Title No. 112-M14

Statistical Comparisons of Creep and Shrinkage Prediction Models Using RILEM and NU-ITI Databases

by Akthem Al-Manaseer and Armando Prado

Six shrinkage and creep compliance models were evaluated according to the NU-ITI and RILEM databases. The prediction models include ACI 209R-92, B3, GL 2000, CEB MC 90-99, fib *MC 2010, and AASHTO 2012. Five statistical methods were used to evaluate the models. The statistical methods include the residual method, the CEB coefficient of variation* V_{CEB}*, the CEB mean square error* F_{CEB}*, the CEB mean deviation* M_{CEB}*, and the new modified coefficient of variation method* ω_m*. Results indicate that for shrinkage predictions, ACI 209R-92 performed best, followed by B3, CEB MC 90-99,* fib *MC 2010, and GL 2000 models. The AASHTO 2012 model received the lowest ranking. For creep compliance, ACI 209R-92 had the best performance, followed by the B3 and GL 2000 models. The CEB MC 90-99 model ranked third, the* fib *MC 2010 model ranked fourth, and the AASHTO 2012 model ranked fifth. It should be noted that the data selection criteria and the database used to assess the models can influence the final ranking conclusions. Other statistical methods might also influence the rankings.*

Keywords: creep; creep prediction models; shrinkage; shrinkage prediction models.

INTRODUCTION

Drying shrinkage and creep cause volume changes in concrete over time. The changes in volume due to drying shrinkage and creep can result in the development of time-dependent excessive stresses, cracking, or deflections. The resulting stresses and flaws influence the durability, serviceability, and safety of a structure.[1,2] The Koror-Babeldaob Bridge, located in the Pacific island nation of Palau, is an example of a structure that suffered severe deflections due to the use of inadequate shrinkage strain and creep prediction models at the time of the bridge's design.[3-5] The bridge was constructed in 1977, and collapsed in 1996 at approximately 19 years of age.[4] To prevent incidents similar to the collapse of the Koror-Babeldaob Bridge from occurring again, different creep and shrinkage models need to be assessed for their prediction accuracy. It is also essential to consider model limitations before their application.

RESEARCH SIGNIFICANCE

This study performs a statistical evaluation of the ACI 209R-92,[6,7] B3,[6,7] GL 2000,[6,7] CEB MC 90-99,[6,7] *fib* MC 2010,[8] and AASHTO 2012[9] shrinkage and creep prediction models. The research significance of this work is to provide an assessment of these models in accordance to the latest RILEM[10] and the new NU-ITI[11,12] databases. Data-elimination criteria and their influence on the sensitivity of the statistical methods are also included as part of this study.

OBJECTIVES

The three objectives of this paper are:

1. Describe five statistical methods to be used for the assessment of the creep and shrinkage prediction models. The statistical methods include the residual method, the CEB coefficient of variation V_{CEB},[1,6] the CEB mean square error F_{CEB},[1,6] the CEB mean deviation M_{CEB},[1,6] and a new method that will be named the modified coefficient of variation ω_m.
2. Use the RILEM and NU-ITI databases for the assessment of the six aforementioned prediction models. Three elimination plans are used to screen the databases. The plans are applied to remove data outside the range of the prediction models and the statistical methods.
3. Determine which shrinkage and creep model provides the most accurate predictions according to the RILEM and NU-ITI databases using the statistical methods mentioned previously as the form of evaluation.

STATISTICAL METHODS USED TO EVALUATE MODELS

Five statistical methods were used to determine the accuracy of the six shrinkage and creep compliance prediction models described as follows.

Residual method

Residuals are calculated by subtracting the experimentally measured creep or shrinkage values from the model predicted values. When the residual value is positive, the model is overestimating, and when it is negative, the model is underestimating. In this study, the residuals are graphed versus time up to 10,000 days. Models that have a balanced distribution between the positive and negative residuals are considered best performing.

CEB coefficient of variation method

In this method, the creep and shrinkage data are divided into six time ranges: 0 to 10 days, 11 to 100 days, 101 to 365 days, 366 to 730 days, 731 to 1095 days, and above 1095 days, as specified in ACI 209.2R-08.[6] The coefficient of variation V_i is calculated for each time interval, and the root mean square coefficient of variation V_{CEB} is then calcu-

ACI Materials Journal, V. 112, No. 1, January-February 2015.
MS No. M-2013-147.R1, doi: 10.14359/51686982, received September 5, 2013, and reviewed under Institute publication policies. Pertinent discussion including author's closure, if any, will be published ten months from this journal's date if the discussion is received within four months of the paper's print publication.

lated. A lower V_{CEB} is obtained by models that are more accurate. The V_{CEB} can be calculated as follows

$$V_{CEB} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} V_i^2} \tag{1}$$

$$V_i = \frac{1}{\bar{y}_i}\sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(Y_{ij} - y_{ij})^2} \tag{2}$$

$$\bar{y}_i = \frac{1}{n}\sum_{j=1}^{n}(y_{ij}) \tag{3}$$

where n is the number of data points in data set i; N is the total number of data sets considered; V_i is the coefficient of variation for interval i; V_{CEB} is the root mean square coefficient of variation; $\bar{y}_i$ is the mean shrinkage strain or creep compliance of data set i; y_{ij} is the observed shrinkage strain or creep compliance at time j of interval i; and Y_{ij} is the predicted shrinkage strain or creep compliance value for the j-th data point in data set i.

CEB mean square error method

The CEB mean square error F_{CEB} computes an overall error of the predicted values. In this statistical method, the percent difference between calculated and observed data points f_j is calculated for each shrinkage and creep compliance prediction. The mean square error F_i is then calculated for each specified time range by combining all the f_j values in that range. F_i for shrinkage strain and creep compliance is calculated for the following six time ranges: 0 to 10 days, 11 to 100 days, 101 to 365 days, 366 to 730 days, 731 to 1095 days, and above 1095 days, as specified in ACI 209.2R-08.[6] F_{CEB} is then calculated by using the F_i values from each interval. Models that perform better produce lower F_{CEB} values. The method used to calculate F_{CEB} is as follows

$$F_{CEB} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} F_i^2} \tag{4}$$

$$F_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n} f_j^2} \tag{5}$$

$$f_j = \frac{(Y_{ij} - y_{ij})}{y_{ij}} \times 100 \tag{6}$$

where y_{ij} is observed shrinkage strain or creep compliance at time j of interval i; Y_{ij} is predicted shrinkage strain or creep compliance value for the j-th data point in data set i; f_j is percent difference between calculated and observed data point j; F_{CEB} is mean square error; n is the number of data points in data set i; and N is the total number of data sets considered.

CEB mean deviation method

This method is used to indicate the systematic overestimation or underestimation of a given prediction model. The CEB mean deviation M_{CEB} method first computes the average ratio of calculated to experimental values M_i for each shrinkage strain or creep compliance time interval. The calculated M_i values for the different time intervals are then combined to compute the overall M_{CEB}. Models that perform better in this statistical method produce an M_{CEB} value closest to 1. In this study, M_i is calculated for the following six time ranges: 0 to 10 days, 11 to 100 days, 101 to 365 days, 366 to 730 days, 731 to 1095 days, and above 1095 days as specified in ACI 209.2R-08.[6] The method used to calculate M_{CEB} is as follows

$$M_{CEB} = \frac{\sum_{i=1}^{N} M_i}{N} \tag{7}$$

$$M_i = \frac{1}{n}\sum_{j=1}^{n}\frac{Y_{ij}}{y_{ij}} \tag{8}$$

where y_{ij} is the observed shrinkage strain or creep compliance at time j of interval i; Y_{ij} is the predicted shrinkage strain or creep compliance value for the j-th data point in data set i; M_i is the ratio of calculated to experimental values in time range i; M_{CEB} is the mean deviation; n is the number of data points in data set i; and N is total number of data sets considered.

Modified coefficient of variation method

The modified coefficient of variation ω_m is a new approach used for the first time in this study. The ω_m method uses a similar concept to the coefficient of variation of regression errors method described by Bažant and Li.[3] In this method, however, the coefficient of variation is calculated based on populations (or groups of data) as opposed to individual points. In addition, the ω_m method applies different statistical weights to different populations of data. The new method was developed to emphasize the comparison of the models at longer ages of loading and drying. Because the analyzed databases contain significantly fewer measurements for extensive ages of loading and drying, higher statistical weights are assigned to boxes having fewer measurements.

