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1 **Modelling compressive basic creep of concrete at early age**

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16 **ABSTRACT**

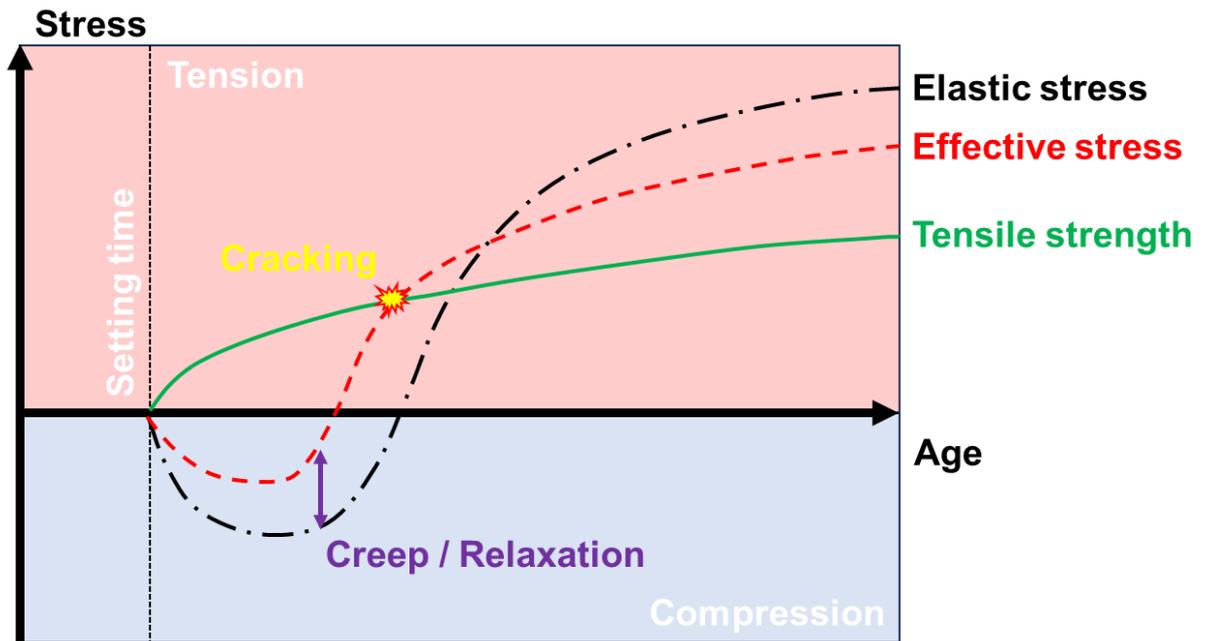
17 Basic creep plays an important role for assessing the risk of early age cracking in massive structures. In recent
18 decades, several models have been developed to characterize how the hydration process impacts the develop-
19 ment of basic creep. This study investigates the basic creep of various concrete mixes across different ages at
20 loading. The focus of analysis includes the very early stages (less than 24 hours) and early stages (less than 28
21 days) of concrete development. It is shown that a logarithmic expression which contains two parameters de-
22 scribing the material can accurately model basic creep from a very early age. One parameter relates to the
23 amplitude of creep and depends solely on the composition of the concrete. The other relates to the kinetics of
24 creep and depends on the age of the material at loading and the nature of the concrete mixture. The logarith-
25 mic expression corresponds to a rheological model consisting of a single dashpot wherein viscosity exhibits a
26 linear evolution over time. The model offers the advantage of eliminating the need to store the entire stress
27 history for computing the stress resulting from the restriction of the free deformation. This approach signifi-
28 cantly reduces computation time. Additionally, a power-law correlation is observed between the material age-
29 ing parameter and the degree of hydration. This relationship depends on the composition. At least two com-
30 pressive creep tests performed at two different degrees of hydration are needed to calibrate the material pa-
31 rameters and consider the effect of ageing on basic creep compliance.

32 **Keywords:**

33 Concrete, creep, early age, rheological models

34 1. Introduction

35 To accurately assess the risk of early age cracking in concrete, it is of the utmost importance to accu-
36 rately model temperature changes, the progress of the hydration reaction (via the degree of hydration, for in-
37 stance) and the development of mechanical properties such as Young's modulus, Poisson's ratio, shrinkage
38 and creep (Benboudjema and Torrenti 2008), (Benboudjema, Carette et al. 2019), (Wyrzykowski, Scrivener et
39 al. 2019), (Fairbairn and Azenha 2019), (Azenha, Kanavaris et al. 2021). At an early age, the development of
40 free deformation is subject to partial or complete restraint, resulting in the emergence of internal stresses. This
41 restraint can manifest internally or externally. In the context of massive structures, internal restraint arises due
42 to temperature gradients between the surface and the core of the concrete element. Specifically, post-setting
43 temperature increases restrain thermal swelling in the core while inducing additional swelling at the surface.
44 This leads to tensile stresses at the surface and compressive stresses in the core, defined by considering the
45 viscoelastic behaviour of concrete through the elastic modulus and creep compliance. Creep strains play a
46 crucial role in mitigating the development of these stresses. Conversely, when a concrete element experiences
47 external restraint (e.g., connection between a new slab and existing beams), the heating phase generates com-
48 pressive stresses followed by tensile stresses during the subsequent cooling period. In this scenario, creep
49 strains continue to mitigate the stresses, but the occurrence of tensile stresses is expedited, happening earlier
50 when the tensile strength is lower. This acceleration in tensile stress may potentially heighten the risk of
51 cracking (refer to Figure 1) (Delsaute and Staquet 2020). It appears that creep can have a dual role, both posi-
52 tive and negative, in predicting the risk of cracking at an early age. Therefore, it becomes imperative to incor-
53 porate creep considerations into the modelling process to provide a comprehensive understanding of the con-
54 crete's behavior during this critical phase.



56

57 Figure 1 – Changes in stresses at early age in the case of restrained boundary conditions (Delsaute and Staquet
58 2020).

59 Because, in general, massive structures undergo major temporal and spatial variations in temperature at
60 early age, drying creep is neglected in concrete as moisture diffusion is slow and the modelling is essentially
61 concerned with basic creep (Cervera, Oliver et al. 1999), (Lackner and Mang 2004), (Gawin, Pesavento et al.
62 2006), (Benboudjema and Torrenti 2008), (Hilaire, Benboudjema et al. 2014), (Klemczak and Knoppik-
63 Wróbel 2015), (Benboudjema, Carette et al. 2019), (Lacarrière, Sellier et al. 2020), (Binder, Königsberger et
64 al. 2023) and (Ghasabeh and Göktepe 2023). In this paper, only compressive basic creep is considered. How-
65 ever, in a structure, as shown in Figure 1, compressive and tensile stresses should be considered when assess-
66 ing the risks of cracking. Consequently, this work assumes that tensile creep strains are the opposite of com-
67 pressive creep strains for a given level of stress. However, such a hypothesis is still debated (Briffaut,
68 Benboudjema et al. 2012), (Rossi, Tailhan et al. 2013), (Ranaivomanana, Multon et al. 2013), (Klausen,
69 Kanstad et al. 2017), (Khan, Castel et al. 2017), (Dabarera, Li et al. 2021).

70 Numerous researchers have experimentally investigated basic creep at early ages (Gutsch 2000),
71 (Atrushi 2003), (De Schutter 1999), (Østergaard, Lange et al. 2001), (Briffaut, Benboudjema et al. 2012),
72 (Wyrzykowski, Scrivener et al. 2019). In each instance, the analysis of basic creep compliance aging involves
73 subjecting various samples to sustained loads lasting weeks or months at different ages. These investigations

74 have led to the development of different models addressing the aging of creep compliance. These models vary
75 in their mathematical expressions, such as hyperbolic, logarithmic, or power, and the variables employed, such
76 as time, equivalent time, and degree of hydration. Based on the findings, several theories have emerged in the
77 literature, aiming to elucidate the physical origins of basic creep (Hilaire, Benboudjema et al. 2014), (Jiang,
78 Yang et al. 2014), (Delsaute, Torrenti et al. 2017), (Wyrzykowski, Scrivener et al. 2019), (Dabarera, Li et al.
79 2021), (Su, Jia et al. 2023), (Binder, Königsberger et al. 2023). As explained in (Delsaute, Torrenti et al.
80 2017), the mechanisms presented in the literature can be divided into two categories : direct and indirect
81 mechanisms. Direct mechanisms are related to the cement paste (water mobility, solidification, sliding of the
82 C-S-H...) and can be divided in short- and long-term phenomena. Indirect mechanisms are related to micro-
83 cracks formation in the cement paste or at the interface transition zone between the cement paste and the ag-
84 gregate. Bažant et al. (Bazant, Hauggaard et al. 1997) explained it with the microprestress theory. In this the-
85 ory, it is postulated that the origin of the creep is the shear slip at overstressed creep sites. As a result of a pro-
86 gressive relaxation of microprestress at the creep sites and consecutive increase of their apparent viscosity, the
87 creep rate observed under constant applied stress declines over time. Bazant has modelled this behaviour by a
88 non-asymptotic relation where a term is logarithmic.

