CONVENTIONAL MODELS FOR CREEP IN NORMAL AND HIGH-STRENGTH CONCRETE

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Abstract

Predicting creep in concrete structures is still highly uncertain, with current models for creep in cement concrete differing in their accuracy and complexity. As high strength concrete is of interest in the building industry the contemporary concrete models should cover higher grades of concrete. This required calibration of creep models for wider range of concrete strengths.

The paper presents and compares the models for creep in cement concrete included in the ACI 209R-92 report, Eurocode 2 and *fib* Model Code 2010. For the presentation and comparison of the creep models, creep coefficients are used as the most common and understandable parameter in the analysis of time-dependent deformation of concrete. The main factors affecting the prediction of concrete creep are outlined, comparing the influence of concrete grade, environmental conditions, member size and loading conditions.

Models currently used for creep in cement concrete are based on many years' theoretical and experimental research. They enable a more accurate analysis and better assessment of the time-dependent deformation of concrete structures at the design stage. Their complexity is significantly reduced and a range of influencing parameters are excluded from the models for simplicity and easy adaptation at the design stage.

Streszczenie

Przewidywanie pełzania betonu jest wciąż zadaniem bardzo trudnym, pomimo stosowania modeli pełzania o znacznej złożoności, ale wciąż nie zapewniających dużej dokładności w fazie projektowania. Wzrost zainteresowania betonem wysokiej wytrzymałości w budownictwie wymógł wprowadzenie do modeli betonu większego zakresu klas wytrzymałości betonu.

W artykule przedstawiono i porównano modele pełzania betonu cementowego stosowane w wytycznych ACI 209R-92, Eurokodzie 2 i modelu *fib* MC2010. Do charakterystyki i porównania modeli zastosowano współczynnik pełzania betonu jako najbardziej powszechny i zrozumiały parametr przyjmowany w analizie odkształceń opóźnionych betonu. Przedstawiono główne czynniki wpływające na pełzanie betonu, porównując wpływ klasy betonu, warunków środowiska, wymiarów nominalnych i warunków obciążenia.

Stosowane obecnie modele pełzania betonu cementowego oparte są oparte są na wieloletnich badaniach teoretycznych i doświadczalnych. Umożliwiają one dokładniejszą analizę i ocenę zależnych od czasu odkształceń betonu już na etapie projektowania. Złożoność modeli i stosowana liczba parametrów zostały w nich znacząco ograniczone, dla uzyskania prostoty opisu i łatwości stosowania modeli już na etapie projektowania.

Keywords: **Creep of concrete; Creep models; Model Code; Time dependent properties.**

1. INTRODUCTION

A wide range of models for creep in cement concrete have been developed over the years [1-9]. Then as well as now the most important problem concerning creep deformation has been the assessment of time-dependent losses of the prestressing forces in PC structures, with other problems associated with deformation and displacement over time barely recognised and omitted in time-dependent structural analyses. Starting from the crude estimation of delayed deformations, formulas for creep were elaborated and calibrated in ongoing research. Later, creep models were adjusted to changing concrete properties and technologies. Models for the description of long-term effects in concrete structures have changed over time and new models are still being introduced, some of which are highly sophisticated and take into account many parameters, while some are still very simple but can easily be adapted in simple problems. The complexity and uncertainty in predicting the effects of creep require the adoption of code-related procedures to give general usage guidance. In this paper, these are called conventional models and they cover the majority of modern standards and codes. They are not formulated to give a detailed description of creep mechanisms but to give guidance for general design purposes.

In this paper, three modern creep models included in the ACI 209R-92 report [1], Eurocode 2 [3] and the recently introduced *fib* Model Code 2010 (final version) [4, 9-11] are discussed and compared. In some cases, in structures vulnerable to creep, simple approaches for creep estimation are too crude, and more sophisticated procedures for time-dependent analysis require formulation [6, 7]. Conventional models assist with this, while retaining simplicity for application. These procedures allow a more precise assessment of the time-dependent deformation and forces in order to design more durable and sometimes safer structures. The progressively evolving CEB-FIP models [2, 8, 12] and their implementation in Eurocode 2 give practical and accurate methods for the prediction of creep effects. The *fib* Model Code 2010 introduced a new and improved formulation to describe creep effects as the sum of basic and drying creep deformations [4, 9-11, 13, 14]. The comparison of models shows that the MC2010 model is more consistent and calibrated to avoid shortcomings in the previous models [9-11, 14].