In the ω_m method, data is divided using the procedures described as follows in an attempt to minimize the amount of boxes (or groups) with boundary ranges that do not coincide with the properties of the data (that is, empty boxes). Empty boxes of data provide no statistical value for the analysis. Therefore, empty boxes need to be reduced or assigned zero weight when they appear to exclude them from the analysis.

The shrinkage strain data is divided into boxes based on the length of drying and effective thickness of the specimen. Shrinkage strain data is divided into 16 boxes in this study. The boxes are made by dividing the duration of drying t-t_c into four intervals, and then dividing each of those intervals into four subintervals based on the effective thickness of the specimen. The duration of drying intervals are the following:

0 to 10 days, 11 to 100 days, 101 to 1000 days, and 1001 to 10,000 days. The effective specimen thickness D is divided into the following intervals: 0 to less than 11 mm (0 to less than 0.4 in.); 11 to less than 21 mm (0.4 to less than 0.8 in.); 21 to less than 31 mm (0.8 to less than 1.2 in.); and above or equal to 31 mm (≥ 1.2 in.). For creep compliance, the data is divided into 20 boxes based on load duration and relative humidity. The boxes are made by dividing the age of loading t-t' into four intervals. Each of those boxes is then subdivided into five subintervals based on the relative humidity. In this study, the age of loading is divided into the following intervals: 0 to 10 days, 11 to 100 days, 101 to 1000 days, and 1001 to 10,000 days. The relative humidity is divided into the following intervals: 0 to 20%, 21 to 40%, 41 to 60%, 61 to 80%, and 81 to 100%.

In this method, a modified standard error s_m is first calculated using the groupings of data mentioned previously. Next, the weighted mean of observed shrinkage or creep compliance measurements $\bar{y}_w$ is calculated by combining the average measurements of each box of data. The ω_m is then computed by comparing the modified standard error to the weighted mean. Prediction models that perform better produce a lower ω_m. The ω_m can be calculated as follows

$$\omega_m = \frac{s_m}{\bar{y}_w} \tag{9}$$

$$s_m = \sqrt{\sum_{i=1}^{N} w_i \cdot \frac{1}{m_i} \sum_{j=1}^{m_i} (Y_{ij} - y_{ij})^2} \tag{10}$$

$$\bar{y}_w = \sum_{i=1}^{N} w_i \cdot \frac{1}{m_i} \sum_{j=1}^{m_i} y_{ij} \tag{11}$$

$$w_i = \frac{1}{m_i \bar{w}}, \bar{w} = \sum_{i=1}^{N} \frac{1}{m_i} \tag{12}$$

where ω_m is the modified coefficient of variation; s_m is the modified standard error; $\bar{y}_w$ is weighted mean of observed shrinkage or creep compliance measurements; m_i is the number of data points in data set i; N is the total number of data sets or boxes considered; w_i is the statistical weight assigned to box or data set i; y_{ij} is the observed shrinkage strain or creep compliance value at time j-th of interval i; and Y_{ij} is the predicted shrinkage strain or creep compliance value for the j-th data point in data set i.

DATABASES USED FOR ANALYSIS AND DATA SELECTION CRITERIA

The RILEM[10] and NU-ITI[11,12] databases were used to evaluate the accuracy of the shrinkage and creep prediction models. The RILEM database is composed of 426 shrinkage data sets (that is, 7153 experimental measurements) and 716 creep data sets (that is, 13,769 experimental measurements).[10] The NU-ITI database consists of 490 shrinkage data sets (that is, 8326 experimental measurements) and 621 creep data sets (that is, 11,821 experimental measurements).[12]

Data sets in the RILEM database having a relative humidity of 101% imply that those specimens were sealed during testing.[10] The NU-ITI database assigns a relative humidity of 99% to specimens that were sealed during testing.[11,12] In the prediction models, sealed testing conditions are defined by different relative humidity input values. A value of 100% is assigned to those specimens when using the ACI 209R-92, AASHTO 2012,[9] and *fib* MC 2010[8] models. A value of 99% relative humidity is assigned when using the CEB MC 90-99 model; 98% is assigned when using the B3 model; and 96% is assigned when using the GL 2000 model.

In this study, different data point elimination scenarios will be used to examine the sensitivity of the statistical methods. The data elimination will be performed in three different plans: Plan A, Plan B, and Plan C. Table 1 summarizes the number of data points used for each prediction model according to each plan.

Plan A

Plan A applies general elimination criteria pertaining to all models and specific elimination criteria pertaining to each model. The general elimination criteria are described as follows:

1. Experimental measurements of zero creep or shrinkage are excluded because such measurements lead to an error when calculating M_{CEB} and F_{CEB}. In both cases, it is required to divide by the experimental value, and dividing by zero causes an error;

2. Repeated data measurements and swelling data points (positive shrinkage measurements) are also omitted for the purpose of this study; and

3. Values of the elastic modulus of concrete at 28 days E_{cm28} and compressive strength at 28 days f_{cm28} are provided in the database for several specimens. A significant number of specimens, however, do not contain E_{cm28}. Therefore, in this study, E_{cm28} will be derived from the experimental f_{cm28} for each model using the procedure described in the corresponding model.[6-9] Data missing f_{cm28} values will not be used in this study.

For the specific elimination criteria, all data from the RILEM and NU-ITI databases was used. Elimination, however, was performed as described in Table 2 when available data was not adequate to perform a complete analysis.

The selection to use general and specific elimination criteria will allow the incorporation of a wider range of data than what is permitted by the model limitations, as summarized in Table 3.

Plan B

Plan B is the implementation of Plan A, but excludes data with f_j^2 (square of percent difference between calculated and observed measurements) that are greater than 50. Data with f_j^2 greater than 50 are excluded because the percent difference between calculated and observed data points (that is, (calculated – observed)/observed) is potentially large for data points in which the observed measurement is significantly smaller than the calculated value. Large values of f_j^2

Table 1—Number of data points used for RILEM and NU-ITI databases

	RILEM database						NU-ITI database					
	Shrinkage (7153)			Creep (13,769)			Shrinkage (8326)			Creep (11,821)		
Model	A	B	C	A	B	C	A	B	C	A	B	C
ACI 209R-92	4360 61%	4348 61%	4250 59%	9184 67%	9184 67%	9090 66%	4531 54%	4518 54%	4344 52%	5485 46%	5485 46%	5390 46%
B3	4134 58%	4067 57%	3926 55%	9944 72%	9944 72%	9870 72%	4327 52%	4260 51%	4000 48%	6178 52%	6178 52%	6104 52%
GL 2000	4394 61%	4338 61%	4197 59%	11,306 82%	11,306 82%	11,212 81%	4593 55%	4537 54%	4271 51%	7149 60%	7147 60%	7053 60%
CEB MC 90-99	4307 60%	4167 58%	4026 56%	11,640 85%	11640 85%	11,546 84%	4506 54%	4358 52%	4093 49%	8354 71%	7892 67%	7637 64%
fib MC 2010	4307 60%	4167 58%	4026 56%	11,640 85%	11,640 85%	11546 84%	4506 54%	4358 52%	4093 49%	8354 71%	7886 67%	7631 65%
AASHTO 2012	3680 51%	3567 50%	3477 49%	9184 67%	9184 67%	9090 66%	3755 45%	3634 44%	3474 42%	5485 46%	5485 46%	5391 46%

Notes: Top values indicate number of points used in each prediction model pertaining to each analysis and bottom numbers indicate percentage of points used in relation to total points available.

Table 2—Applied data elimination criteria specific to each model

	Shrinkage	Creep
ACI 209R-92	Data with relative humidity, H < 40% Type II cement V/S > 205 mm or 2V/S > 410 mm (V/S > 8 in. or 2V/S > 16 in.)	Type II cement Data with relative humidity H < 40%
B3	Data missing water-cement ratio w/c Data missing cement content c Data missing age of concrete when drying commenced t_c Data with relative humidity H < 40%	Age of concrete equal to age at loading ($\Delta t = 0$ gives error in calculations) Data missing cement content c Data missing aggregate-cement ratio a/c Data missing age at end of moist curing t_c Data missing water-cement ratio, w/c Data with relative humidity H < 40% Data in which age at loading is less than age at end of moist curing
GL 2000	Data with relative humidity H < 20%	Data missing age at end of moist curing Data with relative humidity H < 20% Data in which age at loading is less than age at end of moist curing
CEB MC 90-99	Data with relative humidity H < 40% Data missing age of concrete at beginning of drying t_c	Data with relative humidity H < 40%
fib MC 2010	Data with relative humidity H < 40% Data missing age of concrete at beginning of drying t_c	Data with relative humidity H < 40%
AASHTO 2012	Data missing age of concrete at beginning of drying t_c Data with relative humidity H < 40%	Data with relative humidity H < 40%

generate a higher mean square error that does not necessarily represent the evaluated model's predicting performance. Eliminating data that produce an f_j^2 greater than 50 is essential because some prediction models do not have stringent elimination criteria, such as the CEB models. Therefore, this filtering process is necessary.

