rational values of the corresponding material properties.

Table 1. Comparison of Iowa PCC material properties and MEPDG default values

Level of Design	PCC Property	MEPDG Default Value	Iowa Test Result	Recommended Value
3	Modulus of rupture, MOR (psi)	650	646	As default
	Elastic modulus, E_c (psi)	3,928,941	4,820,000*	Need more research
2	Compressive strength at 7, 14, 28, 90 days	Tested data	Not applicable	Tested data
	20-year to 28-day compressive strength ratio	1.44	~1.6*	As default
1	Elastic modulus at 7, 14, 28, 90 days	Tested data	Not applicable	Tested data
	Modulus of rapture at 7, 14, 28, 90 days	Tested data	Not applicable	Tested data
	20-year to 28-day concrete strength ratio	1.2	~1.6*	As default
3, 2, 1	Ultimate shrinkage, wet curing (microstrain)	491	454*	As default
	Ultimate shrinkage, curing compound (microstrain)	578	Not available	As default
	Reversible shrinkage	50	Not available	As default
	Time to develop 50% of ultimate shrinkage (day)	35	32*	As default

* indicates the value from limited Iowa test data

The present study also suggests that appropriately documenting all commonly used concrete properties (such as slump, unit weight, air, compressive and flexural strength, and elastic modulus), together with the information on concrete mix design, is essential for updating the typical Iowa material input values and providing rational prediction equations for implementing MEPDG in Iowa in the future.

1. INTRODUCTION

1.1 Problem Statement

The Iowa Department of Transportation (Iowa DOT) currently uses the Portland Cement Association (PCA) design method for the portland cement concrete (PCC) pavement, which requires only modulus of rupture (MOR) of PCC materials for erosion and fatigue analysis. This simple design method has served the state of Iowa for many years. However, the method is neither able to assess the pavement serviceability over the design life nor accurately predict the service life of a pavement. Differently, the Mechanistic-Empirical Pavement Design Guide (MEPDG) requires more and reliable material properties, together with traffic and climate conditions, for pavement distress and response analyses, and it permits Iowa DOT engineers to design more durable, functional, and economical pavements.

In the new MEPDG, material properties that characterize concrete thermal behavior, dimension stability, and strength are required for pavement distress and response computations. Thus, the MEPDG provides design engineers with a more accurate prediction for the distress development in a pavement throughout its design life. Currently, many of the material properties required by the MEPDG are not available in Iowa. Although some data may be found in literature, it is not clear whether or not those data are suitable to be incorporated in the MEPDG for the Iowa pavement design when the local materials and mix proportions are used. To properly implement and evaluate the benefits of the new design guide for PCC pavement design in Iowa, it is essential to evaluate all Iowa concrete material properties that are required by the MEPDG.

The importance and needs for providing reliable material properties for properly implementing MEPDG have been well recognized by the researchers and engineers in Iowa. However, limited budget is available for extensive research in this area at this moment. In a consideration that Iowa DOT has collected a large volume of the lab and field data on PCC materials, the present research is therefore focused on compiling and analyzing these existing PCC materials data.

1.2 Research Background

In the MEPDG, user-defined inputs include thermal inputs, mixture inputs, and strength inputs. Within each input parameter, there are three levels of pavement design that require different degrees of reliability on the material property data:

- Level 1 requires material properties to be measured directly from laboratory or field tests. This approach represents the highest practically achievable reliability and normally used for a research test section or very high traffic volume road.
- Level 2 requires material properties to be estimated from the available prediction equations. It is intended to be used for the routine pavement designs.
- Level 3 requires material properties to be approximated using the typical values. This level of design provides relatively low accuracy and would typically be used for the roadways with a low traffic volume.

Based on the MEPDG manual (NCHRG 2004), Table 2 summarized the requirements and testing procedures of PCC material properties input for MEPDG at three different levels. As it was shown, most of the input parameters in Level 1 input need to be obtained from experiment, while Level 3 inputs generally can be estimated from typical or historical value or relate to other parameters such as compressive strength (f'_c). Level 2 inputs can be either from test results or estimation.

Currently, Iowa DOT has a great amount of historical data on average compressive strength of PCC and a certain amount of data on flexural strength and unit weight of PCC, which are highly valuable for the Level 3 design. However, these existing data are not compiled as groups and are not associated with detailed mix proportion information. Therefore, the prediction equations that are required for MEPDG Level 2 can not be directly established based on these existing DOT data. More data from other Iowa projects or studies will be obtained and analyzed, and detail study on the Iowa's PCC data will be conducted to establish the relationships.

Table 2. PCC material inputs required for MEPDG

Thermal Inputs				
General Properties				
	Data Input Level			Procedure
	1	2	3	
Unit Weight	Test Result	Not applicable	Estimated (Typical or historical data)	AASHTO T 121 ASTM C 138
Poisson's Ratio	Test Result	Not applicable	Estimated (Typical or historical data)	ASTM C 469
Thermal Properties				
	Data Input Level			Procedure
	1	2	3	
Coefficient of thermal expansion	Test Result	Estimated from mixture	Estimated (Typical or historical data)	AASHTO TP 60
Thermal Conductivity	Test Result	Test Result	Estimated (Typical or historical data)	ASTM E 1952/ ASTM C 177/ CRD C 044
Heat Capacity	Test Result	Test Result	Estimated (Typical or historical data)	ASTM D 2766/ CRD C 124
Mixture Inputs				
Property	Data Input Level			Procedure
	1	2	3	
PCC Shrinkage	Not applicable	Estimated from mixture and f'c (from test)	Estimated from mixture and f'c (from historical records)	AASHTO T 160 /ASTM C 157
Strength Inputs				
Property	Data Input Level			Procedure
	1	2	3	
Modulus of Elasticity, Ec	Test Result	Correlated to f'c	Correlated to f'c or MOR	ASTM C 469
Modulus of Rupture, MOR	Test Result	Correlated to f'c	Correlated to f'c	AASHTO T 97 / ASTM C 78
Compressive Strength, f'c	Not applicable	Test Result	Test Result	AASHTO T 22 / ASTM C 39
Splitting Tensile, f'sp (CRCP only)	Test Result	Correlated to f'c	Correlated to f'c or MOR	AASHTO T198 ASTM C 496

1.3 Project Objectives

The objectives of the proposed research are as follows:

- To identify typical Iowa material input values for Level 3 design used in MEPDG
- To examine existing predictive equations for Level 2 design of Iowa concrete pavement (if sufficient Iowa data are available)

1.4 Project Tasks

The data analysis in this study is intended to provide design engineers with reliable material values for the Level 3 pavement design using MEPDG. The investigators also use these Iowa material data to fit some existing predictive equations and to determine whether or not recalibrating these equations is necessary for the Level 2 pavement design. Three major tasks are included in present study.

1. Task 1: To compile and analyze the available PCC material property data
   The investigators have received some PCC material property data from Iowa DOT. The existing Iowa DOT data are not compiled as groups and can not be used directly to establish the prediction equations at this moment. The investigators will work closely with the DOT members to analyze these data and to check if all material inputs required by the MEPDG are available and reliable. The data in the long term pavement performance (LTPP) program will also be reviewed and evaluated. Recommendations will be provided for the typical material values to be used in the Level 3 pavement design.
2. Task 2: To examine existing predictive equations
   The investigators will examine existing empirical equations for prediction of material properties, such as elastic modulus (E_c) and modulus of rapture (MOR) as well as unit weight of concrete. The suitability of these equations for Iowa concrete materials will be assessed. If sufficient data are available, modification of these existing prediction equations will be performed based on the Iowa data obtained from Task 1. If there are gaps in the existing Iowa data, the investigators will document them and propose details for the next phase of study.
3. Task 3: To investigate equipment for concrete shrinkage test
   Most PCC data available at Iowa DOT are related to concrete mixtures and strength. Little data are available on concrete shrinkage and thermal properties. The concrete thermal properties have been considered in a separate work plan. Therefore, the investigators propose to send one typical Iowa PCC sample to an appropriate material testing and consulting laboratory to obtain the typical values needed for the MEPDG Level 3 design. The investigators have realized that the sample is unable to cover the range of Iowa PCC. However, this decision was made to reflect the available $20,000 budget for this project. Meanwhile, the investigators will also explore the possibility for purchasing or building the equipment for concrete shrinkage tests at the PCC Pavement Center’s research lab.

2. RESEARCH APPROACH

2.1 Literature Survey

Various researches had been performed to relate the elastic modulus, modulus of rupture, and splitting tensile strength with the concrete compressive strength. Most of existing equations are found to follow the power equation. However, different empirical coefficients were obtained from regression analysis on different testing data. A summary of the predicting equations for these strength parameters will be presented in this study. Generally, these equations are valid only in general terms and specific materials, which indicated that the equations for Iowa data should be obtained in order to provide more reliable predictions.

Studies had also been conducted to predict the compressive strength of concrete from its mix design, curing age, and curing conditions. Due to the same reason that most of these prediction equations and models are based on the regression study from available data, a specific study on Iowa concrete pavement data is necessary to find own regression equation and parameters for reliable Iowa MEPDG inputs.

Drying shrinkage of concrete can be related to concrete composition, environmental condition, and pavement dimension. The prediction equations of the drying shrinkage from concrete mix parameters and environmental conditions will be summarized in present study. The correlation of the ultimate shrinkage strain to the shrinkage at different ages will also be studied.

2.2 Data Collection

As the purpose of this project is to serve the state of Iowa, data were primarily obtained from Iowa DOT and Center for Transportation Research and Education (CTRE) project. A survey was performed to obtain available data (including mix design, fresh concrete properties, and strength data) from both printed materials and project website (http://www.operationsresearch.dot.state.ia.us/reports/reports.html and http://www.ctre.iastate.edu/research/reports.cfm). In addition to these data, more than 19,000 class C core 28-day compressive strength data from the year of 1975 to 2005, 243 modulus of rupture data, and 330 unit weight data were obtained from Iowa DOT and used in present study. The Iowa data from Long-term Pavement Performance (LTPP) program, along with available data from three Iowa projects, were also used to estimate the long term concrete properties at approximate 20 years.

Another major source of the data is test results conducted at two undergraduate courses of Department of Civil, Construction, and Environmental Engineering (CCEE) at Iowa State University (ISU): CE382 – *Design of Concretes* and CE383 – *Design of Portland Cement Concretes*). The class data include fresh and hardened concrete properties from various mix design during 2003–2006. Approximately 64 sets of data with compressive strength and modulus of rupture at 7 days and 28 days were obtained and used in present study.

Table 2 lists all data sources and their abbreviations used in this reports. The detail information on the data is provided in Appendix A.

Table 3. Source of Iowa database

	Source
IA DOT	Iowa DOT test results
CW	"Impact of curling, wrapping, and other early-age behavior on concrete pavement smoothness: Early, frequent, and detailed (EFD) study" project (Ceylan et al. 2005, Kim 2006)
MMO-F	"Materials and Mix optimization procedures for PCC pavement" project (field) (Schlorhotz et al. 2006)
MMO-L	"Materials and Mix optimization procedures for PCC pavement" project (lab)
OGS	"Testing program for the evaluation of co-combustion fly ash produced at Ottumwa generating station Phase 2 (Second Trial Burn)" project (Schlorholtz and Stapp 2005)
IPC	"Investigation into improved pavement curing materials and techniques: Part I (Phases I and II)" project (Wang et al. 2002)
HSCPP	"Effect of higher strength concrete on pavement performance" project (Hansen et al. 2001)
FEQMC	"Field evaluation of quality management Concrete" project (Tymkowicz, 1998)
MTE	"Effect of mix times on PCC properties" project (Cable and McDaniel 1998)
FEBCO	"Field evaluation of bounded concrete overlays" project (Tayabji and Ball 1986)
PVT30	"Performance of various thicknesses of Portland cement concrete pavement – 30-Year report" project (Helmers and Marks 1981)
LTPP	Long-Term Pavement Performance (LTPP) Program - Standard Data Release (SDR) 20.0
CCEE	ISU CCEE CE383/CE383 undergraduate class lab results

Totally, more than 20,000 sets of data were used in the present study. The data include information on concrete compressive strength (f'_c), modulus of rupture (MOR), elastic modulus (E_c), splitting tensile strength (f'_{sp}), Poisson ratio (μ) at different ages (from 12 hours up to 27 years) together with the slump (SL), air % (air), unit weight (uw) of concrete, and concrete mix design information. The number of data used for each concrete property analysis is summarized in Table 4

Table 4. Summary of size of available Iowa database

Source	f'_c	MOR	E_c	f'_{sp}	μ	SL	Air	uw	Age
IA DOT	19006[†]	47[‡]	-	-	-	-	35	330	28d
CW*	2	-	2	2	-	-	2	-	12h, 1d, 2d, 4d, 7d, 28d, 56d
MMO-F	8	-	-	-	-	8	8	8	28d
MMO-L*	48	-	-	-	-	48	48	48	7d
OGS*	10	-	-	-	-	10	10	10	3d, 7d, 28d, 90d
IPC*	4	4	-	-	-	-	-	-	3d, 7d
HSCPP	2	-	2	-	-	-	-	-	22-29 year
FEQMC	12	12	-	-	-	-	-	-	14d, 28d
MTE	26	-	-	-	-	25	25	26	28d
FEBCO	5	-	-	5	-	-	-	-	13 to 21 year
PVT30	6	6	-	-	-	-	6	-	28d, 28 year
LTPP	9	6	9	9	9	-	-	-	14d, 28d, 365d, 7 to 27 year
CCEE*	64	46	-	-	-	51	62	44	7d, 28d
Total No.	19202	121	13	16	9	142	196	466	-

* Data with mix design available

[†] Number of samples

[‡] From 243 samples

2.3 Data Analysis

Based on the characteristic of this project, the main component of present study is to perform the analysis from the obtained data. Two major parts of data analysis were included in present study:

1. Examining relationship between commonly used concrete properties
2. Evaluating factors that affect concrete properties

The JMP software from SAS® was primarily used in performing the statistical analysis for this project. JMP is statistical analysis software dynamically linking statistics with graphics to interactively explore, understand, and visualize data; it is designed for users to discover relationships within their data.

The JMP software includes a data table window for entering and editing data, a broad range of graphical and statistical methods for data analysis, a design of experiments module, options to highlight and display subsets data, a formula editor for each table column, a facility for grouping data and computing summary statistics, special plots, charts, communication capacity for quality improvement techniques, and tools for printing and for moving analyses results between applications. JMP is good for business analysis, scientific research, product design and development, and process improvement. Data distribution, regression modeling, and artificial neural network (ANN) were applied in the statistical analysis within this project through JMP software.

The distribution and average value of 28-day compressive strength, fresh concrete slump, air content, and unit weight were analyzed using the distribution analysis method. Compressive strengths were related to design parameters and fresh concrete test results by using (stepwise) multiple-parameters nonlinear regression method and ANN analyses. The correlation between modulus of rupture, splitting tensile strength, elastic modulus, and compressive strength were analyzed using nonlinear regression analysis method.

2.4 Concrete Drying Shrinkage Test

The concrete drying shrinkage is determined by the length change of mortar or concrete mixtures cast in laboratory and exposed to controlled temperature and humidity conditions. The drying shrinkage test was performed at an appropriate material testing and consulting due to the limitation of budget and time in this project. Only one typical Iowa PCC mix (C-3WR-C20) was studied in present study. The drying shrinkage data from 28 days up to one year will be obtained, and the ultimate drying shrinkage can be calculated accordingly and used as the parameters for the typical C-3WR-C20 concrete. Researches have been conducted to investigate equipment for concrete shrinkage tests and the summary is presented in Appendix C.

3. RESULTS AND DISCUSSION

3.1 General Relationships from Literature Survey

Generally, parameters included in the MEPDG strength inputs (compressive strength, elastic modulus, modulus of rupture, and splitting tensile strength) can be affected by different factors, including concrete mix design, material properties, curing age, and environmental condition. However, due to the difference of the stress-strain mechanism of sample before different kinds of failure, the sensitivity of different strength parameters is different (Neville 1996; Mindess et al. 2003), which is summarized in the following Table 5.

The parameters used in prediction of compressive strength and the relations between different strength data for this project were not only based on the sensitivity of these parameters, but also on the availability of the data. Some of the parameters or conditions, such as curing condition, moisture of specimen, and aggregate type, are not commonly available in current data collection; therefore, they are not included in the data analysis in this study. However, they should be collected or recorded in the future for further study.

Table 5. Factors affecting f'$_c$, E$_c$, and MOR/f'$_{sp}$

	f'$_c$	E$_c$	MOR/f'$_{sp}$	Other comments
Age	++		+	As the age (or the strength level) increases, the ratio of tensile to compressive strength decreases.
w/c	–	–	–	
Density	+			Incomplete compaction and air entrainment, affect the compressive strength more than they do the tensile strength.
Curing	+			Compared to moisture curing, air curing reduces the tensile strength more than it does the compressive strength.
Moisture of specimen	–	+		
Aggregate		Sensitive	Sensitive	Crushed coarse aggregate improves the tensile strength more than it does the compressive strength.

Note: "+" – positive (increase), "-" – negative (decrease), "++" – very significant (positive)

3.1.1 Predictions of Compressive Strength Based on Concrete Mix Design

Tremendous amount of research had been conducted to study the factors affecting concrete compressive strength and to predict it. Generally, compressive strength of concrete can relate to different parameters, including characteristics and proportions of materials (w/c, aggregate content, fine-to-coarse aggregate ratio, cement factor, cementitious materials, and chemical admixtures), curing (curing time and condition), and testing parameters (specimen parameters and loading conditions) (Mindess et al. 2003; Mehta and Monteiro 2005; Neville 1996).

In general, the strength of concrete at a given age and curing condition depend primarily on the w/c and compaction. According to Duff Abram's finding at 1919 (Neville 1996), when concrete is fully compacted, the compressive strength can be taken to be inversely proportional to w/c:

$$f_c = \frac{K_1}{K_2^{\,w/c}} \tag{1}$$

where K_1 and K_2 are empirical constants.

A similar but less used equation was established by Feret in 1896 (Neville 1996), which relates concrete strength to the volumes of water, air, and cement:

$$f_c = K\left(\frac{c}{c+w+a}\right)^2 \tag{2}$$

where c, w, and a are the absolute volumetric proportions of cement, water, and air, respectively, and K is a constant.

Based on these two equations, Colak (Colak, 2006) also established an equation to relate the compressive strength with w/c:

$$f_c = \frac{\alpha \frac{w}{c}}{(\beta + \lambda \frac{w}{c})^n} \tag{3}$$

where α, β, γ and n are empirical constants.

At a given w/c, the porosity of a hydrated cement paste is determined by the degree of cement hydration, time, and humidity are therefore important factors in the hydration process and the strength development of concrete. ACI committee 209 (Mehta and Monteiro 2005) recommends the following relationship for moist-cured concrete made with Type I Portland cement:

$$f_{cm}(t) = f_{c,28}\left(\frac{t}{4 + 0.85t}\right) \tag{4}$$

where t is the age of concrete in days, $f_{cm}(t)$ is the mean compressive strength of concrete at t days, and $f_{c,28}$ is the compressive strength of concrete at 28 days.

