MODEL CODE 2010 CREEP AND SHRINKAGE MODELS EXTENSION TO RECYCLED AGGREGATE CONCRETE

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Abstract

Recycled aggregate concrete (RAC) produced with recycled concrete aggregate (RCA) is one of the most promising ways of eliminating concrete waste and saving natural resources. However, shrinkage and creep behaviour of RAC, important for serviceability design of reinforced and prestressed concrete structures, are still insufficiently studied and guidelines for RAC serviceability design are still not incorporated into design codes and standards. This study aims to systematize the knowledge gained on RAC shrinkage and creep behaviour thus far and to offer analytic expressions for predicting RAC shrinkage strain and creep coefficient. For this purpose, databases of previously published results on RAC shrinkage and creep were compiled and the results on RAC were analysed relative to companion natural aggregate concrete (NAC). The results showed a systematically higher shrinkage and creep of RAC relative to NAC. Finally, analytic expressions for correction coefficients, dependent on RAC compressive strength and RCA replacement ratio, were formulated for predicting RAC shrinkage strain and creep coefficient using the fib Model Code 2010.

Keywords: Recycled aggregate concrete, database, shrinkage, creep, Model Code 2010.

1. Introduction

Concrete is the most-used construction material with an annual production of over 20 billion tons (WBCSD, 2009). This causes an equally significant consumption of natural resources which are the constituents of concrete, e.g. the global annual consumption of natural aggregates is around 15 billion tons (Langer et al., 2004). At the same time, huge amounts of construction and demolition waste are being generated, 850 million tons in the EU alone (Fisher and Werge, 2011), with most of it still being landfilled.

One way of addressing both of these problems is the recycling of concrete waste. In this way, natural resources (river or crushed stone aggregates) are saved and the amount of waste being landfilled is reduced.

Recycling of concrete waste usually involves one- or two-stage crushing and sieving to produce recycled concrete aggregate (RCA). Since concrete is composed of natural aggregates bound by hardened cement mortar, after crushing concrete waste, the final product, RCA, is composed of natural aggregate particles with some "residual mortar" attached to them. This residual mortar is one of the defining characteristics of RCA and it influences most of its properties. Since cement paste is more porous, less dense and has greater water absorption than natural aggregates, so does RCA have lower density, higher porosity and greater water absorption compared with natural aggregates. Whereas the water absorption of natural aggregates rarely exceeds 1% by mass, for RCA it can be 3–10% for coarse RCA (particle size > 4 mm) (Rahal, 2007; Xiao et al., 2005) and even more for fine RCA (which is why the use of fine RCA is mostly avoided in concrete).

When RCA is used to produce new concrete, this concrete is called recycled aggregate concrete (RAC). Although currently only 1% of structural concrete worldwide is produced with RAC (Tošić et al., 2015), RCA can reach its full potential only if it is used in structural concrete and not only in non-structural applications such as road base and sub-base as was the case thus far.

The short-term mechanical properties of RAC (henceforth only referring to RAC produced with coarse RCA) are well studied and understood (Ignjatović, 2013; Silva, 2015): the compressive strength, modulus of elasticity and tensile strength of RAC are, on average, lower than those of a "companion" natural aggregate concrete, NAC, defined as having the same "effective" water-cement ratio, *w/c* (based on the amount of water available for cement hydration after compensating for RCA absorption). This difference between RAC and NAC increases with RCA content in RAC, RCA water absorption (*w.a.*) and *w/c* ratio (Ignjatović, 2013; Silva, 2015).

However, much less investigated are the long-term properties of RAC: shrinkage and creep. Because RCA is weaker compared with natural aggregates, it provides less restraint and because of residual mortar on RCA particles, the total volume of cement paste is higher in RAC compared with NAC. Hence, both shrinkage and creep of RAC are usually significantly higher than those of a companion NAC. So far, several literature reviews on studies of RAC shrinkage and creep have been published (C. Lye et al., 2016; C. Q. Lye et al., 2016; Silva, 2015); all of them found that RAC exhibits larger shrinkage and creep relative to companion NAC – for RAC with 100% of coarse RCA, the increases in shrinkage and creep are 20–50% and 20–60%, respectively.