Plan C

Plan C is the third method of analysis which applies Plans A and B in addition to excluding common outliers found in the residual versus time figures. Outliers are defined as data sets that produce relatively large residuals that do not follow the same trend as the rest of the data in the residual-versus-time graphs. Creep or shrinkage data sets that consistently appear as outliers in all the models are known as common outliers, and these are removed for the purpose of Plan C.

DISCUSSION OF RESULTS

The following section will discuss the prediction accuracy of the shrinkage and creep prediction models according to the five statistical methods described previously. A discussion will be provided for the three data elimination plans.

Analysis of shrinkage strain

The percent distributions of positive and negative shrinkage residuals for Plans A, B, and C are summarized in Table 4. Graphical distributions of the residuals for Plan C are shown in Fig. 1 through 6 and in the Appendix.* The table shows that the ACI 209R-92, GL 2000, CEB MC 90-99, and

*The Appendix is available at **www.concrete.org/publications** in PDF format, appended to the online version of the published paper. It is also available in hard copy from ACI headquarters for a fee equal to the cost of reproduction plus handling at the time of the request.

Table 3—Summary of model limitations

	ACI 209R-92	B3	GL 2000	CEB MC90-99	*fib* MC 2010	AASHTO 2012
f_{cm28}*, MPa (psi)	—	17 to 70 (2500 to 10,000)	16 to 82 (2320 to 11,900)	15 to 120 (2175 to 17,400)	20 to 130 (2900 to 18,850)	16 to 70 (2320 to 10,000)
a/c	—	2.5 to 13.5	—	—	—	—
Cement content, kg/m^3 (lb/yd^3)	—	160 to 720 (270 to 1215)	—	—	—	—
w/c	—	0.35 to 0.85	0.4 to 0.6	—	—	0.45 to 0.58
Relative humidity,%	40 to 100	40 to 100	20 to 100	40 to 100	40 to 100	40 to 100
Type of cement European (U.S.)	R or RS (I or III)	R,SL,RS (I,II,III)	R,SL,RS (I,II,III)	R,SL,RS (I,II,III)	R,SL,RS (I,II,III)	R or RS (I or III)
t_c† (moist cured)	≥ 1 day	≥ 1 day	≥ 1 day	—	< 14 days	> 7 day
t_c† (steam cured)	≥ 1 day	—	≥ 1 day	—	—	—
t_o‡	≥ 7 days	$t_o \geq t_c$	$t_o \geq t_c \geq$ 1 day	> 1 day	≥ 1 day	> 7 day

*f_{cm28} is concrete compressive strength at 28 days.

†t_c is age of concrete at beginning of drying.

‡t_o is age of concrete at loading.

Table 4—Distribution of residuals for creep compliance and shrinkage models for 0 to 10,000 days

		RILEM						NU-ITI					
		Shrinkage			Creep			Shrinkage			Creep		
Model		A	B	C	A	B	C	A	B	C	A	B	C
ACI 209R-92	Overestimate, %	54	54	55	45	45	46	53	53	55	33	33	33
	Underestimate, %	46	46	45	55	55	54	47	47	45	67	67	67
B3	Overestimate, %	36	35	36	57	57	57	34	33	35	40	40	40
	Underestimate, %	64	65	64	43	43	43	66	67	65	60	60	60
GL 2000	Overestimate, %	44	43	45	59	59	60	42	42	44	46	46	47
	Underestimate, %	56	57	55	41	41	40	58	58	56	54	54	53
CEB MC 90-99	Overestimate, %	53	52	53	37	37	37	52	50	53	33	29	30
	Underestimate, %	47	48	47	63	63	63	48	50	47	67	71	70
fib MC 2010	Overestimate, %	53	52	53	35	35	35	52	50	53	28	24	25
	Underestimate, %	47	48	47	65	65	65	48	50	47	72	76	75
AASHTO 2012	Overestimate, %	37	35	35	36	36	36	37	35	36	33	33	33
	Underestimate, %	63	65	65	64	64	64	63	65	64	67	67	67

Note: residuals distributed closest to 50% positive and 50% negative perform better.

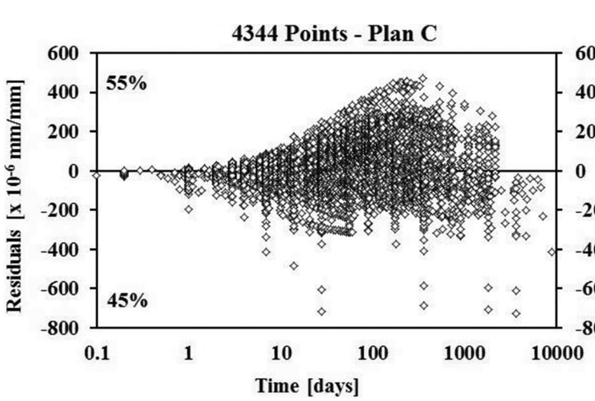

Fig. 1—NU-ITI shrinkage strain residuals for ACI 209R-92 model for 0 to 10,000 days.

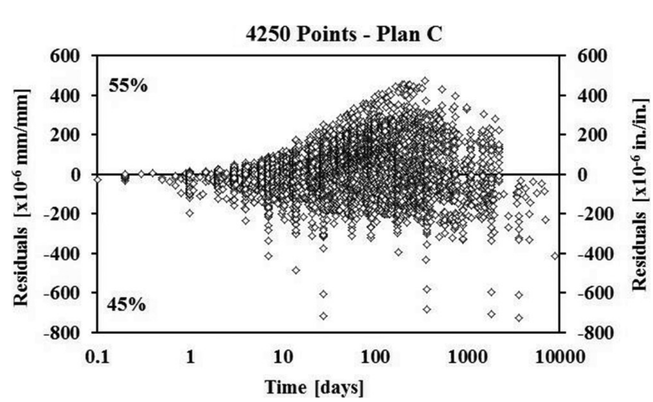

Fig. 2—RILEM shrinkage strain residuals for ACI 209R-92 model for 0 to 10,000 days.

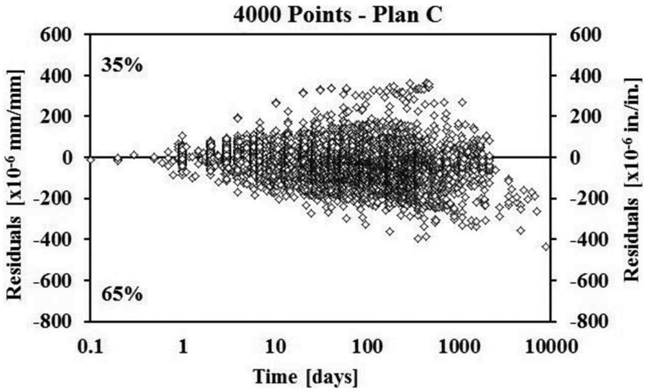

Fig. 3—NU-ITI shrinkage strain residuals for B3 model for 0 to 10,000 days.

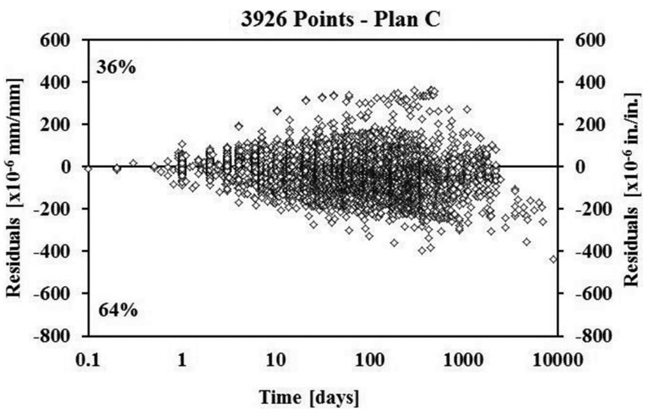

Fig. 4—RILEM shrinkage strain residuals for B3 model for 0 to 10,000 days.

