On-site Study of the Time-dependent Behaviour of Concrete: Evaluation of the Application of EC2 Prediction Models in Algeria

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Abstract

A study of the time-dependent behaviour of concrete carried out on-site in a viaduct in Algeria provides an excellent opportunity to assess the suitability of the use of EC2 in non-European countries. This paper presents creep and shrinkage experimental values measured during five years and compares them with the values predicted by EC2 models. A procedure for experimental identification of the parameters included in EN1992-1-1 prediction models of is proposed and tested.

Keywords: concrete; creep; shrinkage; predictive models; on-site behaviour.

1 Introduction

The concrete creep and shrinkage prediction is strongly related to a great uncertainty due to great variability of many parameters, namely those connected with the in situ environment conditions, such as temperature, humidity or rainfall. This uncertainty should be reflected in the creep and shrinkage modelling to be adequately taken into account in the time dependent behaviour of concrete for the structures analysis.

For this purpose, the concrete codes have been upgrading its prediction models, as it is the case of EC2, currently being used in some other countries outside Europe leading to some doubts about its applicability.

An on-site study of concrete time-dependent behaviour in the Salah Bey Viaduct, in Constantine, Algeria, provides a unique occasion to assess the suitability of the use of EC2 in non-European countries, in very specific environmental conditions. Indeed, the environmental conditions in Constantine, with wide thermo-hygrometric amplitudes, are quite different from those in Europe.

For this study, sixteen specimens have been kept on-site, being exposed to the same environment conditions: six specimens for creep study and other six for the study of shrinkage were placed inside the box girder; four other specimens for shrinkage characterization have been kept on the deck.

In order to contribute to the assessment of the suitability of using EC2 in conditions very different from the Europeans, this paper presents creep and shrinkage experimental values measured during five years, comparing them with the values provided by EN1992-1-1 [1] creep and shrinkage predictions models. A procedure for identifying the parameters included in these models from experimental data is proposed and tested.

2 Description of the Viaduct

The Salah Bey Viaduct is a cable-stayed structure with a single deck, continuous along its total length of 756 m. It is a pre-stressed reinforced concrete structure consisting of two pylons, six piers and nine spans, with a main span 259 m long (Figure 1).

The box-girder deck, carrying four traffic lanes, is 28,3 m wide and 3,75 m high, with diaphragms spaced 7 m each other.

A central cable plane, made by 64 stays in a modified fan system, suspends the deck. The stays rods are anchored in the deck with a longitudinal spacing of 7 m, always in sections with diaphragm.

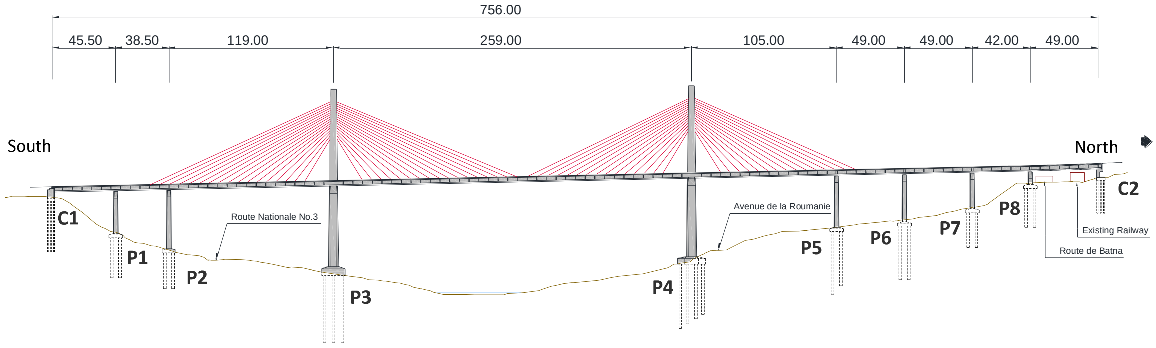

Figure 1. Elevation view of the Salah Bey Viaduct

The pylons are reinforced concrete single shaft with a total height of 127 m (P3) and 130 m (P4), with 65 m above the deck (Figure 2).