For concrete cured at 68°F (20°C), the CEB-FIP Models Code (1990) (Mehta and Monteiro 2005) recommended the following relationship:

$$f_{cm}(t) = \exp\left[s\left(1 - \sqrt{\frac{28}{t/t_1}}\right)\right] f_{cm,28} \tag{5}$$

where $f_{cm,28}$ is the mean compressive strength of concrete at 28 days, s is the coefficient depending on the cement type (s=0.20 for high early strength cements, s=0.25 for normal hardening cement; s=0.38 for slow hardening cements), and t_1 is 1 day.

Due to the complicity of concrete, most of the current prediction models are using artificial neural network (ANN) model (Ni and Wang 2000; Akkurt et al. 2003; Lee 2003). An example shown in Figure 1 indicates that the prediction of compressive strength from ANN analysis can provide a comparable result comparing to the maturity test of concrete. However, the validity of the ANN models in a very high degree depends on the size of the available database.

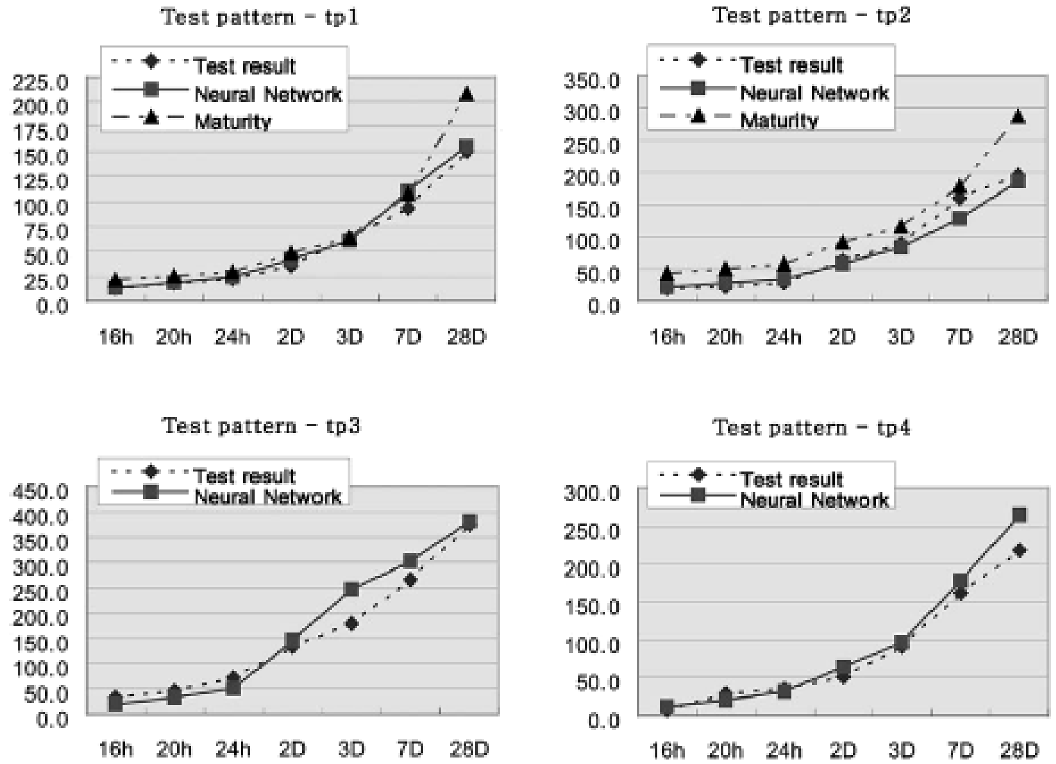


Figure 1. Example of predicted f'$_c$ development by modular ANN (Adopted from Lee 2003)

Other approaches had been performed to predict 7- and 28-day compressive strength of cement paste with chemical composition of cement and 1-day accelerated compressive strength of cement paste and its corresponding ultrasonic pulse velocities and densities (Kheder et al. 2003). Due to limitations of the equipment, this kind of method can not be widely used, and the details of this method will not be included here.

3.1.2 Predictions for Elastic Modulus (E_c) from f'_c

According to ASTM C469, the elastic modulus is measured by recording the load-deformation curve of concrete samples under compression. Comparing with compressive strength measurement, the testing procedure is much more complicated and time consuming. A number of empirical formulae are therefore suggested to relate elastic modulus (E_c) and compressive strength (f'_c), most of them are of the power equation type:

$$E_c = af'^{\,m}_c \tag{6}$$

where E_c is the modulus of elasticity, f'_c is the compressive strength of a standard 6 x 12 in. cylinder sample, and a and m are coefficients which depend on factors such as strength level, aggregate properties, specimen size and shape, etc. This equation can be used to relate elastic modulus and compressive strength or estimate the elastic modulus of concrete when only compressive strength data are available.

Based on numbers of tests, an empirical relationship between compressive strength and modulus of elasticity has been established by ACI (ACI 318, 2005):

$$E_c = 33\rho^{3/2}(f'_c)^{1/2} \tag{7}$$

where E_c is secant modulus of elasticity in psi (at about 45% of the ultimate strength); ρ is the unit weight of concrete in pcf, and f'_c is the compressive strength of concrete.

Due to the reason that the unit weight data are not always available, a more commonly used equation was further obtained according to ACI by assuming a density for normal weight concrete of 145pcf (Mindess et al. 2003):

$$E_c = 57{,}000(f'_c)^{1/2} \tag{8}$$

Some other equations with different empirical coefficients were also obtained by other researchers from different sources of data:

In the CEB-FIP model code, the E_c of normal-weight concrete can be estimated from the following (Mehta and Monteiro 2005):

$$E_c = 275538(f_c)^{1/3} \tag{9}$$

Kim et al. (2002) developed the following equation based on their experimental results:

$$E_c = 77173(f'_c)^{0.46} \tag{10}$$

Turkish standard institute recommends the following relationship (TS500 2000):

$$E_c = 39150(f'_c)^{0.50} + 2030528 \tag{11}$$

Figure 2 presented an example of prediction of elastic modulus from compressive strength from regression analysis. Results showed that the relation between compressive strength and elastic modulus does follow power equation. The accuracy of the prediction, however, depends on the parameters determined from regression analysis.

Most of the mentioned equations were obtained from regression analysis based on different sources of data sets. Recent research (Demir et al. 2006) provided an alternative way by using ANN analysis to relate elastic modulus with compressive stress. A lot of relationships for high-strength concrete had also been studied (ACI 363; Kakizaki et al. 1992). Due to the focus of the study, details of these studies were not considered in present report.

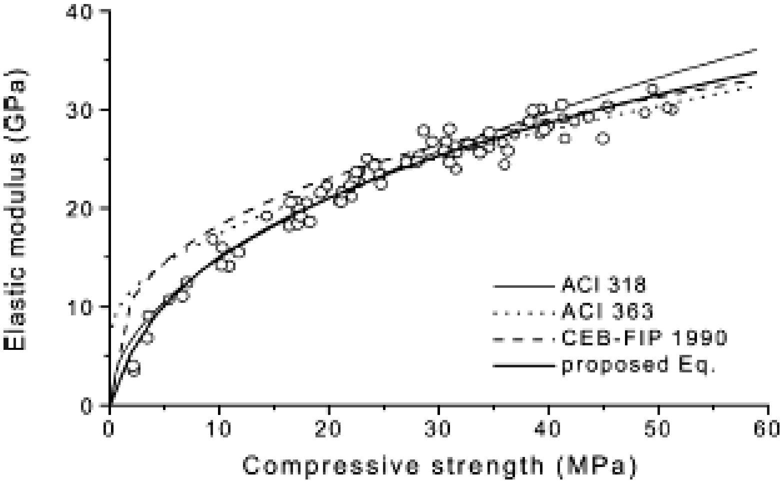


Figure 2. Example of regression curve for elastic modulus (Adopted from Kim 2002)

3.1.3 Predictions for Modulus of Rupture (MOR) from f'_c

It is generally agreed that the theoretical compressive strength was approximately ten times the tensile strength, which implies a fixed relation between these two values. However, it was found that this relation is not a direct proportion. Generally, the ratio of tensile to compressive strengths is lower while the compressive strength increases to higher level (Mindess et al. 2003). Similar to elastic modulus, numbers of empirical formulae have been suggested to relate tensile strength and compressive strength as of the type. Most of these equations are of the power equation type:

$$MOR = bf'^{n}_{c} \tag{12}$$

where b and n are coefficients which depend on factors such as age, strength level, concrete density, aggregate properties, moisture content of specimen, and specimen size and shape.

According to ACI, empirical relationship between compressive strength and modulus of rupture has been established as follows (ACI 318 2005):

$$MOR = 7.5(f'_c)^{1/2} \tag{13}$$

Another equation was obtained on a wider range of data (Mindess et al. 2003):

$$MOR = 2.3(f'_c)^{2/3} \tag{14}$$

Canada (equation [10]) and New Zealand (equation [11]) developed their own codes:

$$MOR = 7.5(f'_c)^{0.5} \tag{15}$$

$$MOR = 9.6(f'_c)^{0.5} \quad (16)$$

Other equations with different empirical coefficients were also obtained by different researchers. Carasquillo et al. (1981) proposed the following expression for concrete strength ranging from 3000 to 12000 psi:

$$MOR = 11.7(f'_c)^{0.5} \quad (17)$$

Legeron and Paultre (2000) proposed an average relation as follows:

$$MOR = 2.63(f'_c)^{2/3} \quad (18)$$

Some other researchers provide lower and upper bound of the equation instead of providing just a single equation (Mindess et al. 2003; Legeron and Paultre 2000). The details will not be presented here due to the lack of space.

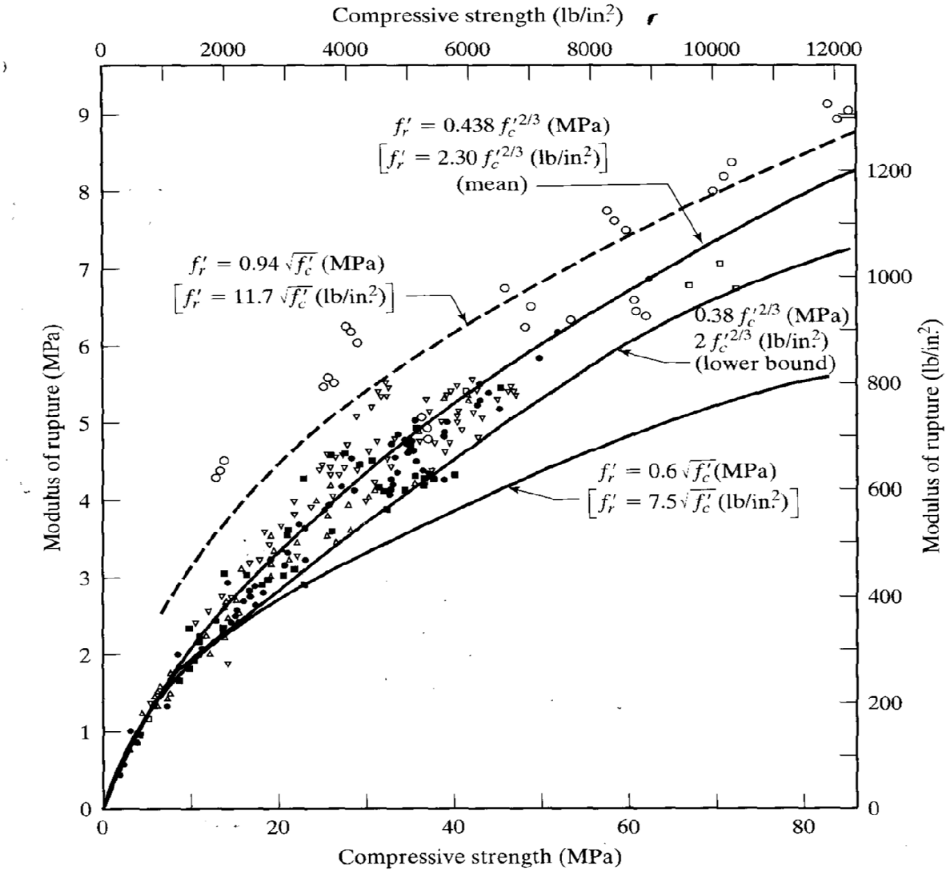


Figure 3. Example of regression curve for modulus of rupture (Adopted from Ahmad and Shah 1985)

Figure 3 showed an example of prediction of modulus of rupture (donated as f'r) from compressive strength from regression analysis. Results showed that the relation between compressive strength and modulus of rupture does follow power equation. The accuracy of the prediction, however, depends on the parameters determined from regression analysis from available data.

3.1.4 Predictions for Splitting Tensile Strength (f'_{sp}) from f'_c

Although MEPDG currently uses mostly the modulus of rupture (MOR) as the tensile strength input, the value of MOR is sometimes not available due to the limitation of the equipment. Another way to reflect concrete tensile strength is to use splitting tensile strength data. In addition, splitting tensile strength is required as an input parameter in CRCP. Therefore, the relations between splitting tensile strength and compressive strength are also summarized here.

Similar to elastic modulus, numbers of empirical formulae have been suggested to relate splitting tensile strength and compressive strength as of the power equation type:

$$f'_{sp} = cf'^{\,l}_c \tag{19}$$

where *c* and *l* are coefficients which depend on factors such as age, strength level, concrete density, aggregate properties, moisture content of specimen, and specimen size and shape.

According to ACI, empirical relationships between compressive strength and modulus of rupture have been established as follows (Zain et al. 2002):

$$f'_{sp} = 7.11(f'_c)^{1/2} \tag{20}$$

Another equation can be obtained on a wider range of data (Mindess et al. 2003):

$$f'_{sp} = 4.34(f'_c)^{0.55} \tag{21}$$

British developed their own codes (Neville 1996):

$$f'_{sp} = 0.53(f'_c)^{0.7} \tag{22}$$

Other equations with different empirical coefficients were also obtained by other researchers (Neville 1996; Kim et al. 2002; Zain et al. 2002):

Iravani (1996) suggested the following equation for concrete strength from 3000psi to 12000psi:

$$f'_{sp} = 7.11(f'_c)^{0.5} \tag{23}$$

Euro-International du Beton used the model code (CEB-PIP 1993):

$$f'_{sp} = 1.56(f'_c)^{2/3} \tag{24}$$

Gardner and Poon (1976) used another equation:

$$f'_{sp} = 1.7(f'_c)^{2/3} \tag{25}$$

A modification by Oluokun (1991) is as follows:

$$f'_{sp} = 0.89(f'_c)^{0.7} \tag{26}$$

Kim et al. (2002) developed the following equation based on their experimental results:

$$f'_{sp} = 1.31(f'_c)^{0.71} \tag{27}$$

Figure 4 showed an example of prediction of splitting tensile strength from compressive strength from regression analysis. Results showed that the relation between compressive strength and splitting tensile strength does follow power equation. The accuracy of the prediction, however, depends on the parameters determined from regression analysis from available data.

Some other researchers provide lower and upper bound of the equation instead of providing just a single equation (Mindess et al. 2003). The details will not be presented here due to the lack of space.

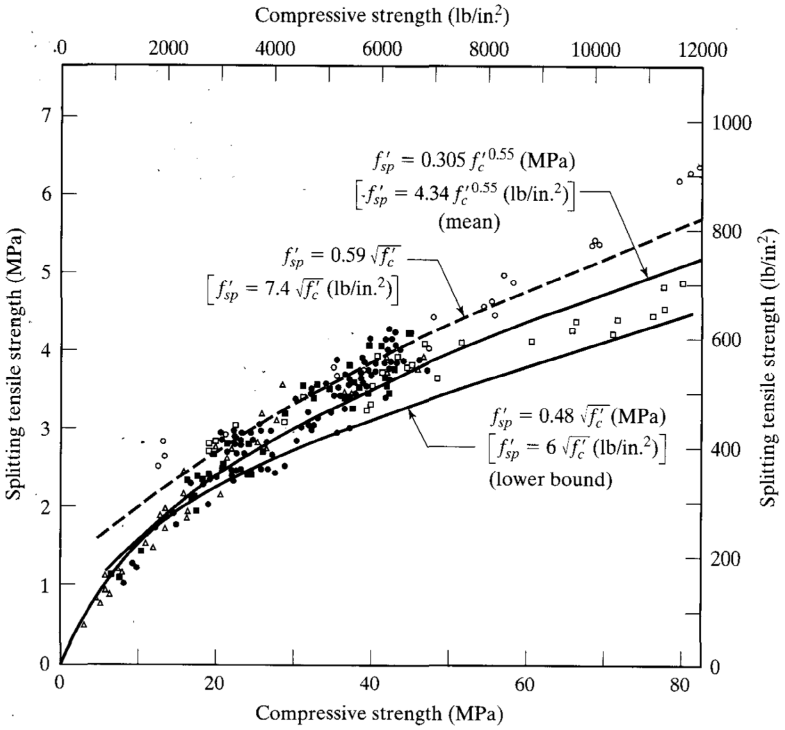


Figure 4. Example of regression curve for splitting tensile strength (Adopted from Ahmad and Shah 1985)

3.1.5 Predictions of Strength Parameters at Different Age

MEPDG calculates the concrete performance at different age; therefore, strength parameters at different age (7, 14, 28, and 90 days) are needed for the calculation. The general relation between age of concrete and different strength parameters can be shown in Figure 5.

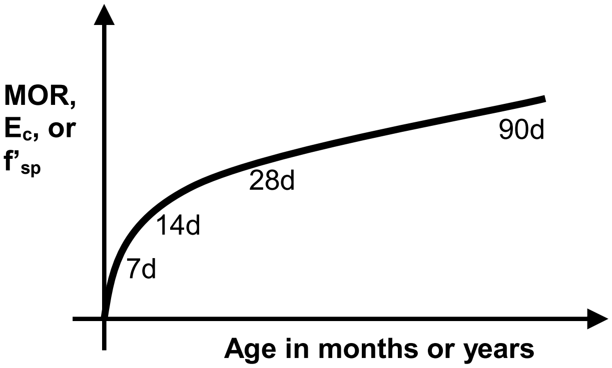


Figure 5. MOR, E_c, or f'_{sp} data required for MEPDG design at different age

In Level 3 input, E_c will be determined indirectly from 28-day estimation of flexural strength or compressive strength. If 28-day MOR is estimated, MOR at different age can be determined using the following formula (NCHRP 2004):

$$MOR(t) = [1 + \log_{10}(\frac{t}{0.0767}) - 0.01566\log_{10}(\frac{t}{0.0767})^2] \times MOR_{28d} \tag{28a}$$

where *MOR(t)* is the modulus of rupture at any given time (*t*, in days), *t* is the age of concrete (day), and MOR_{28d} is the modulus of rupture at 28 days.

