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Comprehensive Database for Concrete Creep and Shrinkage: Analysis and Recommendations for Testing and Recording

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The first large worldwide database of creep and shrinkage tests was assembled at Northwestern University (NU) in 1978. It was expanded as the RILEM database in 1992 and further in 2008. A major expansion, completely restructured and verified, named the NU Database, is now presented. The number of the test curves of creep and drying shrinkage is more than doubled and over 400 test curves of autogenous shrinkage are added. The database covers longer measurement periods and encompasses the effects of admixtures in modern concrete mixtures. The database contains roughly 1400 creep and 1800 shrinkage curves, of which approximately 800 creep and 1050 shrinkage curves contain admixtures. Their analysis shows significant influence of admixtures on the creep and shrinkage behavior. The mixture proportions, testing conditions, and specimen geometries are documented in greater detail, and information on the admixture contents and aggregate types is included. The new database makes it possible to calibrate and verify improved creep and shrinkage prediction models. Additionally, the statistics of the mixture parameters, strength distributions, and scatter of the compliance curves have been extracted for applications in reliability engineering and probabilistic performance assessment. Data analysis brings to light various recommendations for testing and recording, and suggests corrections of various oversights distorting the reported data. These recommendations would make future test data more useful, consistent, complete, and reliable. The NU database is now available for free download at www.civil.northwestern.edu/people/bazant/ as well as at www.baunat.boku.ac.at/creep.html.

Keywords: admixtures; aggregate type; composition; compressive strength; correlation; database; shrinkage; statistics; testing.

INTRODUCTION

Since the discoveries of concrete shrinkage by H. Le Chatelier in Paris in 1887 (presented in his thesis described in Reference 1) and of creep in 1907 by W. K. Hatt at Purdue University,[2] many empirical and theoretical models have been introduced.[3-8] Their accuracy depends greatly on calibration by the available experimental data, especially in regard to multi-decade behavior. Therefore, increasingly comprehensive databases have been compiled over the years[9-12] to be used for model recalibration and validation as more information becomes available and concrete compositions change.

The earliest, though rather limited, data collection was compiled at the Technische Universität in Munich by H. Rüsch and O. Wagner and became the basis for the first CEB creep and shrinkage model.[13] Another data collection was included in Branson and Christiason's paper[14] underlying the 1971 ACI 209 model. The first large database, which was assembled at Northwestern University (NU), was included in the series of six papers presenting the BP Model.[15] At the "Hubert Rüsch Workshop" held during the 1979 Fall ACI Convention, a Joint ACI-RILEM committee was organized to extend the Northwestern University database. This effort was continued in a subcommittee chaired by H. Müller of RILEM Committee TC107. It eventually led to the RILEM-ACI 209 Database (1992), a major part of which consisted of the data from.[15-18] Some further additions were done in 2008 at NU by Bažant and Li[19] and in 2010 by K.-T. Kim.[20]

The most recent database, which is presented herein, was assembled during 2010 to 2013 at NU, mainly under the support of the U.S. Department of Transportation. The information was extracted from numerous journal articles, conference proceedings, and reports. The main motivation for this effort was the lack of data on modern high-performance concretes of very low water-cement ratio (w/c), which heavily rely on cement replacement and on admixtures (the term "modern concrete" herein encompasses all the concretes that are significantly influenced by chemical reactions other than the cement hydration, which includes high-strength concretes, self-consolidating concretes, and green concretes, which are characterized by cement replacement products and additives).

The new database now provides the admixture contents on top of standard mixture design parameters. Furthermore, the previous database included no information on the mineralogical composition of the aggregates, did not distinguish between the design strength and the mean strength at the time of testing, and did not attempt to unify the classification of cement types, aggregate types, and types of test. This is now rectified. Standard cement types, such as rapid-hardening cement, may include unknown admixtures. Such cases were included in the database, with all cement combined in the cement classification and the standard type listed. But nonstandard cement types were included only if their admixtures were specifically given and could be listed separately.

A major obstacle to progress has been the lack of multi-decade laboratory data, especially on creep. While lifetimes

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in excess of 100 years are nowadays required in the design of large bridges and many other large structures, 96% of all laboratory data do not exceed 6 years in duration. Only two data sets[21,22] among hundreds extend beyond 12 years, but the long-term environmental control was questionable. So the information on multi-decade creep must come from observations on structures.

An ideal source of information would be column shortenings of high-rise buildings that are exposed to constant environmental conditions and pure compression. The most useful available data are those on deflections of large-span prestressed bridge girders (>80 m [87.3 yd]), provided that they have deflected excessively (or else very little can be inferred for creep). The reasons are: 1) they are highly sensitive to creep; 2) their multi-decade deflections are caused mainly by creep under self-weight (therefore, the repeated traffic loads have negligible effect); 3) after 3 years since span closing, the deflection evolves approximately proportionally to the compliance function[23,24]; 4) the deflection due to cyclic creep is negligible if the span is large, because it is proportional to the fourth power of the cyclic-mean stress ratio.[23] The short-span bridges are not of interest because the prestress carries mainly the live load and thus offsets the dead load deflection. With realistic inverse analysis, large-span deflection data allow major improvements of multi-decade extrapolation (refer to a recent study of 69 bridges[25]). To this end, the rate-type formulation must be used to ensure that the creep behavior could be separated from other effects, at least on average.

The statistical scatter in the database is dominated by differences in concrete composition, aggregate type, and admixture effects, and is many times higher than the scatter in individual laboratory tests of one and the same concrete. Therefore, it is paramount that, in addition to global statistics of the entire database, the individual tests be used to evaluate the shape of the predicted individual curves.[26-28]

Some engineers might wonder whether the fluctuation of exposure to rain, snow, sun, and various chemicals would render laboratory databases obtained under a controlled steady environment inapplicable to real concrete structures. However, calculations of water diffusion and shrinkage cracking show that, because of the very low permeability of concrete and the relatively high frequency of this fluctuation, only a very shallow surface layer gets affected.[29,30] The humidity and temperature conditions that are relevant to long-time creep and shrinkage are the long-time averages. In those cases where these exposures are serious concerns, it is not a large problem today to assess them realistically using finite element stress and creep analysis that incorporates diffusion and cracking damage, as exemplified in some studies.[31-34] Of course, a creep and shrinkage model, anchored in a large database such as the present one, is an essential pillar of any such analysis of fluctuating exposure. Detailed studies on this subject may be consulted to consider the applicability of this effect for particular regions and designs.[35-37]

RESEARCH SIGNIFICANCE

The importance of sustainability of concrete infrastructure is now generally recognized and emphasized. Recent observations such as excessive multi-decade deflections, extensive cracking, and long-term buckling document that creep and shrinkage can seriously compromise long-term serviceability, durability, and, thus, sustainability. A large database is essential for developing a model to assess these problems.