As for predicting shrinkage and creep of RAC, only two studies dealt with the topic substantially (C. Lye et al., 2016; C. Q. Lye et al., 2016). The authors produced diagrams for an easy assessment of the necessary shrinkage and creep correction coefficients with respect to NAC, intended for use with Eurocode 2 (EN 1992-1-1, 2004). While easy to understand, the proposed correction coefficients are not given in analytic form and are not easily used with computer-based design.

Hence, there is a need for formulating analytic expressions for correction coefficients for RAC shrinkage and creep. This study proposes these correction coefficients for use with the *fib* Model Code 2010 (MC2010) (FIB, 2013). Such analyses should be based on large databases of experimental results in order to cover a wide range of influencing parameter values. For this study two such databases were compiled.

2. Database of RAC shrinkage and creep

2.1. Database of RAC shrinkage

For this study, a database of previously published experimental results on RAC shrinkage was compiled. Care was taken to apply clear and transparent criteria when selecting studies, so that all necessary information about each experiment was provided:

- results on the shrinkage strain of RAC and companion NAC with the same effective *w/c* ratio,
- 28-day compressive strength, f_{cm},
- water absorption of RCA, *w.a.*,
- curing time, t_s,
- specimen notional size, h_0, and
- temperature and relative humidity (RH).

The only assumption which was made when data was missing was regarding the type of cement used: since it was found that a significant number of studies does not report it, in such cases it was assumed as 42.5N for both RAC and NAC. A literature search identified 19 studies from which 125 shrinkage time curves were extracted (39 NAC and 86 RAC) with 424 data points sorted into logarithmic 'time decades' (1–9.9, 10–99.9, 100–999.9, 1000– days) (Amorim et al., 2012; Beltrán et al., 2014; Brand et al., 2015; Castaño et al., 2009; Corinaldesi, 2010; Corinaldesi and Moriconi, 2010; Domingo et al., 2010; Duan and Poon, 2014; Fan et al., 2014; Gómez-Soberón, 2002; Ho et al., 2013; Kou and Poon, 2015; Pedro et al., 2014; Seara-Paz, 2015; Shaikh and Nguyen, 2013; Soares et al., 2014; Sri Ravindrarajah and Tam, 1985; Tošić et al., 2018; Yang et al., 2008).

The database contains concretes with compressive strength in the range of 20–60 MPa, RCA water absorption in the range of 2–7% and drying times up to 1000 days. As a first step in the analysis, a comparison was made between the shrinkage strain of RAC and companion NAC for each result. After eliminating outlier values using a box-and-whiskers technique, the statistical descriptors of the RAC-to-

NAC shrinkage strain, $\varepsilon_{cs,RAC}/\varepsilon_{cs,NAC}$, are given in Table 1 in terms of mean value (μ) and coefficient of variation (CoV).

Table 1. Statistical descriptors of the $\varepsilon_{cs,RAC}/\varepsilon_{cs,NAC}$ ratio.

RCA (%)	Mean (μ)	CoV (%)
1–25	1.08	12.1
26–50	1.17	19.2
51–75	1.06	23.5
76–100	1.35	21.9

An increase of the $\varepsilon_{cs,RAC}/\varepsilon_{cs,NAC}$ ratio with increasing RCA content can be seen, except for the RCA range of 51–75% which actually contained a significantly smaller number of data points compared with other ranges. Graphically, this result is shown in Figure 1. The correlation coefficient between the $\varepsilon_{cs,RAC}/\varepsilon_{cs,NAC}$ ratio and RCA content in the dataset is 0.411. Other potentially influential parameters showed significantly lower correlation: 0.155 and –0.136 for compressive strength and RCA water absorption, respectively. This is an expected result as concrete shrinkage is a phenomenon dependent on many parameters for which it is very difficult to precisely isolate the influence of each one.