Similar to MOR, the elastic modulus and splitting tensile strength at any given time can be related to the elastic modulus and splitting tensile strength at respectively:

$$Ec(t) = [\alpha_1 + \alpha_2 \log_{10}(t) - \alpha_3 \log_{10}(t)^2] \times Ec,_{28d} \tag{28b}$$

$$f'sp(t) = [\beta_1 + \beta_2 \log_{10}(t) - \beta_3 \log_{10}(t)^2] \times f'sp,_{28d} \tag{28c}$$

where *Ec(t) and f'sp(t)* are the elastic modulus and splitting tensile strength at any given time (*t*, in days), α_1, α_2, α_3, β_1, β_2, and β_3 are regression constants, *t* is the age of concrete (day), and *Ec(28d)* and *f'sp(28d)* are the elastic modulus and splitting tensile strength at 28 days. Unlike the modulus rupture, the regression parameters are not currently available for elastic modulus and splitting tensile strength.

In the MEPDG input, the fc(t) can be first estimated from MOR(t) and then converted to Ec(t). If f'c, 28 is available (from estimation), the value can also be first converted into MOR value, and then equation can be used to project MOR over time.

3.1.6 Poisson's Ratio and Unit Weight

As shown in Table 2, Poisson's ratio and unit weight of concrete are required as general properties input for MEPDG. There appears to be no consistent relationship between Poisson's ratio and concrete characteristics such as w/c, curing age, and aggregate gradation. For a material subjected to simple axial load, the ratio of the lateral strain to axial strain within the elastic range is called Poisson's ratio, which generally varies between 0.11 and 0.21 for normal concrete, and values between 0.15 and 0.18 are typically assumed for PCC design unless more reliable information is available (NCHRP 2004).

Unit weight of concrete can be estimated from testing in accordance with AASHTO T121 for Level 1 input or according to user's selection based upon agency historical data or from typical values between 140 to 160 lb/ft^3 for normal weight concrete.

3.1.7 Drying Shrinkage of Concrete

Drying shrinkage of hardened concrete is an important factor affecting the performance of PCC pavement, such as crack development in CRCP and slab warping in JPCP. The magnitude of drying shrinkage depends on various factors, including water per unit volume, cement type, aggregate type and content, ambient temperature and relative humility, curing of concrete, and PCC thickness. Based on the multiple regression analysis from the testing data, direct function of the w/c and shrinkage value was obtained (Eguchi and Teranishi 2005).

$$\varepsilon_t = \frac{t}{\alpha w/c + \beta + t}(\lambda w/c + \delta) \tag{29}$$

where ε_t is the drying shrinkage strain of the cement paste, t is the drying period (day), and α, β, λ, and δ are the constants determined by the type of cement. Examples of prediction of this equation and relation between the aggregate percentages, w/c, and drying period was presented in Figure 6. Results showed that the drying shrinkage of concrete can be affected by the volume percentage of aggregate and also the w/c. The drying shrinkage of concrete increases with drying period nonlinearly. The relationship between drying period and drying shrinkage can be used to obtain the ultimate shrinkage from relative shorter term of drying shrinkage measurement.

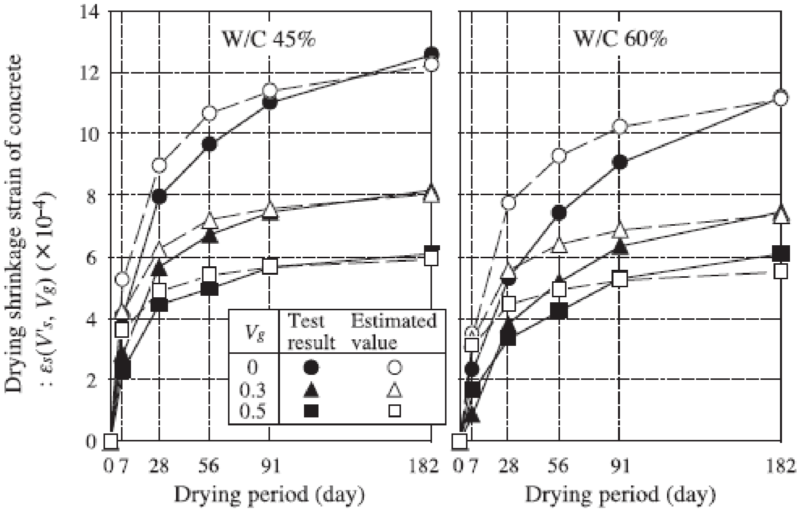


Figure 6. Time-dependent changes in drying shrinkage strain for concrete (Adopted from Eguchi and Teranishi 2005)

Videla et al. (2004) proposed a model to relate the ultimate drying shrinkage of concrete to the water content of mixture, concrete compressive strength at the beginning of drying, and the size of the aggregate as follows:

$$\varepsilon_{su} = dW^{c}[1 - eD(f_{c,t0})^{-0.5}] \tag{30}$$

where *c*, *d*, and *e* are constants determined statistically, ε_{su} is the ultimate shrinkage strain (x 10^{-6}), *W* is water content of the mixture in kg/m^3, $f_{c,t0}$ is the concrete compressive strength at the beginning of drying in MPa, and *D* is the nominal maximum size of aggregate in mm.

The best fit of equation (25) to the according data and the relevant statistical parameters is as follows:

$$\varepsilon_{su} = 11.9W^{0.9}[1 - 0.0229D(f_{c,t0})^{-0.5}] \tag{31}$$

In MEPDG, drying shrinkage-related inputs include ultimate shrinkage strain, time required to develop 50% of the ultimate shrinkage strain, anticipated amount of reversible shrinkage, and mean monthly ambient relative humidity of the project site. According to NCHRP (2004), the ultimate shrinkage of the particular concrete mixture should be required as mix input. However, there is no practical approach to obtain this value since it could take several years to realize the ultimate shrinkage strain (i.e., to attain a value that is time stable) (Bazant and Baweja 2000). At input Level 2 and Level 3, the ultimate shrinkage can be estimated from a standard correlation based on concrete mix proportion, concrete 28-day compressive strength, and curing conditions according to the following equation (Bazant and Baweja 2000; Bazant 2000):

$$\varepsilon_{su} = C_1 \cdot C_2 \cdot \left[26w^{2.1}(f'_c)^{-0.28} + 270\right] \tag{32}$$

where ε_{su} is the ultimate shrinkage strain (x10^{-6}), C_1 is the cement type factor (1.0 for type I cement, 0.85 for type II cement, and 1.1 for type III cement), C_2 is the type of curing factor (0.75 if steam cured, 1.0 if cured in water or 100% relative humidity, and 1.2 if sealed during curing [curing compound]), w is water content (1b/ft^3 of concrete), and f'_c is the 28-day compressive strength (psi).

Another common way to predict the ultimate shrinkage is to predict the ultimate shrinkage from short-term measurements, i.e., relate to the shrinkage at different ages (Al-Sugair and Almudaiheem 1990; Almudaiheem and Hansen 1989):

$$\varepsilon_t = \frac{t}{N+t}\varepsilon_{ult} \tag{33}$$

where ε_t is the shrinkage after t days since the end of moisture curing, ε_{ult} is the ultimate shrinkage, N is the time to reach half of the ultimate shrinkage, and t is the time in days since the end of moisture curing.

According to ACI 209R-92 (ACI Committee 209 1994), the N can be considered as 35 days in general case; the development of shrinkage with time therefore follows the equation:

$$\varepsilon_t = \frac{t}{35+t}\varepsilon_{ult} \tag{34}$$

The time to reach half of the ultimate shrinkage was found to be able to relate to the size and shape of the concrete (Almudaiheem and Hansen 1987):

$$N = 13.28e^{(0.764V/S)} \tag{35a}$$

when $V/S \geq 0.3$in., or

$$N = 0.33e^{(13.251V/S)} \tag{35b}$$

when $V/S < 0.3$in., where V/S is the volume-to-surface ratio in inches.

Since this ratio between volume and surface is not always available at all input levels, unless more reliable information is available, a value of 35 days can be used for the time required to develop 50% of ultimate shrinkage (ACI Committee 209 1994). Correspondingly, at all input levels, unless more reliable information is available, a value of 50% can be used for the anticipated amount of reversible shrinkage.

3.2 Iowa Data Analysis

3.2.1 Typical Strength Values to be used in the Level 3 Input

In the MEPDG, the modulus of rupture, compressive strength, and elastic modulus are required to be known as Level 3 inputs (Table 2). The historical date from state of Iowa was therefore analysis. The mean values are to be used as the Level 3 input values of state of Iowa. The distribution of the data was analyzed to evaluate the reliability of the data.

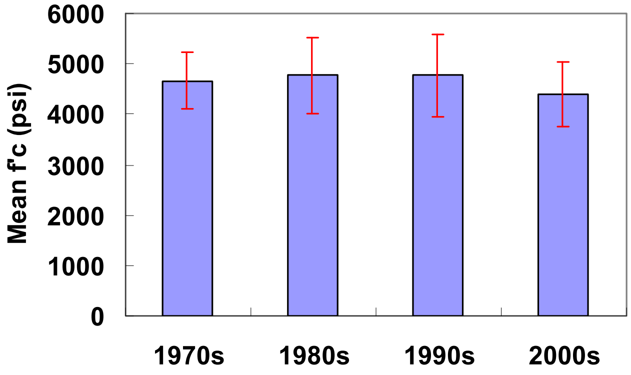


Figure 7. Distribution of Iowa DOT compressive strength data (by decades)

Over 19,000 data of class C core cylinder strength sample was obtained from Iowa DOT. A study was performed to analyze the mean value and standard deviation of the compressive strength values and the change in compressive strength of Iowa pavement concrete between decades. As shown in Figure 7 and Table 6, during 1970s –1990s, the mean value of the 28-day Iowa core compressive strength was approximate 4,700 psi and the standard deviation was approximate 700 psi. After the year of 2000, the mean value of the 28-day core compressive strength decreased to 4,397 psi with a standard deviation of 638 psi, which is probably cause by the change of the mix design of the Quality Management Concrete (QMC). Based on the analysis of the data collected by Iowa DOT from 1,596 CWRC/QMC samples after the year of 2000, 28-day compressive strength of 4397 ± 638 psi was recommended for the Level 3 input.

A similar analysis was also performed to demonstrate the change in concrete compressive strength between years within each project, and the results are shown in appendix (Table B.1 and Figure B.1).

Table 6. Analysis results of Iowa DOT $f'_{c,28}$ analysis (within year, normalized*)

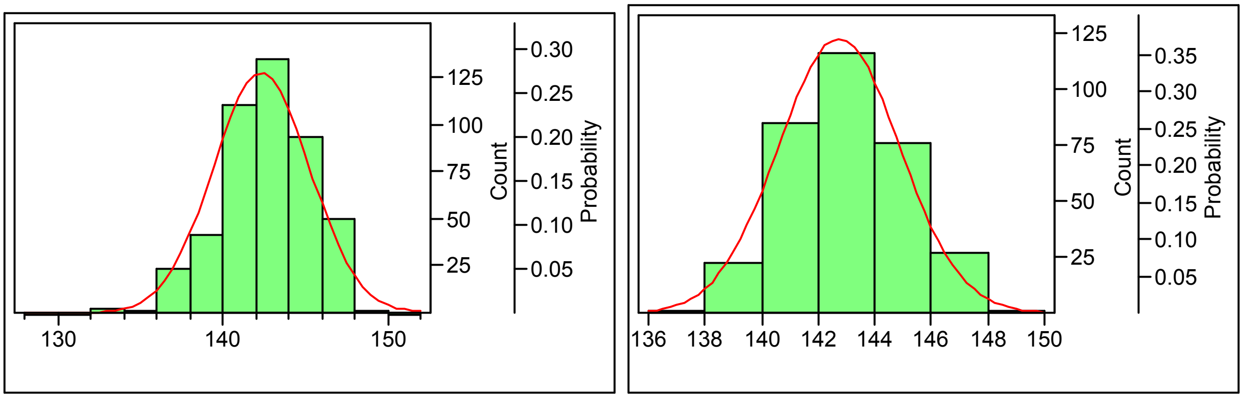
	f'_c per year	STD per year	Total # of samples (Year)
1970s	4667	564	992 (1977-1979)
1980s	4768	750	8780 (1980-1989)
1990s	4767	809	7638 (1990-93, 1996-99)
2000s	4397	638	1596 (2000-2005)
Total	4731	755	19006 (1971-2005)

* Due to the limitation of the available data, normalized value as the sum of each year's strength * number of samples divided by the total number of samples was used as the average strength value.

Concrete unit weight is also studied since it is one of the input parameters for MEPDG and has significant influence on concrete strength. Table 7 presents the average values and the standard deviations of concrete unit weight from data sources. Table 7 indicates that the mean unit weight of the Iowa pavement concrete is around 142 pcf. Figure 8 shows the distribution of the unit weight values from Iowa DOT QMC projects and all Iowa pavement data, both of which are close to normal distribution. A mean value of 142.7pcf with a standard deviation of 2.1pcf is recommended according for MEPDG level 3 inputs according to the 330 QMC project data from Iowa DOT.

Table 7. Average value and standard deviation of unit weight from Iowa data

Project	**IA DOT**	**MMO-F**	**MMO-E**	**OGS**	**MTE**	**CCEE**	**Total**
Mean	142.7	142.4	145.0	142.0	139.8	138.2	142.4
Std Dev	2.1	1.3	2.1	1.5	3.3	3.7	2.9
Std Err Mean	0.1	0.5	0.3	0.5	0.7	0.6	0.1
Upper 95% Mean	143.0	143.5	145.6	143.1	141.2	139.3	142.6
Lower 95% Mean	142.5	141.3	144.4	141.0	138.5	137.1	142.1
Number of data	330	8	48	10	25	45	466



(a) Iowa DOT QMC project data **(b) All Iowa pavement data**

Figure 8. Unit weight distribution

Table 8 and Table 9 show the results of Iowa concrete air content and slump data. As observed in the Table 7, the average values of air content are 6.3% for the Iowa DOT data and 6.4% for all Iowa pavement concrete data. Standard deviations of the air content are 0.3% for the data from 35 Iowa DOT QMC projects and 1.4% for all Iowa pavement data. Table 8 shows that the mean slump value from all Iowa pavement data is 2.34 in and standard deviation is 0.95 in. Figure 9 and Figure 10 also showed the distribution of the air content and slump values from Iowa DOT QMC projects and all Iowa pavement data, both are close to normal distribution. Statistic analysis justified that the most of the concrete mixtures used in present study are within the acceptable ranges.

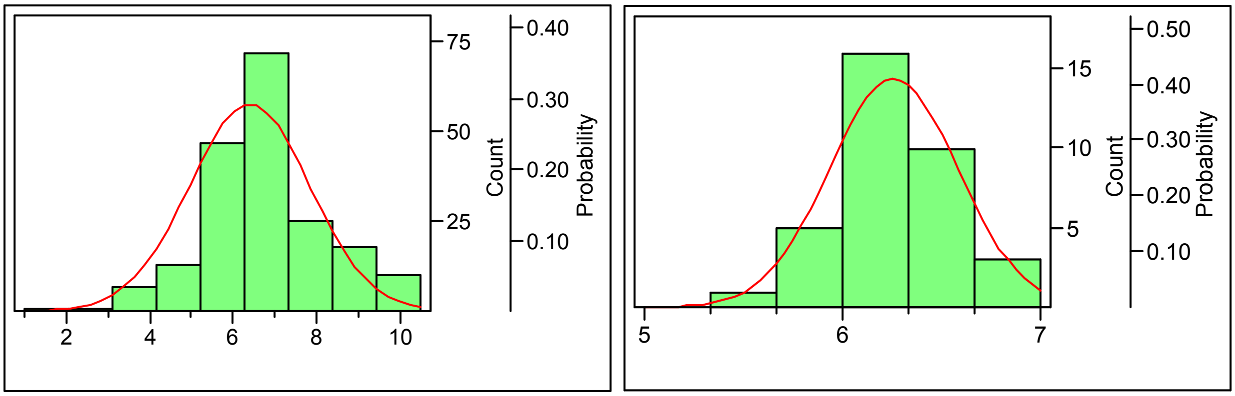
Table 8. Average value and standard deviation air% from Iowa data

Project	IA DOT*	CW	MMO-F	MMO-L	OGS	MTE	CCEE	PVT30	Total
Mean	6.3	6.0	6.9	6.3	5.7	7.3	6.5	3.8	6.4
Std Dev	0.3	0.0	1.0	1.3	0.9	1.2	1.8	1.4	1.4
Std Err Mean	0.1	0.0	0.3	0.2	0.3	0.2	0.2	0.6	0.1
Upper 95% Mean	6.4	6.0	7.7	6.7	6.4	7.8	6.9	5.3	6.6
Lower 95% Mean	6.1	6.0	6.1	5.9	5.1	6.8	6.0	2.3	6.2
Number of data	35	2	8	48	10	25	62	6	196

* After paving

Table 9. Average value and standard deviation slump from Iowa data

Project	MMO-F	MMO-L	OGS	MTE	CCEE	Total
Mean	1.72	2.33	2.68	2.42	2.34	2.34
Std Dev	0.34	0.95	0.39	0.79	1.12	0.95
Std Err Mean	0.12	0.14	0.12	0.16	0.16	0.08
Upper 95% Mean	2.00	2.61	2.96	2.75	2.66	2.50
Lower 95% Mean	1.44	2.05	2.39	2.09	2.03	2.18
Number of data	8	48	10	25	51	142



(a) Iowa DOT QMC project data **(b) All Iowa pavement data**

Figure 9. Air percentage distribution

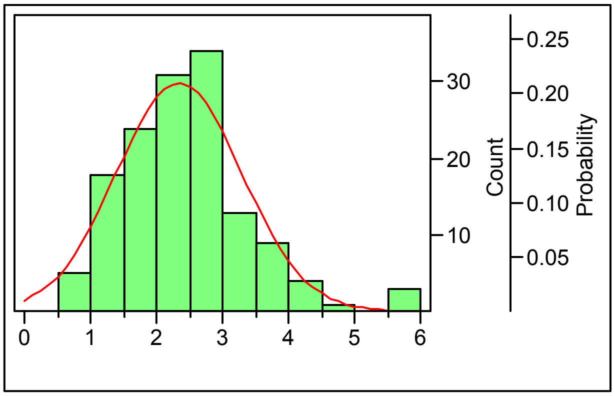


Figure 10. Slump distribution

Statistical analyses were further conducted for the data from individual projects so as to find out the typical property value and deviation within the projects. The results are summarized in

Table 10, Table 11, Table 12, and Table 13.. It is noted that some values do have significant differences comparing to other data sources, such as the CCEE $(f'_c)_{28}$ and MOR_{28} data, which have significantly higher standard deviation on the compressive strength and modulus of rupture data because of the larger differences in concrete mix design. (The water-to-cement ratio of CCEE data varies from 0.4 to 0.7.)