The pylons, piers and abutments are supported on piles of 2,0 m and 0,80 m in diameter.

Figure 2. General view of the Salah Bey Viaduct

3 Experimental procedures

A comprehensive structural health monitoring system was set up during construction, including a large number of sensors and covering different issues: the weather conditions, the structural behaviour (static, dynamic and seismic), the durability and the study of the time-dependent behaviour of concrete.

The on-site study of the creep and shrinkage of concrete was based on sixteen specimens made simultaneous with two staves of the deck, with the same concrete.

Each specimen, 0,70 m long, has a square cross-section of a 0,225 m side. Two opposite faces were sealed, so that moisture exchange could take place only by the other two sides. Concrete strains are measured by a vibrating-wire gauge placed inside each specimen. In addition, the temperature inside the concrete is measured by the thermistor integrated into the vibrating-wire strain gauge.

The shrinkage specimens are not loaded, being subjected only to environmental conditions. The creep specimens are subjected to a constant axial load of 3,8 MPa, imposed by hydraulic jacks, which maintain the pressure level. Creep deformations follow from the difference between the values measured in the creep specimens and the values measured in the shrinkage specimens, made simultaneously and kept in the same environmental conditions.

The specimens stay in two sections of the deck. In each section, three creep and three shrinkage specimens are inside the box girder (Figure 3) and two shrinkage specimens are over the deck.

Figure 3. Creep and shrinkage specimens inside the box girder

4 EC2 prediction models

4.1 General remarks

The part 1 of EC2 [1] provides a general prediction models for concrete creep and shrinkage. In addition, part 2 of the same document [2] provides an alternative approach to evaluate creep and shrinkage for high strength concrete.

The C50/60 concrete strength class used in the presented case study lead to the use of the prediction models of part 1.

4.2 Shrinkage

The total shrinkage strain (ε_{cs}) is composed of two components: the autogenous shrinkage strain (ε_{ca}) and the drying shrinkage strain (ε_{cd}).

According to EN1991-1-1 [1], the autogenous shrinkage strain depends only from f_{ck} (characteristic compressive cylinder strength of concrete at 28 days) and may be calculated by the following expression:

$$\varepsilon_{ca}(t) = \beta_{as}(t)\, \varepsilon_{ca}(\infty) \qquad (1)$$

where

$$\varepsilon_{ca}(\infty) = 2{,}5\, (f_{ck} - 10)\, 10^{-6} \qquad (2)$$

According to EN1991-1-1 [1] the development of the drying shrinkage strain follows from expression (3). In this expression, the computation of $\beta_{ds}(t,t_s)$ requires only h_0 (the notional size of the member in mm) and t_s; K_h requires only h_0.

$$\varepsilon_{cd}(t) = \beta_{ds}(t, t_s)\, k_h\, \varepsilon_{cd,0} \qquad (3)$$

The basic equations for determining $\varepsilon_{cd,0}$ are presented in Annex B of EN1991-1-1 [1]. Those equations involve f_{cm} (mean compressive strength of concrete in MPa at the age of 28 days), *RH* (relative humidity of the ambient environment in %) and the type of cement as input.

4.3 Creep

The EC2 defines the creep coefficient of concrete:

$$\varphi(t, t_0) = \frac{\varepsilon_{cc}(t,t_0)}{\sigma_c / E_c} \qquad (4)$$

Where $\varepsilon_{cc}(t,t_0)$ is creep deformation of concrete at time *t* for a constant compressive stress σ_c applied at the concrete age t_0 and E_c is the tangent modulus of elasticity of concrete at 28 days.