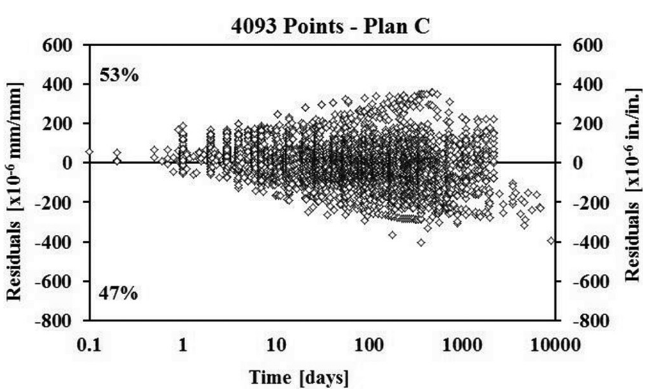

Fig. 5—NU-ITI shrinkage strain residuals for CEB MC 90-99/ fib *MC 2010 model for 0 to 10,000 days.*

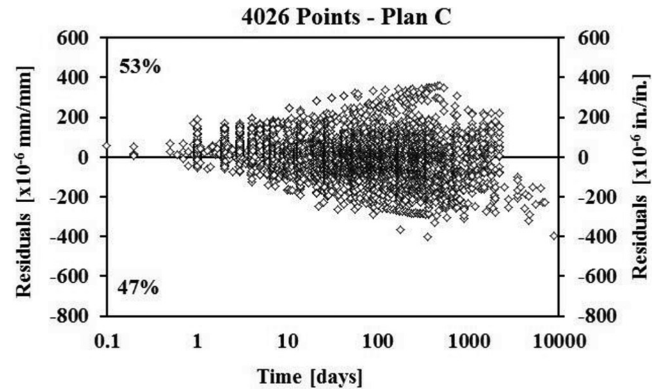

Fig. 6—RILEM shrinkage strain residuals for CEB MC 90-99/ fib *MC 2010 model for 0 to 10,000 days.*

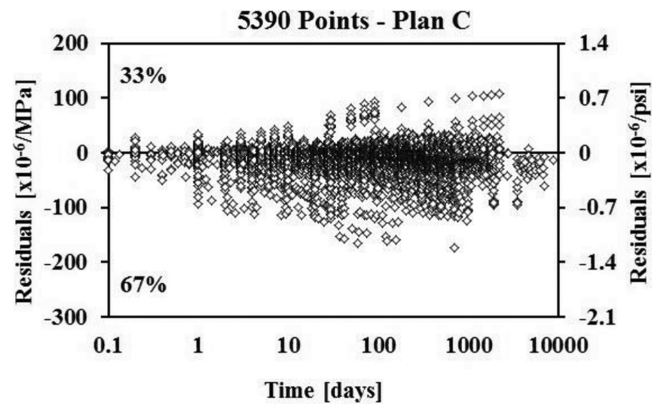

Fig. 7—NU-ITI creep compliance residuals for ACI 209R-92 model for 0 to 10,000 days.

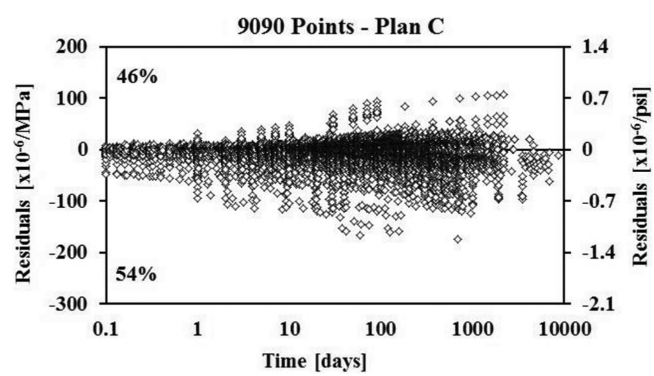

Fig. 8—RILEM creep compliance residuals for ACI 209R-92 model for 0 to 10,000 days.

fib MC 2010 models demonstrate more balanced distribution of residuals. In contrast, the B3 and AASHTO 2012 models tend to underestimate the experimental data. Table 4 also shows that the residual distribution is not significantly affected when elimination of data is conducted according to Plans B and C.

Tables 5 and 6 summarize the statistical values of F_{CEB}, M_{CEB}, V_{CEB}, and ω_m for the shrinkage prediction models according to the NU-ITI and RILEM databases. F_{CEB}, M_{CEB}, V_{CEB}, and ω_m are compared in accordance to Plans A, B, and C. Table 5 shows that elimination of data with respect to Plans B or C significantly improves the F_{CEB} and M_{CEB} values when compared with Plan A. The V_{CEB} values are not greatly affected in all three plans. Table 6 shows that the elimination of data according to Plans A, B, or C has less influence on the predicted value of ω_m.

Analysis of creep compliance

The creep compliance residuals for the six prediction models are shown in Table 4 for Plans A, B, and C. Graphical distributions of the residuals for Plan C are shown in Fig. 7 through 12 and in the Appendix. The table shows that for all plans, the ACI 209R-92 and B3 creep compliance prediction models tend to underestimate when analyzed with

Table 5—Comparison of F_{CEB}, M_{CEB}, and V_{CEB} results using the NU-ITI and RILEM shrinkage database

Model name		F_{CEB}*			M_{CEB}†			V_{CEB}*		
		A	B	C	A	B	C	A	B	C
ACI 209R-92	NU-ITI	100%	72%	71%	1.07	1.05	1.07	50%	50%	45%
	RILEM	102%	73%	72%	1.05	1.03	1.04	47%	47%	45%
B3	NU-ITI	411%	81%	81%	1.27	1.00	1.04	48%	47%	39%
	RILEM	421%	81%	81%	1.31	1.03	1.04	43%	41%	39%
GL 2000	NU-ITI	312%	86%	85%	1.22	1.02	1.06	53%	52%	46%
	RILEM	319%	86%	85%	1.27	1.05	1.07	49%	48%	46%
CEB MC 90-99	NU-ITI	994%	101%	103%	2.01	1.18	1.23	54%	50%	44%
	RILEM	1015%	102%	103%	2.05	1.21	1.23	49%	45%	44%
fib MC 2010	NU-ITI	994%	101%	103%	2.01	1.18	1.23	54%	50%	44%
	RILEM	1015%	102%	103%	2.05	1.21	1.23	49%	45%	44%
AASHTO 2012	NU-ITI	2343%	122%	113%	2.07	1.12	1.13	78%	64%	66%
	RILEM	601%	112%	113%	1.70	1.12	1.13	78%	66%	66%
Mean	NU-ITI	859.0%	93.8%	92.7%	1.61	1.09	1.13	56.2%	52.2%	47.3%
	RILEM	578.8%	92.7%	92.8%	1.57	1.11	1.12	52.5%	48.7%	47.3%
Standard deviation	NU-ITI	743%	16%	15%	0.43	0.07	0.08	10%	6%	9%
	RILEM	342%	14%	14%	0.39	0.08	0.08	12%	8%	8.63%
Coefficient of variation	NU-ITI	87%	17%	16%	27%	7%	7%	18%	11%	18%
	RILEM	59%	15%	15%	25%	7%	7%	22%	17%	18%

*F_{CEB} and V_{CEB} are smaller values give better prediction.

†M_{CEB} are values closest to 1 give better prediction.

Table 6—Comparison of ω_m results using the NU-ITI and RILEM database

Model name	NU-ITI						RILEM					
	Shrinkage			Creep compliance			Shrinkage			Creep compliance		
	A	B	C	A	B	C	A	B	C	A	B	C
ACI 209R-92	71%	71%	71%	39%	39%	37%	71%	71%	71%	41%	41%	40%
B3	79%	78%	78%	31%	31%	30%	78%	77%	77%	46%	46%	45%
GL 2000	88%	87%	87%	36%	36%	35%	87%	87%	87%	45%	45%	44%
CEB MC 90-99	76%	74%	74%	39%	35%	31%	76%	74%	74%	38%	38%	37%
fib MC 2010	76%	74%	74%	41%	36%	32%	76%	74%	74%	38%	38%	36%
AASHTO 2012	120%	104%	104%	44%	44%	44%	120%	104%	104%	46%	46%	45%
Mean	85%	81%	81%	38%	37%	35%	85%	81%	81%	42%	42%	41%
Standard deviation	16%	11%	11%	4%	4%	5%	17%	11%	11%	3%	3%	4%
Coefficient of variation	19%	14%	14%	11%	11%	13%	20%	14%	14%	8%	8%	9%

Note: Smaller ω_m values give better predictions.

the NU-ITI database, but show more balance when analyzed with the RILEM database. The GL 2000 model appears to be balanced when analyzed with the NU-ITI database, but it tends to overestimate predictions when analyzed with the RILEM database. The CEB MC 90-99, *fib* MC 2010, and the AASHTO 2012 models consistently underestimate the experimentally measured values in both databases. In summary, different databases can potentially influence a compliance prediction model's tendency to overestimate or underestimate the experimental measurements. The behavior is most likely a result of the diversity of concrete specimens and experimental conditions contained within each database.