89 Ulm et al. (Ulm, Le Maou et al. 1999), using Le Roy's tests (Leroy, Le Maou et al. 2017) have shown
90 that the rate of basic creep compliance J_{bc}^* - i.e. the basic compliance J_{bc} without the elastic part - has a linear
91 evolution with time on a logarithmic scale. In this case, the basic creep compliance $J_{bc}^*(t, t_0)$ could be ex-
92 pressed, whatever the age at loading t_0 , using a logarithmic function of time after loading, $t - t_0$ (Eq. 1):

$$93 \quad J_{bc}^*(t, t_0) = \frac{1}{c} \cdot \ln \left(1 + \frac{t-t_0}{\tau(t_0)} \right) \quad (1)$$

94 This equation corresponds to the response of a dashpot with a viscosity that evolves linearly with time
95 (this is highlighted later in Equation 3 and 4). There are now several experimental pieces of evidence that the
96 basic creep compliance $J_{bc}^*(t, t_0)$ could be expressed with this equation. This behaviour has been observed at a
97 macroscopic scale (see (Hanson 1953), (Larson and Jonasson 2003), (Muller, Anders et al. 2013), (Leroy, Le
98 Maou et al. 2017) or (Torrenti 2018) and at a lower scale using micro-indentation (see (Vandamme and Ulm
99 2013), (Zhang, Le Roy et al. 2014), (Frech-Baronet, Sorelli et al. 2017), (Suwanmaneechot, Aili et al. 2020) or
100 (Liu, Wei et al. 2022)). It was introduced in the *fib* Model Code 2010 (Walraven and Bigaj-van Vliet 2013) and
101 is now adopted for the next-generation Eurocode 2 (CEN 2023). Delsaute et al. have also demonstrated that

102 this equation may be used successfully at early age for both conventional concrete (Delsaute, Torrenti et al.
103 2017) and concrete containing recycled concrete aggregates (Delsaute and Staquet 2019).

104 However, in the initial stages of loading, additional phenomena may influence creep development, de-
105 viating from a logarithmic trend as reported in previous studies (Irfan-ul-Hassan, Königsberger et al. 2017),
106 (Irfan-ul-Hassan, Pichler et al. 2016); (Delsaute, Torrenti et al. 2017). As demonstrated in (Delsaute, Torrenti
107 et al. 2017), the basic creep compliance can be delineated into three components: (1) an initial short-term term
108 characterized by a logarithmic expression, (2) a solidification term modelled using Kelvin-Voigt chains, and
109 (3) a long-term described by a power expression. However, the model's complexity requires the knowledge of
110 additional properties such as the evolution of the elastic modulus since setting and making it challenging for
111 implementation in finite element analysis. Additionally, as discussed in (Mohammad, Rahimi-Aghdam et al.
112 2018), creep strain begins developing from the onset of load application and should be considered from that
113 moment. However, for practical reasons, creep strains are typically set to zero upon reaching the target load.
114 Consequently, the initial development of creep compliance or creep coefficient lacks well-defined experimen-
115 tal characterization. To address this issue, Bazant's team (Mohammad, Rahimi-Aghdam et al. 2018) proposed
116 a methodology that involves fitting the initial data to a power law, where the exponent is a function of the
117 loading duration and varies mainly between 0.10 and 0.35. Irfan et al. (Irfan-ul-Hassan, Königsberger et al.
118 2017), and subsequently Ali et al. (Naqi, Delsaute et al. 2023), demonstrated that it is feasible to model short-
119 duration loading (5 minutes) by incorporating creep strains occurring during loading using a power law. The
120 exponent for this model varies between 0.2 and 0.3 for cement paste and between 0.1 and 0.3 for slag mortar
121 which is in agreement with the results obtained by (Mohammad, Rahimi-Aghdam et al. 2018). As the duration
122 of tests extends, the logarithmic evolution aligns closely with the experimental results, as observed in
123 (Mallick, Anoop et al. 2019). Therefore, this study focuses on excluding the very early period, which may
124 account for some of the disparities between the test results and the model predictions during this early age.

125 In Eq. 1, C [MPa] is a constant that depends on the concrete composition and τ [days or hours] is a pa-
126 rameter that depends on the age at loading t_0 [days or hours]. In case of incorporation of mineral additions, an
127 additional term is needed to consider the influence of the mineral additions (Delsaute and Staquet 2020).

128 As, in Eq. 1, basic creep is described by a stress-linear rheological model consisting of one single dash-
129 pot, no creep recovery can be predicted. The authors' choice is to consider the easiest possible model that cor-

130 responds to the behaviour of the material under loading and that can be easily implemented in calculation
131 codes. For stress histories involving partial or full unloading, a more advanced model is required. This model
132 must be able to separate reversible and irreversible creep to correctly consider the phenomenon of recovery. In
133 addition, if the stress level varies, the model must also be adapted to consider the consolidation stage reached
134 during the previous loading which can affect the behaviour of concrete (Sellier, Multon et al. 2016).

135 In the first part of this paper, the results of a novel creep campaign that was conducted on four different
136 concretes with a moderate loading time (in the range of 5 to 10 days) are presented and modelled using the
137 logarithmic function (Eq. 1). The accuracy of the function is then analysed for previously published creep tests
138 with shorter loading times. In the second part of the paper, rheological modelling, which is frequently used
139 because it is straightforward to implement in FE models, is compared to the experimental results to evaluate
140 their robustness. Indeed, rheological models are very useful tools that allow to fit the results of experimental
141 creep tests (Bažant and Prasannan 1989), (De Schutter 1999), (Briffaut, Benboudjema et al. 2012). These
142 models could be embedded in finite element modelling where, at each time step, the differential equation of
143 the model is solved without storing all the history of the deformations at each Gauss point, see for example
144 (Torrenti, Nedjar et al. 2023).

145 **2. Experimental basic creep at early age**

146 The constitutive relations at early age that are used to consider the principal ways in which temperature
147 affects the kinetics of reactions are usually based on changes in the degree of hydration of the cementitious
148 materials. Consequently, only creep tests where the degree of hydration (ξ) or the degree of heat development
149 (*DoHd*) (De Schutter and Taerwe 1996) is known are considered in the present study. The degree of hydration
150 corresponds to the fraction of the cement that has reacted, while the *DoHd* corresponds to the ratio between
151 the heat release at time t , $Q(t)$, that results from cement hydration and the maximum heat release from cement
152 hydration Q_{max} for a given water-to-cement ratio as indicated in Eq. 2. Both parameters can be linked if the
153 heat release at complete hydration Q_{tot} is known as shown in Eq. 2.

$$DoHd(t) = \frac{Q(t)}{Q_{max}} = \xi(t) \cdot \frac{Q_{tot}}{Q_{max}} \quad (2)$$

154 Furthermore, this study exclusively focuses on compressive creep tests. Numerous investigations have
155 highlighted that creep behavior differs between compression and tension (Rossi, Charron et al. 2014). Specifi-

156 cally, it has been observed that creep is generally more pronounced in compression during the early age, while
 157 the reverse is true for later loading ages (Benboudjema, Briffaut et al. 2012). Rossi et al (Rossi, Charron et al.
 158 2014) attribute these differences to two mechanisms: (1) the coupling between microcracking induced by
 159 specimen loading and additional water transfer, leading to additional self-drying shrinkage, and (2) the self-
 160 healing process also induced by microcracking. Those mechanisms result in additional shrinkage which will
 161 increase compressive creep strain and reduces tensile creep strain. While there are studies considering the
 162 aging of tensile creep function, knowledge in this area, especially at early ages, is scarce. Additionally, these
 163 studies lack information on the degree of hydration at the time of loading and during setting, to the best of the
 164 authors' knowledge.