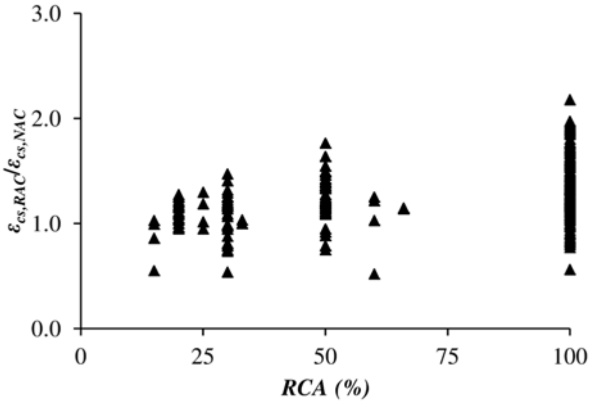

Figure 1. The $\varepsilon_{cs,RAC}/\varepsilon_{cs,NAC}$ ratio relative to RCA content in RAC.

The differences between RAC and NAC shrinkage can be separated into two types: (1) differences in magnitude (vertical scaling) and (2) differences in shrinkage development over time (horizontal scaling). Therefore, the $\varepsilon_{cs,RAC}/\varepsilon_{cs,NAC}$ ratio can point to both types of differences between RAC and NAC shrinkage. In order to check for 'horizontal' differences between RAC and companion NAC shrinkage, individual shrinkage curves must be checked for any trend in the development of the $\varepsilon_{cs,RAC}/\varepsilon_{cs,NAC}$ ratio with time within individual shrinkage curves. For the compiled RAC database, no trend was observed at the level of individual RAC shrinkage curves; thus, no evidence for the need for horizontal scaling can be found, and only vertical scaling of shrinkage magnitude should be considered.

2.2. Database of RAC creep

Similar to RAC shrinkage, a database of previously published results on RAC creep was compiled. The database was formed using similar criteria as for the shrinkage database, i.e. all necessary information had to be provided:

- results on the creep of RAC and companion NAC with the same effective *w/c* ratio,
- 28-day compressive strength, f_{cm},
- water absorption of RCA, *w.a.*,
- loading age, t_0,
- stress-to-strength at loading age ratio, $\sigma_c(t_0)/f_{cm}(t_0)$, lower than 0.4,
- specimen notional size, h_0, and
- temperature and relative humidity (RH).

As for shrinkage, the only assumption was regarding the cement type which was assumed as 42.5R for both RAC and companion NAC if it was not reported. The $\sigma_c(t_0)/f_{cm}(t_0) < 0.4$ criterion was necessary in order to ensure that all results related to linear creep (FIB, 2013). A literature search yielded 10 studies (describing 9 experimental investigations) with a total of 46 creep time curves (14 NAC and 32 RAC) and a total of 233 data points sorted into logarithmic time decades (Castaño et al., 2009; Domingo et al., 2010; Fan et al., 2014; Fathifazl et al., 2011; Fathifazl and Razaqpur, 2013; Gholampour and Ozbakkaloglu, 2018; Manzi et al., 2013; Paul and van Zijl, 2013; Seara-Paz, 2015; Sri Ravindrarajah and Tam, 1985).

The comparison of RAC and companion NAC creep was slightly more complex than shrinkage since creep results were reported in different ways in different studies: as experimental creep coefficient $\varphi_{exp}(t,t_0)$, creep strain $\varepsilon_{cc}(t,t_0)$ or specific creep $\varepsilon_{cc}(t,t_0)/\sigma_c(t_0)$ (creep strain divided by stress). In order to consistently compare the results between RAC and NAC as well as between experiments and MC2010 predictions, all results were converted to the MC2010 creep coefficient $\varphi_{MC}(t,t_0)$ defined from the creep compliance function $J(t,t_0)$:

$$\varepsilon_{ci}(t_0) + \varepsilon_{cc}(t,t_0) = \frac{\sigma_c(t_0)}{E_c(t_0)} + \frac{\varphi_{MC}(t,t_0)}{E_{ci}} \cdot \sigma_c(t_0) \tag{1}$$

where $\varepsilon_{ci}(t_0)$ represents the initial strain upon loading, $E_c(t_0)$ represents the modulus of elasticity at loading age and E_{ci} the 28-day modulus of elasticity. Then, results were converted to the MC2010 creep coefficient using (2) if the experimental creep coefficient was reported (i.e. $\varepsilon_{cc}(t,t_0)/\varepsilon_{ci}(t_0)$) and using (3) if creep strain or specific creep were reported.