Essential first check: Is the functional shape of the creep and shrinkage curves realistic?—A majority of the creep and shrinkage tests do not have a sufficient range to provide information on the functional form giving the correct shape of time curves and correct trends of the effects of loading age, structure thickness, and environmental humidity. Therefore, it is necessary to identify the tests that can provide such information.

Time shape of creep curves: To check whether it is realistic, only the following data have sufficient range:

1. 18-year tests of Russell and Larson[38] and Burg and Orst[39];
2. 12-year tests of Browne and Bamforth[40];
3. Several 12-year test series of the Bureau of Reclamation[41,42];
4. 23-year tests of Troxell et al.[22]; and
5. Tests of L'Hermite et al.[43] that, despite their duration of only 5 years, are valuable for their broad range of humidity and thickness.

Although the 30-year data of Brooks[21] have a record duration, only the first 6 years could be accepted because afterward, the slope of all of Brooks' creep and shrinkage test curves in log-time scale suddenly increased, which suggests a lapse in environmental control.

Further creep influencing factors: To check the function giving the effect of the age at loading, use References 43 to 47. To check the function giving the effect of environmental humidity, use References 43 and 48 to 52. To check for the effect of specimen size, use References 43 and 53 to 55. To check the effect of ambient temperature, use References 47 and 56.

Drying shrinkage curves and influencing factors: For the effect of environmental humidity, use References 22, 43, 49, 57, and 58; for ambient temperature, use References 59 to 61; for specimen size, use References 52 and 55, and for the age at exposure to environment, use References 45, 62, and 63. However, for the shape of shrinkage time curves, only References 45 and 49 are useful because they are the only ones that reveal, in a logarithmic time plot, the approach to the final asymptotic shrinkage value, and at the same time the only ones whose initial evolution follows a straight line of slope 1/2 dictated by diffusion theory and verified by References 43, 52, and 63. Note that the time to reach the final value is proportional to the thicknesses and thus can be many decades if the thickness square is large.

As for the autogenous shrinkage, there is such a variety of curves for diverse combinations of admixtures that it is impossible to show a typical curve (refer to Fig. 5 in Reference 64). Because the amount of reactants is finite, the autogenous shrinkage must have a final asymptotic value, even though no tests with long enough duration to reveal it have been published.

OVERVIEW OF ENTIRE DATABASE OF LABORATORY TESTS

The database contains 636 tests of "basic creep," observed on sealed specimens, and 734 tests of "total creep," observed on specimens exposed to environment. Ten additional curves are available for very low humidity and four for water immersion. Tests that lacked the sufficient information on the test conditions could not be included. This was the case for the recent large-scale tests of Aguilar,[65] in which the specimens were cured in water, doubtless undergoing swelling due to water imbibition simultaneously with autogenous shrinkage. Both of these deformations were not measured, even though each of them can have a major effect on later shrinkage.

Typically, three physical sources of shrinkage are distinguished: drying from the environment; self-desiccation; and chemical reactions leading to volume reduction. The last two are jointly referred to as "autogenous shrinkage" (the database contains 417 such curves). The observed response of unsealed load-free specimens is called the "total shrinkage" (1217 curves). "Drying shrinkage" (117 curves) is the difference between the total shrinkage and autogenous shrinkage.

Sixty-eight percent of the creep curves and 80% of the shrinkage curves are measured on concretes made with regular cement (Type R or equivalent). The remaining curves are almost equally distributed between concretes with rapid-hardening cement (Type RS; 12% of creep and 11% of shrinkage tests) and concretes with slow-hardening cement (Type SL; 16% of creep and 16% of shrinkage tests). Approximately 800 creep curves and 1050 shrinkage curves contain admixtures.

Preferably, a shrinkage database should also provide water-loss measurements. It is impossible to estimate the final shrinkage beforehand, whereas the final water loss can be estimated quite well in various ways.[6] Thus, a combination of short-time shrinkage and weight loss data allows a much better prediction of the long-time shrinkage, and especially its asymptotic value. Unfortunately, there are hardly any significant data of this kind.

For consistency, the reported creep strains and initial deformations have all been converted to the compliance—that is, the strain per unit stress—for both creep and the initial instantaneous strain. Shrinkage measurements are reported in the units of strain (that is, dimensionless), negative for shortening.

To convert concrete compositions to consistent units, an average hydrated cement density was assumed as 2350 kg/m^3 (147 lb/ft^3). For calculating volume-surface ratio V/S, the specimen ends were assumed to have been sealed whenever the experimenter gave no information. When sealed, the surface area of the end caps was not exposed to the environment and thus not included in the total surface area. Because the admixture contents were occasionally given in terms of weight instead of volume while typically no mass density data were provided, no conversion was done and whichever value was supplied is reported.

Few creep tests on modern concretes provide a sufficient time range, and the data on old concretes provide the bulk of the information. They are relevant because creep in both old and modern concretes resides solely in the calcium silicate hydrates, while the other components provide merely restraining effects that scale the creep magnitude but do not alter the shape of creep curves. However, the existing multi-decade creep tests tell very little about concrete composition and environmental effects, and so all this information must be taken from short-term data.

To the extent provided by the experimenter, the new laboratory database now lists for each data set the following entries: Test ID; File Name; Author; Region; Year; Paper Reference ID; time scale used (linear, log, table); data type (total, autogenous, or drying shrinkage; total, basic, or drying creep); whether the initial elastic strain was reported; w/c; aggregate content a/c; cement content c; aggregate type (round, broken, mineralogical classification); silica fume (all by mass percentage); fly ash; slag; filler; viscosity agent (VA); accelerator; water reducer; retarder; superplasticizer; air-entraining agent (AEA); E_{28} modulus; $f'_{c,28}$ compressive strength; compressive strength f_c' at the time of loading; applied stress; specimen geometry; V/S; temperature T and relative humidity h during curing; and T and h during test.

DATABASE OF CREEP DEFLECTIONS OF BRIDGES

To obtain long-term information, excessive deflections of long-span prestressed segmentally erected box-girder bridges are useful[66] (note that, because of cautious design and clever tendon layout, many bridges do not suffer excessive deflections, but such deflections do not give useful information on the compliance function). A database of multi-decade deflection histories of 69 excessively or almost excessively deflecting bridges around the world has been compiled. Their analysis revealed that the existing creep and shrinkage models cannot predict the magnitude and trend of multi-decade creep.[24,33,34] Beginning at approximately 3 years after bridge closing, the deflections of all these bridges grow approximately as a logarithmic function of time. This implies proportionality to the compliance function for creep, which was exploited in Reference 66. Further, it implies that the shrinkage had either been mostly finished or was merely causing shortening of the bridge with no deflection.