Table 10. Average value and standard deviation of (f'c)28 within Iowa projects

Project	CW	MMO-F	OGS	FEQMC	MTE	PVT30	CCEE	Total
Mean	6639	5528	6323	6028	5189	5565	4257	5087
Std Dev	73	435	387	480	810	243	1292	1214
Std Err Mean	51.5	153.9	122.5	138.6	162.0	99	197.0	118
Upper 95% Mean	7293	5892	6600	6333	5524	5820	4655	5321
Lower 95% Mean	5984	5164	6046	5723	4855	5310	3860	4853
Number of data	2	8	10	12	25	6	43	106

Table 11. Average value and standard deviation of $(MOR)_{28}$ within Iowa projects

Project	IA DOT	FEQMC	PVT30	LTPP	CCEE	Total
Mean	646	682	792	647	567	628
Std Dev	51	55	15	113	108	98
Std Err Mean	7	16.0	6	46	16.5	9
Upper 95% Mean	661	718	807	766	600	646
Lower 95% Mean	631	647	776	528	534	610
Number of data	47	12	6	6	43	114

Table 12. Average value and standard deviation of $(Ec)_{28}$ within Iowa projects

Project	CW	Total
Mean	4822662	4822662
Std Dev	284779	284779
Std Err Mean	201370	201370
Upper 95% Mean	7381304	7381304
Lower 95% Mean	2264019	2264019
Number of data	2	2

Table 13. Average value and standard deviation of $(f'_{sp})_{28}$ within Iowa projects

Project	CW	Total
Mean	393	393
Std Dev	25.5	25.5
Std Err Mean	18.0	18.0
Upper 95% Mean	622	622
Lower 95% Mean	164	164
Number of data	2	2

An additional analysis was performed to study the variation of the air content (before and after paving) and 28-day modulus of rupture (MOR) between years. The results indicate that there is no obvious difference between each year within the QMC projects after 2000. Forty seven (47) sets from a total of 243 samples of modulus of rupture samples were used in this study. The detailed information of the modulus of rupture of individual project within each year can be found in Appendix B.

Table 14. Analysis of air content and $(MOR)_{28}$ data within each year (Iowa DOT QMC projects, 2000 to present)*

	Air content, %							
	Before paver		After paver		w/c		MOR_{28d}, psi	
Year	AVG	STD	AVG	STD	AVG	STD	AVG	STD
2000	8.1	0.4	6.4	0.4	0.403	0.022	661	51
2001	7.9	0.5	6.3	0.2	0.414	0.009	642	57
2002	7.9	0.4	6.2	0.4	0.404	0.019	637	36
2003	7.8	NA	5.8	NA	0.395	NA	682	65
2004	8.2	0.2	6.1	0.2	0.404	0.004	624	41
2005	8.3	0.2	6.0	0.2	0.402	0.002	628	47
Total	8.0	0.4	6.3	0.3	0.406	0.016	646	51

*The data used in this table are the average value of each project in a given year.

In order to give a recommendation of existing pavement properties at approximately 20 years for pavement overlay design, historical data from LTPP database were obtained. Data from both general pavement studies (GPS) and specific pavement studies (SPS) from LTPP were used in present study. Pavement concrete strength data after five years were used here as long term performance study. 22 compressive strength data (9 from LTPP, 6 from “PVT30” project, 2 from “HSCPP” project and 5 from “FEBCO” project), 11 elastic modulus data (9 from LTPP, and 2 from “HSCPP” project), 8 Poisson ratio (from LTPP), and 14 splitting tensile strength (9 from LTPP and 5 from “FEBCO” project) were obtained for the present study.

Unfortunately, the properties of the Iowa concrete measured at different ages were from different projects, rather than given projects (see Appendix FigureC.4). No systematical data or complete sets of data are available. Therefore, the average property values of the Iowa concrete at the age of 5-30 years are simply listed in Table 14 and recommended as the long term performance pavement properties for the necessary use in MEPDG. As shown in Table 15, the recommended values are compressive strength of 7627 (±811) psi, elastic modulus 4.48 (±0.56) x10^6psi, Poisson ratio of 0.211 (±0.029), and splitting tensile strength of 587 (±71) psi.

Table 15. Long term performance pavement properties analysis

	f'c		Ec		Poisson Ratio		f'sp	
	Age (year)	Value (psi)	Age (year)	Value (psi)	Age (year)	Value	Age (year)	Value (psi)
Avg.	20.8	7,627	17.8	4,482,926	17.1	0.211	17.1	587
STD	6.7	811	6.9	555,378	5.8	0.029	5.4	71
Count	22	22	11	11	8	8	14	14

3.2.2 Predictive Equations Based on Iowa Data

3.2.2.1. Prediction of Compressive Strength

A lot of factors can affect concrete compressive strength, including water-to-cement ratio, sand-to-aggregate ratio, aggregate-to-cement ratio, fineness modulus of sand, maximum size of coarse aggregate, dosage of water, dosage of cement, and dosage of admixtures. However, whether the information on these inputs, such as aggregate type and curing condition, going to be available or quantitatively described is questionable. In MEPDG mix inputs, only the basic parameters are required, including cement type (Type I, II, or III), cementitious material content, w/c ratio, aggregate type (quartzite, limestone, dolomite, granite, rhyolite, basalt, syentite, gabbro, or chert), and PCC zero-stress temperature (optional). Considering the availability of data, parameters, including age, water-to-binder ratio (w/b), cementitious material factor, and unit weight, were applied in the predicted equation.

A statistical study of nonlinear regression was used to obtain the equation to predict the compressive strength from the parameters mentioned above. The cross interaction between these parameters was considered in the model to predict the compressive strength. Backward stepwise fitting with a full factorial of these four factors was used with the level possibility to enter at 0.25 and the level possibility to leave at 0.10. One hundred seventy (170) sets of data with different age (t), water-to-binder ratio (w/b), cementitious material factor (CMF), and unit weight (uw) from four Iowa DOT and CTRE projects (“CW”, “MMO-L”, “OGS”, and “IPC”) and Iowa State University CCEE undergraduate classes were used in the study. An R-square value of 0.76 prediction relationship, as shown in Figure 11, was obtained with all parameters with significance level higher than 0.95 (Prob>F less than 0.05).

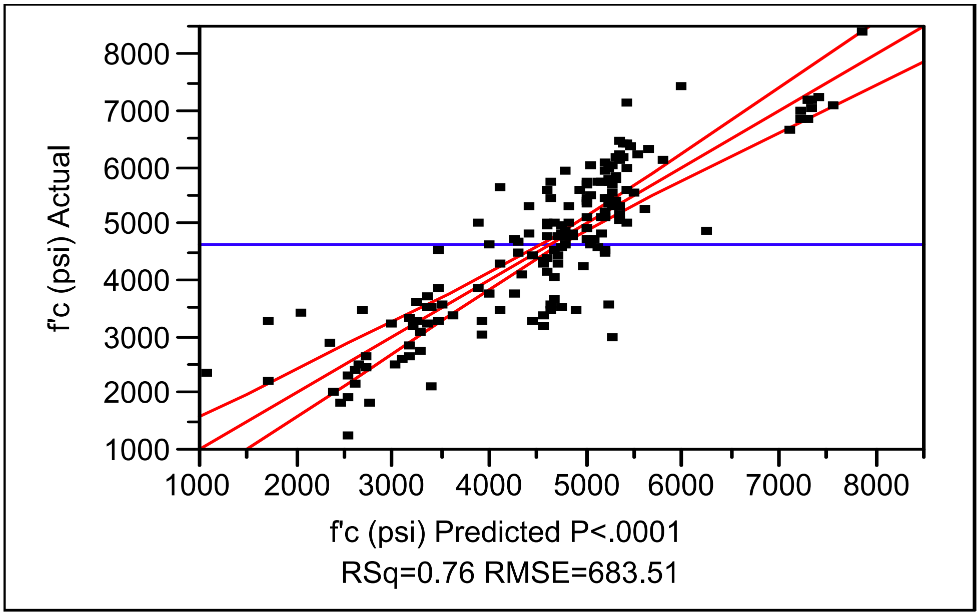


Figure 11. Actual to predicted plot of compressive strength from regression analysis

Table 16. Level of significance and coefficient of parameters used in the regression model

Entered	Parameter	Estimate	nDF	SS	"F Ratio"	"Prob>F"
X	Intercept	-134118.53	1	0	0.000	1.0000
X	w/b	103000.698	2	3646646	3.903	0.0221
X	Unit wt (pcf)	978.177066	3	30742165	21.934	0.0000
X	w/b*Unit wt (pcf)	-751.52733	1	3612458	7.732	0.0061
X	CMF (pcy)	124.949924	2	19261166	20.614	0.0000
	w/b*CMF (pcy)	0	1	334618.8	0.715	0.3990
X	Unit wt (pcf)*CMF (pcy)	-0.865266	1	5764694	12.339	0.0006
	w/b*Unit wt (pcf)*CMF (pcy)	0	2	1317101	1.417	0.2455
X	log(age)	30.5870102	1	62658332	134.118	0.0000
	w/b*log(age)	0	1	18892.9	0.040	0.8413
	Unit wt (pcf)*log(age)	0	1	25775.25	0.055	0.8151
	w/b*Unit wt (pcf)*log(age)	0	3	547936.8	0.387	0.7629
	CMF (pcy)*log(age)	0	1	195.3215	0.000	0.9838
	w/b*CMF (pcy)*log(age)	0	4	716033.6	0.377	0.8246
	Unit wt (pcf)*CMF (pcy)*log(age)	0	3	418720.5	0.295	0.8291
	w/b*Unit wt (pcf)*CMF (pcy)*log(age)	0	9	2946655	0.689	0.7183

According to the results of regression analysis, the following equation was obtained from the available Iowa data:

$$\begin{aligned} f'_{c,t} &= -134119 + 103000w/b + 978uw + 125CMF + \\ &30.6\log(t) - 752w/b \times uw - 0.865uw \times CMF \end{aligned} \tag{36}$$

where f'$_{c,t}$ is the compressive strength of concrete at *t* days, *w/b* is the water-to-binder ratio, *uw* is the unit weight of concrete, *CMF* is the cementitious material factor, and *t* is the age of concrete (in days). The prediction profile, as shown in Figure 12, showed that water-to-binder ratio (w/b), unit weight (uw), and the age of concrete (logt, in hours) do have very significant effect on compressive strength. Effect of cementitious material factor (CMF) is relatively low even though it is still statistically significant at a level of 95%.

According to Equation 36, a prediction equation for 28 day compressive strength can also be derived by replace *t* with 28 days:

$$\begin{aligned} f'_{c,28} &= -134077 + 103000w/b + 978uw + 125CMF \\ &- 752w/b \times uw - 0.865uw \times CMF \end{aligned} \tag{37}$$

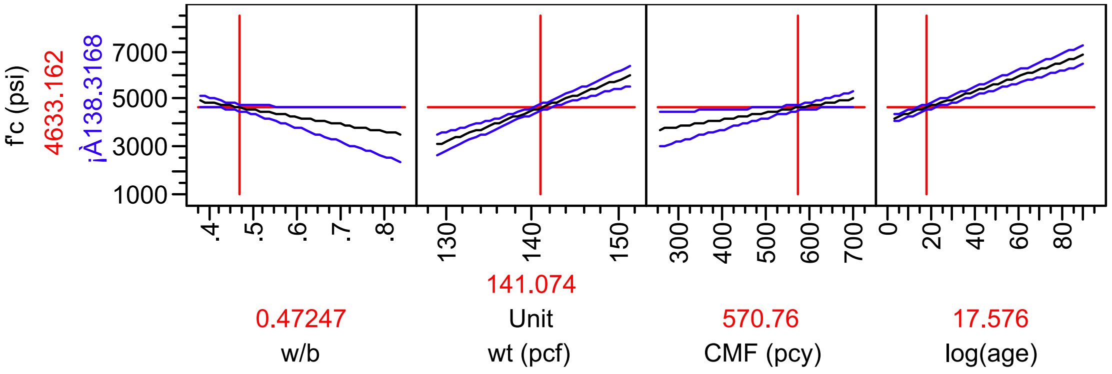


Figure 12. Prediction profile on compressive strength from regression analysis

Another analysis was performed using Artificial Neural Network with a 5-fold cross validation (CV). The parameters used in the ANN analysis are overfit penalty 0.001, number of tours 20, maximum iterations 50, and converge criterion 0.00001. Same input parameters (w/b, uw, CMF, and t) were included. ANN structure with one input layer (of four parameters), one hidden layer, and one output layer with compressive strength was used. In order to obtain best ANN structure, different number of hidden nodes from 3 to 7 was used. The results of the model with different number of nodes are summarized in Table 17.

Table 17. Fitting history with different number of nodes

Nodes	R-square	CV R-square
3	0.86237	0.59374
4	0.88145	0.63939
5	0.90251	0.58272
6	0.91980	0.40796
7	0.92842	0.27224

According to the efficiency of the model based on the R-square and CV R-square values of prediction, the model with 4 nodes in the hidden layer, as shown in Figure 13, was used as the final ANN model.

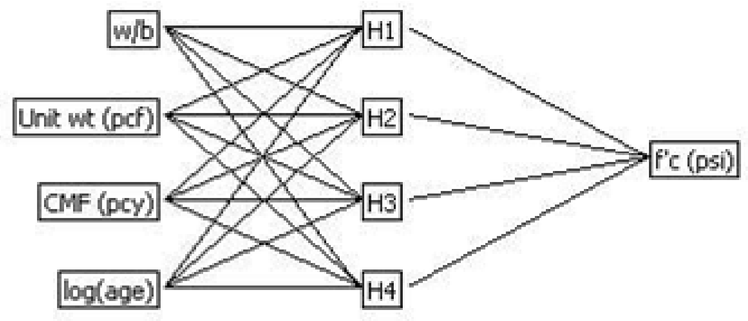


Figure 13. ANN model of compressive strength prediction

The actual to predicted plot from the ANN analysis is shown in Figure 14. As shown in the figure, the coefficient of correlation of the prediction is 0.88, which is higher than the value of 0.76 from the nonlinear regression. The results indicate that this model provides a more reliable prediction comparing to the previously presented multiple-parameters nonlinear regression model.

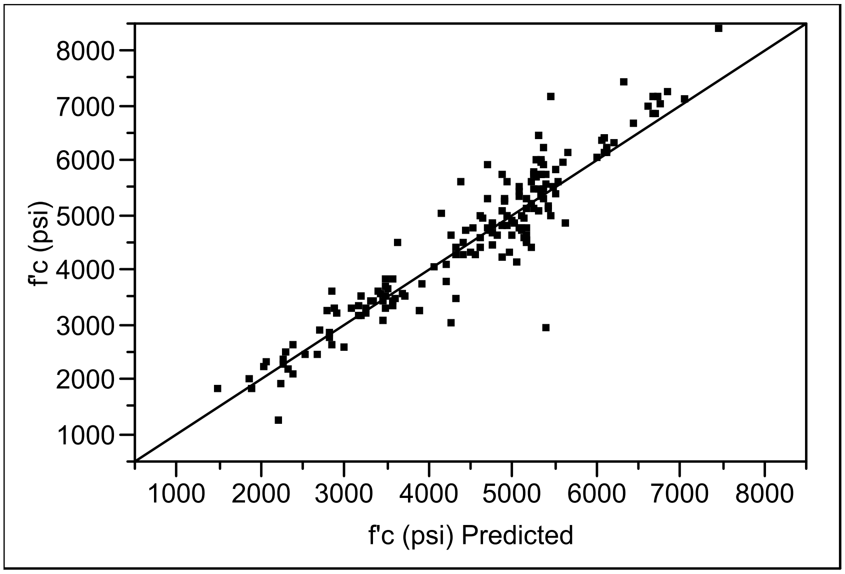


Figure 14. Measured strength versus predicted strength from ANN analysis

The prediction profile, as shown in Figure 15, showed that water-to-binder ratio (w/b), unit weight (uw), and the age of concrete (logt, in hours) all have very significance effect on compressive strength. With the increase of age and unit weight, the compressive strength increases, while the strength will decrease with the w/b. The prediction profile showed nonlinear effect from different parameters, which was not reflected on the regression analysis. The effect of cementitious material factor (CMF) varying on different range, which may be caused by the fact that the change of CMF also relates to the change of the aggregate amount, and the percentage of the cementitious materials, which was not be able to distinguished in current analysis.

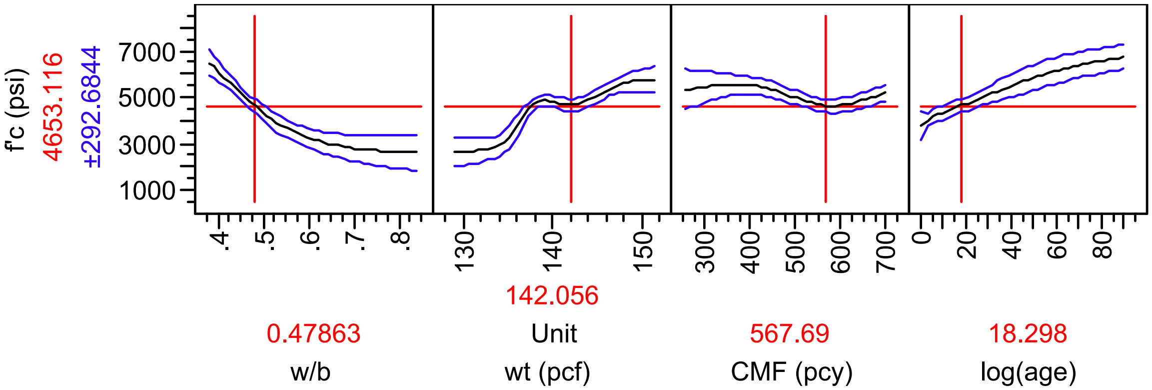


Figure 15. Prediction profile on compressive strength from ANN analysis

Results showed that with the design parameters and some test results from fresh concrete, the compressive strength at different ages can be predicted to a certain degree. Both models can be used for concrete with relative wide range of input parameters at w/b from 0.40 to 0.80, unit weight from 130 to 150pcf, CMF from 300 to 700pcy and age from 3 day to 90days. However, due to the limitations in the data availability and size of the database, factors such as aggregate and cement type and proportion cannot be included in present study. Other factors have not been considered, including amount and type of cementitious materials (Hwang et al. 2004), size of cylinder samples (Tymkowicz 1998), vibration (Tymkowicz 1998), mixing time, and curing condition, which should also be considered in later study. A more rational study of the prediction of compressive strength should be obtained based on a larger database with more data from different sources.

3.2.2.2. Prediction of Elastic Modulus from Compressive Strength

Based on the previous research as described in section 2, the relationship between compressive strength and elastic modulus generally follows power equations, which were therefore applied in regression analysis. Analysis was performed to evaluate the ability of prediction of Ec from f'c using available Iowa testing data. Results of the coefficient of correlation from different equations are shown in Table 18. Sixteen (16) sets of data, including 14 from "CW" project and 2 from"HSCPP" project, were used in this analysis.

Table 18. Prediction for elastic modulus on Iowa data

	Equation	a	m	other	R^2 with Iowa Data
ACI*	Equation 2	33	0.50	$\rho^{3/2}$	0.67
ACI	Equation 3	57000	0.50		0.69
CEB-FIP	Equation 4	275538	0.33		0.63
Kim	Equation 5	77173	0.46		0.59
TS500	Equation 6	39150	0.50	+2030528	0.41

*14 sets of data from CW project were used

A single-parameter nonlinear regression using power equation was performed using the available Iowa data. The following equation was obtained from the regression:

$$E_c = 80811 f'_c{}^{0.4659} \tag{38}$$

The result of the accuracy of analysis and estimated parameters is shown in Figure 16. As can be observed in Figure 16, the regression analysis gives a better estimate of E_c from the f'_c using data from state of Iowa. Comparing to the default equation from ACI, the coefficient of correlation (R^2) increases from 0.69 to 0.80. This indicates that the new equation is able to improve the accuracy of the input parameters and calculations of MEPDG.