$$\varphi_{MC}(t,t_0) = \varphi_{exp}(t,t_0) \cdot \frac{E_{ci}}{E_c(t_0)} \tag{2}$$

$$\varphi_{MC}(t,t_0) = E_{ci} \cdot \frac{\varepsilon_{cc}(t,t_0)}{\sigma_c(t_0)} \tag{3}$$

In the end, the database contained concretes with compressive strength in the range of 20–60 MPa, RCA water absorption in the range of 3–9% and times under loading up to 1000 days. As with shrinkage, a comparison was made between the RAC and companion NAC for each result. After eliminating outlier values using a box-and-whiskers technique, the statistical descriptors of the RAC-to-NAC MC2010 creep coefficient, $\varphi_{MC,RAC}/\varphi_{MC,NAC}$, are given in Table 2.

Table 2. Statistical descriptors of the $\varphi_{MC,RAC}/\varphi_{MC,NAC}$ ratio.

RCA (%)	Mean (μ)	CoV (%)
1–25	1.16	15.9
26–50	1.18	22.3
51–75	0.97	29.3
76–100	1.39	17.6

Again, similar to shrinkage, an increase of the $\varphi_{MC,RAC}/\varphi_{MC,NAC}$ ratio with increasing RCA content can be seen, except for the RCA range of 51–75% which contained a significantly smaller number of data points compared with other ranges and results from studies in which concretes were prepared with a special Equivalent Mortar Volume method, which was shown to lead to equal creep of RAC and companion NAC (Fathifazl et al., 2011). These results are shown in Figure 2. The correlation coefficient between the $\varphi_{MC,RAC}/\varphi_{MC,NAC}$ ratio and RCA content in the dataset is 0.411. Other potentially influential parameters showed significantly lower correlation: –0.555 and –0.318 for compressive strength and RCA water absorption, respectively. The correlations are somewhat higher compared with shrinkage, but still not enough to reveal clear and conclusive influences of these parameters.

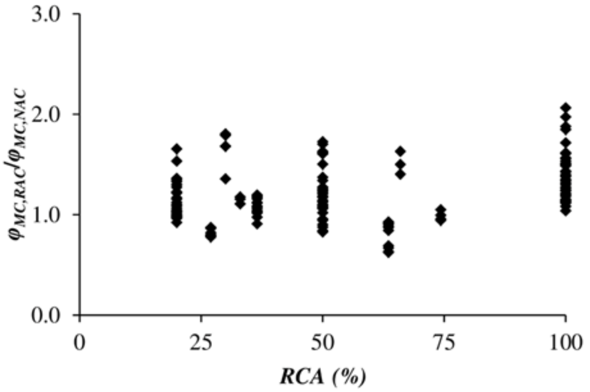

Figure 2. The $\varphi_{\mathrm{MC,RAC}}/\varphi_{\mathrm{MC,NAC}}$ ratio relative to RCA content in RAC.

Similar to shrinkage, the differences between RAC and NAC creep can be separated into two types: (1) differences in magnitude (vertical scaling) and (2) differences in creep development over time (horizontal scaling). Therefore, the $\varphi_{\mathrm{MC,RAC}}/\varphi_{\mathrm{MC,NAC}}$ ratio can point to both types of differences between RAC and NAC creep. In order to check for 'horizontal' differences between RAC and companion NAC creep, individual creep curves must be checked for any trend in the development of the $\varphi_{\mathrm{MC,RAC}}/\varphi_{\mathrm{MC,NAC}}$ ratio with time within individual creep curves. For the compiled RAC database, no trend was observed at the level of individual RAC creep curves; thus, no evidence for the need for horizontal scaling can be found, and only vertical scaling of creep magnitude should be considered.