The bridge database provides the following quantities when available: span, location, year it was built, bridge type, and test duration. An additional set of estimated parameter values is inferred from the data. The concrete strength and other properties have been estimated as the typical values used at the time and place of construction.[66] The error of this estimate has little effect on the mean creep of this bridge collection, but introduces bias regarding the influence of composition on the multi-decade behavior. Further reported parameters include the maximum tolerable deflection for the design of this kind of bridge, the maximum deflection from the measured record, and two true-or-false entries indicating whether or not the measured deflection already exceeds the design value or will do so within a 100-year lifetime. Therefore, despite its limitation, the bridge database can, and should, be used as a companion information source of multi-decade information.

LABORATORY DATABASE INFORMATION AND LAYOUT

The creep data included in the database come from specimens exposed to constant environmental conditions and subjected to a sustained uniaxial compressive stress within the service stress range—that is, not exceeding 40% of the standard compressive strength. Within that range, the creep of concrete is linear in terms of stress σ in sealed conditions, though only approximately linear when drying. Therefore, creep can be fully characterized by compliance $J(t,t')$, which is defined as the strain at age t caused by a unit stress applied at age t' (and thus includes the initial elastic strain). The testing configurations for the autogenous shrinkage measurements vary. The reported data depend strongly on how early in the hydration process the measurement was initiated. The intrinsic and extrinsic conditions characterizing each test curve consist of the mixture proportions, specimen geometry, environmental conditions, curing conditions, the compression strength measured on a companion specimen and, if known, Young's modulus. Figure 1 illustrates the naming convention of the time points describing the creep and shrinkage tests.

The database is structured in agreement with the principles of a relational database, avoiding redundant entries as much as possible. This reduces the storage demands and ensures data integrity. The test details and measured data are presented in two separate sheets. Both sheets are linked through a unique specimen identification string. In a similar fashion, the referenced sources for all the authors are stored on a separate sheet, linked through a reference number.

Unfortunately, only in rare cases is all the relevant information provided by the experimenter in the source document. Thus, some of the parameters listed could not be entered. A zero is entered only when a quantity is reported as absent.

ANALYSIS OF ENTIRE DATABASE TO IDENTIFY CONCRETE STRENGTH AND COMPOSITION EFFECTS

First it must be emphasized that the database as a whole is useless for verifying the mathematical form, or shape, of the compliance and shrinkage functions. The reason is that the scatter in the database is dominated by the differences among various concretes, which are an order of magnitude bigger than the errors in the shape. However, the analysis of the whole database is essential for identifying the effects of concrete strength and various parameters of concrete composition (or the mix parameters).

The database compiled from test data in the literature contains various biases, errors, and uncertainties that must be quantified, filtered, and compensated before conclusions are drawn from the data. The database is strongly biased toward short test durations (up to a few years), low ages at loading, small specimens (up to 150 mm [6 in.] in diameter), and typical concrete compositions. Ignoring this bias would lead to results misleading for multi-decade behavior, large thicknesses, and special compositions. Refer to Fig. 2 and 3, in which the distributions of input parameters are seen to be far from uniform. Reference 26 presents a successful approach to coping with this heteroscedastic nature of data, using n-dimensional hyperboxes to counteract bias.

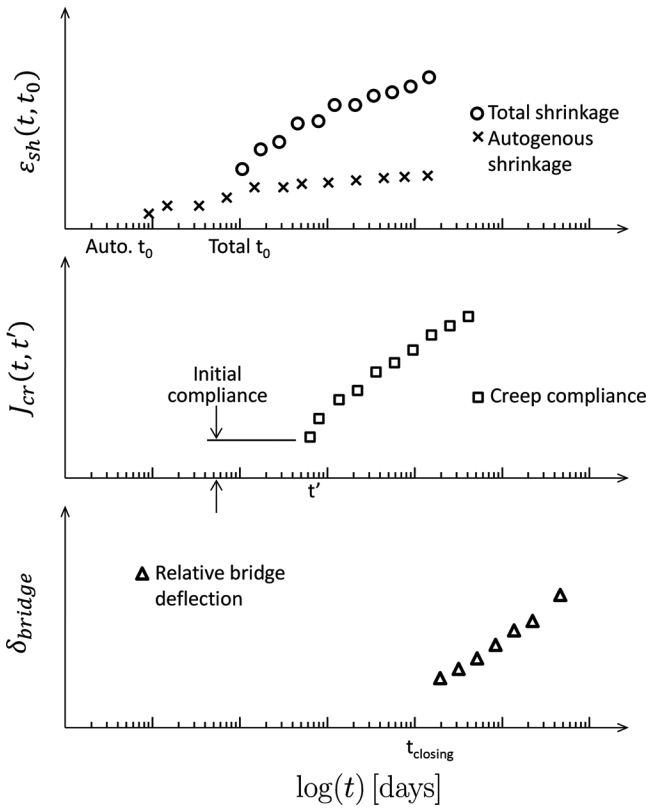

Fig. 1—Sketches of relative timing and approximate durations available for each data type presented in the laboratory creep, shrinkage, and bridge deflection databases. Measurements for autogenous shrinkage ε_{au} typically begin at the end of curing, t_c*, or shortly before. Total shrinkage measurements ε_{sh} are reported upon exposure to the environment at* t_0*. Strain due to creep is characterized by the instantaneous response at time of load application,* t′ *and deformation thereafter. This is sketched in terms of the material compliance* J*. Bridge deflections δ typically begin 3 to 4 years after curing and their start is characterized by the closing of bridge construction* t_{close}.

The distributions of the compliance and shrinkage data in Fig. 2 and 3 provide interesting insights. While the range of w/c for the creep tests is broadly populated between 0.3 and 0.7, it does not directly correlate to a similar distribution in the mean strength, $\overline{f}_c$, as would be anticipated from the well-known relation between $\overline{f}_c$ and w/c.