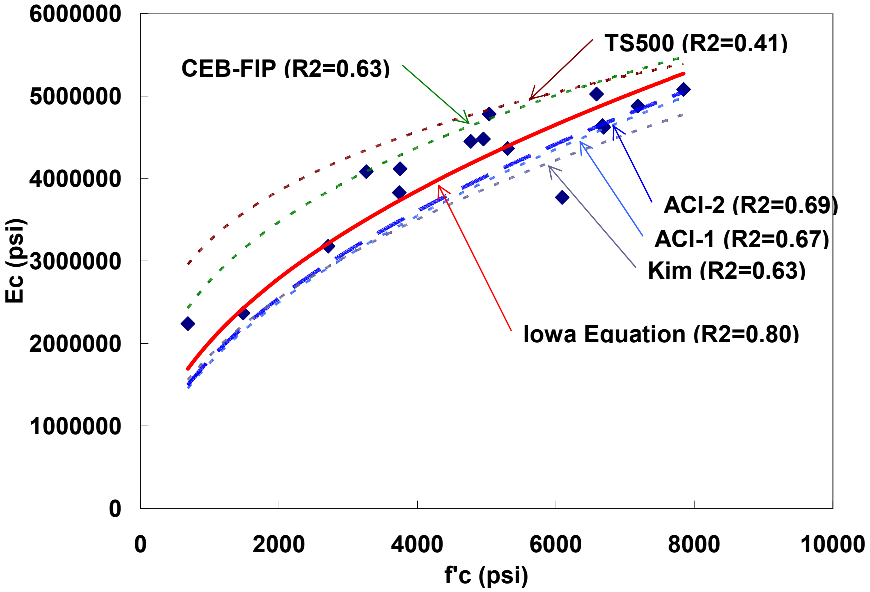


Figure 16. Prediction of elastic modulus from compressive strength

Based on this new equation, in Level 2 input at MEPDG, E_c can be determined indirectly from compressive strength at various ages (7, 14, 28, and 90 days), provided that the compressive strength is available.

3.2.2.3. Prediction of Modulus of Rupture from Compressive Strength

Iowa test data were first used to check the validity of existing relationships as described in Section 2. A total of 80 sets of data, including 46 from “CCEE”, 24 from “FEQMC” project, 4 from “IPC” and 6 from “PVT30” project were used in this analysis. Results of the coefficient of correlation from different equations are shown in Table 19.

Table 19. Prediction for modulus of rupture on Iowa data

	Equation	b	n	R^2 with Iowa Data
ACI	Equation 8	7.5	0.50	NA*
Mindess	Equation 9	2.3	0.67	0.16
Canada	Equation 10	7.5	0.50	NA*
New Zealand	Equation 11	9.6	0.50	0.24
Caraquillo	Equation 12	11.7	0.50	NA*
Legeron&Paultre	Equation 13	6	0.67	NA*

*NA represents negative R^2 values

The negative R^2 values in Table 18 indicate that the difference between a predicted value and the tested value is higher than the difference between this predicted value and the average value of the tested data used in the analysis. The definition of the coefficient of correlation (R^2) is

$R^2 = \frac{S_{yy} - SSE}{S_{yy}}$, where $S_{yy} = \sum y_i^2 - \frac{\left(\sum y_i\right)^2}{n}$, $SSE = \sum\left(y_i - \hat{y}_i\right)^2$, y_i is the individual output value, $\hat{y}_i$ is the individual predicted output value from predication equation, and n is the number of individual output data. The negative R^2 numbers and the numbers much less than 1 suggest that these existing equations do not appropriately predict the Iowa concrete property.

To improve the prediction equation, a power equation was applied in the regression analysis of Iowa testing data. The following result was obtained from the regression analysis:

$$MOR = 12.93 f'_c{}^{0.4543} \qquad (R^2=0.54) \qquad (39)$$

As shown in Figure 17, the new regression equation has a coefficient of correlation of 0.54. The prediction ability of the equation is relatively low comparing to elastic modulus, which is probably due to the fact that the data involved in this part of analysis come from a much wider range of mix design, which increases the variability between the testing results. A detailed analysis by dividing the current data into different categories according to the mix design and materials might be able to improve the accuracy of the model. However, due to the limitations in the data availability, this part of study cannot be accomplished.

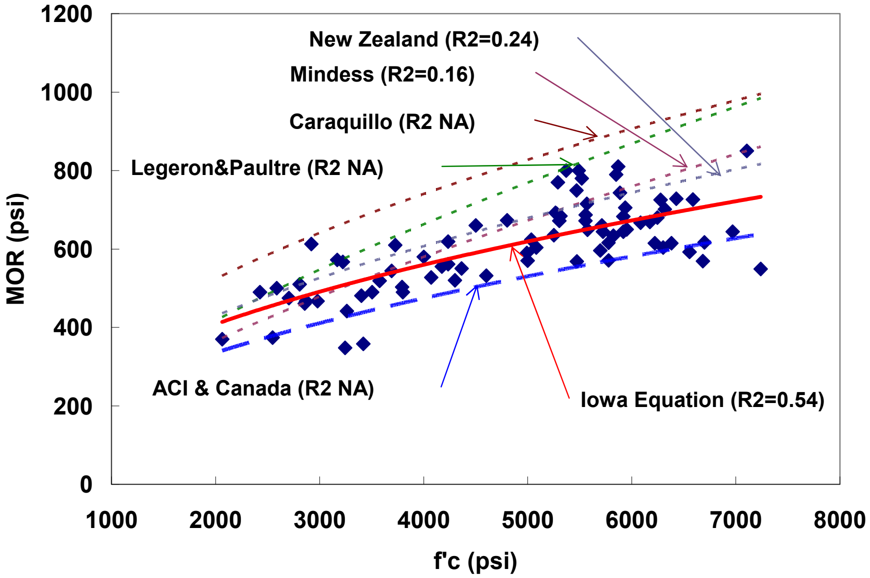


Figure 17. Prediction of modulus of rupture from compressive strength

Based on this new equation, in Level 2 input at MEPDG, modulus of rupture can be determined indirectly from compressive strength at various ages (7, 14, 28, and 90 days), provided that the compressive strength is available.

3.2.2.4. Prediction of Splitting Tensile Strength from Compressive Strength

Based on previous research as described in section 2, the relationship between compressive strength and splitting tensile strength generally follows power equations, which were therefore applied in regression analysis. Analysis was performed to evaluate the ability of prediction of f'sp from f'c using available Iowa testing data. Results of the coefficient of correlation from different equations are shown in Table 20. (19 sets of data, including 14 from "CW" project, and 5 from "FEBCO" project were used in this analysis.)

Table 20. Prediction for splitting tensile strength on Iowa data

	Equation	c	l	R^2 with Iowa Data
ACI	Equation 15	7.11	0.50	0.50
Mindess	Equation 16	4.34	0.55	0.64
Neville	Equation 17	0.53	0.70	NA*
Iravani	Equation 18	7.11	0.50	0.50
CEB-FIP	Equation 19	1.56	0.67	0.63
Gardner&Poon	Equation 20	1.7	0.67	0.37
Oluokun	Equation 21	0.89	0.70	0.47
Kim	Equation 22	1.31	0.71	NA*

*NA represents negative R^2 values

With the coefficient of correlation value lower than zero, results showed that most of the current equations cannot be used to reflect the relationship between compressive strength and splitting tensile strength from the available Iowa data. A single-parameter nonlinear regression using power equation was performed using the available Iowa data. The following equation was obtained from the regression:

$$f'_{sp} = 1.019 f'^{\,0.7068}_{c} \tag{40}$$

The result of the accuracy of analysis and estimated parameters is shown in Figure 18. As can be observed in the figure, the regression analysis gives a better estimate of f'sp from the f'_c using data from state of Iowa. Comparing to the default equation from ACI, the coefficient of correlation increases from 0.50 to 0.73, which indicates that the new equation is able to improve the accuracy of the input parameters and calculations of MEPDG.

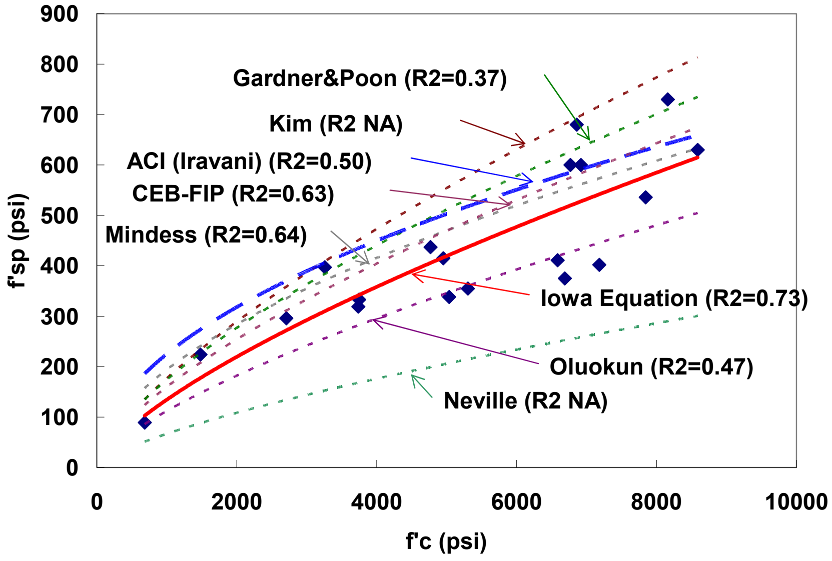


Figure 18. Prediction of splitting tensile strength from compressive strength

Based on this new equation, in Level 2 input at MEPDG, *f'sp* can be determined indirectly from compressive strength at various ages (7, 14, 28, and 90 days), provided that the compressive strength is available.

Results from the regression analysis in present section showed that the new obtained equations are able to better predict the elastic modulus, modulus of rupture, and splitting tensile strength from compressive strength used in the state of Iowa. However, due to the limitations in the data availability, factors such as aggregate and cement type and proportion, and cementitious materials content cannot be incorporated into present study. A more rational relationship between compressive strength and elastic modulus and modulus of rupture should be obtained based on a larger database with more data from different sources.

3.3 Preliminary Drying Shrinkage Results

The magnitude of drying shrinkage depends on numerous factors, including cement type and content, aggregate type and content, water per unit volume, ambient temperature and relative humility, concrete shape, and thickness. The comprehensive study of concrete drying shrinkage will require a systematic study with different concrete mix designs and conditions of Iowa PCC materials. Due to the limitation of budget and time, only one typical Iowa PCC mix can be applied in the preliminary study.

The concrete drying shrinkage is determined by the length change of mortar or concrete mixtures cast in laboratory and exposed to controlled temperature and humidity conditions in the laboratory. The summary of the information of the commonly used concrete shrinkage testing device is also presented in Appendix B. A typical Iowa PCC mix (C-3WR-C20) was sent out for a drying shrinkage test at CTL Group. Concrete batching and mixing were performed according to ASTM C192. A Lancaster counter current revolving-pan mixer was used. A 1.0 ft^3 mix was made in order to fabricate the test specimens. The standard mixing time of three minute mixing, three minute rest and two minute mixing was using. Fresh concrete with properties of 2.25" slump, 6.0 air % and 143.6pcf unit weight was obtained.

The basic experimental setup applied in present study is shown in Figure 19. Three specimens (3x3x11.25 in. prisms) were cast in cold-rolled steel molds (Figure 20a). After 24 hours, the prisms were removed from molds and initial lengths of specimens were measured by Humboldt length comparator with a digital gauge (Figure 20b) according to ASTM C157. The specimens were stored at moisture condition until they were 28 days old, and then stored at dry condition according to ASTM C157 for the remainder of testing. The length changes of specimens were record at different time to obtain drying shrinkage at different periods according to ASTM C157 (see Table D.1 and Table D.2).

(a) Steel mold (3"x3"x11.25")

(b) Length comparator and storage area in Environmental room

Figure 19. Drying shrinkage testing device

The results of the concrete drying shrinkage at different ages are presented in Figure 20. Results show that, as expected, the concrete drying shrinkage increases dramatically at the early age, and as the age increases, while the specimens become drier, the trend of the increasing gradually decreases. The results of drying shrinkage test in Figure 20 showed very similar trends comparing to testing results from mixture with close w/c (0.45) according to existing reference (BASF, Mokarem 2003). The details of the original drying shrinkage data can be seen in Appendix C.

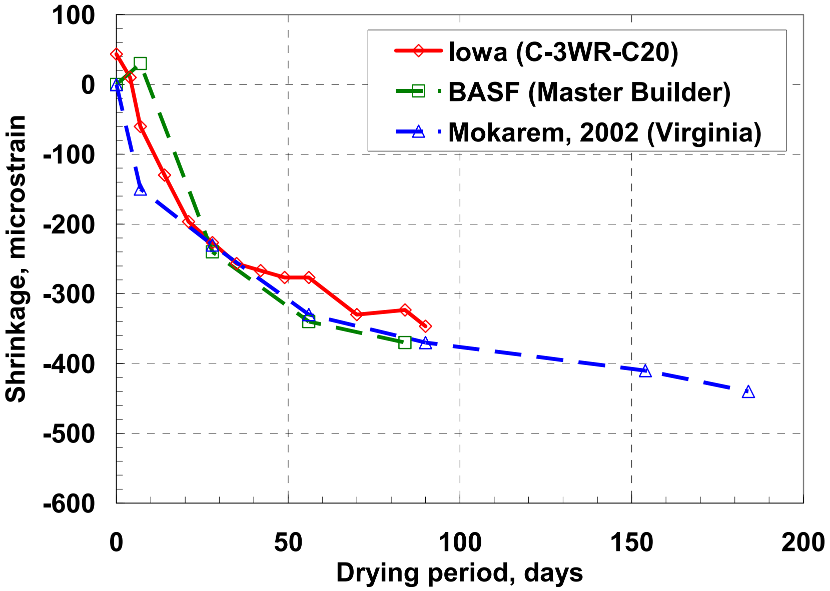


Figure 20. Drying shrinkage of Iowa C-3WR-C20 mix and its comparison with others

Based on the obtained drying shrinkage data, according to equation (33) in Section 3.1.7, a best fitting with R-square value of 0.96 as shown in Figure 21 was obtained. The ultimate shrinkage of 454 microstrain and the time to 50% shrinkage at approximately 32 day for Iowa C-3WR-C20 pavement mix are estimated. The shrinkage value from present study can be tentatively used for the MEPDG Level 3 approaches. Since various concrete mixes are often used in Iowa, a systematic study is necessary to obtain a set of shrinkage data for Iowa concrete pavement design.

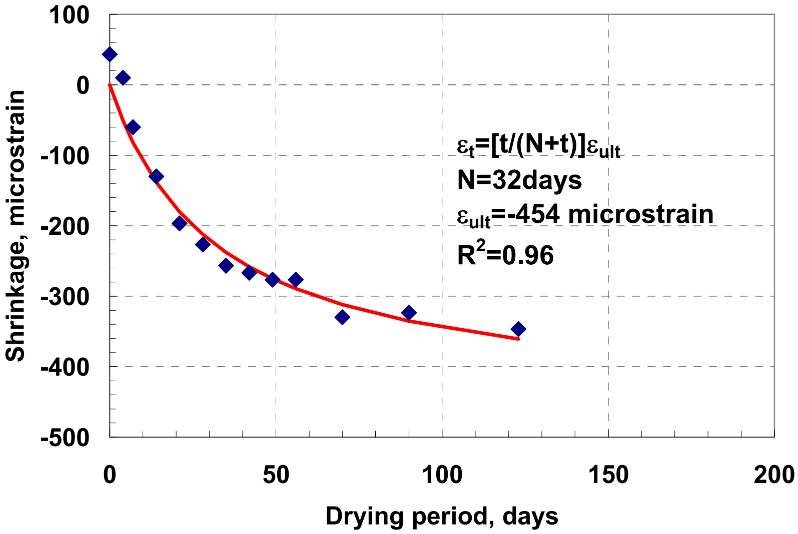


Figure 21. Prediction of ultimate shrinkage

4. PROPOSED IOWA CONCRETE PROPERTY INPUTS FOR MEPDG

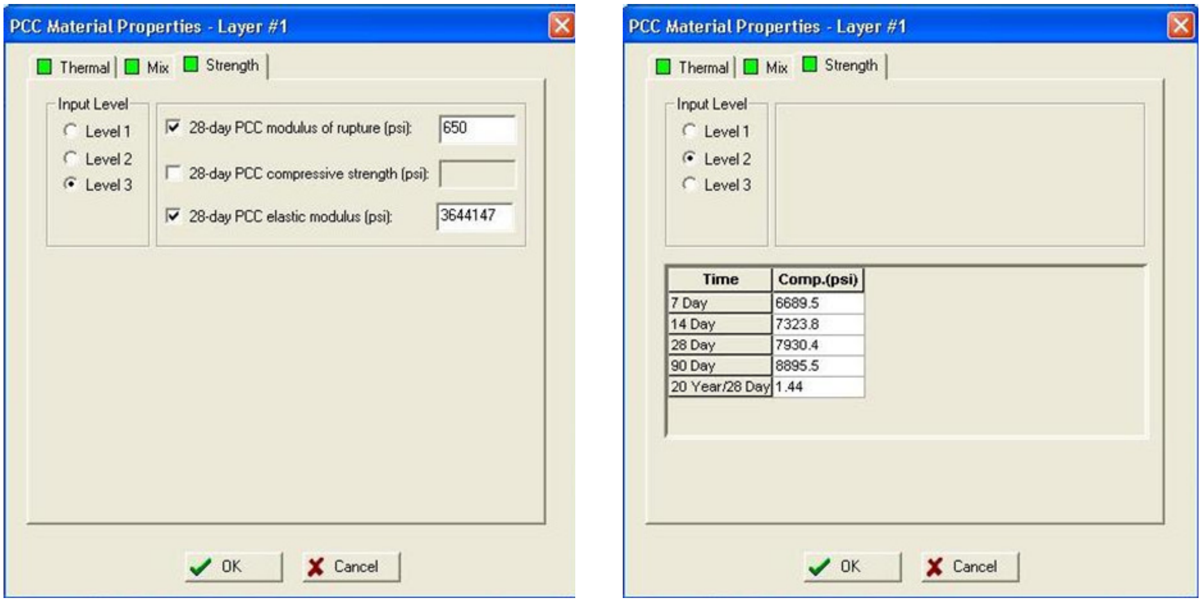
In order to provide rational inputs for Iowa pavement design, the concrete properties required by MEPDG at three different levels and their default values in MEPDG have been carefully reviewed and compared with those from the Iowa data analyses (see Section 3). The recommendations are drawn based on the comparisons and discussions below.