Table 7 shows the F_{CEB}, M_{CEB}, and V_{CEB} values for creep compliance using the NU-ITI and RILEM databases. The table shows that when the NU-ITI database is used for the analysis, the F_{CEB} and M_{CEB} statistical parameters for the *fib* MC 2010 and CEB MC 90-99 prediction models are significantly influenced by the application of Plans B and C compared with Plan A. As a result, the means and standard deviations of F_{CEB} and M_{CEB} for the prediction models notably reduce from Plan A to B when analyzed with the

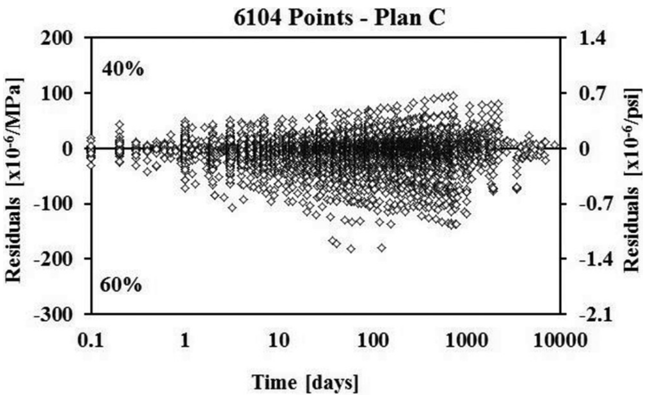

Fig. 9—NU-ITI creep compliance residuals for B3 model for 0 to 10,000 days.

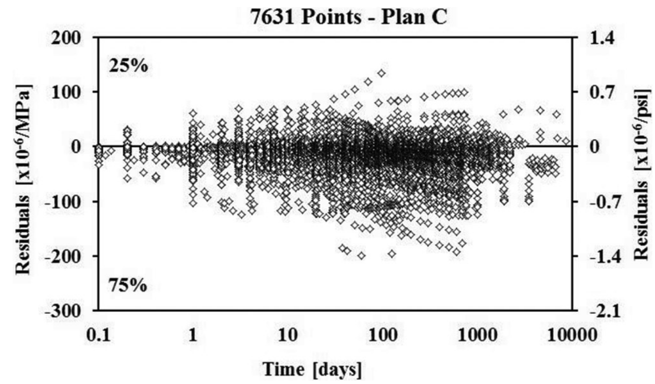

Fig. 11—NU-ITI creep compliance residuals for fib MC 2010 model for 0 to 10,000 days.

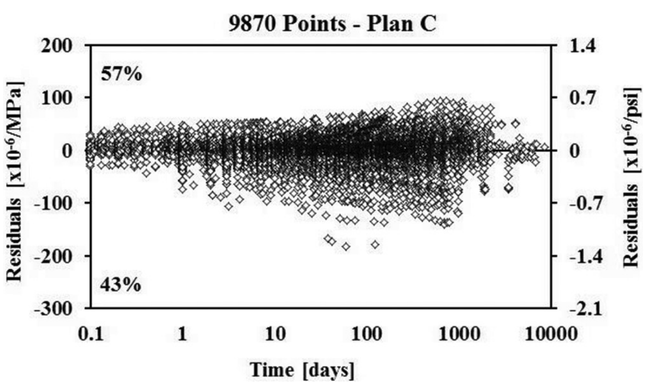

Fig. 10—RILEM creep compliance residuals for B3 model for 0 to 10,000 days.

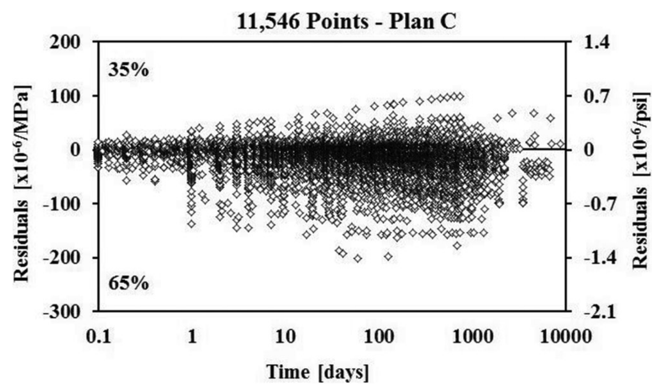

Fig. 12—RILEM creep compliance residuals for fib MC 2010 model for 0 to 10,000 days.

Table 7—Comparison of F_{CEB}, M_{CEB}, and V_{CEB} results using the NU-ITI and RILEM creep compliance database

Model name		F_{CEB}*			M_{CEB}†			V_{CEB}*		
		A	B	C	A	B	C	A	B	C
ACI 209R-92	NU-ITI	36%	35%	34%	0.90	0.90	0.91	47%	47%	40%
	RILEM	33%	33%	32%	0.98	0.98	0.98	45%	45%	39%
B3	NU-ITI	34%	34%	34%	0.97	0.97	0.97	42%	42%	36%
	RILEM	44%	44%	44%	1.13	1.13	1.14	43%	43%	39%
GL 2000	NU-ITI	39%	36%	36%	0.99	0.99	0.99	44%	44%	37%
	RILEM	43%	43%	43%	1.10	1.10	1.10	44%	44%	40%
CEB MC 90-99	NU-ITI	1677%	49%	48%	3.30	0.90	0.91	61%	57%	42%
	RILEM	33%	33%	33%	0.89	0.89	0.89	48%	48%	44%
fib MC 2010	NU-ITI	1982%	48%	48%	3.42	0.85	0.86	62%	58%	43%
	RILEM	32%	32%	32%	0.87	0.87	0.87	47%	47%	42%
AASHTO 2012	NU-ITI	43%	43%	43%	0.85	0.85	0.85	50%	50%	46%
	RILEM	38%	38%	38%	0.86	0.86	0.86	50%	50%	47%
Mean	NU-ITI	635.2%	40.8%	40.5%	1.74	0.91	0.92	51.0%	49.7%	40.7%
	RILEM	37.2%	37.2%	37.0%	0.97	0.97	0.97	46.2%	46.2%	41.8%
Standard deviation	NU-ITI	849%	6%	6%	1.15	0.05	0.05	8%	6%	3.45%
	RILEM	5%	5%	5%	0.11	0.11	0.11	2%	2%	3%
Coefficient of variation	NU-ITI	134%	15%	15%	66%	6%	6%	15%	12%	8%
	RILEM	13%	13%	14%	11%	11%	11%	5%	5.22%	7%

*For F_{CEB} and V_{CEB}, smaller values give better prediction.

†For M_{CEB}, values closest to 1 give better prediction.

Table 8—Summary of results and rating for shrinkage strain prediction models

	Time range	ACI 209R-92		B3		GL 2000		CEB MC 90-99		*fib* MC 2010		AASHTO 2012	
		NU[*]	RI[*]	NU	RI	NU	RI	NU	RI	NU	RI	NU	RI
1—Distribution of residuals[†]													
Positive range	0 to 10,000 days	55%	55%	35%	36%	44%	45%	53%	53%	53%	53%	36%	35%
Negative range	0 to 10,000 days	45%	45%	65%	64%	56%	55%	47%	47%	47%	47%	64%	65%
Away from 50-50		±5	±5	±15	±14	±6	±5	±3	±3	±3	±3	±14	±15
Rating 1-5[‖]		2	2	5	3	3	2	1	1	1	1	4	4
2—RMS coefficient of variation V_{CEB}[‡], %													
	Six time ranges	45%	45%	39%	39%	46%	46%	44%	44%	44%	44%	66%	66%
Rating 1-5[‖]		3	3	1	1	4	4	2	2	2	2	5	5
3—Mean square error F_{CEB}[‡], %													
	Six time ranges	71%	72%	81%	81%	85%	85%	103%	103%	103%	103%	113%	113%
Rating 1-5[‖]		1	1	2	2	3	3	4	4	4	4	5	5
4—Mean deviation M_{CEB}[§]													
	Six time ranges	1.07	1.04	1.04	1.04	1.06	1.07	1.23	1.23	1.23	1.23	1.13	1.13
Rating 1-5[‖]		3	1	1	1	2	2	5	4	5	4	4	3
5—Modified coefficient of variation ω_m[‡], %													
	Six time ranges	71%	71%	78%	77%	87%	86%	74%	74%	74%	74%	104%	104%
Rating 1-5[‖]		1	1	3	3	4	4	2	2	2	2	5	5
Added model rating (1 + 2 + 3 + 4 + 5)		10	8	12	10	16	15	14	13	14	13	23	22
Average of NU and RI model rating sum		9		11		15.5		13.5		13.5		22.5	
Overall ranking		1		2		4		3		3		5	

[*]NU is NU-ITI database and RI is RILEM database.