To predicting the creep coefficient the EN1992-1-1 [1] proposes the following expression:

$$\varphi(t, t_0) = \varphi_0 \cdot \beta_c(t, t_0) \qquad (5)$$

The procedures to predict the long-term creep, φ_0, as well its development with time, $\beta_c(t,t_0)$, are described in Annex B of EN1992-1-1 [1]. Those procedures include a set of equations for computing the creep coefficient using f_{cm}, *RH*, h_0, t_0 and the type of cement as input data. The effect of elevated or reduce temperature may also be taking into account.

5 Evaluation of the use of EC2 prediction models

5.1 Environmental conditions

The huge influence of the environmental conditions in the development of creep and shrinkage of concrete requires a characterization of those conditions, especially the temperature and relative humidity since they are used in the EC2 prediction models.

On the Salah Bey Viaduct, the monitoring of weather monitoring includes the measurement of wind speed and direction, atmospheric pressure, precipitation, temperature and relative humidity over the deck and the temperature and the relative humidity inside the box-girder [3].

The ambient temperatures measured during almost five years, with an hourly frequency, on the deck (T.ext) and inside the box-girder (T.int) are presented in Figure 4. The seasonal variation is quite clear, with a temperature range of 30°C outside the deck and 25°C inside the box-girder.

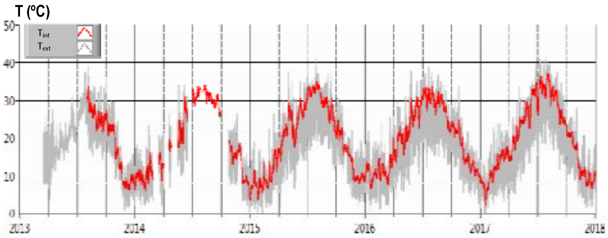

Figure 4. Air temperature outside (T_{ext}) and inside the box-girder (T_{int})

To emphasize the wide seasonal temperature variations, Figure 5 presents the monthly average of maximum and minimum values measured since august 2013.

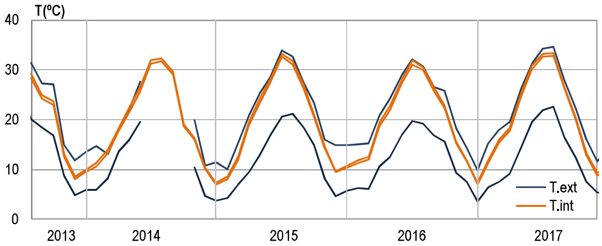

Figure 5. Air temperature outside (T_{ext}) and inside the box-girder (T_{int}): monthly average of maximum and minimum values

This figure also highlights, on one hand, the small difference between the maximum and minimum values inside the box-girder, as well as the large variation of these values in the external environment.

Despite the wider variability of the temperatures measured outdoor, the average values in both environments are not so different: 16,5°C, outside the box-girder, and 18,9°C, inside the box-girder.

Figure 6 presents the relative humidity measured on an hourly basis on the deck (RH_{ext}) and inside the box-girder (RH_{int}). The seasonal variation is quite clear, as well the wider variability of the outdoor RH.

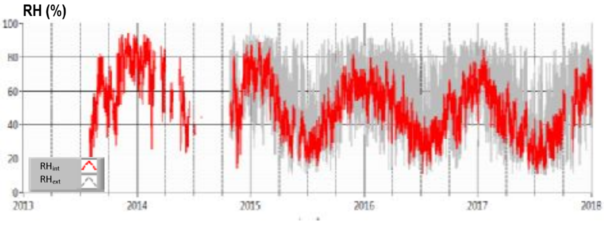

Figure 6. Relative humidity outdoor (RH_{ext}) and inside the box-girder (RH_{int})

Using the same procedure, Figure 7 shows the monthly average of maximum and minimum values of relative humidity measured outdoor and inside the box-girder.