The 28-day compressive strength shows a bimodal distribution with peaks at the typical strength values around 45 to 50 MPa (6500 to 7300 psi) for normal concretes, and at high values near 100 MPa (14,500 psi), typical of concretes with modern cements. This trend is much less pronounced for the shrinkage tests because shrinkage is typically tested on shorter time scales. For creep, the mean test duration is only 240 days (mode of 126 days), whereas for shrinkage the mean test duration is even less—180 days (mode of 83 days). The measured values of strength and Young's modulus are nearly consistent across the creep and shrinkage data sets. The mean 28-day Young's modulus varies only

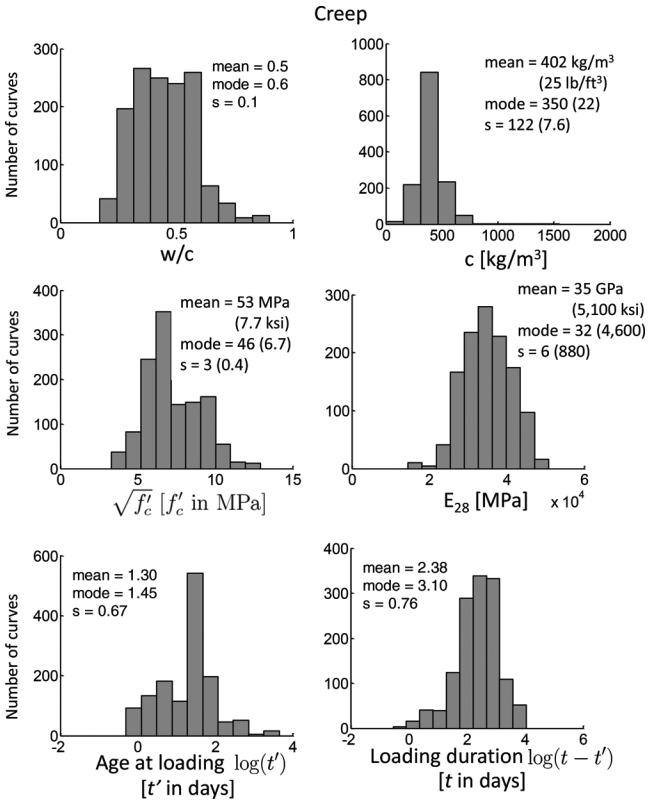

Fig. 2—Distributions of creep input parameters with the mean, mode, and standard deviation of data. The unequal representation of input parameters across the range of available values requires a bias correction when the full database is used for model calibration.

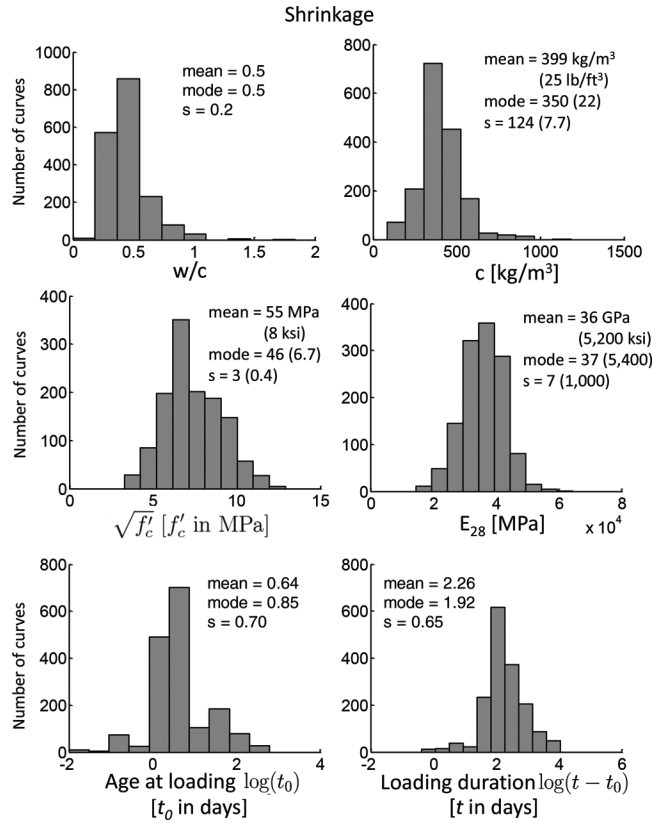

Fig. 3—Distributions of shrinkage input parameters with the mean, mode, and standard deviation of data.

by 1000 MPa (145 ksi) between the two sets and the mean 28-day compressive stress by 2 MPa (290 psi). This makes it possible to draw combined trends from both data sets even when each source might not have provided information for both creep and shrinkage.

Many important time points and response variables, which are needed for accurate creep and shrinkage estimates, are not consistently reported in the literature. For example, autogenous shrinkage begins already at the time of set of the mixture, but the measurements typically start only at some later time. Creep measurements begin at any time between 0.1 second and several hours after the beginning of loading and, even worse, often the initial deformation was not reported. Other details that are of interest include the geographic region of testing and the source of the cement material. Data from different countries have been shown to correlate differently to input parameters. The recommendations in the following section suggest methods to reduce the uncertainty in the reports on future creep and shrinkage experiments.

STATISTICAL INFERENCES FROM DATA

From the database, one can derive conditional stochastic models for the mixture proportions in a certain strength class, which may be used as inputs for developing more refined prediction models such as Model B4[67] as well as for performing reliability analyses.[68-70] One can also extract a number of statistical characteristics such as the coefficients of variation of composition parameters as presented in Fig. 4. The top two tables give the mean and standard deviation of input values as a function of different strength ranges. For each strength class, the statistical correlation between the composition parameters and the 28-day strength f_{28} or the 28-day modulus E_{28} are given.

The traditional linear correlation coefficients provide only a limited insight into the dependence structure. Copulas[71,72] are able to capture also the shape of the correlation field and thus provide a superior representation of the statistical dependence, which is one of the most important inputs for probabilistic calculations. For illustration purposes, the copula parameters are compared to the linear correlation coefficients for the strength class 30 to 35 GPa (4400 to 5000 psi) in Table 1.