165 Moreover, only linear creep is considered. The possibility of coupling with damage (Bazant 1995),
 166 (Cervera, Oliver et al. 1999), (Mazzotti and Savoia 2003), (Benboudjema, Meftah et al. 2005), (Rossi, Tailhan
 167 et al. 2012), (Saliba, Loukili et al. 2012) that could also exist at early age (Briffaut, Benboudjema et al. 2011),
 168 (Switek-Rey, Denarié et al. 2016), (Han, Xie et al. 2017), (Torrenti 2018) is not considered here, meaning that
 169 only linear creep tests have been selected. After a brief presentation of these tests, the results are compared to
 170 a prediction using Eq. 1. Table 1 presents all the concrete mixes that are tested with some properties.

171 Table 1 - Mixture proportions (kg/m³) and properties of the tested concretes

	Bourchy				Delsaute		Briffaut
	R1	G27	C3	G7	Vercors	OC	
Cement type	CEM I	CEM II/A-LL	CEM I	CEM II/A-LL	CEM I	CEM I 52.5 N	CEM II/A-LL
Cement quantity (kg/m ³)	410.0	316.8	360.0	90.0	320.0	340	350
SCM type	-	SF	-	BFS	-	-	
SCM quantity (kg/m ³)	-	43,2	-	270.0	-	-	
Sand (kg/m ³)	863.8	866.7	865.4	859.1	830	739	772
Gravel (kg/m ³)	958.7	1,059.4	1,057.7	1,050.0	995	1072	1100
Plasticizer (kg/m ³)	-	3.60	2.16	1.86	2.4	-	1,225
Water (kg/m ³)	188.6	150.3	160.2	160.4	170.9	184	201
E at 28 days (GPa)	39.0	44.0	41.8	41.6	35	40	33
f_c at 28 days (MPa)	44.1	76.8	55.4	42.4	41	40	38
Semi-adiabatic temperature rise (°C)	35.8	18.9	18.7	7.7	-	-	-
ξ at setting (/)	0.129	0.034	0.021	0.026	0.061	0.046	0.115

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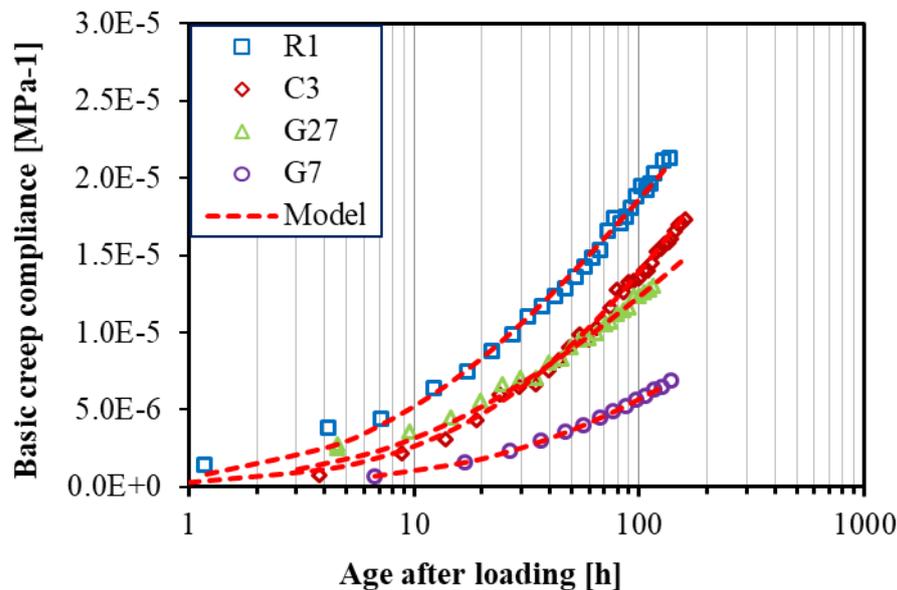
173 2.1. Bourchy's tests (Bourchy 2018)

174 During her PhD, Bourchy conducted a comprehensive examination of the early-age behavior of various
175 concrete formulations (Bourchy 2018). This paper focuses on four distinct concrete mix designs, which are
176 detailed in Table 1, denoted as concretes R1, G27, C3, and G7. These selections were made deliberately due to
177 their diverse compositions and properties. R1 represents a conventional concrete previously used in Martin's
178 study on Delayed Ettringite Formation (DEF) and composed of CEM I cement (Martin 2010). Notably, this
179 formulation was designed to possess a high heat of hydration. The composition C3 also uses CEM I cement
180 and it differs from the R1 formulation by exhibiting a lower heat of hydration. Both G27 and G7 compositions
181 use the same CEM I cement as C3 but incorporate additional cementitious materials into their composition.
182 Specifically, G27 incorporates a blended cement (consisting of 20% limestone) and maintains a silica fume-to-
183 cement ratio of 12%. In contrast, G7 is produced using CEM I cement but incorporates a substantial 60% blast
184 furnace slag content within the binder. These diverse concrete formulations were chosen to explore a wide
185 spectrum of early-age behaviors, enabling a comprehensive analysis of their properties and performance in
186 various conditions.

187

188 To evaluate these concrete formulations, the tests were performed in two steps. First, the evolution of
189 the Young's modulus is measured since setting using a specially designed device named BTJASPE. A cylin-
190 drical specimen with a diameter of 100 mm and a height of 200 mm was manufactured. The device safeguards
191 the concrete samples from desiccation by employing a protective mould since casting till the end of the test
192 (Boulay, Staquet et al. 2013). A thermal regulation is incorporated in the mould and is set at 20 °C. Displace-
193 ments were measured by using 3 LVDT sensors. The tests were carried out in a climate-controlled room at a
194 temperature of 20 °C. Repeated loadings were applied by the testing device, involving the imposition of a
195 consistent displacement during each loading, followed by a full unloading. Secondly, this apparatus enables to
196 conduct creep tests, exerting a sustained load equivalent to 20% of the compressive strength on each concrete,
197 for a minimum of four days. This testing procedure has been initiated between 8 and 14 days after casting, as
198 described by Delsaute et al. (Delsaute, Boulay et al. 2016). For the purposes of this study, only compressive
199 creep results are presented. The autogenous strain has been monitored in parallel with the BTJADE device
200 (Delsaute and Staquet 2017) to define the creep strain.

201 Figure 2 shows the comparison between the experimental results and Eq. 1 (Model). Good agreement
 202 was obtained for all the concretes. The fitted parameters of Eq. 1 are presented in Table 2. The degree of hy-
 203 dration was estimated using a semi-adiabatic test (Briffaut, Benboudjema et al. 2012) and a maturity evolution
 204 based on the Arrhenius law.



205
 206
 207 Figure 2 - Comparison between the Bourchy's experimental results and Eq. 1. The fitted parameters are set out
 208 in Table 2.

209
 210 Table 2 - Parameters of Equation 1 for Bourchy's concretes

R1		G27		C3		G7	
t_0 (hours) = 312		t_0 (hours) = 194		t_0 (hours) = 252		t_0 (hours) = 343	
$\xi(t_0) = 0.74$		$\xi(t_0) = 0.66$		$\xi(t_0) = 0.73$		$\xi(t_0) = 0.40$	
C (GPa)	$\tau(t_0)$ (d)						
120	0.50	170	0.58	100	1.38	220	1.67

211
 212
 213 2.2. Delsaute's tests: VeRCORs concrete (Delsaute, Torrenti et al. 2016)

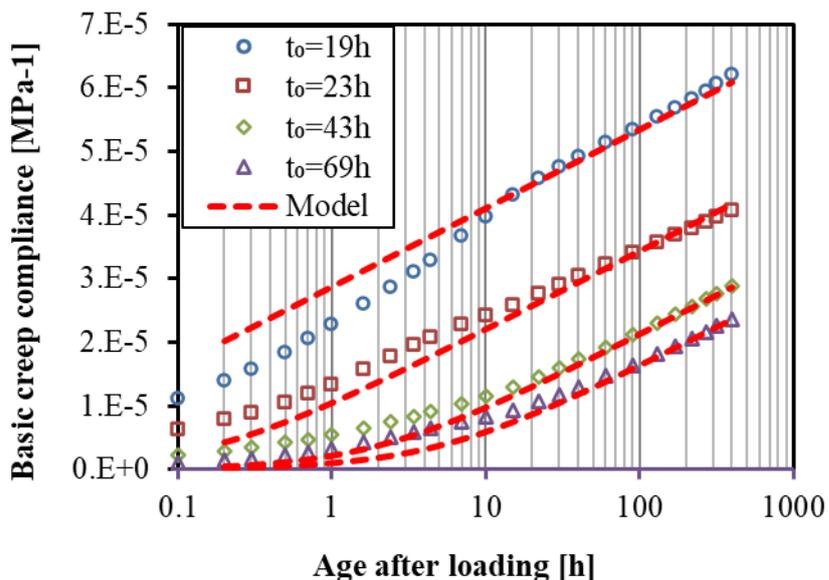
214 In the framework of nuclear safety and efforts to extend the service life of existing nuclear power plants
 215 in France, EDF (Electricité De France) has built a 1/3 scale experimental mock-up of a reactor containment
 216 building. The project is called VeRCORs and includes the study of the early age behaviour of cement-based
 217 materials (Charpin, Niepceron et al. 2021).