These PCC materials inputs and their default values in MEPDG are summarized in Figure 22. As seen in Figure 22a, 28-day elastic modulus and strength (either modulus of rupture or compressive strength) are required for the MEPDG Level 3 design. Considering that pavement concrete is generally subjected to, and often fails due to, flexural loading and that concrete can be designed with the same compressive strength but different flexural strength, depending significantly on size of coarse aggregate, the investigators recommend selecting modulus of rupture as a preferred input. In MEPDG, the default value for 28-day PCC modulus of rupture is 650 psi, which is almost the same as that of Iowa concrete test data, 646 psi (see Section 3). Therefore, the default value of 28-day PCC modulus of rupture (650 psi) is recommended as the Iowa Level 3 MEPDG input.

Figure 22a also shows that the default 28-day elastic modulus in MEPDG is 3,942,355 psi. However, the average value of the available Iowa test data (from the Iowa curling and warping project only) is 4,820,000 psi, which is quite different from the default value. Further research on the elastic modulus of Iowa concrete is necessary to provide a rational recommendation for the MEPDG Level 3 design based on the analysis of more available test data.

Figure 22b illustrates that compressive strength data at 7, 14, 28, and 90 days, and the 20-year to 28-day concrete strength ratio are required by MEPDG for the Level 2 design. Based on MEPDG, these compressive strength values at different ages should be the tested values and the 20-year to 28-day concrete strength ratio should be an estimated value. According to the concrete compressive strength gain values, concrete elastic modulus and modulus of rupture at the given ages are estimated based on the prediction equations used in the MEPDG for Level 2 design.

At Iowa DOT, facilities are available for testing not only concrete compressive strength (required for Level 2 design) but also elastic modulus and modulus of rupture at given ages (required for Level 1 design). Therefore, using the estimated values recommended MEPDG may not be necessary since the prediction equations used in MEPDG might not fit Iowa concrete materials well. It is recommended that the Iowa DOT directly use the tested compressive strength, elastic modulus, and modulus of rupture data for both the MEPDG Level 2 and Level 1 design. For other Iowa pavement agencies where the equipment for testing concrete elastic modulus is not available, elastic modulus and modulus of rupture can be estimated based on the prediction equations provided by MEPDG for the Level 2 design. (Please note that although Figures 22b and 22c show some default values in the MEPDG program, only the actual test data should be used as the Levels 2 and 3 design inputs.)



Input Level

○ Level 1
○ Level 2
● Level 3

☑ 28-day PCC modulus of rupture (psi): 650
☐ 28-day PCC compressive strength (psi):
☑ 28-day PCC elastic modulus (psi): 3644147

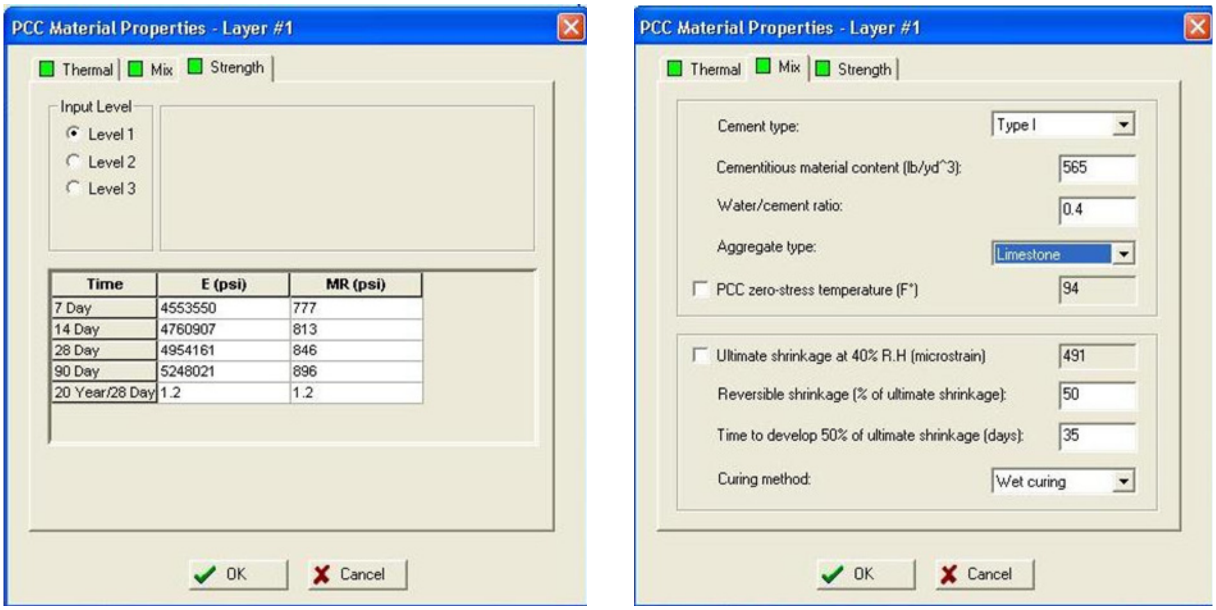
Input Level

○ Level 1
● Level 2
○ Level 3

Time	Comp.(psi)
7 Day	6689.5
14 Day	7323.8
28 Day	7930.4
90 Day	8895.5
20 Year/28 Day	1.44

(a) Level 3 (28-d strength & elastic modulus)

(b) Level 2 (strength development)



Input Level

● Level 1
○ Level 2
○ Level 3

Time	E (psi)	MR (psi)
7 Day	4553550	777
14 Day	4760907	813
28 Day	4954161	846
90 Day	5248021	896
20 Year/28 Day	1.2	1.2

Cement type: Type I
Cementitious material content (lb/yd^3): 565
Water/cement ratio: 0.4
Aggregate type: Limestone
☐ PCC zero-stress temperature (F°) 94
☐ Ultimate shrinkage at 40% R.H (microstrain) 491
Reversible shrinkage (% of ultimate shrinkage): 50
Time to develop 50% of ultimate shrinkage (days): 35
Curing method: Wet curing

(c) Level 1 (MR & elastic modulus with time)

(d) All Levels (mix and shrinkage inputs)

Figure 22. MEPDG PCC material property inputs and their default values

Figure 22b also shows that the MEPDG default value of the 20-year to 28-day compressive strength ratio is 1.44. Based on the available Iowa concrete test data (Section 3), this ratio is approximate 1.60 [7630 psi (long-term strength from the data of LTPP and three Iowa projects) divided by 4768 psi (28-day strength from Iowa DOT 1980s and 1990s test data], which is higher than the default value. Considering the limited long-term property data available for Iowa concrete, the investigators suggest using the MEPDG default value for Iowa concrete pavement before further research is conducted.

Figure 22c illustrates that concrete elastic modulus and modulus of rupture at different ages are required for the MEPDG Level 1 design. These values should come from the concrete tests of the designed pavement. The MEPDG default values of the 20-year to 28-day elastic modulus and modulus of rupture ratios should be used, since the corresponding Iowa data are not available.

For all three levels of pavement design, MEPDG requires inputting concrete mix design information (Figure 22d), which can be easily obtained based on Iowa typical concrete mixes. In addition, the ultimate shrinkage, reversible shrinkage, and the time to develop 50% of ultimate shrinkage values of concrete are also required as MEPDG input data. The default values of concrete ultimate shrinkage, reversible shrinkage, and the time to develop 50% of ultimate shrinkage are 491 microstrain, 50%, and 35 days, respectively, for the concrete under a wet curing condition. According to the result of one Iowa concrete mix (C-3-WR-C20) tested at CTL, the ultimate shrinkage of 454 microstrain and the time to reach 50% of ultimate shrinkage at 32 days, which are very close to the MEPDG default values. (Note: The reversible shrinkage was not obtained from this project due to the limitation of time.) Therefore, the default shrinkage values are recommended for Iowa pavement design at this time. Since Iowa DOT uses various concrete mixes but only one is tested during this research project, it is recommended that further research be conducted if concrete shrinkage becomes a potential problem in Iowa.

Table 21. Comparison of Iowa PCC material properties and MEPDG default values

Level of Design	PCC Property	MEPDG Default Value	Iowa Test Result	Recommended Value
3	Modulus of rupture, MOR (psi)	650	646	As default
	Elastic modulus, E_c (psi)	3,928,941	4,820,000*	Need more research
2	Compressive strength at 7, 14, 28, 90 days	Tested data	Not applicable	Tested data
	20-year to 28-day compressive strength ratio	1.44	~1.6*	As default
1	Elastic modulus at 7, 14, 28, 90 days	Tested data	Not applicable	Tested data
	Modulus of rapture at 7, 14, 28, 90 days	Tested data	Not applicable	Tested data
	20-year to 28-day concrete strength ratio	1.2	~1.6*	As default
3, 2, 1	Ultimate shrinkage, wet curing (microstrain)	491	454*	As default
	Ultimate shrinkage, curing compound (microstrain)	578	Not available	As default
	Reversible shrinkage	50	Not available	As default
	Time to develop 50% of ultimate shrinkage (day)	35	32*	As default

* indicates the value from limited Iowa test data

Table 20 summarizes the comparison of the default PCC input values from MEPDG and the values from the analyses of Iowa test data. Based on the discussions above, the recommendations for the Iowa PCC input values to be used in MEPDG are also included in the table.

5. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

1. Over 20,000 data produced during 1971–2005 were collected from the Iowa Department of Transportation (Iowa DOT) and other sources. The results indicate that during 1980s–1990s, the mean value of the 28-day core compressive strength was approximately 4,700 psi. After the year of 2000, the mean value of the 28-day core compressive strength decreased to 4,397 psi and with a standard deviation of 638 psi. The trend is probably related to the increasing use of supplementary cementitious materials (SCMs) in concrete. In the consideration of the slow pozzolanic reaction of the SCMs, the 56-day, rather than 28-day, strength may be employed in the concrete pavement design.

2. Over 450 data on concrete unit weight (uw), 300 data on modulus of rupture (MOR), but much less data on the concrete elastic modulus (E_c), and splitting tensile strength (f'_{sp} were also collected and studied. According to the data analyses, the following mean values were obtained as typical Iowa values:

    - Unit weight = 142.7 ± 2.1pcf pcf
      (330 data from Iowa DOT 15 QMC projects)
    - $MOR_{28}=646 \pm 51$ psi
      (Data of 243 samples from Iowa DOT QMC projects)
    - $E_{c28}=4.82 \pm 0.28 \times 10^6$ psi
      (Only two data available from Iowa "CW" project)

    The results indicate that the Iowa test result of 28-day modulus of rupture (646 psi) is almost the same as the MEPDG default value (650 psi). Therefore, the default value can be used as the Level 3 input. The Iowa test result of 28-day elastic modulus ($4.82 \pm 0.28 \times 10^6$ psi) is quite different from the MEPDG default value (3,942,355 psi). Further research is needed to obtain the more reliable elastic modulus value as the Level 3 input for typical Iowa concrete.

3. Over 20 sets of long term concrete properties data were collected from LTPP database. The properties of the Iowa concrete provided by the LTPP database were measured from different projects at different ages, rather than from given projects at different ages. There are no clear differences in the properties of the concrete between the ages of 5 years and 30 years As a result, the average property values of the Iowa concrete at the age of 5-30 years are recommended for overlay design:
    - $f'_{c,20y} \approx 7{,}627 \pm 811$ psi
      (22 data from LTPP, "PVT", "HSCPP", and "FEBCO" project)
    - $E_{c,20y} \approx 4.48 \pm 0.56 \times 10^6$ psi
      (11 data from LTPP and "HSCPP" project)

Due to lack of sufficient and appropriate test data for Iowa concrete, the MEPDG default values of the 20-year to 28-day compressive strength, elastic modulus, and modulus of rupture ratios are recommended unless future research is performed.

4. According to MEPDG, the concrete compressive strength at 7, 14, 28, and 90 days shall be tested for Level 2 design. Based on the concrete strength gain, concrete elastic modulus and modulus of rupture at these given ages will be estimated from the prediction equations programmed in the MEPDG. At Iowa DOT, facilities are available for testing not only concrete compressive strength but also elastic modulus and modulus of rupture. Therefore, it is recommended that Iowa DOT can directly use the tested compressive strength, elastic modulus, and modulus of rupture data for Level 2 design, thus elevating the PCC input data from Level 2 to Level 1.

5. The available equations for predicting common concrete properties were assembled for potential use in the MEPDG Level 2 design. Due to lack of necessary data sets, the relationships between Iowa concrete properties were established only based on the limited data from CP Tech Center's projects and ISU classes. The validity of the existing equations for Iowa concrete test data was examined. The results confirmed that there is a strong relationships between concrete compressive strength (f'_c) and elastic modulus (E_c) and splitting tensile strength (f'_{sp}), and an acceptable relationship between concrete compressive strength (f'_c) and modulus of rupture (MOR). Multiple-parameters nonlinear regression and artificial neural network (ANN) analyses also suggested that the f'_c of Iowa concrete materials was related to not only the water-to-binder ratio (w/b) but also the (uw) and cementitious material factor (CMF) at a given age (t). The following equations resulted from the statistical analysis of the available Iowa test data:

   - $f'_{c,t}$ (psi) = $-134119+10300(w/b)+978(uw)+125(CMF)+30.6[\log(t)]-752\,(w/b*uw) - 0.865(uw)*(CMF)$ $\quad (R^2=0.76)$
   - $E_c=80811 f'^{\,0.4659}_c$ $\quad (R^2=0.80)$
   - $MOR=12.93 f'^{\,0.4543}_c$ $\quad (R^2=0.54)$
   - $f'_{sp}=1.019 f'^{\,0.7068}_c$ $\quad (R^2=0.73)$

   These relationships can be used as references for Iowa pavement design engineers.

6. A survey on the currently available testing device for concrete drying shrinkage tests was conducted. An Iowa mix (C-3WR-C20) was selected and sent to Concrete Technology Laboratory (CTL) for a shrinkage test. The test was done according to ASTM C157, and the shrinkage value of the concrete at 123 days was 350 microstrain. The test result is consistent with published results of concrete mixes having a similar w/b. Based on the short-term measurements of C-3WR-C20 concrete, the ultimate shrinkage value of the concrete and the time at 50% shrinkage were predicted as 450 microstrain and 32 days respectively. Both values are close to the MEPDG default values (491 microstrain and 35 day respectively in wet curing). Therefore, it is recommended that the MEPDG default shrinkage values be used for Iowa pavement design until more Iowa test data are obtained.

7. It was noted that many concrete property data collected in the present study were lacking a complete set and had no information on concrete mix design, which made the study of the prediction equation more difficult. Appropriately documenting all commonly used concrete properties (such as slump, unit weight, air, compressive and flexural strength, and elastic modulus), together with the information on concrete mix design, is essential for updating the typical Iowa material input values and providing rational prediction equations for concrete pavement design in the future.

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APPENDIX A: IOWA MATERIAL—RAW DATA

Table A.1 Iowa DOT compressive strength data

Year	Mix Type	# Samples	f'c, 28 (psi)	Std Dev	Max	Min
1971	C	NA	4943	NA	NA	NA
1972	C	NA	4838	NA	NA	NA
1973	C	NA	4527	NA	NA	NA
1974	C	NA	4760	NA	NA	NA
1975	C	NA	4531	NA	NA	NA
1976	C	NA	4361	NA	NA	NA
1977	C	90	4442	620	NA	NA
1978	C	337	5023	562	NA	NA
1979	C	565	4490	557	NA	NA
1980	C	296	4843	532	NA	NA
1981	C	320	4745	590	NA	NA
1982	C	509	4512	590	NA	NA
1983	C	487	4359	639	NA	NA
1984	C	539	4704	701	NA	NA
1984	CWR	204	4699	678	NA	NA
1985	C	637	4863	702	NA	NA
1985	CWR	702	4910	782	NA	NA
1986	C	414	4726	818	NA	NA
1986	CWRC	672	4501	798	NA	NA
1987	C	418	5091	778	NA	NA
1987	CWRC	570	4617	836	NA	NA
1988	C	398	4950	892	NA	NA
1988	CWRC	1121	4893	752	NA	NA
1989	C	356	4746	813	NA	NA
1989	CWRC	1137	4893	836	NA	NA
1990	C	254	4779	782	NA	NA
1990	CWRC	736	4780	752	NA	NA
1991	C	750	4875	734	NA	NA
1991	CWRC	71	4841	549	NA	NA
1992	C	178	4877	787	NA	NA
1992	CWRC	1659	4723	751	NA	NA
1993	C	89	4898	949	NA	NA
1993	CWRC	903	4890	957	NA	NA
1994	CWRC	NA	5027	NA	NA	NA
1995	CWRC	NA	4876	NA	NA	NA
1996	CWRC	1090	4691	865	9865	7830
1997	CWRC	393	4612	797	8110	2690
1998	CWRC/QMC	720	4731	885	7690	2010
1999	CWRC/QMC	795	4771	769	8050	2240
2000	CWRC/QMC	336	5007	734	6920	3130
2001	CWRC/QMC	305	4087	589	5030	2430
2002	CWRC/QMC	626	4322	668	6320	2410
2003	CWRC/QMC	171	4284	560	5720	2660
2004	CWRC/QMC	129	4095	459	5300	2720
2005	CWRC/QMC	29	4216	632	5320	2770

Table A.2 Iowa DOT - QMC project data (2000 to Present)