[†]Distribution of residuals: residuals distributed closest to 50% positive and 50% negative perform better.

[‡]For V_{CEB}, F_{CEB}, and ω_m, smaller values receive better rating.

[§]For M_{CEB}, values closest to 1 receive better rating.

[‖]Rating 1-5: models are rated according to the NU-ITI and RILEM databases, respectively (1 = best performing, 5 = worst performing).

NU-ITI database. In contrast, the RILEM database does not show significant change in the results of V_{CEB}, F_{CEB}, or M_{CEB} for all three plans. The reason why the CEB MC 90-99 and *fib* MC 2010 models produce relatively large errors when analyzed with the NU-ITI database, but produce more accurate predictions with the RILEM database, is because the CEB models are calibrated using the RILEM database. The ω_m, as shown in Table 6, did not show significant change in either database for the creep compliance prediction models with the application of Plans B or C when compared with Plan A. All statistical methods are significant for the evaluation of the models, regardless of their sensitivity. Sensitive statistical methods assist in finding potentially flawed data, and they demonstrate the effects of removing such information. Statistical methods that are not significantly influenced by the elimination of data are useful because the overall comparison of the models is more consistent despite the appearance of conflicting data. Tables 6 and 7 also show that the selection of the statistical approach is sensitive to the database used for the creep compliance analysis.

RANKING METHOD

A rating scale of 1 to 5 is used to rank the shrinkage prediction models in Table 8, where 1 is assigned to best-performing models. For creep compliance, a rating scale of 1 to 6 is used in Table 9 to assess the prediction models, where 1 is also assigned to the best performing models. The two rating scales differ because for shrinkage prediction, the CEB MC 90-99 and *fib* MC 2010 models provide similar predictions that result in only five distinct models, whereas for creep, there are six distinct models. Each of the models is first rated according to the NU-ITI and RILEM databases, respectively. The ratings obtained by each model in each statistical method are then added together for each database, respectively. The total points obtained per model for the NU-ITI and RILEM databases are then averaged together, and an overall rating is performed on the models. Models that obtain a smaller average receive a better rating. In this study, the overall rating of the models was performed on Plan C, as it is the plan that will give the most accurate assessment of all models.

Table 8 summarizes the results and ratings of the shrinkage prediction models. The data shows that the ACI 209R-92 shrinkage prediction model demonstrated the best perfor-

Table 9—Summary of results and rating for creep compliance prediction models

	Time range	ACI 209R-92		B3		GL 2000		CEB MC 90-99		*fib* MC 2010		AASHTO 2012	
		NU*	RI*	NU	RI	NU	RI	NU	RI	NU	RI	NU	RI
1—Distribution of residuals†													
Positive range	0 to 10,000 days	33%	46%	40%	57%	47%	60%	30%	37%	25%	35%	33%	36%
Negative range	0 to 10,000 days	67%	54%	60%	43%	53%	40%	70%	63%	75%	65%	67%	64%
Away from 50-50		±17	±4	±10	±7	±3	±10	±20	±13	±25	± 15	±17	±14
Rating 1-6‖		3	1	2	2	1	3	4	4	5	6	3	5
2—RMS coefficient of variation V_{CEB}‡, %													
	Six time ranges	40%	39%	36%	39%	37%	40%	42%	44%	43%	42%	46%	47%
Rating 1-6‖		3	1	1	1	2	2	4	4	5	3	6	5
3—Mean square error F_{CEB}‡, %													
	Six time ranges	34%	32%	34%	44%	36%	43%	48%	33%	48%	32%	43%	38%
Rating 1-6‖		1	1	1	5	2	4	4	2	4	1	3	3
4—Mean deviation M_{CEB}§													
	Six time ranges	0.91	0.98	0.97	1.14	0.99	1.1	0.91	0.89	0.86	0.87	0.85	0.86
Rating 1-6‖		3	1	2	5	1	2	3	3	4	4	5	5
5—Modified coefficient of variation ω_m‡, %													
	Six time ranges	37%	40%	30%	45%	35%	44%	31%	37%	32%	36%	44%	45%
Rating 1-6‖		5	3	1	5	4	4	2	2	3	1	6	5
Added model rating (1 + 2 + 3 + 4 + 5)		15	7	7	18	10	15	17	15	21	15	23	23
Average of NU and RI model rating sum		11		12.5		12.5		16		18		23	
Overall ranking		1		2		2		3		4		5	

*NU is NU-ITI database and RI is RILEM database.

†Distribution of residuals: residuals distributed closest to 50% positive and 50% negative perform better.

‡For V_{CEB}, F_{CEB}, ω_m, smaller values receive better rating.

§For M_{CEB}, values closest to 1 receive better rating.

‖Rating 1-6: models are rated according to the NU-ITI and RILEM databases, respectively (1 = best performing, 6 = worst performing).

mance, followed by the B3 as second. The CEB MC 90-99 and *fib* MC 2010 models ranked third. The GL 2000 and AASHTO 2012 models ranked fourth and fifth, respectively. All shrinkage prediction models perform better when analyzed with the RILEM database.

Table 9 summarizes the results and ratings of the creep compliance prediction models. The table shows that the creep compliance results seem to be dependent on the database used. For example, the B3 and GL 2000 models performed better when analyzed with the NU-ITI database. The ACI 209R-92, *fib* MC 2010, and CEB MC 90-99 models demonstrated better performance when analyzed with the RILEM database. The behavior noted in this analysis is to be expected because different models are calibrated to different sources of data. After combining the results of the two databases, as shown in Table 9, the data shows that the ACI 209R-92 model had the best performance, followed by the B3 and GL 2000 as second. The CEB MC 90-99 model ranked third, the *fib* MC 2010 model ranked fourth, and the AASHTO 2012 model ranked fifth.

In this paper, the rankings for shrinkage and creep models were found to be different from those obtained from a previous study by Al-Manaseer and Lam.[1] Different elimination criteria were incorporated in this analysis to permit the inclusion of a wider range of data. It can be concluded that data selection criteria and imposed model limitations can influence the final ranking of the models. Additionally, for the purpose of this study, more models have been incorporated (including the CEB MC 90-99, *fib* MC 2010, and AASHTO 2012), and rankings are obtained by combining results from the most current RILEM and NU-ITI databases, whereas the previous study used an older version of the RILEM database.

CONCLUSIONS

This study used the RILEM and NU-ITI databases to evaluate the ACI 209R-92, B3, GL 2000, CEB 90-99, *fib* MC 2010, and AASHTO 2012 shrinkage and creep prediction models. The residual method, the CEB coefficient of variation V_{CEB}, the CEB mean square error F_{CEB}, the CEB mean deviation M_{CEB}, and the new modified coefficient of variation ω_m methods were used for the evaluation. An overall rating approach was applied to rank the models. The following conclusions were drawn from this study:

1. Model ratings can be influenced by the selected database because models are calibrated to different sources of

data. For the purpose of this study, the results obtained from each database were combined to obtain an overall ranking of the models. Further evaluation of the prediction models under different statistical methods, however, can potentially result in a different conclusion of the ranking of the models;

2. The data selection criteria and imposed model limitations can influence the final ranking of the models.

3. This study shows that the ACI 209R-92 shrinkage prediction model demonstrated the best predicting performance, followed by the B3 model. The CEB models ranked third, the GL 2000 model ranked fourth, and the AASHTO 2012 model ranked fifth.

4. For creep compliance, this study found that the best-performing model is the ACI 209R-92 model, followed by the B3 and GL 2000 models. The CEB MC 90-99 model ranked third, the *fib* MC 2010 model ranked fourth, and the AASHTO 2012 model ranked fifth.