218 For the creep test, a cylindrical specimen with a diameter of 97 mm and a height of 350 mm was manu-
 219 factured as well as a dummy specimen with the same dimensions for each test. After casting, all the specimens

220 were placed in a climate-controlled chamber at 20 °C and a relative humidity of 90%. The specimens were
 221 then demoulded, ground on both circular end faces and enclosed in two self-adhesive aluminium sheets to seal
 222 them. Compressive creep tests were performed on a frame designed at Université libre de Bruxelles (Delsaute,
 223 Boulay et al. 2016). A force cell was placed on the top of the sample. Displacements were measured with an
 224 extensometer consisting of two aluminium rings spaced 200 mm apart and three INVAR® rods onto which
 225 the three displacement sensors were fixed, 120° apart. The tests were carried out in a climate-controlled room
 226 at a temperature of 20 °C and relative humidity of 50%.

227 Compressive creep tests were carried out for different ages at loading: 19 h, 23 h, 43 h and 69 h. The
 228 load was kept constant for 17 days and the stress/strength ratio at the age at loading was 40%. For each age,
 229 tests were carried out on two specimens to ensure repeatability. The change in the specific creep is shown in
 230 Figure 3 for each age at loading and compared with a fitting of the parameters from Eq. 1 assuming that the
 231 parameter C is independent of the loading age. Table 3 gives the values of the fitted parameters. The parame-
 232 ters were fitted using a least square minimization of the difference between the experimental results. The de-
 233 gree of hydration was estimated by isothermal calorimetry at 20 °C. Figure 3 shows good agreement in the
 234 long term while, at very early age, a difference is apparent in the very short term.

235



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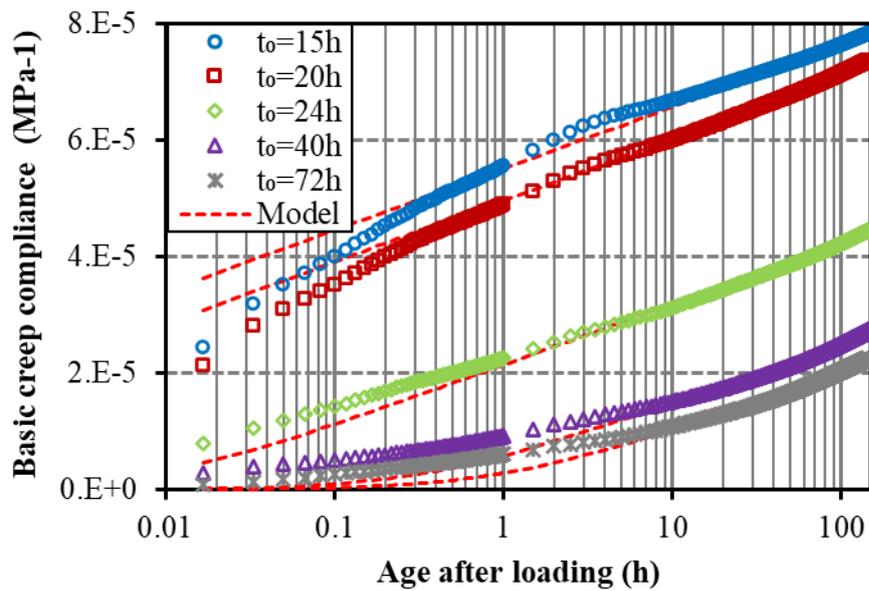
237 Figure 3 - Comparison between the Vercors's experimental results and Eq. 1. The fitted parameters are set out
 238 in Table 3

239

240 2.3. Delsaute tests: ordinary concrete (Delsaute, Boulay et al. 2016)

241 Delsaute, et al. also studied the basic creep at early age for an Ordinary Concrete (with a compressive
242 strength of 49 MPa at 28 days, as measured on a cube with 100 mm side). The same methodology that has
243 been presented in the previous section is used. Table 3 sets out the fitted creep parameters for this concrete
244 based on Eq. 1, and Figure 4 shows a comparison between the experimental results and modelling with this
245 equation. This shows good agreement, with a slight difference before 1 hour of loading.

246



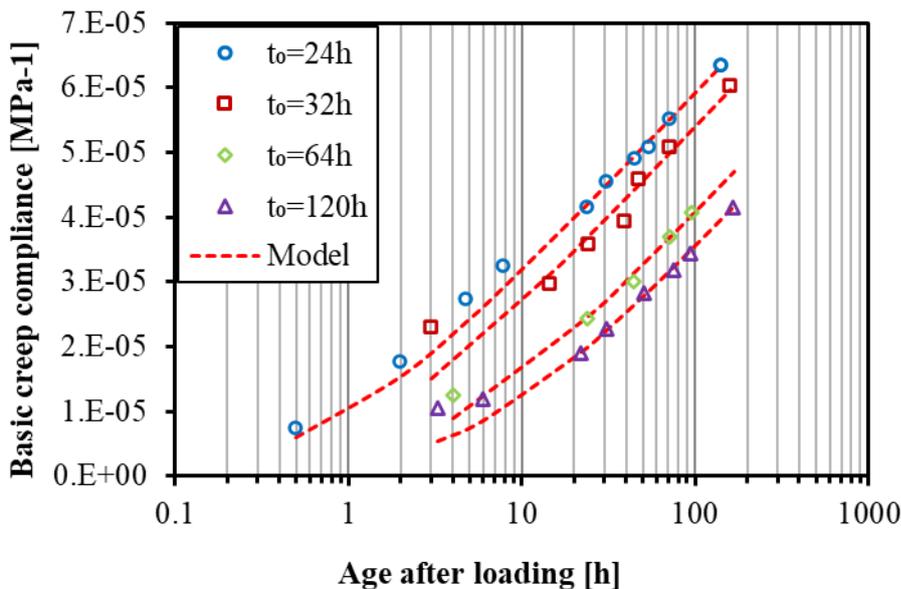
247

248 Figure 4 - Comparison between Delsaute's experimental results and Eq. 1. The fitted parameters are set out in
249 Table 3

250 2.4. Briffaut's tests (Briffaut, Benboudjema et al. 2012)

251 In the creep tests performed by Briffaut et al. (Briffaut, Benboudjema et al. 2012), the ages of loading
252 were between 24 h and 120 h. The loading level was less than 30% of the compressive strength at the age of
253 loading. The prismatic specimens measured 70x70x280 mm³ and were placed in a temperature-controlled
254 room at 20 °C and protected from drying with a double-thickness self-adhesive aluminium sheath (a control
255 specimen was used to check that the sealing was sufficient for the duration of the tests) and loaded with a hy-
256 draulic loading frame. The strain measurements were performed on four generating lines to eliminate any
257 bending effects due to a slight possible decentering of the loading. Each measuring channel consisted of two 6
258 mm steel marbles spaced 200 mm apart. The strain was calculated by measuring the relative displacement of
259 the two marbles (performed with an LVDT). For each loading age, at least three specimens were tested. The

260 details of the experiments and the mix design of the concrete are presented in (Briffaut, Benboudjema et al.
 261 2012) and in Table 1. The compressive strength at 28 days is 38 MPa. The degree of hydration was measured
 262 by semi-adiabatic tests and confirmed by measurement of the loss of ignition at 550°C (Briffaut,
 263 Benboudjema et al. 2012). Table 3 presents the fitted creep parameters for Eq. 1, and Figure 5 shows a com-
 264 parison between the experimental results and modelling. This shows good agreement between both except
 265 during the first hours after loading.



266
 267 Figure 5 – Comparison between Briffaut’s experimental results and Eq. 1. The fitted parameters are set out in
 268 Table 3

269 2.5. Conclusion

270 The experimental results from the early age creep tests performed by several authors with different ex-
 271 perimental devices and concrete mix designs show that early age creep follows a logarithmic course except, in
 272 some cases, at very early age during the first few hours after loading. This type of behaviour should therefore
 273 be used to model concrete at early age. Table 3 below summarises all the results obtained for the Vercors, OC
 274 and Briffaut compositions. The C parameter values vary significantly between the different compositions.
 275 According to the Model Code 2010, the value of C is linked to the compressive strength at 28 days. However,
 276 here, no correlation has been observed between C, f_c or even E. In the next section, the practical implementa-
 277 tion of this modelling is discussed.