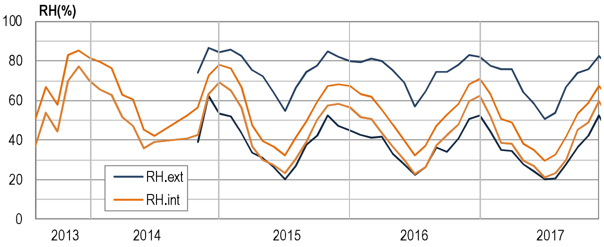

Figure 7. RH_{ext} and RH_{int}: monthly average of maximum and minimum values

Once again, the wider variability outdoor does not imply a huge difference in the RH average values: the mean value measured over this period is 59% for the outside environment, and 54% for the inside of the box-girder.

5.2 Shrinkage

The strains measured in the three specimens cast with the section S2 are presented in Figure 8. In the same way, Figure 9 shows the creep coefficients from the specimens of section S4, cast in November 2013. In both figures, the curves resulting from the application of the EC2 prediction model for RH=55% (inside environment) and RH=60% (outside environment) are also plotted.

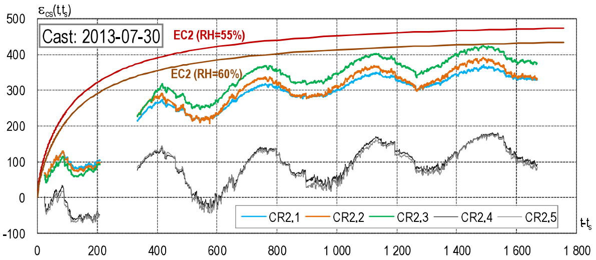

Figure 8. Shrinkage strains from section S2

It shall be noted that the thermal compensation of the strains presented in both figures was already done. Therefore, the clearly seasonal effects are not a result of the thermal dilatation.

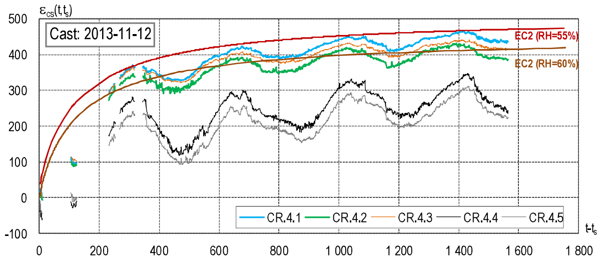

Figure 9. Shrinkage strains from section S4

Analysing these figures leads to some interesting issues: the great difference between the values measured in different environments; the higher level of the strains measure in the section S4 (both inside and outside); the reasonable performance of the prediction model of EC2 for the inside specimens and its poor accuracy for those placed on the deck (outdoor conditions).

The huge difference between the values measured in different locations of the same section is, naturally, due to the major influence of the environments conditions in the shrinkage development. Indeed, the more pronounced annual wave of the strains measured outside the box-girder shows the higher importance of the seasonal effects in those strains.

The higher level of the strains measure in the section S4 is, probably due to the different environment conditions during early ages of concrete: section S2 was cast in July and section S4 was concreted in November.

Finally, the poor performance of the shrinkage prediction model of EC2 for the specimens placed outside the deck lead to the conclusion that the difference of 5% between the average values of indoor and outdoor RH are not enough to explain the huge differences. Factors like the rainfall, the variability of RH and temperature have also a relevant influence on the shrinkage development [5] and are not taken into account in this prediction model.

5.3 Creep

The evolution of the creep coefficient obtained from the concrete strains measured daily in the three specimens cast simultaneously with the section called S2 (cast in July 2013), is presented in Figure 10. Similarly, Figure 11 shows the creep coefficients from the specimens of section S4, cast in November 2013.

Both figures include also the curve resulting from the application of the EC prediction model with a relative humidity of 55%.