5. All shrinkage prediction models demonstrated better performance when analyzed with the RILEM database. All creep compliance prediction models demonstrated better performance when analyzed with the RILEM database, with the exception of the B3 and GL 2000 models.

6. The statistical values F_{CEB} and M_{CEB} for all shrinkage prediction models, calculated from the RILEM and the NU-ITI databases, were significantly influenced when data points with f_j^2 (square of percent difference between calculated and observed measurements) greater than 50 were eliminated.

7. For creep compliance, only the CEB MC 90-99 and *fib* MC 2010 models showed sensitivity to the statistical parameters F_{CEB} and M_{CEB} when analyzed with the NU-ITI database after data points with f_j^2 greater than 50 were eliminated.

AUTHOR BIOS

Akthem Al-Manaseer, *FACI, is a Professor of civil engineering at San Jose State University, San Jose, CA. He is a member of ACI Committees 209, Creep and Shrinkage in Concrete; 231, Properties of Concrete at Early Ages; and 552, Cementitious Grouting. He is a past President of the Northern California and Western Nevada Chapter – ACI. His research interests include structural concrete and concrete materials and structures.*

Armando Prado *is a PhD student in the Department of Civil Engineering at the University of California, Davis, Davis, CA. He received his MS in civil engineering from San Jose State University in 2013.*

ACKNOWLEDGMENTS

The authors would like to thank H. S. Muller and R. Breiner for providing the RILEM database and the new *fib* MC 2010 model code. The authors also wish to thank Z. P. Bažant for providing the NU-ITI database and for his discussion on the statistical methods.

REFERENCES

1. Al-Manaseer, A., and Lam, J.-P., "Statistical Evaluation of Shrinkage and Creep Models," *ACI Materials Journal*, V. 102, No. 3, May-June 2005, pp. 170-176.

2. Al-Manaseer, A., and Lakshmikantan, S., "Comparison between Current and Future Design Code Models for Creep and Shrinkage," *Revue francaise de genie civil*, J.-A. Calgaro and F. Darve, eds., V. 3, No. 3-4, 1999, pp. 39-59.

3. Bažant, Z. P., and Li, G. H., "Unbiased Statistical Comparison of Creep and Shrinkage Prediction Models," *ACI Structural Journal*, V. 105, No. 6, Nov.-Dec. 2008, pp. 610-621.

4. Burgoyne, C., and Scantlebury, R., "Lessons Learned from the Bridge Collapse in Palau," *Proceedings of the Institution of Civil Engineers,* Civil Engineering 161, No. CE 6, Nov. 2008, pp. 28-34.

5. Bažant, Z. P.; Yu, Q.; and Li, G. H., "Excessive Long-Time Deflections of Prestressed Box Girders. I: Record-Span Bridge in Palau and Other Paradigms," *Journal of Structural Engineering*, ASCE, V. 138, No. 6, June 2012, pp. 676-686.

6. ACI Committee 209, "Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete (ACI 209.2R-08)," American Concrete Institute, Farmington Hills, MI, 2008, pp. 8-13.

7. Hassoun, N. M., and Al-Manaseer, A., "Structural Concrete Theory and Design," fifth edition, John Wiley & Sons, Hoboken, NJ, 2012, pp. 15-45.

8. Special Activity Group 5, "Model Code 2010-Final Draft," *fib Bulletin*, V. 1, No. 65, 2012, pp. 139-148.

9. American Association of State Highway and Transportation Officials (AASHTO), "AASHTO LRFD Bridge Design Specifications," sixth edition, AASHTO, 2012, pp. 5-15 to 5-17.

10. RILEM Data Bank, provided by Dr. Harald S. Muller, Universitat Karlsruhe (TH), Institute fur Massivbau und Baustofftechnologie, Abteilung Baustofftechnologie, Postfach, D-76128 Karlsruhe, Germany.

11. Bažant, Z. P., and Li, G.-H., "NU Database of Laboratory Creep and Shrinkage Data," available for download from www.civil.northwestern.edu/people/bazant.html or from the website of the Infrastructure Technology Institute of Northwestern University http://iti.northwestern.edu, Evanston, IL.

12. Bažant, Z. P., and Li, G. H., "Comprehensive Database on Concrete Creep and Shrinkage," Infrastructure Technology Institute, McCormick School of Engineering and Applied Science, Northwestern University, Evanston, IL, Mar. 2008, pp. 1-11.

NOTES:

APPENDIX

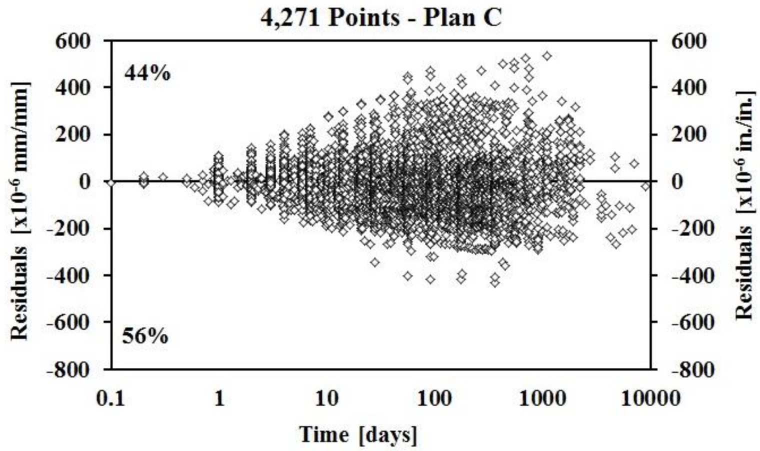

Figure 13-NU-ITI shrinkage strain residuals for GL 2000 model for 0-10,000 days

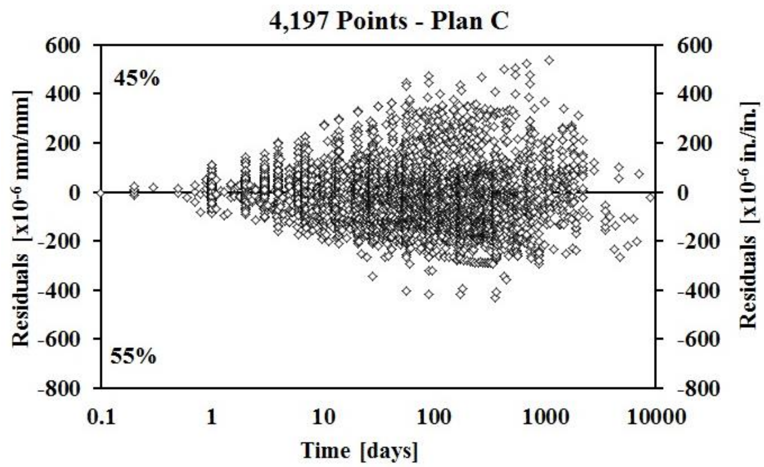

Figure 14-RILEM shrinkage strain residuals for GL 2000 model for 0-10,000 days

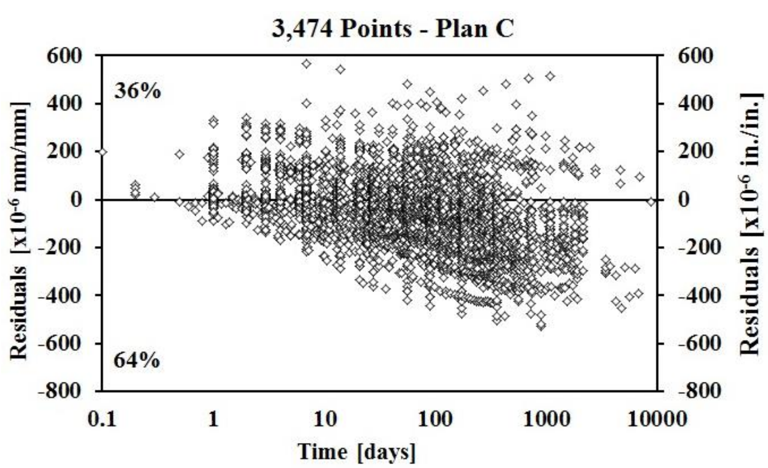

Figure 15-NU-ITI shrinkage strain residuals for AASHTO 2012 model for 0-10,000 days