278 Table 3 - Fitted parameters of Equation 1 for the Vercors, OC and Briffaut concretes

Vercors concrete	
C (GPa)	197

t_0 (hours)	19	23	43	69	
$\tau(t_0)$ (days)	9.23E-5	5.04E-3	5.69E-2	1.55E-1	
$\xi(t_0)$	0.24	0.32	0.48	0.56	
OC					
C (GPa)	218				
t_0 (hours)	15	20	24	40	72
$\tau(t_0)$ (days)	2.49E-07	8.20E-07	3.90E-04	1.62E-02	4.76E-02
$\xi(t_0)$	0.23	0.30	0.33	0.39	0.46
Briffaut's concrete					
C (GPa)	93				
t_0 (hours)	24	32	64	120	
$\tau(t_0)$ (days)	1.82E-02	3.02E-02	1.01E-01	1.58E-01	
$\xi(t_0)$	0.45	0.53	0.64	0.72	

279

280 3. Modelling

281 Eq. 1 could of course be used in the framework of a finite element code with the assumption of the su-
282 perposition principle. Nevertheless, dealing with such an equation and the superposition principle requires the
283 entire stress history to be stored, for example at each Gauss point, leading to very long computation times
284 (Hermerschmidt and Budelmann 2015). This explains why rheological models like a series of Kelvin-Voigt
285 elements are very often used to predict creep in concrete (Bažant and Prasanna 1989), (Hauggaard, Damkilde
286 et al. 1999).

287 Here, based on the microprestress theory (Bazant, Hauggaard et al. 1997), it was proposed to use a
288 unique dashpot instead of a series of Kelvin-Voigt elements. If the viscosity η of this dashpot changes linearly
289 with time (Eq. 3), the integration of the strain ε in a dashpot corresponds to Eq. 4:

$$\eta = C \cdot (t + \tau - t_0) \quad (3)$$

with C and τ are the parameters characterising the evolution of the viscosity.

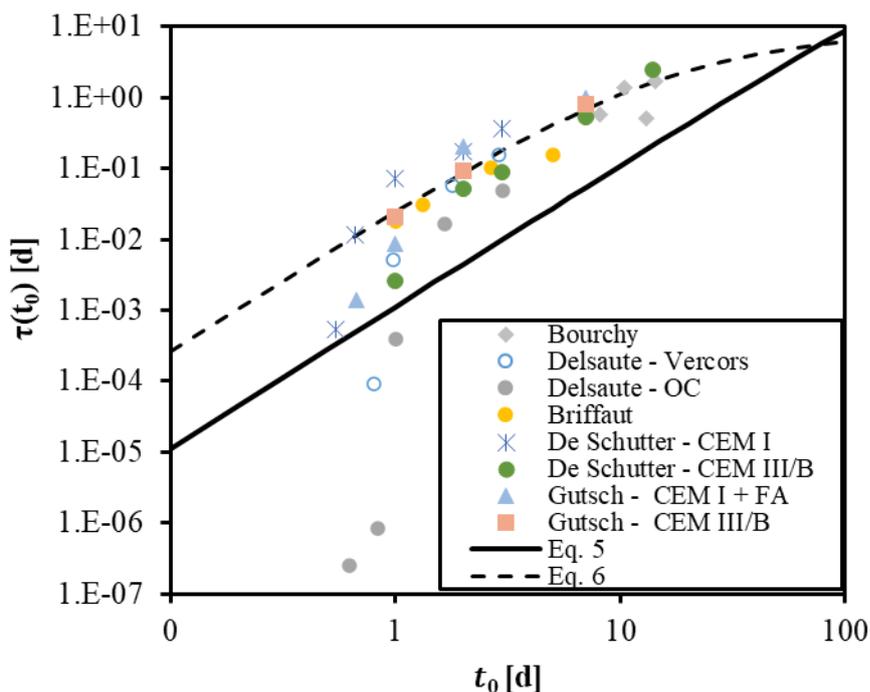
$$\sigma = \eta \cdot \dot{\varepsilon} = C \cdot (t + \tau - t_0) \cdot \dot{\varepsilon} \Rightarrow d\varepsilon = \frac{\sigma \cdot dt}{C \cdot (t + \tau - t_0)} \Rightarrow \varepsilon = \frac{\sigma}{C} \cdot \ln \left(1 + \frac{t - t_0}{\tau} \right) \quad (4)$$

290 where σ is the applied stress. The parameters C and τ of the dashpot can be fitted to the experimental results
291 (as it was done in the first part of this paper, because Eqs. 1 and 4 are similar). To determine C, it is possible
292 to perform a creep test on a hardened concrete. Micro-indentation can also be used to estimate this parameter
293 (Vandamme and Ulm 2013), (Frech-Baronet, Sorelli et al. 2020). τ could also be estimated by creep tests.

294 Finally, it is also possible to evaluate this parameter by using the equation proposed by the fib model code
 295 MC2010 (Torrenti, Nedjar et al. 2023), for example, which has the form:

$$\tau(t_0) = \frac{1}{(0.035 + 30/t_0)^2} \quad (5)$$

296 Where t_0 is expressed in days and varies depending on the type of cement, Figure 6 reveals that the equation
 297 fails to provide an accurate estimation of this parameter for all tested concretes during the early age. The pa-
 298 rameter τ is consistently underestimated, except for the very early age. For comparison, results from previous
 299 studies by De Schutter (De Schutter 1999) and Gutsch (Gutsch 2000) have been included. It is generally ob-
 300 served that the evolution of τ does not adhere to a single trend when considering results based on the loading
 301 age during the very early age. However, at later ages, the development of τ remains relatively stable across
 302 different concrete compositions.



303
 304 Figure 6 – $\tau(t_0)$ against t_0 , including a comparative analysis with Equation 5 and Equation 6

305 Given the observations made from Figure 6 and aiming to enhance the prediction of τ , a new expression for τ
 306 in terms of loading age is proposed in Equation 6.

307

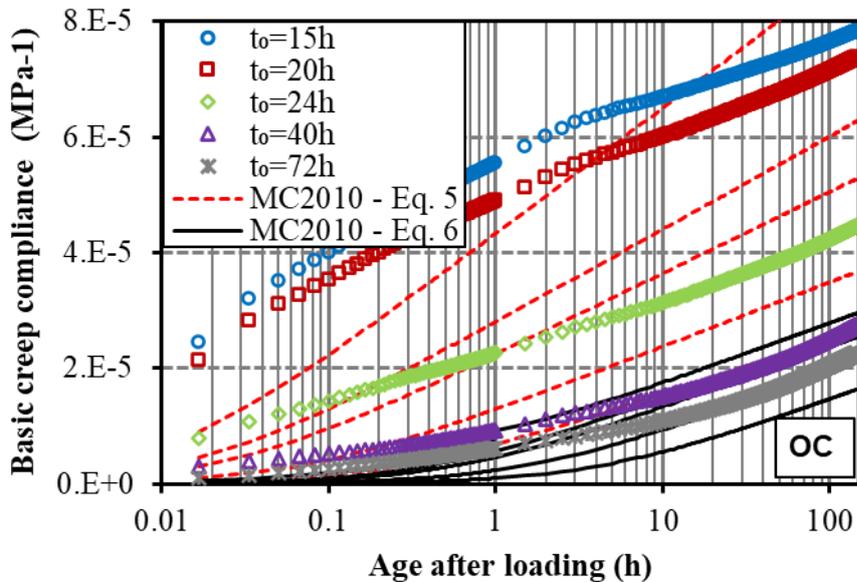
$$\tau(t_0) = \frac{0.052}{(0.078 + 1.39/t_0)^2} \quad (6)$$

308 Where t_0 is expressed in days. Equation 6 is compared to experimental results and Equation 5 in Figure 6. As
 309 anticipated, Equation 6 demonstrates an improved overall alignment with loading ages across ages at loading
 310 higher than 1 day. However, it is noteworthy that Equation 5 more accurately replicates τ values at a very
 311 early age. To quantitatively assess the performance of Equations 5 and 6, errors derived from both equations
 312 are calculated and presented in Table 4 for the compositions outlined in sections 2.2 to 2.4. The error is com-
 313 puted based on the sum of the squares of the differences obtained. Illustratively, the outcomes of Equations 5
 314 and 6 are depicted in Figure 7. It becomes evident that neither of the two equations can predict basic creep at
 315 both very early and older ages.