Project No.	County	Year	Coarseness	Workability	Incentive	Air Before	Air After	w/c	MOR$_{28}$ (psi)
IM-80-2(156)73--13-01	Adair	2000	55.8	34.2	102	8.2	6.5	0.415	593
NHSX-520-5(34 & 64)--3H-38	Grundy	2000	61.2	35.7	101	7.6	6.3	0.418	729
NHS-61-4(80)--3H-70	Muscatine	2000	61.5	36.0	101	8.6	6.5	0.395	690
NHSX-61-5(92)--3H-82	Scott	2000	55.9	34.9	102	7.9	5.5	0.417	675
NHSX-18-6(58)--3H-34	Floyd	2000	55.3	34.4	102	7.8	6.5	0.388	705
NHSX-5-5(40)-3H-77	Polk	2000	56.3	35.6	102	8	6.6	0.380	
NHSX-75-1(55)--39-97	Woodbury	2000	57.6	33.2	103	8.4	6.4	0.431	621
STP-5-3(15)--2C-63	Marion	2000	58.2	33.2	103	7.7	6.3	0.366	618
IM-35-3(116)85--13-77	Polk	2000	63.1	33.5	102	8.5	6.9	0.416	
NHSX-71-5(38)--3H-14	Carroll	2001							
NHSX-151-4(60)--3H-53	Jones	2001	51.9	34.3	103	7.7	6.4	0.422	673
NHSX-151-3(112)--3H-57	Linn	2001							601
NHS-61-1(103)	Lee	2001	58.2	39	100	7.3	6.5	0.425	657
STP-92-9(74)	Washington	2001	59.2	34.1	103	8.2	6.1	0.405	608
NHS-75-1(75)	Woodbury	2001	59.8	33.4	103	9	6.2	0.418	531
NHSX-218-2(51 &57)	Henry	2001	61	34.9	101	8.1	6.2	0.414	641
NHS-63-8(17)	Chickasaw	2001	59	34	103	7.4	6.3	0.420	694
NHSX-520-5(40 & 111)	Hardin	2001	59.7	33.2	103	7.8	6.5	0.415	620
NHSX-63-8(44)	Chickasaw	2001	61.7	33.9	103	7.9	6.2	0.397	743
NHSX-63-8(21)	Chickasaw	2001	61	34	103	7.3	6.5	0.409	650
NHSX-5-5(57)	Polk	2002							614
STP-32-1(2)	Dubuque	2002	57.2	33.3	103	7.3	5.9	0.408	602
NHSX-330-1(19)	Marshall	2002	60.3	34.5	103	7.8	6	0.393	613
NHSX-65-4(77)	Polk	2002							
NHSX-330-2(39)	Jasper	2002	62.3	33.9	103	8.8	6.6	0.399	615
NHSX-218-8(43)	Bremer	2002	60.1	33.1	103	7.7	6.9	0.424	716
STPN-5-3(43)	Warren	2002							583
NHSX-520-5(38)	Hardin	2002	61.3	33.3	103	7.8	6.2	0.380	647
NHSX-520-5(116)	Hardin	2002	59.1	33.8	103	7.8	5.7	0.412	614
NHSX-520-5(112)	Hardin	2002	63.1	34.8	102	8	6.1	0.410	657
STP-13-2(33) (4" OVERLAY)	Delaware	2002		34.5	103	7.5	6.8	0.438	664
NHSX-151-4(56)	Jones	2002	50.7	34.4	103	7.9	6	0.377	681
NHSX-151-4(85)	Jones	2002	59.7	34	103	7.9	6.3	0.419	647
IM-35-6(94)140	Hamilton	2003	56.3	33.9	103	7.8	5.8	0.395	
STP-5-3(19)	Marion	2002	63.5	34.3	103	7.9	6.1	0.389	633
IM-80-1(251)6	Pott	2003							
NHSX-394-1(28)	Lee	2003							630
NHSX-394-1(29)	Lee	2003							661
NHSX-394-1(30)	Lee	2003							815
NHSX-218-8(67)	Bremer	2003							640
NHSX-34-9(92)	Henry	2003							
NHSX-34-8(53)	Jefferson	2003							717
NHSX-137-3(21)	Mahaska	2003							652
NHSX-34-7(94)	Wapello	2003							660
NHSX-218-2(117)	Henry	2004	52.7	36.6	103	8.4	6.1	0.403	
NHSX-218-1(51)	Lee	2004							

NHSX-151-5(55)	Dubuque	2004	52.8	36	103	8.1	5.9	0.408	662
NHSX-151-4(90)	Jones	2004	52.2	36.8	103	8	6.3	0.400	634
NHSX-34-8(71)	Jefferson	2004							
NHSX-394-1(31)	Lee	2004							
NHSX-394-1(32)	Lee	2004							
NHSX-060-2(34)--3H-84	Sioux	2004							564
NHSX-30-5(146)--3H-64	Marshall	2004							658
NHSX-30-6(104)--3H-86	Tama	2004							601
NHSX-394-1(33)	Lee	2005							
IM-NHS-235-2(498)11	Polk	2005							
NHSX-218-1(52)	Lee	2005	56.1	36.7	103	8.1	5.8	0.400	
NHSX-60-2(55)	Sioux	2005							582
NHSX-60-1(48)	Plymouth	2005							584
NHSX-60-1(21)	Plymouth	2005							
NHSX-34-8(72)	Jefferson	2005							685
NHSX-34-9(123)(121)	Des Moines	2005	57.5	34.8	103	8.4	6.1	0.403	668
NHSX-30-6(105)	Tama	2005							
NHSX-20-3(130)	Webster	2005							621

Table A.3 Iowa DOT - QMC project unit weight data

Unit Weight (pcf)									
148.4	145.6	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0
147.2	145.6	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0
147.2	145.6	144.6	144.0	143.2	142.8	142.4	141.4	140.8	140.0
147.2	145.6	144.4	144.0	143.2	142.8	142.0	141.2	140.8	140.0
147.2	145.6	144.4	144.0	143.2	142.8	142.0	141.2	140.8	140.0
147.2	145.6	144.4	143.6	143.2	142.8	142.0	141.2	140.4	140.0
146.9	145.6	144.4	143.6	143.2	142.8	142.0	141.2	140.4	140.0
146.8	145.6	144.4	143.6	143.2	142.8	142.0	141.2	140.4	140.0
146.8	145.2	144.4	143.6	143.2	142.8	142.0	141.2	140.4	140.0
146.8	145.2	144.4	143.6	143.2	142.8	142.0	141.2	140.4	139.9
146.8	145.2	144.4	143.6	143.2	142.7	142.0	141.2	140.4	139.7
146.8	145.2	144.4	143.6	143.2	142.6	142.0	141.2	140.4	139.6
146.4	145.2	144.4	143.6	143.2	142.5	142.0	141.2	140.4	139.6
146.4	145.2	144.4	143.6	143.2	142.5	142.0	141.2	140.4	139.6
146.4	145.2	144.4	143.6	143.2	142.4	142.0	141.2	140.4	139.6
146.4	145.2	144.4	143.6	143.2	142.4	142.0	141.2	140.4	139.6
146.4	145.2	144.2	143.6	143.2	142.4	142.0	141.0	140.3	139.6
146.2	145.2	144.0	143.6	143.2	142.4	142.0	140.8	140.3	139.2
146.0	145.2	144.0	143.6	143.2	142.4	142.0	140.8	140.2	139.2
146.0	145.2	144.0	143.6	143.2	142.4	142.0	140.8	140.0	139.2
146.0	145.2	144.0	143.6	143.0	142.4	142.0	140.8	140.0	139.2
146.0	145.2	144.0	143.6	142.8	142.4	142.0	140.8	140.0	139.1
146.0	145.0	144.0	143.6	142.8	142.4	142.0	140.8	140.0	138.8
146.0	144.8	144.0	143.2	142.8	142.4	141.8	140.8	140.0	138.8
146.0	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	138.4
146.0	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	138.4
146.0	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	138.4
146.0	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	138.4
145.8	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	138.0
145.8	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	138.0
145.6	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	138.0
145.6	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	138.0
145.6	144.8	144.0	143.2	142.8	142.4	141.6	140.8	140.0	137.4

Table A.4 “CW” project data

ID	Age (day)	f'c (psi)	Ec (psi)	f'sp (psi)
CW-B	0.5	685	2239424	89
CW-B	1.0	1481	2369168	224
CW-B	2.0	2710	3178214	296
CW-B	4.0	3738	3829728	319
CW-B	7.0	4952	4479009	415
CW-B	28.0	6690	4621292	375
CW-B	56.0	7846	5080550	536
CW-M	0.5	3260	4081588	397
CW-M	1.0	3750	4117468	333
CW-M	2.0	4770	4449651	437
CW-M	4.0	5036	4781834	338
CW-M	7.0	5303	4363452	355
CW-M	28.0	6587	5024031	411
CW-M	56.0	7183	4879745	402

Table A.5 “MMO-F” project data

ID	Age (day)	f'c (psi)	Air%	SL. (in.)	Unit wt (pcf)
MMO-4A	28.0	4772	7.80	2.00	140.9
MMO-4B	28.0	5510	7.20	1.50	141.8
MMO-4B	28.0	5550	7.20	2.00	141.8
MMO-5A	28.0	5460	6.00	2.00	143.1
MMO-5B	28.0	6260	5.20	1.00	144.8
MMO-5B	28.0	5930	6.10	1.75	143.6
MMO-6A	28.0	5340	7.70	1.75	141.6
MMO-6B	28.0	5400	7.80	1.75	141.8

Table A.6 “MMO-L” project data

	f'c,7 (psi)	unit wt (pcf)	Sl. (in.)	Air (%)	Cement (pcy)	Fly Ash (pcy)	Water (pcy)	F.A. (pcy)	C.A. (pcy)	W/b
C3-S1-1	6416	147.7	1.63	5.1	624	0	268	1467	1511	0.43
C3-S1-2	5969	146.9	1.38	4.8	624	0	268	1467	1511	0.43
C3-N1-1	5689	146.6	1.75	4.9	624	0	268	1467	1511	0.43
C3-N1-2	5647	146.9	1.63	5.0	624	0	268	1467	1511	0.43
C4-S1-1	5659	144.7	2.13	6.1	603	0	260	1339	1684	0.43
C4-S1-2	5689	145.4	2.25	6.2	603	0	260	1339	1684	0.43
C4-N1-1	5415	146.2	2.75	6.3	603	0	260	1339	1684	0.43
C4-N1-2	5510	146.6	2.75	6.2	603	0	260	1339	1684	0.43
C3WR-S1-1	5808	146.6	0.88	5.4	572	0	246	1370	1716	0.43
C3WR-S1-2	5939	147.3	1.13	5.4	572	0	246	1370	1716	0.43
C3WR-N1-1	5701	144.7	1.50	7.6	572	0	246	1370	1716	0.43
C3WR-N1-2	5546	142.0	2.25	8.0	572	0	246	1370	1716	0.43
C4WR-S1-1	5987	145.0	1.38	7.2	593	0	254	1503	1538	0.43
C4WR-S1-2	5689	145.8	1.13	6.4	593	0	254	1503	1538	0.43
C4WR-N1-1	5248	140.5	2.63	9.7	593	0	254	1503	1538	0.43
C4WR-N1-2	5391	142.0	2.25	8.7	593	0	254	1503	1538	0.43
C3WRC-S1-1	5331	146.6	1.63	5.5	487	86	246	1365	1706	0.43
C3WRC-S1-2	5272	143.5	2.63	7.3	487	86	246	1365	1706	0.43
C3WRC-N1-1	4961	142.0	3.25	8.3	487	86	246	1365	1706	0.43
C3WRC-N1-2	5421	144.7	2.00	6.6	487	86	246	1365	1706	0.43
C4WRC-S1-1	5307	144.7	1.50	6.7	503	86	256	1494	1529	0.43
C4WRC-S1-2	5361	144.7	1.38	6.6	503	86	256	1494	1529	0.43
C4WRC-N1-1	4651	139.7	4.25	9.5	503	86	256	1494	1529	0.43
C4WRC-N1-2	4425	139.7	4.25	9.6	503	86	256	1494	1529	0.43
C3C-S1-1	5116	147.3	1.38	4.4	513	91	260	1334	1675	0.43
C3C-S1-2	5896	146.2	1.75	5.3	513	91	260	1334	1675	0.43
C3C-N1-1	5480	148.5	2.88	4.7	513	91	260	1334	1675	0.43
C3C-N1-2	4961	147.7	3.63	5.0	513	91	260	1334	1675	0.43
C4C-S1-1	5683	146.6	1.38	4.8	529	95	268	1463	1502	0.43
C4C-S1-2	5760	146.6	1.75	4.6	529	95	268	1463	1502	0.43
C4C-N1-1	5421	146.6	3.88	5.4	529	95	268	1463	1502	0.43
C4C-N1-2	5099	146.2	5.63	5.9	529	95	268	1463	1502	0.43
C3F-S1-1	4663	145.4	2.50	5.2	513	127	271	1303	1638	0.43
C3F-S1-2	4544	145.8	2.38	5.7	513	127	271	1303	1638	0.43
C3F-N1-1	4478	146.6	3.38	5.7	513	127	271	1303	1638	0.43
C3F-N1-2	4455	146.6	2.88	5.7	513	127	271	1303	1638	0.43
C4F-S1-1	4860	145.0	3.13	5.8	529	131	280	1427	1470	0.43
C4F-S1-2	4860	145.0	2.88	5.8	529	131	280	1427	1470	0.43
C4F-N1-1	4604	145.4	3.00	6.0	529	131	280	1427	1470	0.43
C4F-N1-2	4794	146.6	2.25	5.9	529	131	280	1427	1470	0.43
C3WRF-S1-1	4085	141.6	2.75	7.7	487	118	256	1339	1675	0.43
C3WRF-S1-2	4580	143.1	2.63	7.7	487	118	256	1339	1675	0.43
C3WRF-N1-1	4902	142.7	1.50	6.8	487	118	256	1339	1675	0.43
C3WRF-N1-2	4717	143.1	2.13	7.0	487	118	256	1339	1675	0.43
C4WRF-S1-1	4735	143.1	1.50	6.0	503	127	266	1463	1497	0.43
C4WRF-S1-2	5164	146.6	1.63	5.9	503	127	266	1463	1497	0.43
C4WRF-N1-1	4711	143.5	2.50	6.9	503	127	266	1463	1497	0.43
C4WRF-N1-2	5087	144.7	2.25	6.6	503	127	266	1463	1497	0.43

Table A.7 “OGS” project data

Mix	w/c	Slump (in.)	Unit wt. (pcf)	Air%	$f'_{c,3}$ (psi)	$f'_{c,7}$ (psi)	$f'_{c,28}$ (psi)	$f'_{c,90}$ (psi)
Control	0.43	2.25	143.0	5.1	4000	4950	6320	6990
Ash 1-20%	0.41	3.25	142.8	5.2	3470	4780	6170	7210
Ash 1-28%	0.39	2.50	143.2	5.2	3400	4690	6290	7070
Ash 1-36%	0.38	2.50	145.0	4.0	3540	5250	7370	8360
Ash 2-20%	0.40	2.50	141.8	5.7	3620	4820	6370	7140
Ash 2-28%	0.39	2.50	141.4	6.3	3400	4550	6140	6800
Ash 2-36%	0.38	2.75	140.8	6.5	3110	4240	6100	6810
Ash 3-20%	0.40	2.50	141.6	6.0	3500	4760	6350	7130
Ash 3-28%	0.39	3.50	140.0	6.8	3250	4290	6010	6620
Ash 3-36%	0.38	2.50	140.6	6.6	3310	4470	6110	6940

Table A.8 “IPC” project data

	f'c, 3 (psi)	f'c, 7 (psi)	MOR, 7 day (psi)
CU-Ref	3300	3800	490
CU-C98.1	4300	5000	570
CU-C95.9	4200	4500	660
CU-C89.0	3800	4300	520

Table A.9 “HSCPP” project data

LTPP Section ID	Test Age (year)	f'_c, psi	E_c, psi	MOR, psi*
19-3006	22	6672	4641206	725
19-3055	29	6092	3770980	624

* Estimated

Table A.10 “FEQMC” project data

ID	Age (day)	f'c (psi)	MOR (psi)	ID	Age (day)	f'c (psi)	MOR (psi)
FE-1A	14.0	7239	549	FE-1A	28.0	6317	701
FE-1B	14.0	6683	569	FE-4B	28.0	5887	743
FE-1C	28.0	6698	617	FE-4C	14.0	5712	660
FE-1D	28.0	6301	604	FE-4D	14.0	5919	644
FE-2A	28.0	6587	726	FE-5A	28.0	5569	715
FE-2B	14.0	6380	615	FE-5B	14.0	5776	616
FE-2C	28.0	5776	571	FE-5C	14.0	5696	596
FE-2D	14.0	6221	615	FE-5D	28.0	5267	692
FE-3A	28.0	6428	728	FE-6A	14.0	5951	650
FE-3B	14.0	6969	644	FE-6B	28.0	5919	683
FE-3C	14.0	5823	634	FE-6C	28.0	5314	684
FE-3D	28.0	6277	725	FE-6D	14.0	5251	635

Table A.11 “MTE” project data

	Air (%)	Slump (in.)	Unit weight (pcf)	$f'_{c,28}$ (psi)
MT3015-30s	4.9	0.69	145.7	7281
MT3022-30s	5.7	1.44	146.7	5649
MT3057-30s	7.0	2.69	145.0	5450
MT3057-45s	5.9	1.07	143.4	5954
MT3059-45s	6.1	1.00	146.1	6744
MT3016-45s	6.6	3.63	134.5	4595
MT3019-45s	7.8	2.57	140.2	4939
MT3020A-45s	6.0	2.28	140.1	5322
MT3021A-45s	5.7	2.69	138.7	5138
MT3016-60s	7.6	2.28	140.1	4810
MT3019-60s	7.8	3.13	141.1	4709
MT3020A-60s	7.7	2.94	138.7	5032
MT3021A-60s	6.4	1.88	139.5	4455
MT3058-60s	8.2	2.88	138.0	5139
MT3016-90s	8.9	3.25	137.5	4568
MT3019-90s	8.8	2.19	137.2	4502
MT3021B-90s	8.9	2.94	138.5	4021
MT3058-90s	8.6	2.44	140.0	4934
MT3020B-45s	8.4	2.44	136.5	4651
MT3021B-45s	8.8	2.81	136.5	4004
MT3058-45s	8.7	2.19	136.5	4538
MT3016-60s	NA	NA	136.5	NA
MT3020B-60s	7.6	3.13	137.8	5461
MT3021B-60s	5.5	1.44	136.5	6522
MT3016-90s	7.4	3.69	140.5	5527
MT3058-90s	7.1	2.77	140.5	5782

Table A.12 “FEBCO” project data

Test Section	Test Age (year)	f'_c, psi	f'_{sp}, psi
1	21	8590	630
2	21	8160	730
3	13	6860	680
4	19	6920	600
5	20	6770	600

Table A.13 “PVT30” project data

Section Number	Air %	$(MOR)_{28}$, psi	Cylinders $(f'_c)_{28}$, psi	Cores $(f'_c)_{28year}$, psi
1, 5	3.5	800	5370	8090
2, 6	2.6	780	5520	8070
3, 7	3.2	790	5850	8100
4, 9	3.4	800	5490	7500
9	3.5	810	5870	7820
10*	6.6	770	5290	7540

* Air entrained

Table A.14 LTPP f'$_c$ data (from table "TST_PC01")

SHRP_ID	Construction Date	Test Date	Test Age (Year)	f'c (psi)
19-3006	01-Oct-75	01-Jul-91	16	8480
19-3009	01-Dec-75	01-Jul-91	16	6875
19-3028	01-Nov-84	01-Jul-91	7	7035
19-3033	01-Aug-83	01-Jul-91	8	7515
19-3055	01-Nov-68	07-Dec-89	21	8545
19-5042	01-Sep-75	07-Jun-91	16	8145
19-5046	01-Sep-75	10-Aug-90	15	7495
19-9116	01-Jun-72	26-Apr-90	18	6985
19-9126	01-Dec-64	27-May-91	27	9530

Table A.15 LTPP f'$_{sp}$ data (from table "TST_PC02")

SHRP_ID	Construction Date	Test Date	Test Age (year)	f'sp (psi)
19-3006	01-Oct-75	02-Jul-91	16	493.5
19-3009	01-Dec-75	02-Jul-91	16	558.5
19-3028	01-Nov-84	02-Jul-91	7	514.5
19-3033	01-Aug-83	02-Jul-91	8	496.5
19-3055	01-Nov-68	03-Jan-90	22	568.5
19-5042	01-Sep-75	13-Jun-91	16	630
19-5046	01-Sep-75	14-Sep-90	15	612
19-9116	01-Jun-72	26-Apr-90	18	495.5
19-9126	01-Dec-64	27-May-91	27	604.5

Table A.16 LTPP long term E$_c$ and Poisson ratio data (from table "TST_PC04")