The extensive collection of concrete compositions with recorded strength and E-modulus information can further be used to investigate composition-based prediction equations for the strength and E-modulus as well as an empirical relationship between them. For instance, according to the database, the ACI and *fib* Model Code relationships between the strength and the E-modulus can be updated as

$$\text{ACI:}\quad E_{28} = 4735\left(\frac{f_{28}}{1\ \text{MPa}}\right)^{1/2} \quad (\text{COV} = 0.1803) \tag{1}$$

$$\rightarrow E_{28} = 4428\left(\frac{f_{28}}{1\ \text{MPa}}\right)^{1/2} \quad (\text{COV} = 0.1699) \tag{2}$$

Data

(mean, std.)		Strength Range									
parameter	[MPa]	15 - 20	20 - 25	25 - 30	30 - 35	35 - 40	40 - 45	45 - 50	50 - 55	55 - 60	overall
	[psi]	2175 - 2900	2900-3626	3626-4351	4351-5076	5076-5802	5802-6527	6527-7252	7252-7977	7977-8702	
w/c [-]		(0.48, 0.16)	(0.48, 0.17)	(0.48, 0.16)	(0.47, 0.15)	(0.48, 0.15)	(0.47, 0.14)	(0.45, 0.14)	(0.46, 0.14)	(0.45, 0.15)	(0.5, 0.14)
a/c [-]		(5.3, 2.5)	(5.4, 2.6)	(5.5, 2.8)	(5.3, 2.6)	(5.4, 2.7)	(5.2, 2.4)	(5.0, 2.3)	(5.1, 2.4)	(5.0, 2.5)	(5.4, 2.3)
c [kg]		(390, 138)	(383, 139)	(378, 141)	(382, 134)	(380, 136)	(382, 125)	(397, 125)	(397, 131)	(404, 136)	(365, 112)
	[lb]	(860, 304)	(844, 306)	(833, 311)	(842, 295)	(838, 300)	(842, 276)	(875, 276)	(875, 289)	(891, 300)	(805, 247)
f_{28} [MPa]		(17, 2)	(23, 2)	(27, 1)	(33, 1)	(37, 1)	(43, 2)	(47, 1)	(52, 2)	(57, 1)	(40, 11)
	[psi]	(2465, 290)	(3336, 290)	(3916, 145)	(4786, 145)	(5366, 145)	(6236, 290)	(6817, 145)	(7542, 290)	(8267, 145)	(5802, 1595)
E_{28} [GPa]		(25, 4)	(26, 4)	(29, 3)	(31, 4)	(33, 2)	(32, 4)	(35, 7)	(35, 4)	(36, 3)	(33, 5)
	[ksi]	(3626, 580)	(3771, 580)	(4206, 435)	(4496, 580)	(4786, 290)	(4641, 580)	5076, 1015)	(5076, 580)	(5221, 435)	(4786, 725)

Lognormal Fit

(μ, σ)		Strength Range									
parameter	[MPa]	15 - 20	20 - 25	25 - 30	30 - 35	35 - 40	40 - 45	45 - 50	50 - 55	55 - 60	overall
	[psi]	2175 - 2900	2900-3626	3626-4351	4351-5076	5076-5802	5802-6527	6527-7252	7252-7977	7977-8702	
w/c [-]		(-0.8, 0.34)	(-0.79, 0.34)	(-0.78, 0.34)	(-0.79, 0.32)	(-0.79, 0.33)	(-0.79, 0.31)	(-0.83, 0.31)	(-0.83, 0.32)	(-0.84, 0.32)	(-0.74, 0.3)
a/c [-]		(1.6, 0.39)	(1.6, 0.4)	(1.6, 0.41)	(1.6, 0.38)	(1.6, 0.41)	(1.6, 0.36)	(1.5, 0.36)	(1.6, 0.37)	(1.5, 0.38)	(1.6, 0.35)
c [kg]		(5.9, 0.36)	(5.9, 0.37)	(5.9, 0.38)	(5.9, 0.35)	(5.9, 0.37)	(5.9, 0.32)	(5.9, 0.32)	(5.9, 0.34)	(5.9, 0.35)	(5.9, 0.31)
	[lb]	(13, 0.79)	(13, 0.82)	(13, 0.84)	(13, 0.77)	(13, 0.82)	(13, 0.71)	(13, 0.71)	(13, 0.75)	(13, 0.77)	(13, 0.68)
f_{28} [MPa]		(2.8, 0.09)	(3.1, 0.06)	(3.3, 0.04)	(3.5, 0.03)	(3.6, 0.03)	(3.8, 0.03)	(3.8, 0.03)	(3.9, 0.03)	(4, 0.02)	(3.6, 0.3)
	[psi]	(406, 13)	(450, 9)	(479, 6)	(508, 4)	(522, 4)	(551, 4)	(551, 4)	(566, 4)	(580, 3)	(522, 44)
E_{28} [GPa]		(3.22, 0.16)	(3.26, 0.16)	(3.35, 0.12)	(3.43, 0.14)	(3.49, 0.07)	(3.46, 0.13)	(3.53, 0.2)	(3.54, 0.13)	(3.58, 0.11)	(3.46, 0.17)
	[ksi]	(4670, 23)	(4728, 23)	(4859, 170)	(4975, 20)	(5062, 10)	(5018, 19)	(5120, 29)	(5134, 19)	(5192, 16)	(5018, 25)

15 - 20 MPa(2175 - 2900 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.68	-0.48	0.13	0.27
a/c	-	1	-0.93	0.41	0.37
c	-	-	1	-0.46	-0.34
f_{28}	-	-	-	1	0.63
E_{28}	-	-	-	-	1

20 - 25 MPa(2900 - 3626 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.77	-0.75	0.14	0.37
a/c	-	1	-0.97	0.43	0.42
c	-	-	1	-0.45	-0.41
f_{28}	-	-	-	1	0.51
E_{28}	-	-	-	-	1

25 - 30 MPa(3626 - 4351 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.83	-0.73	-0.19	0.34
a/c	-	1	-0.91	-0.13	0.38
c	-	-	1	0.30	-0.41
f_{28}	-	-	-	1	0.06
E_{28}	-	-	-	-	1

30 - 35 MPa(4351 - 5076 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.82	-0.80	-0.09	0.07
a/c	-	1	-0.92	-0.06	0.19
c	-	-	1	-0.01	-0.23
f_{28}	-	-	-	1	0.42
E_{28}	-	-	-	-	1

35 - 40 MPa(5076 - 5802 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.92	-0.95	-0.01	0.67
a/c	-	1	-0.91	0.06	0.80
c	-	-	1	0.01	-0.64
f_{28}	-	-	-	1	0.31
E_{28}	-	-	-	-	1

40 - 45 MPa(5802 - 6527 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.69	-0.72	-0.32	-0.15
a/c	-	1	-0.85	-0.21	0.07
c	-	-	1	0.25	0.18
f_{28}	-	-	-	1	0.15
E_{28}	-	-	-	-	1

45 - 50 MPa(6527 - 7252 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.75	-0.81	0.27	-0.04
a/c	-	1	-0.95	0.39	0.08
c	-	-	1	-0.41	0.01
f_{28}	-	-	-	1	-0.14
E_{28}	-	-	-	-	1