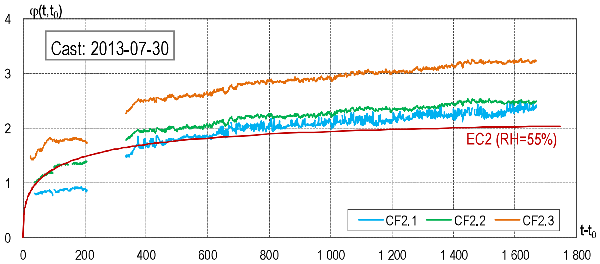

Figure 10. Creep coefficients from section S2

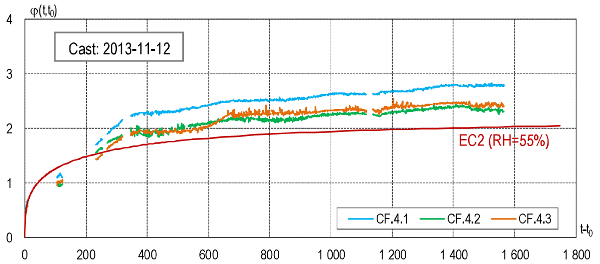

Figure 11. Creep coefficients from section S4

Both figures show that the predictive model of EN1992-1-1 [1] slightly underestimates the creep. However, except on the specimen CF2.3 coefficients, the values are within the 95% confidence interval associated to the CV of 20% indicated in this norm.

6 Experimental identification procedure

6.1 General remarks

The huge influence of many exogenous and endogenous factors to the concrete in the creep and shrinkage development motivate an important uncertainty of these phenomena, leading to the convenience of its experimental study when their contribution for the structural behaviour is relevant. This is mainly the case of large structures and in particular when their structural systems changes during construction, as in bridges built by the cantilever method.

An experimental assessment of these effects is recommended on EC2 for structures sensitive to the effects of retraction and creep. In fact, the part 2 of this document [2] includes a procedure for the treatment of the experimental values for high strength concrete but there is no procedure proposed in EN1992-1-1 [1] for high strength concrete ($f_{ck} > 50$MPa).

In these circumstances, it seems to be appropriate to propose a way to use the data obtained in the studies carried out with concrete with f_{ck} up to 50 MPa, as is the case presented in this paper.

The procedure proposed was developed according to the approach presented in annex B of EN1992-2. For the creep equation, as well as for the equations of each component of shrinkage, two parameters were introduced in order to allow the fitting of these equations to experimental values measured in both early ages and long-term. Those parameters are computed by nonlinear regression.

6.2 Shrinkage

According to EN1991-1-1 [1], the autogenous shrinkage strain may be calculated by the equation (1). For the above mentioned nonlinear regression the parameters β_{ca1} and β_{ca2} were introduced in the equations for determining the autogenous shrinkage long-term value (6) and its development over time (7):

$$\varepsilon_{ca}(\infty) = 2{,}5\,\beta_{ca1}(f_{ck} - 10)\,10^{-6} \qquad (6)$$

$$\beta_{as}(t) = 1 - exp(-0{,}2)^{(0{,}5\,\beta_{ca2})} \qquad (7)$$

For the evaluation of the drying shrinkage strains, EN 1992-1-1 uses equation (3). For regression purposes, the parameters β_{cs1} and β_{cs2} were introduced for determining the drying shrinkage long-term value (8) and its evolution over time (9):

$$\varepsilon_{cd}(t) = \beta_{ds}(t,t_s)\,k_h\,\varepsilon_{cd,0}\,\beta_{cd1} \qquad (8)$$

$$\beta_{ds}(t,t_s) = \left[\frac{(t-t_s)}{(t-t_s)+0{,}04\sqrt{h_0^3}}\right]^{\beta_{cd2}} \qquad (9)$$

Applying this approach to the experimental values of section S2, the curves presented in Figure 12 were obtained. The curves achieved from the experimental values of section S4, in a similar way, are included in Figure 13.