316 Table 4 – Performance evaluation of Equations 5 to 7: error analysis

	Error			
	Eq. 5	Eq. 6	Eq. 7 / Case A	Eq. 7 / Case B
OC	1.61E-07	1.65E-06	9.40E-08	1.05E-07
Vercors	1.39E-08	1.33E-08	7.53E-10	1.45E-09
Briffaut	2.42E-09	8.51E-10	1.58E-10	1.68E-10

317



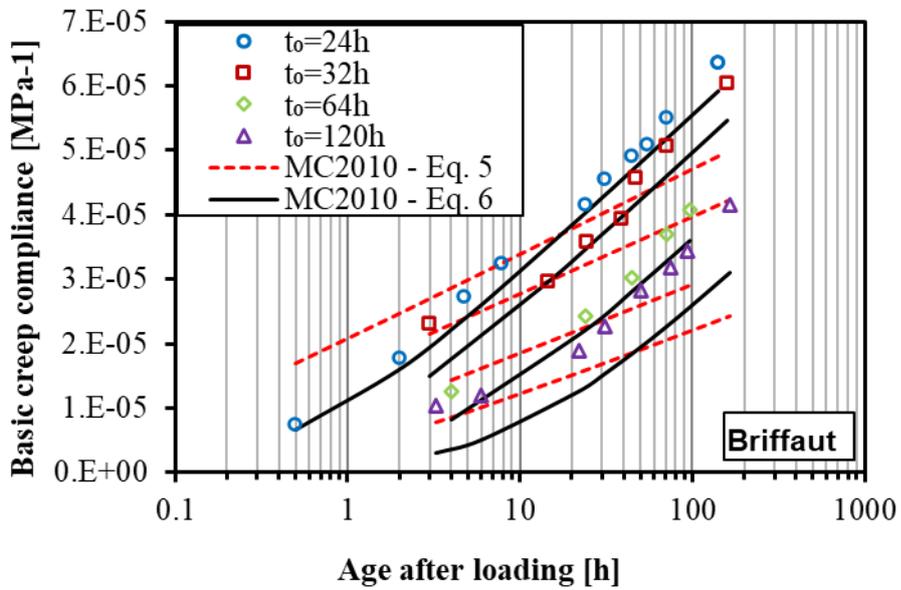
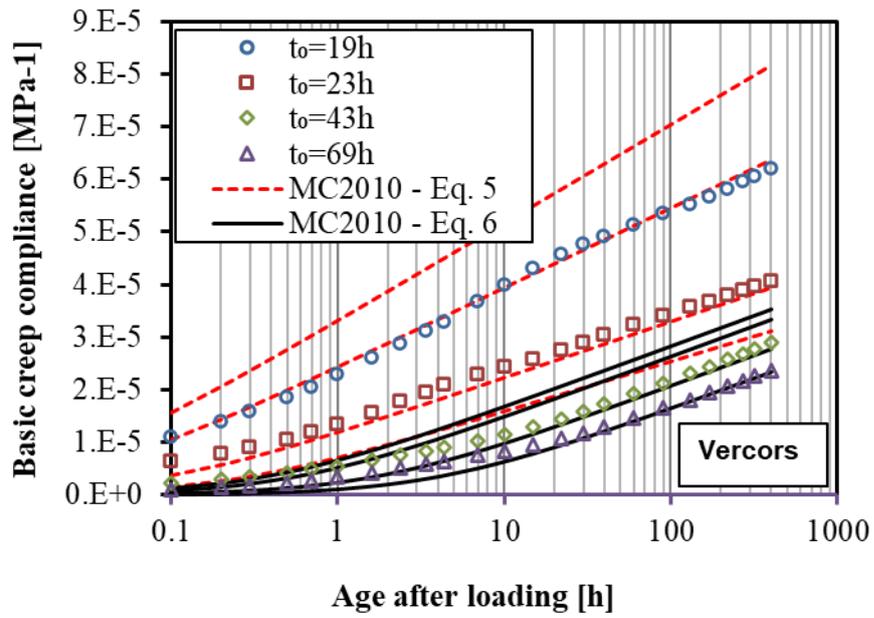


Figure 7 – Performance evaluation of Equation 5 to 6 on the OC (a), Vercors (b) and Briffaut's (c) concrete compositions.

318 As indicated in section 2, the maturity of cement-based materials can also be expressed by means of the
 319 degree of hydration. Figure 8 shows how the parameter τ varies according to the degree of hydration.

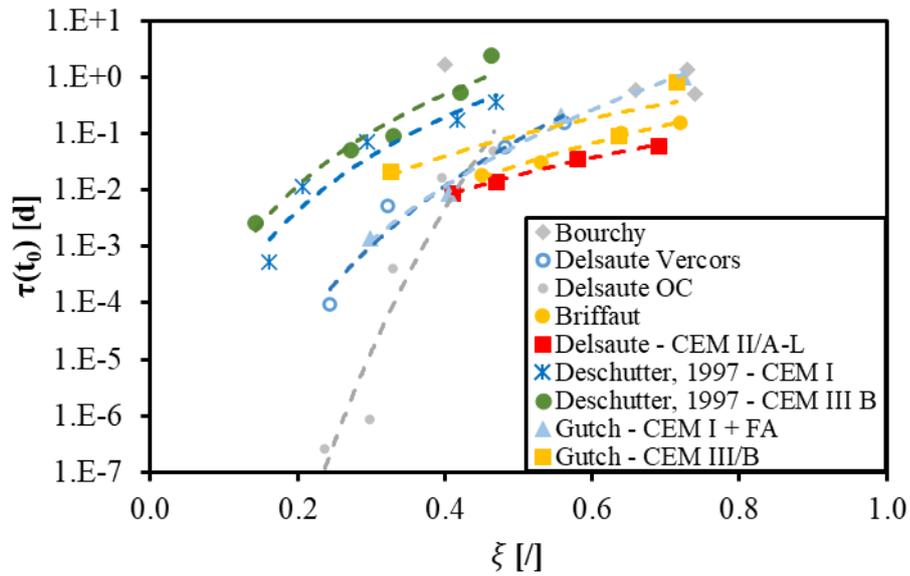


Figure 8 - $\tau(t_0)$ against ξ . Dashed lines delineate the power trend line.

320

321 It is apparent that the relationship between both parameters differ for different concretes. It can be
 322 mainly observed that:

- 323 - A shift is observed in the development of τ between the different compositions.
- 324 - The relationship between τ and ξ follows a power trend.

325 One notable distinction among various shifts in τ concerning the degree of hydration lies in the initia-
 326 tion point of the curve, exhibiting considerable variability across compositions. This divergence is attributed
 327 to the fact that, for certain compositions, the material undergoes setting at a significantly lower degree of hy-
 328 dration compared to others. This underscores the importance of accounting for the degree of hydration at the
 329 time of setting ξ_0 when modelling τ . Figure 9 presents the results for τ as a function of $\xi - \xi_0$, revealing a
 330 dispersion of outcomes, particularly during the very early age when the degree of hydration is low. No dis-
 331 cernible trend is observed between the nature (e.g., type of cement, water-cement ratio, etc.) or performance
 332 characteristics (e.g., compressive strength) of the compositions and the relationship between τ and $\xi - \xi_0$.
 333 This fact is discussed at the end of the section.

334

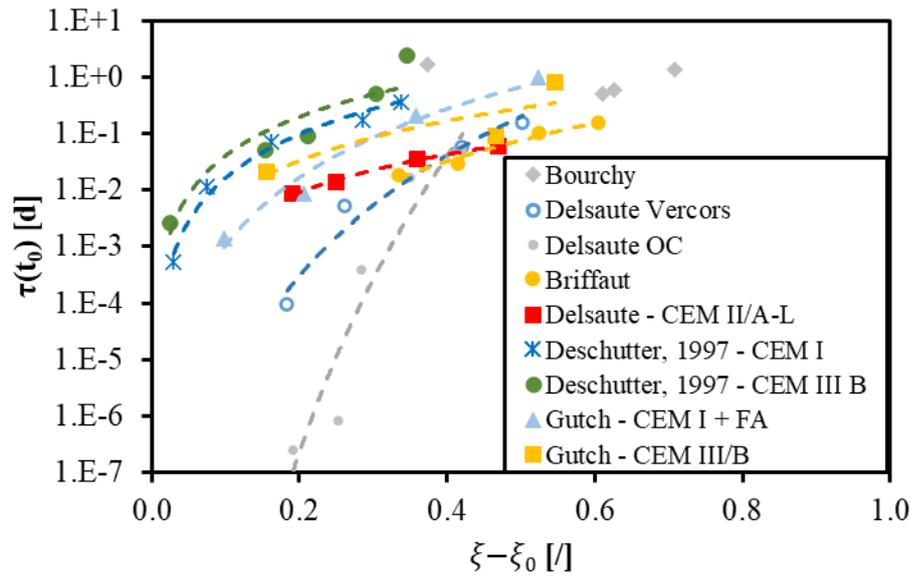


Figure 9 - Plot of $\tau(t_0)$ against $\xi - \xi_0$. The dashed lines delineate the power trend line.