50 - 55 MPa(7252 - 7977 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.84	-0.88	-0.07	-0.14
a/c	-	1	-0.92	-0.04	-0.06
c	-	-	1	0.01	0.13
f_{28}	-	-	-	1	-0.16
E_{28}	-	-	-	-	1

55 - 60 MPa(7977 - 8702 psi)

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.86	-0.89	-0.36	-0.18
a/c	-	1	-0.92	-0.28	-0.06
c	-	-	1	0.33	0.13
f_{28}	-	-	-	1	-0.03
E_{28}	-	-	-	-	1

overall

	w/c	a/c	c	f_{28}	E_{28}
w/c	1	0.81	-0.82	-0.63	-0.32
a/c	-	1	-0.88	-0.42	-0.12
c	-	-	1	0.54	0.25
f_{28}	-	-	-	1	0.58
E_{28}	-	-	-	-	1

Fig. 4—Inferences from data can be made for practical applications such as stochastic models. Coefficient of variation of data for basic mixture information, given a certain strength class, illustrate the variability of information available in literature.

Table 1—Statistical correlations of key composition and strength parameters reported for mid-range concretes with compressive strength between 30 and 35 GPa (4400 to 5000 psi)

Correlations to f_{28}				Correlations to E_{28}			
	Linear	t-dist. copula			Linear	t-dist. copula	
Parameter	ρ	τ	*n*	Parameter	ρ	τ	*n*
w/*c*	–0.09	–0.65	*	*w*/*c*	0.07	–0.40	11.68
a/*c*	–0.06	–0.50	23.39	*a*/*c*	0.19	–0.25	23.69
c	–0.01	0.56	16.53	c	–0.23	0.33	7.89

*Gaussian copula.

Notes: As illustrated for this parameter set, correlations between the database variables may be captured through pairwise linear Pearson correlation coefficients or through Copulas. ρ – Pearson correlation, τ – rank correlation, and *n* – degree of freedom parameter.

$$\text{MC2010:}\quad E_{28} = 21{,}500\left(\frac{f_{28}}{1\ \text{MPa}}\right)^{1/3} \quad (\text{COV} = 0.1455) \tag{3}$$

$$\rightarrow E_{28} = 8786\left(\frac{f_{28}}{1\ \text{MPa}}\right)^{1/3} \quad (\text{COV} = 0.1421) \tag{4}$$

Optimized exponential form:

$$E_{28} = 9383\left(\frac{f_{28}}{1\ \text{MPa}}\right)^{0.317} \quad (\text{COV} = 0.1419) \tag{5}$$

$$\text{GL:}\quad E_{28} = 3500 + 4300\left(\frac{f_{28}}{1\ \text{MPa}}\right)^{1/2} \quad (\text{COV} = 0.1659) \tag{6}$$

$$\rightarrow E_{28} = 12{,}035 + 2849\left(\frac{f_{28}}{1\ \text{MPa}}\right)^{1/2} \quad (\text{COV} = 0.1424) \tag{7}$$

These relations provide the modulus in terms of MPa to match the units provided in the database.

RECOMMENDATIONS FOR TESTING AND REPORTING

While most testing standards for measuring creep and shrinkage[73-79] agree with the main testing guidelines presented by RILEM in 1995,[80] they do not agree on the specimen-sealing procedure, aspect ratio, gauge placement, and measurement timing. These differences in testing procedure introduce uncertainty and errors, which complicate comparisons of data sets and models unless a full 3-D inverse analysis is performed.

As pointed out in ACI 209.2R,[3] further inconsistencies are introduced by differences in the definition of the existing categories for the types of cement and concrete in various countries. The Type II cements from the United States, Asia, and Europe do not have the same chemical composition. Laboratory studies do not always report which classification is being specified. This causes ambiguity. For example, the ASTM cement types refer to compositions based on the typical applications while the European EN197 has a dual classification system based on the strength development and cement composition. Additionally, the properties of standard portland cement have been changing over time. For example, modern cements display a higher alkali content. These changes lead to higher early strength (this causes the strength of mortar in the Unit to increase from 1977 to 1991 by 3.8 MPa [550 psi]).[81] In addition, the range of allowed admixture types and quantities that are grouped under the same cement type might not be reported separately and can cover a large range of behaviors. To reconcile these differences, a cement categorization system based on the reactivity is desirable.

The comprehensiveness of the new database allows identifying a series of common testing and reporting deficiencies. Nine of them are sketched in Fig. 5. Figure 5(a) illustrates the vertical scaling caused by an inadvertent increase in environmental humidity during testing. This may be caused by a leaking seal or by inadequate chamber control (refer to Fig. 5(a)), as observed in the data reported in Reference 21. As seen in Fig. 5(b), when a series of tests is collected, a change in environmental temperature causes an increased rate of creep and shrinkage in the entire series. This error cannot be identified from individual test curves nor from plots in linear time scale. Also seen in Reference 21 is a combination of temperature and humidity control failure that results in a randomly fluctuating curve like the one in Fig. 5(c). Another common reporting deficiency is omission of the initial deformation upon loading. It causes the deviations shown in Fig. 5(d). Furthermore, measurements made before the initial set of concrete mixture show a high degree of variability (refer to Fig. 5(e)) and would require pointwise modeling of the chemical reactions involved.

Figure 5(f), and in more detail Fig. 6, illustrate false initial steepness of the creep or shrinkage curve caused by starting deformation readings with a delay after the start of loading or of drying exposure, or by reporting the data in the linear (rather than logarithmic) scale, which does not allow distinguishing short times. Unfortunately, because plotting in a linear, rather than logarithmic, time scale has been so prevalent, each curve had to be classified according to its reported scale. Figure 6 illustrates two columns showing horizontal error bars in uncertainty in time measurements associated with one data set of creep compliance tests. The left column shows the uncertainty associated with an error of one-fourth of a day when the data are provided in linear scale (plot a) and in logarithmic scale (plot c). The right column illustrates the same effect for an error of 1 day in linear scale (plot b) and logarithmic scale (plot d) for the same data set. For clarity, the plots should be in logarithmic time scale and the