3. RAC correction coefficients for Model Code 2010

3.1. Model Code 2010 model form verification for RAC

As stated in the introduction, the aim of this study was to formulate correction factors to be used with the MC2010 shrinkage and creep model for predicting RAC behaviour. Before this can be done, for any model, it is first necessary to consider the mathematical form of the shrinkage and creep compliance time development functions, i.e. the ability of a model to qualitatively describe the time evolution of these phenomena. For this purpose, individual shrinkage and creep compliance curves were analyzed and the model's free parameters were calibrated to minimize the CoV of the residuals. In MC2010, calibration is possible either globally at the level of shrinkage strain and creep coefficient (basic and drying) or at the level of free parameters in the model's time development functions.

Equations (4), (5), and (6) are examples of possible calibrations of the MC2010 shrinkage model using coefficients $\xi_{\mathrm{cbs},1}$, $\xi_{\mathrm{cbs},2}$, $\xi_{\mathrm{cds},1}$ and $\xi_{\mathrm{cds},2}$. Calibration coefficients $\xi_{\mathrm{cbs},1}$ and $\xi_{\mathrm{cds},1}$ are vertical scaling factors since they simply multiply the calculated ultimate basic and drying shrinkage strain values, respectively, whereas calibration coefficients $\xi_{\mathrm{cbs},2}$ and $\xi_{\mathrm{cds},2}$ are horizontal scaling factors since they alter the parameters of the basic and drying shrinkage time evolution functions, respectively.

$$\varepsilon_{cs}(t,t_s) = \xi_{cbs,1} \cdot \varepsilon_{cbs}(t_0) + \xi_{cds,1} \cdot \varepsilon_{cds}(t,t_s) \tag{4}$$

$$\beta_{bs}(t,t_s) = 1 - \exp\left(-0.2 \cdot \xi_{cbs,2} \cdot \sqrt{t}\right) \tag{5}$$

$$\beta_{ds}(t,t_s) = \left[\frac{(t-t_s)}{0.035 \cdot \xi_{cds,2} \cdot h_0^2 + (t-t_s)}\right]^{0.5} \tag{6}$$

where $\beta_{\mathrm{bs}}(t)$ is the time evolution function of basic shrinkage and $\beta_{\mathrm{ds}}(t,t_{\mathrm{s}})$ is the time evolution function of drying shrinkage. Using this procedure, shrinkage curves for NAC and RAC specimens from (Seara-Paz, 2015) are shown in Figure 3. Specimen H50-0 is NAC whereas specimens H50-50 and H50-100 are RAC with 50% and 100% of coarse RCA, respectively.

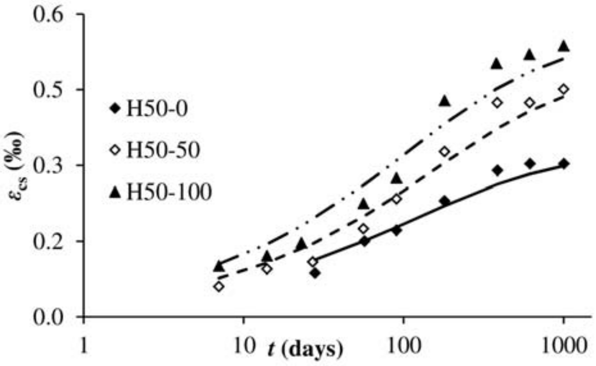

Figure 3. Calibration of individual shrinkage curves from (Seara-Paz, 2015).

Good agreement with experimental results can be seen, both for NAC and RAC, thus proving that MC2010 shrinkage prediction model is capable of qualitatively describing RAC shrinkage.

Equations (7), (8), and (9) are examples of possible calibrations of the MC2010 shrinkage model using coefficients $\xi_{bc,1}$, $\xi_{bc,2}$, $\xi_{dc,1}$ and $\xi_{dc,2}$. Calibration coefficients $\xi_{bc,1}$ and $\xi_{dc,1}$ are vertical scaling factors since they simply multiply the calculated creep coefficient value, whereas calibration coefficients $\xi_{bc,2}$ and $\xi_{dc,2}$ are horizontal scaling factors since they alter the parameters of the basic and drying creep time evolution functions, respectively.