SHRP_ID	Construction Date	Test Date	Test Age (year)	Poisson Ratio	Ec (psi)
19-3006	01-Oct-75	08-Jul-91	16	0.21	4825000
19-3009	01-Dec-75	08-Jul-91	16	0.22	4525000
19-3028	01-Nov-84	08-Jul-91	7	0.205	4400000
19-3033	01-Aug-83	08-Jul-91	8	--	4325000
19-3055	01-Nov-68	13-Jun-90	22	0.16	3475000
19-5042	01-Sep-75	17-Jun-91	16	0.215	4350000
19-5046	01-Sep-75	01-Oct-90	15	0.215	4525000
19-9116	01-Jun-72	28-Jun-90	18	0.265	4900000
19-9126	01-Dec-64	31-May-91	27	0.2	5575000

Table A.17 LTPP MOR data (from table "TST_PC09")

SHRP_ID	Construction Date	(MOR)14, psi	(MOR)28, psi	(MOR)365, psi
19-0213	25-Jul-94	500	590	610
19-0214	25-Jul-94	700	770	890
19-0219	22-Jul-94	440	530	590
19-0220	22-Jul-94	770	720	770
19-0223	26-Jul-94	460	520	680
19-0224	26-Jul-94	790	750	930
Avg.		610	647	745
STD		161	113	143

Table A.18 ISU CE382/CE383 data

ID	w/c	Air%	SL. (in.)	Unit wt (pcf)	f'c,7 (psi)	f'c,28 (psi)	MOR28 (psi)
CE382-F05-s1-1	0.55	6.0	NA	NA	3112	3112	NA
CE382-F05-s1-2	0.40	6.0	NA	NA	5395	5395	NA
CE382-F05-s2-1	0.42	5.0	1.50	146.0	5053	6083	667
CE382-F05-s2-2	0.55	6.8	4.00	NA	3696	4365	550
CE382-F05-s2-3	0.84	9.0	5.50	132.0	1948	2428	490
CE382-F05-s3-1	0.58	6.0	NA	NA	2141	2141	NA
CE382-F05-s3-2	0.78	6.0	NA	NA	2561	2561	NA
CE382-F05-s3-3	0.78	6.0	NA	NA	1259	1259	NA
CE383-S06-s0-1	NA	NA	NA	NA	6246	6246	680
CE383-S06-s0-2	NA	NA	NA	NA	4538	4538	NA
CE383-S06-s0-3	NA	NA	NA	NA	3506	3506	490
CE383-S06-s1-1	0.45	5.5	NA	NA	4602	4602	NA
CE383-S06-s1-2	0.55	5.8	NA	NA	3687	3687	NA
CE383-S06-s1-3	0.70	6.4	NA	NA	2348	2348	NA
CE383-S06-s2-1	0.43	1.4	NA	NA	4370	4370	NA
CE383-S06-s2-2	0.55	6.5	NA	NA	3462	3462	NA
CE383-S06-s2-3	0.70	7.0	NA	NA	2392	2392	NA
CE383-F05-s1-1	0.49	5.3	1.75	142.0	4923	5937	705
CE383-F05-s1-2	0.55	6.3	3.00	138.5	3309	3727	610
CE383-F05-s1-3	0.61	10.0	2.00	136.4	1868	2587	500
CE383-F05-s2-1	0.41	4.5	2.00	151.4	5218	4802	673
CE383-F05-s2-2	0.47	7.1	2.38	142.0	4037	4175	555
CE383-F05-s2-3	0.59	9.0	1.50	129.0	2285	3223	567
CE383-S05-s1-1	0.42	5.5	3.00	139.6	4914	4914	NA
CE383-S05-s1-2	0.53	5.3	0.50	138.4	3516	3516	NA
CE383-S05-s1-3	0.70	7.0	0.75	137.5	2397	2397	NA
CE383-S05-s2-1	0.48	7.0	1.50	141.5	4376	4376	NA
CE383-S05-s2-1	0.55	6.5	3.50	137.6	3450	3450	NA
CE383-S05-s2-1	0.62	5.5	2.50	138.3	3171	3171	NA
CE383-F04-s1-1	0.47	8.5	4.50	NA	4332	4001	580
CE383-F04-s1-2	0.65	6.2	1.25	NA	4878	5472	568
CE383-F04-s2-1	0.45	4.3	2.50	NA	6048	6554	593
CE383-F04-s2-2	0.55	8.5	2.50	NA	4251	4072	528
CE383-F04-s2-3	0.67	8.0	1.50	NA	3187	2869	467
CE383-S04-s1-1	0.42	3.6	0.50	141.0	5893	7105	850
CE383-S04-s1-2	0.55	6.2	1.25	138.0	4472	5575	649
CE383-S04-s1-3	0.70	8.0	2.50	137.0	2130	3577	519
CE383-S04-s2-1	0.53	5.2	4.00	135.0	4762	5469	749
CE383-S04-s2-2	0.49	9.0	2.25	133.8	1767	2064	370
CE383-S04-s2-3	0.66	8.5	2.00	138.0	3394	3401	481
CE383-F03-s1-1	0.42	7.0	2.50	138.4	4717	2921	613
CE383-F03-s1-2	0.50	10.0	3.00	136.7	3035	2981	467
CE383-F03-s1-3	0.70	9.5	3.25	131.4	2177	2857	461
CE383-F03-s2-1	0.46	5.2	3.00	139.9	5715	5277	690
CE383-F03-s2-2	0.67	6.5	3.75	137.2	3464	3692	544
CE383-F03-s2-3	0.75	9.5	2.00	136.9	2475	2706	475
CE382-F06-s1-1	0.43	5.8	1.60	141.8	4589	5554	672
CE382-F06-s1-2	0.56	5.7	2.00	136.3	3581	4991	590
CE382-F06-s1-3	0.54	9.0	2.25	137.0	2255	3262	442
CE382-F06-s2-1	0.41	3.8	2.75	138.7	4734	6174	669
CE382-F06-s2-2	0.55	5.7	3.50	141.4	3209	4234	561

ID	w/c	Air%	SL. (in.)	Unit wt (pcf)	f'c,7 (psi)	f'c,28 (psi)	MOR28 (psi)
CE382-F06-s2-3	0.60	8.3	2.75	136.8	2340	3245	348
CE382-F06-s3-1	0.42	3.5	2.00	138.4	4376	5034	624
CE382-F06-s3-2	0.46	5.5	3.50	143.2	4350	5304	672
CE382-F06-s3-3	0.62	7.6	1.00	137.4	2600	3168	572
CE382-F06-s4-1	0.42	4.0	2.00	138.3	4959	5722	644
CE382-F06-s4-2	0.54	5.5	1.00	136.9	3661	4602	532
CE382-F06-s4-3	0.55	5.8	2.50	139.3	3124	3792	503
CE383-F06-s1-1	0.48	4.5	1.25	140.3	4271	5082	604
CE383-F06-s1-2	0.51	6.5	2.00	137.3	3800	3419	358
CE383-F06-s1-3	0.51	6.0	2.00	136.3	1781	2547	374
CE383-F06-s2-1	0.43	4.3	1.25	140.3	4689	5556	687
CE383-F06-s2-2	0.51	6.5	1.50	137.3	3236	4234	619
CE383-F06-s2-3	0.62	8.0	1.50	136.3	1207	2808	510

APPENDIX B: SUPPLEMENTAL IOWA STRENGTH DATA ANALYSIS

Results in Table B. 1 and Figure B. 1 showed that similar as the results indicated in

Table 6, with the improvement of quality control, the strength increases from 1970s to 1990s, however decrease at 2000s because of the apply of QMC mixes. The standard deviation between each years decreases from 1970s to 1990s, which showed the opposite trend at 2000s, which might be due to the relative smaller size of available data (6 years, 1596 data).

Table B.1 Analysis results of Iowa DOT core sample analysis (by year)

	1970s	1980s	1990s	2000s	Total
f'_c by year (psi)	4657	4753	4812	4335	4697
STD by year (psi)	238	189	106	343	251

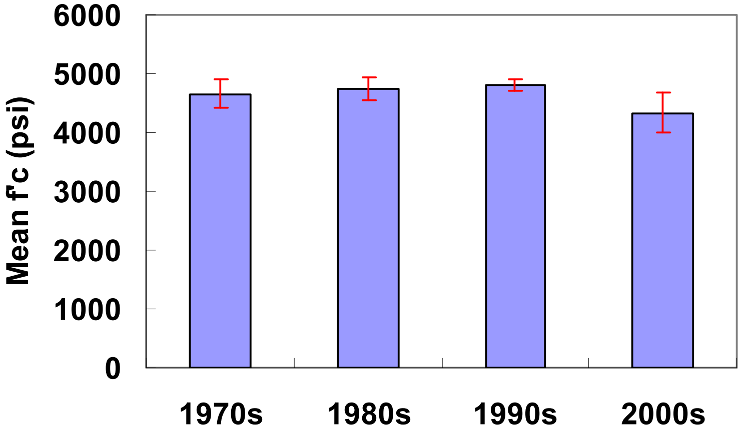
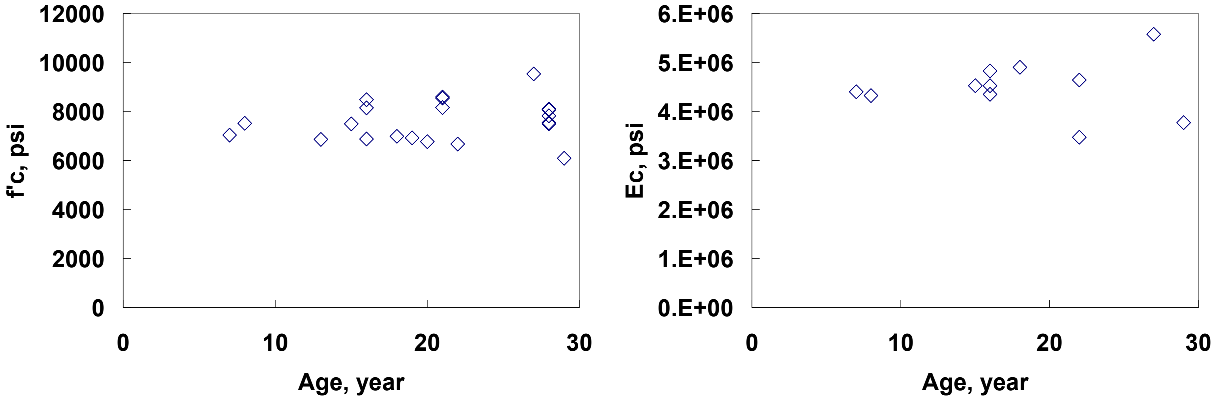


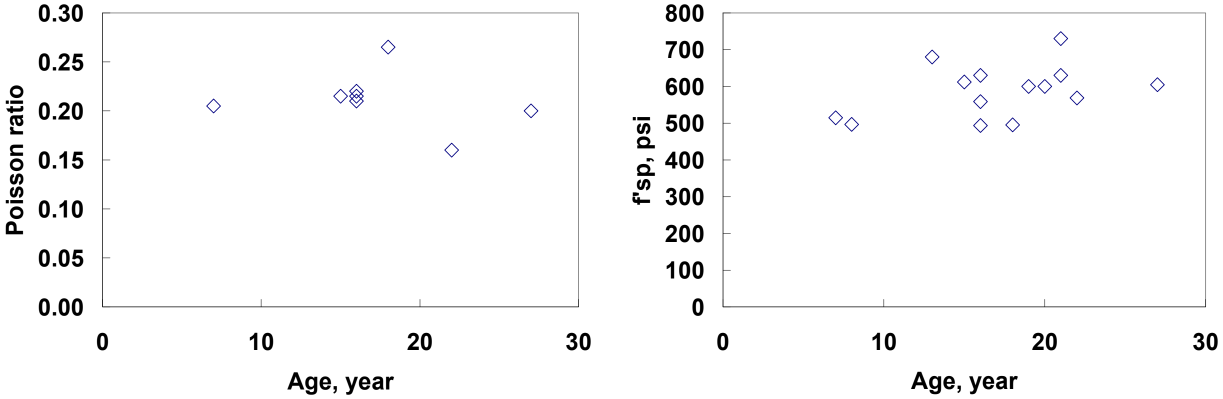
Figure B. 2 Mean $f'_{c,28}$ and standard deviation between each years

Table B.2 Analysis of Iowa DOT MOR_{28} data within an individual project

Year	Projects	MOR_{28}	MOR_{28} STD	# of Beam Tested	Avg MOR_{28}	Avg MOR_{28} STD	Avg # of beam per project
2000	1	593	70	6	661	70	6.0
	2	729	NA	NA			
	3	690	NA	NA			
	4	675	NA	NA			
	5	705	NA	NA			
	6	621	NA	NA			
	7	618	NA	NA			
2001	1	673	51	12	642	38	6.3
	2	601	47	10			
	3	657	36	6			
	4	608	43	6			
	5	531	38	6			
	6	641	37	9			
	7	694	42	4			
	8	620	55	6			
	9	743	4	2			
	10	650	28	2			
2002	1	614	45	8	637	40	6.3
	2	602	39	4			
	3	613	11	2			
	4	615	35	2			
	5	716	31	4			
	6	583	44	4			
	7	647	59	16			
	8	614	48	8			
	9	657	60	6			
	10	664	40	6			
	11	681	25	8			
	12	647	38	8			
	13	633	46	6			
2003	1	630	75	4	682	51	4.0
	2	661	89	4			
	3	815	35	2			
	4	640	43	4			
	5	717	39	6			
	6	652	46	6			
	7	660	28	2			
2004	1	662	33	8	624	40	7.6
	2	634	36	10			
	3	564	46	14			
	4	658	39	2			
	5	601	46	4			
2005	1	582	42	10	628	26	5.2
	2	584	36	6			
	3	685	7	2			
	4	668	32	4			
	5	621	14	4			
Total	47	---	---	243	646	40	5.9



(a) Compressive strength (b) Elastic modulus



(c) Poisson ratio (d) Splitting tensile strength

Figure B. 2 Distribution of long term concrete properties

APPENDIX C: DRYING SHRINKAGE TEST DEVICE

Researches have been conducted to investigate equipment for concrete shrinkage tests, seven commercial available devices as shown in Figure 22 had been found. The possibility for purchasing or building the equipment for concrete shrinkage tests at the CP Tech Center's research lab was evaluated based on the price and specification of the equipments (Table B.1).

(a) Retractometer (Laval lab Inc.)

(b) Length Comparator (ILE)

(c) Length comparator (ELE)

(d) Drying shrinkage and moisture movement apparatus (Intec)

(e) Length Comparator (with Mechanical Indicator HM-250; with Digital Indicator HM-250D) (Gilson and Humboldt)

(f) 'Plastic Shrinkage' Tester (Wexham Developments)

Figure C.1 Commercial available concrete shrinkage test device

Table C.1 Information of Commercial available concrete shrinkage test device

Company	Device	Specification	Price
Laval lab Inc.	Retractometer	Dimensional variations on 100 to 400mm (approx. 4 to 15 in.) samples RS232C interface, Canada	Quotation
ILE	Length Comparator, IL-144	Length comparator with 0.002x5mm dial gauge	$110
ELE	Length comparator	Digital/Dial Dial Indicator: 0.3"x0.0001" (8mmx0.002mm) divisions	PCC Lab
Intec	Drying shrinkage and moisture movement apparatus	Dial gauge of 25mm travel x 0.002mm division, Malaysia	$940 (length comparator, steel frame) $342 (2 gang prism mould) $40 (steel inserts, 10 pcs per pack)
Gilson/ Humboldt	Length Comparator, (HM-250/ HM-250D)	Sample length: 10" (254mm) (1"x1" up to 4"x4" cross section) Resolution: 0.0001" (0.0025mm)	$691 / $810 (HM-250 / HM-250D)
Wexham Developments	'Plastic Shrinkage' Tester	Specimen dimensions: 45mmx45mmx285mm Resolution: 0.001mm (earlier stages of hydration), UK	£916 (comprises – stainless steel mould, calibrated LVDT, cast-in inserts)

According to ASTM C157, special storage devices are necessary since drying shrinkage testing specimens are required to be stored in constant temperature and relative humidity conditions. Therefore, the investigators also conducted a survey to summarize the currently available curing chamber suitable for concrete sample storage. The pictures and producers of some available devices are presented in Figure B.2.

(a) Hotpack

(b) Norlake Scientific Environmental Chambers

(c) BioResearch

(d) Darwin Chamber

(e) CSZ industrial

(f) Parameter Generation & Control (PGC)

Figure C.2 Commercial available environmental chamber

The costs of the chambers range from $12,500 (Norlake Scientific EW-37755-22 Humidity Stability Chamber) to up to $16,054 (Darwin KB056 Environmental Chamber). A detailed feasibility study on this should be conducted after the decision of the plan of drying shrinkage measurement for Iowa pavement concrete can be made.

APPENDIX D: CONCRETE DRYING SHRINKAGE TEST RESULTS

Table D.1 Shrinkage test – specimen measurements

Date	Age, days	Condition	Specimens A	Specimens B	Specimens C
10/19/2006	0	moist	-351	-1164	-1258
11/15/2006	28	moist	-348	-1158	-1254
11/19/2006	32	dry	-350	-1163	-1257
11/22/2006	35	dry	-356	-1171	-1264
11/29/2006	42	dry	-362	-1178	-1272
12/6/2006	49	dry	-368	-1184	-1280
12/13/2006	56	dry	-373	-1188	-1280
12/20/2006	63	dry	-375	-1191	-1284
12/27/2006	70	dry	-377	-1192	-1284
1/3/2007	77	dry	-379	-1193	-1284
1/10/2007	84	dry	-379	-1193	-1284
1/24/2007	98	dry	-383	-1197	-1292
2/13/2007	118	dry	-383	-1196	-1291
3/18/2007	151	dry	-387	-1199	-1291
4/18/2007	182	dry			
5/18/2007	212	dry			
6/18/2007	243	dry			
7/18/2007	273	dry			
8/18/2007	304	dry			
10/18/2007	365	dry			

Table D.2 Concrete shrinkage data

Drying Period, days	**Condition**	**Shrinkage, %** A	B	C	Average	Predicted Shrinkage, %
0	moist	0.003	0.006	0.004	0.004333	0
4	dry	0.001	0.001	0.001	0.001	-0.00506
7	dry	-0.005	-0.007	-0.006	-0.006	-0.00818
14	dry	-0.011	-0.014	-0.014	-0.013	-0.01386
21	dry	-0.017	-0.020	-0.022	-0.020	-0.01803
28	dry	-0.022	-0.024	-0.022	-0.023	-0.02123
35	dry	-0.024	-0.027	-0.026	-0.026	-0.02376
42	dry	-0.026	-0.028	-0.026	-0.027	-0.02581
49	dry	-0.028	-0.029	-0.026	-0.028	-0.02751
56	dry	-0.028	-0.029	-0.026	-0.028	-0.02894
70	dry	-0.032	-0.033	-0.034	-0.033	-0.0312
90	dry	-0.032	-0.032	-0.033	-0.032	-0.03353
123	dry	-0.036	-0.035	-0.033	-0.035	-0.03606
154	dry					
184	dry					
215	dry					
245	dry					
276	dry					
337	dry					