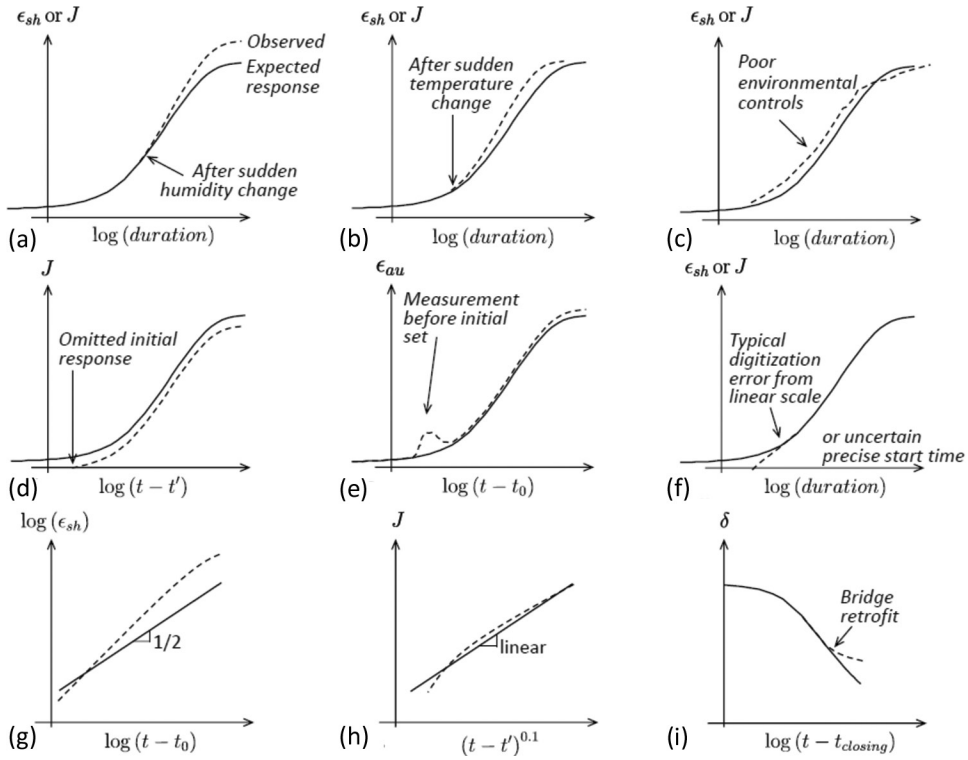

Fig. 5—Sketches of commonly observed deviations in data curves due to testing procedures or reporting (refer to Fig. 1 caption for variable definitions): (a) change of relative humidity condition; (b) change of temperature condition; (c) environmental controls were insufficient; (d) instantaneous response may have been removed; (e) measurement began before initial set; (f) possible digitization error; (g) initial drying shrinkage measurement does not follow diffusion theory; (h) initial creep strain does not follow asymptotic creep trend (both (g) and (h) indicate delayed measurement start); and (i) structure has been retrofit.

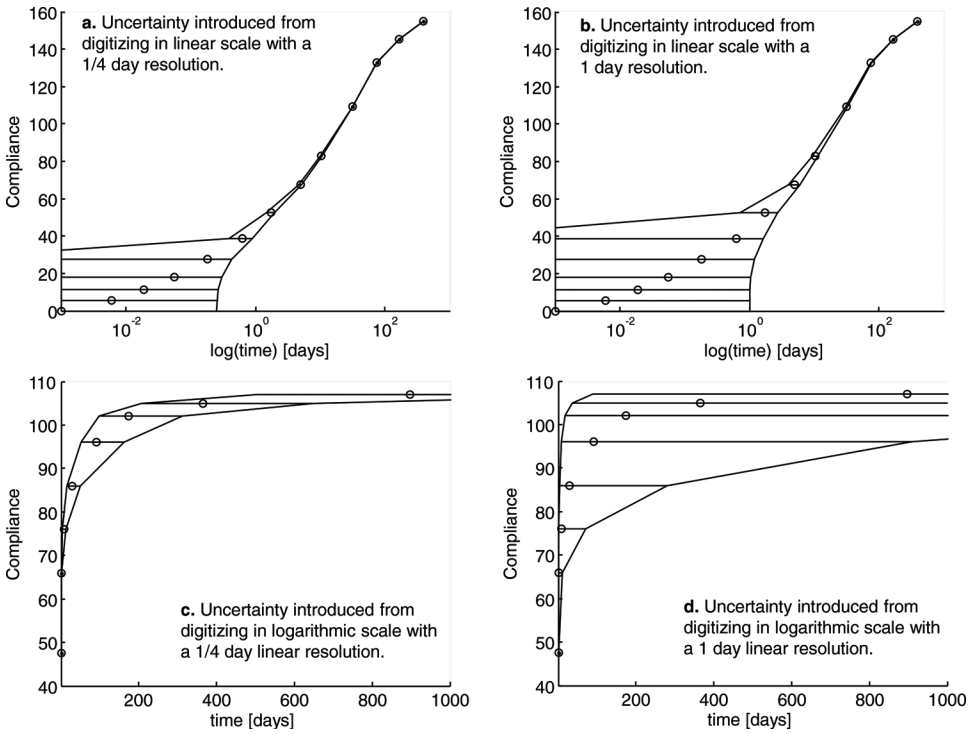

Fig. 6—Effect of digitization uncertainty in linear, instead of logarithmic, time scale. The inevitable errors introduced by fitting data in a time scale different from experimenter's report needs to be corrected considering theoretical functional form. Data points are taken from a random experiment[46] to illustrate this point.

best is to report the data in the form of a table, as in References 82 to 84.

Based on the diffusion theory, the initial slope of shrinkage data in a log-log plot must be a straight line of slope 1/2, refer to Fig. 5(g) (a deviation from this property can be caused by finite surface emissivity, but because the emissivity is typically equivalent to an added surface layer of concrete only about 1 mm [0.0394 in.] thick, the surface emissivity cannot appreciably affect cylinders of diameter > 50 mm [2 in.]). Similarly, as verified by fitting of accurate short-time creep data,[85] the initial compliance curve should be a straight line (of slope circa 0.1) when plotted as the logarithm of compliance versus the logarithm of load duration. Many data sets in the database violate the aforementioned initial properties. Inevitably, this implies that, because of a delayed start of deformation measurements, a certain time period Δt of loading and a certain initial compliance ΔJ or shrinkage strain $\Delta\varepsilon_{sh}$ were missed.