$$\varphi_{MC}(t,t_0) = \xi_{bc1} \cdot \varphi_{bc}(t,t_0) + \xi_{dc1} \cdot \varphi_{dc}(t,t_0) \tag{7}$$

$$\beta_{bc}(t,t_0) = ln\left(\left(\frac{30}{t_0} + 0.035\right)^2 \cdot \frac{(t-t_0)}{\xi_{bc2}} + 1\right) \tag{8}$$

$$\beta_{dc}(t,t_0) = \left[\frac{(t-t_0)}{\beta_h \cdot \xi_{dc2} + (t-t_0)}\right]^{\gamma(t_0)} \tag{9}$$

where $\beta_{bc}(t,t_0)$ is the time evolution function of basic creep and $\beta_{dc}(t,t_0)$ is the time evolution function of drying creep and $\gamma(t_0)$ and β_h are functions of loading age and notional size and compressive strength, respectively. Using this procedure, creep compliance curves for NAC and RAC specimens from (Seara-Paz, 2015) are shown in Figure 4. As is the case of shrinkage, specimen H50-0 is NAC whereas specimens H50-50 and H50-100 are RAC with 50% and 100% of coarse RCA, respectively.

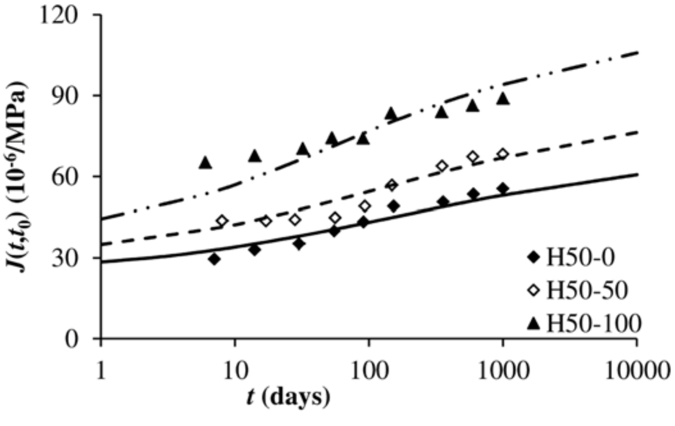

Figure 4. Calibration of individual creep compliance curves from (Seara-Paz, 2015).

For creep as well as for shrinkage, good agreement with experimental results can be seen, equal between NAC and RAC, thus proving that MC2010's creep prediction model is capable of qualitatively describing creep of RAC.

This analysis was only used to demonstrate that the mathematical form of MC2010 can adequately model the time evolution of RAC shrinkage creep. In the following section the global behaviour of

MC2010 on a database of results is performed with default parameter values of MC2010 shrinkage and creep models. In other words, none of the calibration coefficients from this section were used in the following analyses.

3.2. Correction coefficient for RAC shrinkage

The next step in the study was to evaluate the overall performance of the MC2010 shrinkage prediction model on the previously compiled database of RAC results. For this purpose, both NAC and RAC shrinkage strain was calculated for the entire data-base and a calculated-to-experimental shrinkage strain ratio, $\varepsilon_{cs,calc}/\varepsilon_{cs,exp}$, was analysed. The statistical descriptors of the ratio are shown in Table 3 with outlier values eliminated using a box-and-whiskers technique.

Table 3. Statistical descriptors of the $\varepsilon_{cs,calc}/\varepsilon_{cs,exp}$ ratio.

RCA (%)	Mean (μ)	CoV (%)
0 (NAC)	1.28	25.1
1–25	1.54	27.6
26–50	1.39	25.5
51–75	1.33	21.7
76–100	0.92	20.4

The results in Table 3 show that for this particular NAC sample, MC2010 overestimates shrinkage strain by 28%. However, for RAC the overestimation is even larger except, most importantly, for RAC with 76–100% of RCA. If only these RCA results were analysed, it could be concluded that the model's behaviour is adequate. However, it must be kept in mind that it was shown that RAC has higher shrinkage strain relative to companion NAC and this difference cannot be explained by different compressive strength (as the only input parameter related to concrete mechanical properties), since the average ratio of RAC-to-NAC compressive strength is 0.93. Therefore, it must be concluded that for high RCA contents, MC2010's shrinkage prediction model actually underestimates shrinkage and this must be corrected in the model.