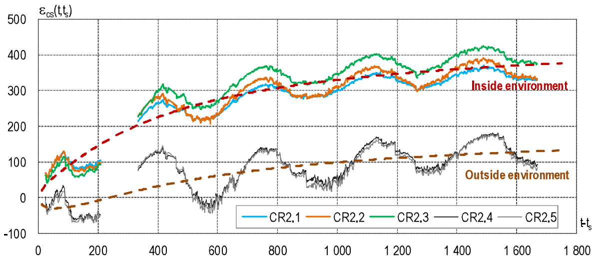

Figure 12. Nonlinear regression of the section S2 shrinkage strains

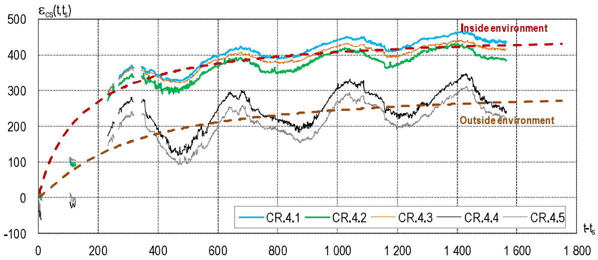

Figure 13. Nonlinear regression of the section S4 shrinkage strains

The observation of these figures shows the good nonlinear regression adjustment achieved, despite the seasonal effect evidenced by the experimental values. The improvement of fitting achieved by the nonlinear regression can be evaluated by the CEB statistical indicators, as the coefficient of variation (V_{CEB}) and the mean deviation (M_{CEB}), suggested by Muller and Hilsdorf [5].

The coefficient of variation V_{CEB} is a function of the sum of squares of differences between predicted and observed values. The better the fit between the expected and observed values, the smaller the V_{CEB} value.

The mean deviation M_{CEB} is based on the relation between predicted values and experimental values. It indicates systematic overestimation or underestimation of the model. The better the prediction of the model closer to 1 will be M_{CEB}. Values bigger than 1 indicates that the model overestimates the experimental values; values lower than 1 means the opposite.

Muller and Hilsdorf [5] indicate that both indicators are calculated in six time ranges: 0-10 days, 11-100 days, 101-365 days, 366-730 days, 731-1095 days, and above 1095 days. The final values are the RMS (root mean square) of the six interval values. Due to space limitation, only these global values of RMS are presented in Table 1. In general, this table shows a clear improvement of fitting after the nonlinear regression (NLR), with lower values of V_{CEB} and values of M_{CEB} closer to 1.

Table 1. Shrinkage strains: CEB statistical indicators

Environment	Statistical indicator	Section S2		Section S4	
		EC2[1]	NLR	EC2[1]	NLR
Indoor	V_{CEB}	90,8	39,9	223,7	85,2
	M_{CEB}	1,70	0,89	2,37	1,42
Outdoor	V_{CEB}	945,3	151,5	435,8	214,1
	M_{CEB}	-0,03	0,55	0,66	0,58

These RMS values are, in general, negatively influenced by the values from the initial life of the concrete (1 to 10 days and 11 to100 days). The long-term values (> 1950 days) are mostly better than the global RMS values shown in Table 1.

6.3 Creep

The nonlinear regression of the creep coefficient experimental values were carried out through the introduction of the parameters β_{cc1} and β_{cc2} were introduced in the equations for determining the creep coefficient long-term value (*10*) and its development over time (*11*):

$$\varphi_0 = \beta_{cc1}\, \varphi_{RH}\, \beta(f_{cm})\, \beta(t_0) \tag{10}$$

$$\beta_c(t, t_0) = \left[\frac{(t - t_0)}{(\beta_H + t - t_0)}\right]^{0,3\,\beta_{cc2}} \tag{11}$$

The curves resulting from this approach are presented in Figure 14 (section S2) and Figure 15 (section S4).