In principle, the reported data should be corrected by shift Δt of the initial time and shift ΔJ or $\Delta\varepsilon_{sh}$ of the initial measurement value until the plots of initial creep and shrinkage data become straight in the scale of strain versus $(t - t_0)^{1/2}$ for shrinkage and strain versus $(t - t')^{0.1}$ for creep. This shrinkage property is model-independent and was justified by both the calculations based on diffusion theory and by careful experiments.[52,86,87] For creep, this property was verified by detailed short-time creep data (refer to, for example, Reference 85). Unfortunately, though, these corrections can be considered only for a small fraction of the data in the database because many experimenters did not measure shrinkage and creep for sufficiently short times. Therefore, no such corrections were applied to the reported data. Alternative approaches to identify the unknown shifts in the absence of short-term measurements are discussed in Reference 26. Based on the experience gained in analyzing close to 1000 papers, theses, and reports, a number of recommendations for performing and reporting creep and shrinkage tests can be made:

Creep tests—

1. The creep compliance curves should always be plotted against the logarithm of load duration (a linear scale can show clearly only the part of response corresponding to only one decade in the logarithm of duration, while the values for shorter times cannot be distinguished and the values for longer times lie outside the diagram).

2. The reported data should always include the total deformation, including the initial value upon load application (euphemistically called "instantaneous"), and the experimenter's report should confirm it. The RILEM recommendation[80] defines how to measure the deformation during load application. This quantity, though, is not specifically addressed in other testing standards, yet it is of great importance for model calibration.

3. The rate or duration of load application at the beginning of creep tests is essential information and should always be reported. According to Fig. 2.8 in Reference 7, the deformations at 10 seconds, 10 minutes, and 2 hours increase in the ratio 1, 1.30, and 1.54 if the concrete is 7 days old. If a frame with hydraulic system is used, a sudden opening of a valve applies the load within 0.1 seconds, while in manually operated spring frames it may take 2 hours.

4. All the measurements should start before the load is applied and the short-time deformation during the load application must be included.

5. If the stress-strength ratios are reported, the reference strength value must be specified, too. If the strains are normalized by strength, the strength at the time of load application should be used and reported.

6. The measurements should not be reported in terms of the creep coefficient, but directly as the compliance, because this avoids uncertainty regarding the *E*-modulus value that was used to convert the measured strains into the creep coefficient (the *E*-modulus measured by standardized tests [ASTM C469/C469M-10] should never be used because such a test involves cycles of loading and unloading; it gives stiffness suitable for live loads or vibrations, which is very different from the stiffness for the initial deformation in a creep test). What matters for long-term stuctural analysis is only the total compliance, while its subdivision into creep and instantaneous (or short-time) deformation is almost irrelevant.

7. If anything other than raw data is presented, the methods of data preparation should always be explained. This includes filtering, interpolation, extrapolation, and in particular, the combination of data from different experiments such as those required for drying creep. For example, if the concrete exhibits appreciable autogenous shrinkage, the measurements of total creep, drying creep, and drying shrinkage without simultaneous measurement of autogenous shrinkage are next to useless.

8. The specimens should always be cured in a moist chamber. Curing in water should be avoided because delayed swelling and simultaneous autogenous shrinkage in the core of a water-imbibing specimen distorts the data in a complicated way.

9. Each term used for the classification of creep data (for example, drying creep, total creep) should be clearly defined.

Shrinkage tests—

1. Autogenous shrinkage measurements should ideally start as closely as possible to the time of set of the concrete mixture. The phase right after set should be recorded along with the test data to provide insight into the magnitude of shrinkage that may have occurred during very short times.

2. The drying shrinkage specimen should be instrumented before stripping the seal and the readings should begin within a few seconds after that.

3. Installing the gauge only after stripping the seal is undesirable. If done, the gauge installation must be as fast as possible and the readings must start immediately. Even delays of several seconds matter because shrinkage initially evolves as the square root of the duration of exposure.

4. Because the shrinkage strain distribution near the specimen ends is highly non-uniform, it is important to use long specimens (aspect ratio 6:1 is recommended) and the distance of the gauge contact points from the specimen ends should not be less than two diameters. Sealing of the specimen ends alleviates this non-uniformity only partly and insufficiently. The placement of the gauge contact points should always be

reported. For short unsealed specimens, the measurements on the surface and those along the specimen axis should both be made.

5. A test of drying shrinkage should always be accompanied by a companion test of autogenous shrinkage extending beyond the time of drying exposure. The reason is that the autogenous shrinkage continues in the core of drying specimen for a long time, until the drying front reaches the core, which may take months or years.

Creep and shrinkage tests—

1. The specimen dimensions, a detailed description of the test setup, and the testing procedure should be provided. The sensor type, location, and gauge length should always be reported.

2. The environmental conditions during curing should be reported. Although the use of wet burlap and spraying by water is common and accepted for moist curing in construction, it is not sufficient for laboratory creep and shrinkage tests, during curing as well as afterward.

3. For samples tested in a sealed condition, the quality of the seal should be checked at regular intervals during the test. An unexpected increase in strain, which is often observed in long-term autogenous shrinkage measurements or multi-decade basic creep tests, is most likely caused by degradation of the environmental seal. The seal should be resistant to multi-year or multi-decade aging. The best long-term seals are metallic foils.

4. In general, the temperature and relative humidity of environment should be monitored automatically, along with the deformation data, for the entire test duration. This information can serve for a statistical characterization of the testing conditions and can provide explanations for unexpected trends.

5. If the specimens are unsealed or, especially, partly sealed, the exact description of the boundary conditions during curing and testing are important for later analysis.

6. One should use multiple specimens for creep and shrinkage tests. From these, both the mean curve and the envelope of measurements or confidence limits should be plotted, and outlier curves identified. If some individual tests show conflicting trends, the individual test curves rather than just their average should be published.

7. The concrete composition should be specified precisely. Aside from the class of cement and type of code used, the mixtures proportions, the admixtures, and the type and treatment of aggregate should also all be stated. The gradation curve and the mineralogical composition are useful. Companion tests of the strength and modulus of elasticity should be reported. For mechanism-based theoretical models, these tests should be performed at the time of loading and supplemented by 28-day values required by design standards. The age of the specimens in strength and modulus tests should always be reported.

8. Because of the gradual decay of the creep and shrinkage rates, the RILEM recommendation states that the readings should be spaced roughly uniformly in the logarithmic scale of test duration, and that the time accuracy should be judged by error in the log-scale. Thus the early times should be recorded in seconds, minutes, and hours; for multi-year tests, days; and for multi-decade tests, months.

9. Particular care is needed to give a precise report of the early measurement points because these points serve to anchor smooth formulas to be used for long-term extrapolation.

CONCLUDING REMARKS

The present database, with its unprecedented scope and detail, should allow development of better creep and shrinkage models. One such model, named B4,[67] was recently completed at Northwestern University. At the same time, the compilation of the database reveals various widespread shortcomings in the testing, recording, and reporting procedures. This revelation has led to recommendations for more useful future testing procedures.

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