For this purpose, a correction coefficient was proposed in terms of parameters which showed the highest correlation to the RAC-to-NAC shrinkage strain ratio: RCA content (*RCA%*), compressive strength (f_{cm}) and RCA water absorption (*w.a.*). The correction coefficient is proposed to be applied directly to the calculated shrinkage strain according to MC2010, i.e. as a global correction coefficient.

$$\varepsilon_{cs,RAC}(t,t_s) = \xi_{cs,RAC} \cdot \varepsilon_{cs}(t,t_s) \tag{9}$$

The proposed coefficient is a vertical scaling factor and the approach adopted in (9) amounts to taking the $\xi_{cbs,1}$ and $\xi_{cds,2}$ in (4) as equal to 1. In other words, basic and drying shrinkage components will be equally vertically scaled. The coefficient was calibrated using the following form:

$$\xi_{cs,RAC} = x_1 \cdot (f_{cm})^{x_2} \cdot (RCA\%)^{x_3} \cdot (w.a.)^{x_4} \tag{10}$$

The calibration was carried out first by determining which values of the correction coefficient would lead to equal performance of MC2010 on RAC and companion NAC (mean calculated-to-experimental value ratio of 1.28), for each experimental shrinkage curve. Then, expression (10) was calibrated to fit these values as closely as possible. The calibration revealed a very low sensitivity to RCA water absorption, at least for the range of values in the database. Hence, this parameter was excluded ($x_4 = 0$) and the correction coefficient $\xi_{cs,RAC}$ was determined as

$$\xi_{cs,RAC} = \left(\frac{RCA\%}{f_{cm}}\right)^{0.3} \geq 1.0 \tag{11}$$

In (11), *RCA%* is inserted in percentages and f_{cm} in MPa. A limit of $\xi_{cs,RAC} \geq 1.0$ was set to ensure RAC shrinkage was always predicted as greater than that of companion NAC. Graphically, the correction coefficient is represented in Figure 5 for various compressive strengths and RCA contents.

In the usual range of RAC compressive strengths, i.e. 30–40 MPa, for RAC with 100% of RCA, the correction coefficient is 1.32–1.44 which is consistent with results in Table 1.

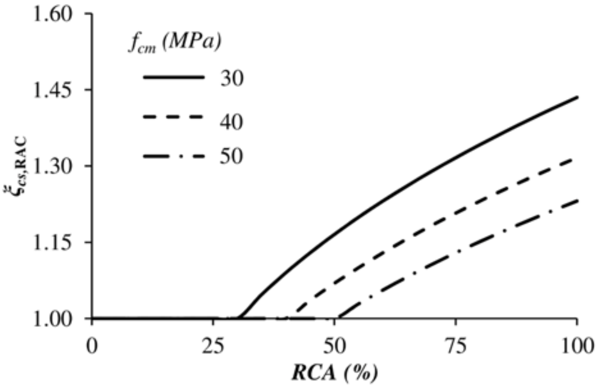

Figure 5. Correction coefficient $\xi_{cs,RAC}$ for RAC shrinkage strain.

3.3. Correction coefficient for RAC creep

The final part of the study was to evaluate the overall performance of the MC2010 creep prediction model on the previously compiled database of RAC results. Both NAC and RAC MC2010 creep coefficients were calculated for the entire database and a calculated-to-experimental creep coefficient ratio, $\varphi_{MC,calc}/\varphi_{MC,exp}$, was analysed. The statistical descriptors of the ratio are shown in Table 4 with outlier values eliminated using a box-and-whiskers technique.

Table 4. Statistical descriptors of the $\varphi_{MC,calc}/\varphi_{MC,exp}$ ratio.