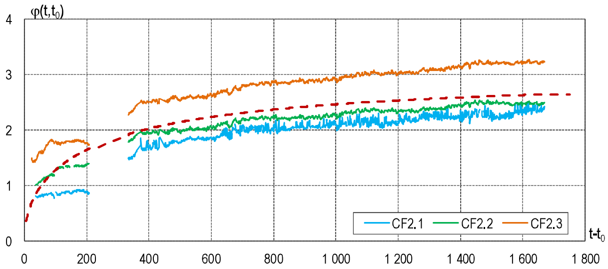

Figure 14. Nonlinear regression of the section S2 creep coefficients from section S2

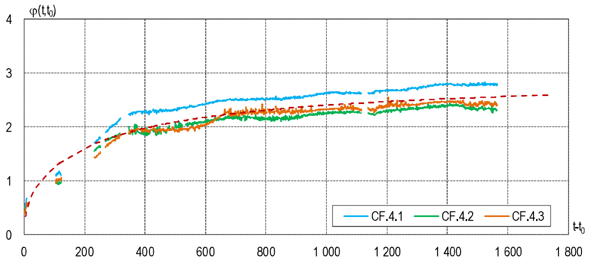

Figure 15. Nonlinear regression of the section S4 creep coefficients from section S4

The improvement of fitting of these curves with experimental values is clear, especially in the long-term. Using, once again, the CEB statistical indicators [5] for evaluating these improvements, the values of V_{CEB} and M_{CEB} presented in Table 2 are obtained. To show the very good fitting achieved for the long-term, this table includes, besides the global values (RMS), the values of the 6th period considered (t>1095). In fact, for both sections, in this time range, the values of V_{CEB} achieved with the nonlinear regression are very close to zero and the values of M_{CEB} are nearly 1.

Table 2. Creep coefficient: CEB statistical indicators

Time range	Statistical indicator	Section S2		Section S4	
		EC2[1]	NLR	EC2[1]	NLR
> 1095	V_{CEB}	23,41	0,02	0,11	0,01
	M_{CEB}	0,77	0,99	0,80	1,00
RMS	V_{CEB}	21,64	0,68	0,13	0,74
	M_{CEB}	0,83	0,90	0,86	1,01

7 Conclusions

An on-site study of the time-dependent behaviour of concrete carried out in the Salah Bey Viaduct, in Constantine, Algeria, provides a good opportunity to assess the applicability of the EC2 creep and shrinkage prediction models out of Europe, in very specific environmental conditions.

The experimental data provided by the six specimens kept inside the box-girder and the four specimens maintained over the deck have showed, once more, the high influence of the ambient conditions in the evolution of shrinkage. The comparison of these data with the values predicted by the shrinkage model of EN1991-1-1 [1] reveals a reasonable accuracy of this model for the strains obtained from the specimens kept inside the deck but a poor performance for the values measured outdoor, with a significant overestimation of the measured values.

The accuracy of this prediction model with the shrinkage strains from the specimens kept inside the deck is higher in long-term; on the contrary, the model predicts an excessive shrinkage development in the early ages.

The EN1991-1-1 [1] creep prediction applied to this case study also shows a reasonable accuracy with the experimental creep coefficients calculated from the strains measured in the six specimens kept inside the box-girder with a constant load applied.

An alternative procedure was proposed that considers the experimental values in predicting the development of retraction and creep through the EN1992-1-1 [1], consistent with the method proposed in EN1992-2 [2], allowing the use of nonlinear regression. The application of this procedure has been proven to be efficient, significantly increasing the fitting of the prediction models to the experimental values, achieving an excellent performance in the long-term. This procedure is easy to use and can be improved, especially for short histories of measurements, through Bayesian updating [4].

In general, the presented case study leads to the conclusion that the EC2 creep and shrinkage prediction models can be used outside Europe, obviously with the same precautions advised for internal use, resulting from the relevant uncertainty of these phenomena.

8 References

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