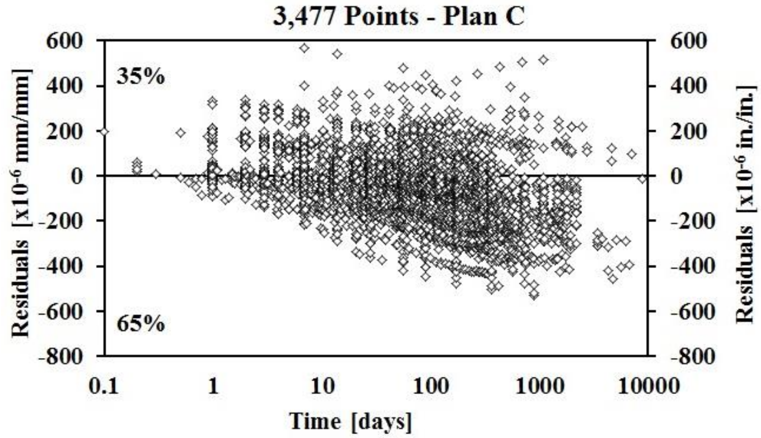

Figure 16-RILEM shrinkage strain residuals for AASHTO 2012 model for 0-10,000 days

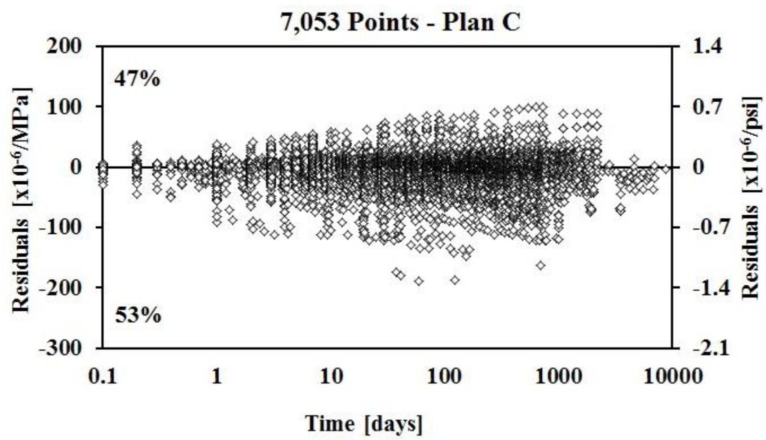

Figure 17-NU-ITI creep compliance residuals for GL 2000 model for 0-10,000 days

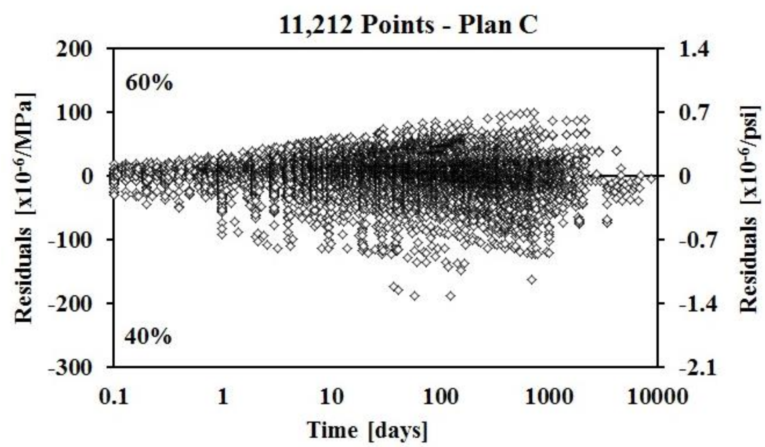

Figure 18-RILEM creep compliance residuals for GL 2000 model for 0-10,000 days

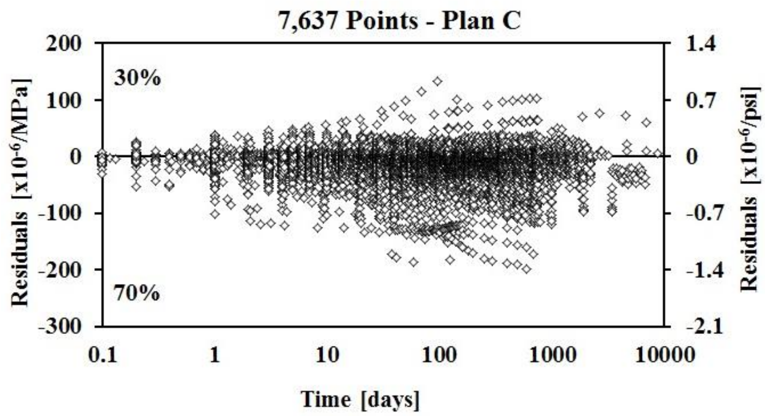

Figure 19-NU-ITI creep compliance residuals for CEB MC 90-99 model for 0-10,000 days

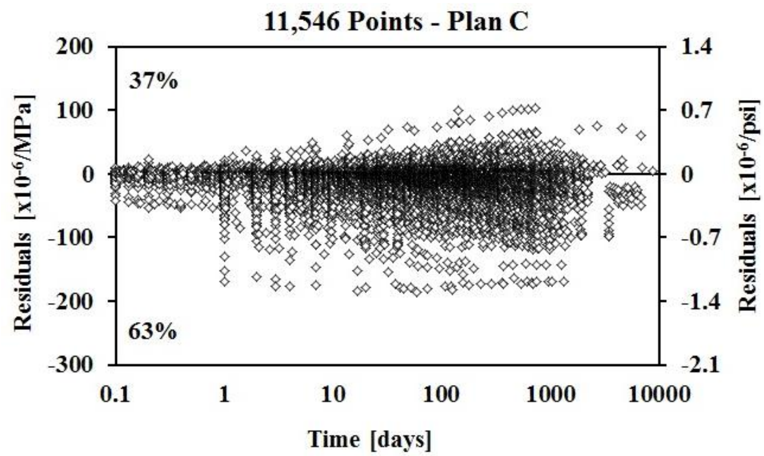

Figure 20-RILEM creep compliance residuals for CEB MC 90-99 model for 0-10,000 days

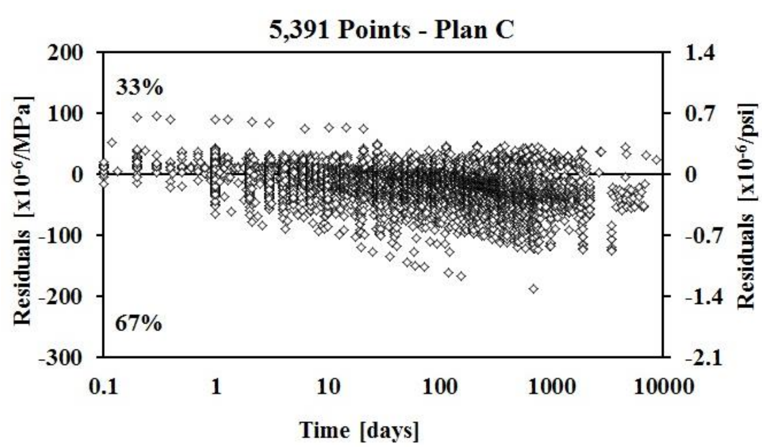

Figure 21-NU-ITI creep compliance residuals for AASHTO 2012 model for 0-10,000 days

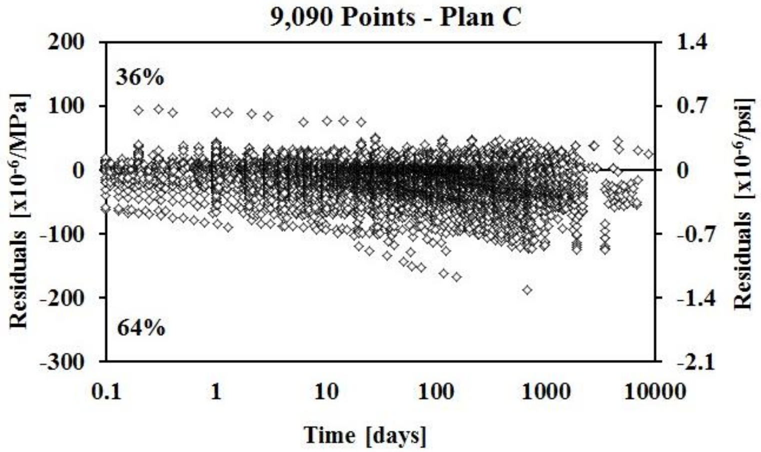

Figure 22-RILEM creep compliance residuals for AASHTO 2012 model for 0-10,000 days