RCA (%)	Mean (μ)	CoV (%)
0 (NAC)	1.17	38.0
1–25	1.06	25.1
26–50	0.95	40.8
51–75	0.73	20.5
76–100	0.97	35.7

The results in Table 4 show that for this particular NAC sample, MC2010 overestimates the creep coefficient by 17%. However, for RAC the results point to and underestimation. Therefore, it is clear that for RAC, MC2010's creep prediction model underestimates the creep coefficient and this must be corrected in the model. As for shrinkage, a correction coefficient was proposed in terms of parameters which showed the highest correlation to the RAC-to-NAC shrinkage strain ratio: RCA content (*RCA%*), compressive strength (f_{cm}) and RCA water absorption (*w.a.*). The correction coefficient is proposed to be applied directly to the calculated creep coefficient according to MC2010, i.e. as a global correction coefficient.

$$\varphi_{MC,RAC}(t,t_0) = \xi_{cc,RAC} \cdot \varphi_{MC}(t,t_0) \tag{12}$$

The proposed coefficient is a vertical scaling coefficient and the approach adopted in (12) amounts to taking the $\xi_{bc,1}$ and $\xi_{dc,2}$ in (7) as equal to 1. In other words, basic and drying creep components will be equally vertically scaled. The coefficient was calibrated using the following form:

$$\xi_{cc,RAC} = y_1 \cdot (f_{cm})^{y_2} \cdot (RCA\%)^{y_3} \cdot (w.a.)^{y_4} \tag{13}$$

The calibration was carried out in the same way as described for shrinkage in the previous section. The calibration revealed a very low sensitivity to RCA water absorption for the range of values in the database. Hence, this parameter was excluded (y_4 = 0) and the correction coefficient $\xi_{cc,RAC}$ was determined:

$$\xi_{cc,RAC} = 1.12 \cdot \left(\frac{RCA\%}{f_{cm}}\right)^{0.15} \geq 1.0 \qquad (14)$$

In (14), *RCA%* is inserted in percentages and f_{cm} in MPa. A limit of $\xi_{\text{cc,RAC}} \geq 1.0$ was set to ensure the RAC creep coefficient was always predicted as larger than that of companion NAC. Graphically, the correction coefficient is represented in Figure 6 for various compressive strengths and RCA contents. In the usual range of RAC compressive strengths, i.e. 30–40 MPa, for RAC with 100% of RCA, the correction coefficient is 1.21–1.43 which is consistent with results in Table 2.

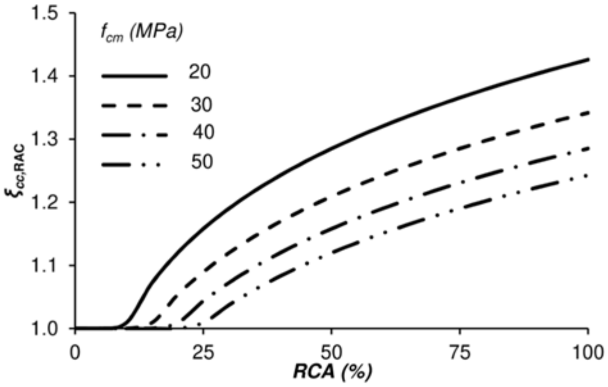

Figure 6. Correction coefficient $\xi_{\text{cc,RAC}}$ for RAC creep coefficient.

4. Conclusions

This paper described the process of formulating analytic correction factors for shrinkage and creep of RAC to be used with the fib Model Code 2010. Using a comparison of experimental results on RAC and companion NAC shrinkage and creep on com-piled databases and analysis carried out in the study, the following conclusions can be drawn:

- on average, RAC has a higher shrinkage strain and creep coefficient than a companion NAC produced with the same effective w/c ratio; the difference between them increases with increasing RCA content and decreasing compressive strength;
- based on analysis of individual RAC shrinkage and creep time curves, it can be said that the *fib* Model Code 2010 shrinkage and creep prediction models are able to adequately describe the evolution of these long-term properties of RAC;
- predictions of RAC shrinkage strain and creep coefficient, based on default parameter values of the model, underestimate these properties of RAC relative to companion NAC;
- correction coefficients $\xi_{\text{cs,RAC}}$ and $\xi_{\text{cc,RAC}}$ for RAC shrinkage strain and creep coefficient, respectively, were proposed as bivariate power functions of RCA content and compressive strength; the coefficients are intended for multiplying the shrinkage strain and creep coefficient calculated according to the *fib* Model Code 2010 shrinkage and creep prediction models. The use of $\xi_{\text{cs,RAC}}$ and $\xi_{\text{cc,RAC}}$ is practical since the required variables are available in the design stage.

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