335 The τ values at the time of setting exhibit notable variations among different compositions when attempting to
 336 extrapolate the obtained results. However, the τ value at the time of loading is directly linked to concrete vis-
 337 cosity through the parameter C (see Eq. 3). Although the viscosity of concrete at the time of setting is un-
 338 known, it is considerably lower than the measured values in the studied concretes. Given the substantial fluc-
 339 tuations in τ at the time of setting, it becomes evident that, during and shortly after setting, the τ value is prone
 340 to significant underestimation or overestimation, depending on the situation. This can lead to a pronounced
 341 over- or under-estimation of the creep phenomenon in the initial hours post-setting. To address this, the model
 342 should incorporate a minimum value for τ at the time of setting. For fresh concrete, the plastic viscosity can
 343 vary between 20 and 800 Pa.s (Chidiac and Mahmoodzadeh 2009). By comparison, water has a viscosity of
 344 0.002 Pa.s. Assuming a τ value of 2.49E-7 day and a C value of 218 GPa, the resulting viscosity at the time of
 345 loading is estimated to be 4.69E9 Pa.s. This value surpasses the viscosity of fresh concrete by more than 1E6
 346 times. Conversely, in the opposite scenario, considering a plastic viscosity of 1000 Pa.s and the same C value,
 347 the resulting τ is estimated to be 5.31E-14 day. This value could be considered as a lower bound of τ . How-
 348 ever, for a more accurate estimation of τ at the setting time, additional data is needed. One method to estimate
 349 this value involves using oscillatory shear during the fresh stage until setting (Banfill 1991). Consequently, it
 350 is reasonable to assume that this lower threshold value will have minimal impact on the subsequent develop-
 351 ment of τ . It is crucial to note that this study focuses on the material's behaviour from the time of setting, and

352 thus, the data from this study cannot be applied before the material has set. Considering these observations, a
 353 new relationship between τ and the degree of hydration is proposed in Equation 7:

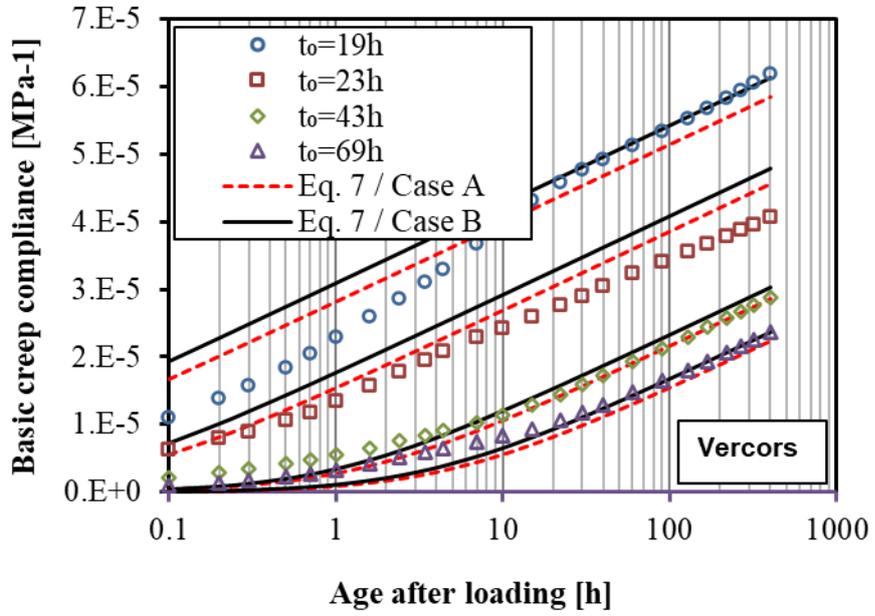
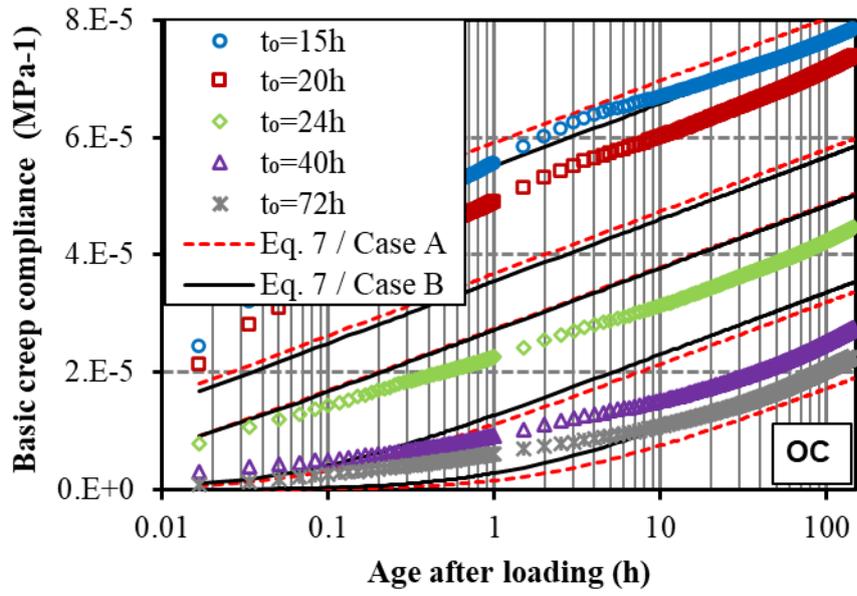
$$\tau = \tau_0 + a \cdot (\xi - \xi_0)^b \text{ for } \xi > \xi_0 \quad (7)$$

354 Where τ_0 corresponds to the value of τ at final setting time and is expressed in day, a and b are dimensionless
 355 material parameters and are presented in Table 5. In this case, for an accurate evaluation of early age creep, at
 356 least two creep tests for two different ξ_0 are needed.

357 Table 5 – Fitted parameters and resulting R^2 from Eq. 7

	ξ_0	C [MPa]	Case A: all data			Case B: data from 2 tests		
			a	b	R ²	a	b	R ²
Deschutter, 1997 - CEM I	0.132	159498	5.98	2.56	0.96	6.65	2.68	0.97
Deschutter, 1997 - CEM III/B	0.118	118861	7.65	2.27	0.74	38.42	2.60	0.77
Delsaute, 2017 - OC - CEM I	0.046	217846	338688.20	17.41	0.91	28826.24	15.41	0.92
Delsaute, 2016 - Vercors - CEM I	0.061	196000	27.00	7.08	0.99	24.67	7.36	0.99
Delsaute, 2019 - CEM II/A-L	0.220	180000	0.33	2.22	1.00	0.31	2.16	1.00
Briffaut, 2010 - CEM II/A-LL	0.115	93190	1.09	3.84	0.99	0.99	3.65	0.99
Gutsch, 2000 - CEM I + FA	0.200	104970	10.92	4.03	1.00	12.64	3.92	1.00
Gutsch, 2000 - CEM III/B	0.170	88131	1.43	2.34	0.64	4.77	2.93	0.69

358 Equation 7 is compared to experimental results in Figure 10. For every age at loading, a good agreement is
 359 obtained between the experimental results and Equation 7. To quantitatively assess the performance of Equa-
 360 tions 7, the error is calculated, as for Equation 5 and 6 previously, and is presented in Table 4. It appears that
 361 the error is strongly reduced by using Equation 7 and data from Table 5 (case A). While this model effectively
 362 captures the aging of the creep function, noticeable variations in the coefficients a and b are observed across
 363 different compositions. The parameter a ranges between 1.09 and 338688, while the parameter b varies be-
 364 tween 2.22 and 17.41. Despite the inherent differences in compositions due to binder nature and admixture
 365 presence, the expectation was for these variations to be smaller. Notably, the OC composition stands out from
 366 the rest. Excluding this data, the parameter a varies between 1.09 and 27.00, and the parameter b varies be-
 367 tween 2.22 and 7.08, indicating significantly narrower ranges.



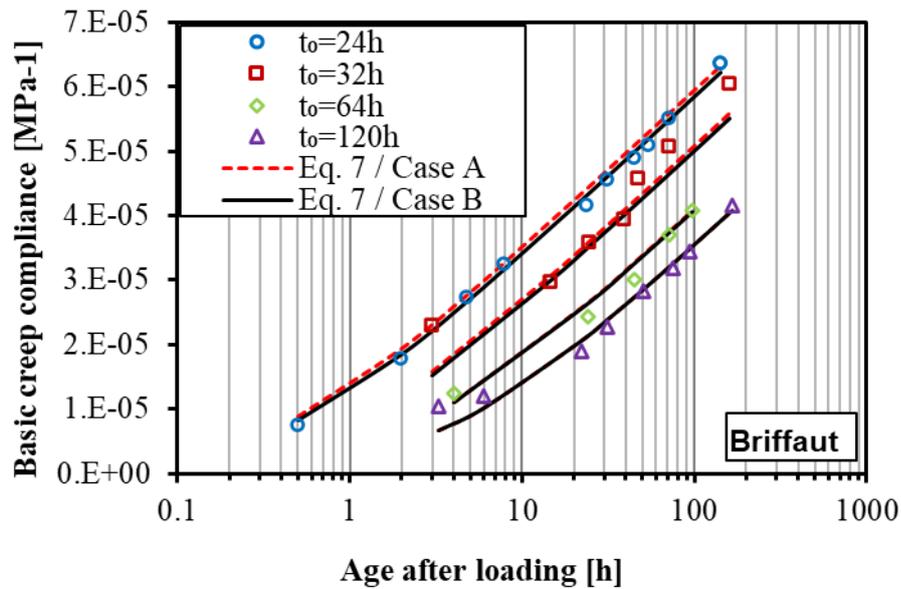


Figure 10 – Performance evaluation of Equation 7 on the OC (a), Vercors (b) and Briffaut’s (c) concrete compositions for cases A and B.

368 These substantial variations can be attributed to the inclusion of data from multiple laboratories at different
 369 times, employing diverse technologies and test protocols. Moreover, significant disparities arise in determin-
 370 ing fundamental parameters such as the degree of hydration (measured by isothermal calorimetry, semi-
 371 adiabatic calorimetry, or adiabatic calorimetry) and the final setting time (determined through ultrasonic
 372 measurement or based on a mechanical percolation threshold linked to compressive or tensile strength or
 373 modulus of elasticity). The devices and the geometry of the samples used in those studies are also different.
 374 The impacts of these differences are challenging to quantify, underscoring the need to establish consistent
 375 protocols across laboratories for characterizing and modelling the aging of the creep function.

376 This also highlights the challenges posed by existing databases, including those proposed by Bazant's team
 377 (Mija H. Hubler and Zdenek), as previously indicated by (Rasoolinejad, Rahimi-Aghdam et al. 2018). While it
 378 may be impractical to establish a universal relationship between the degree of hydration and the parameter τ ,
 379 which represents the aging factor of the creep function, this work demonstrates that these two parameters are
 380 connected by a power law. Hence, it appears that such a simple law can be characterized with just 2 short-
 381 duration tests (< 1 month) conducted at sufficiently spaced degrees of hydration. To directly validate this as-
 382 sertation, parameters a and b in Equation 7 are computed using the τ data acquired for the first and last loading
 383 ages across different datasets. The corresponding results are presented in Table 5 (case B). Notably, it is ob-

384 served that the values for coefficients a and b closely align with those obtained from the comprehensive data-
 385 set (case A). This close agreement is further illustrated in Figure 10, demonstrating a high degree of concor-
 386 dance. Furthermore, through the assessment of the calculated error, it appears that the error increases by
 387 21.3% when relying on 2 tests instead of 4 to 5 tests for determining the aging of τ as a function of the $\xi - \xi_0$.
 388 Finally, it was observed that the proposed model is unable to accurately fit the initial hours of loading and
 389 tends to underestimate the creep function. This discrepancy is particularly noticeable when loading is con-
 390 ducted at a very early age. It appears that during the initial 3 hours of loading, the creep function follows a
 391 power law with the exponent n varying between 0.15 and 0.60. An average value of 0.33 is determined. Fig-
 392 ure 11 illustrates all the obtained results. For a more precise modelling of creep behaviour from loading, this
 393 observed power-law behavior could be considered, as proposed in more complex models that account for mul-
 394 tiple creep components (see, for example, (Delsaute, Torrenti et al. 2017)).
 395

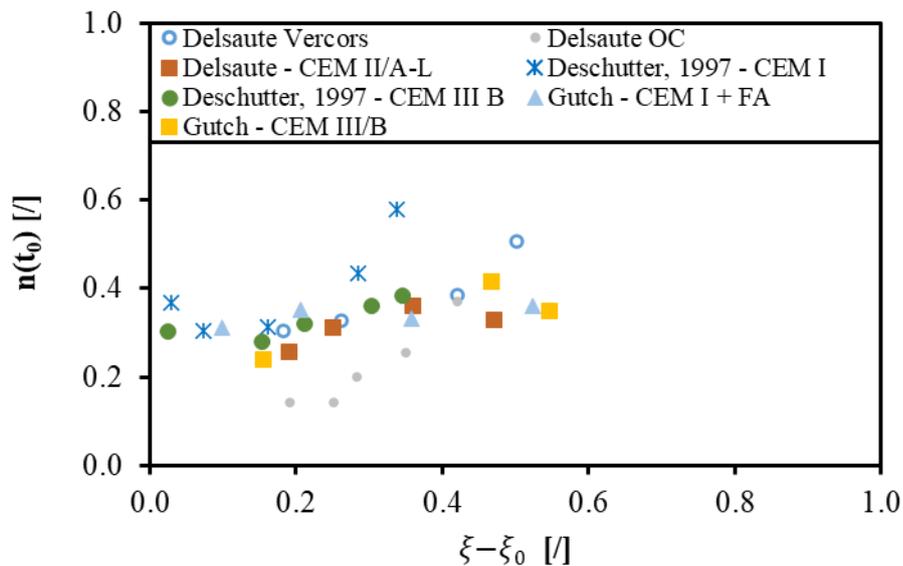


Figure 11 –Power law exponent $n(t_0)$ against $\xi - \xi_0$

396
 397 **4. Conclusions**
 398 This study analyses the basic creep of various concrete mixes for several ages at loading, especially at very
 399 early age ($t_0 < 24h$) and early age ($t_0 < 28$ days). It is shown that:

- 400 - A logarithmic expression that contains two parameters that describe the material (C and τ) can ac-
401 curately model basic creep from very early age except for the first hours of loading. Parameter C re-
402 lates to the amplitude of creep and depends solely on the composition of the concrete. The other pa-
403 rameter τ relates to the kinetics of creep and depends on the age of the material at loading and the
404 nature of the concrete mixture.
- 405 - The logarithmic expression corresponds to a rheological model consisting of a single dashpot for
406 which viscosity changes linearly with time. This model has the advantage that it removes the need
407 to store the entire stress history to compute the stress generated by the restraint of free deformation
408 which greatly reduces computation time.
- 409 - The material ageing parameter τ varies according to a power law when plotted according to the de-
410 gree of hydration. This relationship depends on the composition. At least two compressive creep
411 tests performed at two different degrees of hydration are needed to calibrate the material parameters
412 and consider the effect of ageing on basic creep compliance.
- 413 - Furthermore, the introduction of a new relationship (Equation 7) between creep and degree of hy-
414 dration represents a significant advancement in modelling accuracy. This relationship, which re-
415 duces error and aligns more closely with experimental results, underscores the importance of ac-
416 counting for the degree of hydration at the age of loading and the time at setting. The proposal of
417 material parameters (a and b) within Equation 7, while showing substantial variation across differ-
418 ent compositions, emphasizes the challenges posed by diverse testing methodologies and the need
419 for standardized protocols in concrete testing and modelling.
- 420 - The initial development of the basic creep compliance (< 3 hours of loading) follows a power trend
421 with an average exponent of 0.33.

422

423 This study deals only with basic compressive creep for moderate levels of stress and for a curing temperature
424 of 20 °C. Further studies are needed to assess cracking risks at early age, for example by investigating basic
425 tensile creep and the influence of the curing temperature, stress level, drying and creep recovery.

426

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