Predicted values for creep in concrete over different conventional models indicate that the results calculated for creep coefficients may differ significantly. Precise prediction of the magnitude of creep in concrete structures is still extremely difficult and sometimes requires individually-calibrated models for the accurate prediction of the time-dependent behaviour of concrete structures. Conventional models currently in use may differ in the final values of the creep coefficients, but adapting the appropriate procedure of time-dependent analysis in creep-vulnerable structures under changing environmental conditions usually allows accurate rheological analysis [6, 7].

2. FACTORS INFLUENCING CREEP

The great number of both variable and uncertain factors influence the time-dependent deformation of concrete. The magnitude and development of load dependent strains depend on a wide range of factors including the stress range, element size, concrete mix, coarse gravel content, cement content, type of cement, water/cement ratio, relative humidity, temperature, time of loading, type and duration of curing and maturity. Including most of these in creep effect calculations is tedious and sometimes practically impossible. As a result of many of the parameters being unknown to a concrete structure designer during the design stage, more comprehensive code-related models for creep in concrete were created. These models try to limit the number of influencing factors for simplicity of use. Therefore, to avoid using concrete mix parameters, usually unknown at the design stages, strength of concrete is developed [2-4]. As considerable progress in concrete technology and types of concrete has been made over the last few decades, more factors influencing concrete creep should be taken into account when calibrating the creep formulas.

Physically, several components and types of creep strain can be distinguished. These are used extensively in the literature to describe the creep phenomenon. Methods for time-dependent analysis given in the literature and codes are sometimes too simplified, leading to misunderstandings in the real-time behaviour of concrete structures [6-8, 12, 13]. The many variable parameters induce significant differences in the long-term deformation estimation and lead to serviceability problems if they are treated too crudely.

3. CREEP COEFFICIENT

In code-related concrete models, creep is usually described by so-called creep coefficient φ, which represent the ratio of delayed deformation – creep strain $\varepsilon_{cc}(t,t_0)$ to initial elastic strain ε_{ci} in concrete at the age of 28 days under the same stress $\sigma_c(t_0)$ applied at the age of concrete t_0. The creep coefficient $\varphi(t, t_0)$ can be expressed as:

$$\varphi(t,t_0) = \frac{\varepsilon_{cc}(t,t_0)}{\varepsilon_{ci}} = \frac{\varepsilon_{cc}(t,t_0)}{\sigma_c(t_0)} E_{ci} \qquad (1)$$

where t is the age of the concrete, t_0 is the age of the concrete at loading in days and E_{ci} is the tangent modulus of elasticity of the concrete at 28 days. For simple time-dependent analysis the majority of codes introduced values of final creep coefficient $\varphi(\infty,t_0) = \varphi(t,t_0)$ taking into account $t = 50$ or 70 years. The values are tabulated or given in graphs for practical usage. Such an approach is sufficient for typical concrete structures where the creep effects are not significant. For larger concrete structures or for structures with staged construction, delayed deformation may be more relevant and the development of creep over time is calculated using numerical formulas. Creep models usually use a product time function expressing a notional creep coefficient and a function describing creep development with time after loading. The creep coefficient is calculated from the formula:

$$\varphi(t,t_0) = \varphi_0 \cdot \beta(t,t_0) \tag{2}$$

where φ_0 is the notional creep coefficient and $\beta(t,t_0)$ is a coefficient to describe the development of creep over time after loading. Many factors are used in calculating these coefficients depending on the creep model. For *fib* Model Code 1990 and Eurocode 2, the concrete mix parameters are replaced by concrete strength. This is not the case with ACI 209.2R-08, which still takes into account some concrete mix parameters as well as the curing affect. In the recently established *fib* Model Code 2010 [4, 9 10, 11], a new formulation was introduced by representing the total creep deformation by the sum of two deformation components: basic and drying creep. The product type approach is taken for each component. The creep coefficient is calculated from the formula:

$$\varphi(t,t_0) = \varphi_{0,b} \cdot \beta_{bc}(t,t_0) + \varphi_{0,d} \cdot \beta_{dc}(t,t_0) \tag{3}$$

where $\varphi_{0,b}$ and $\varphi_{0,d}$ are the notional basic and drying creep coefficients, respectively. Functions $\beta_{bc}(t,t_0)$ and $\beta_{dc}(t,t_0)$ are coefficients to describe development of basic and drying creep with time after loading. Basic creep is defined as the creep that occurs when concrete is sealed (no moisture movement) and drying creep is the additional creep that occurs when concrete dries while under load. The creep formulation in MC2010 is similar to shrinkage modelling and is necessary to accurately describe delayed deformations in high strength concrete. Separation of creep into basic creep and drying creep was introduced earlier in some models for creep recovery. Basic creep is well established and describes creep which occurs when loaded concrete is prevented from drying.

For the comparison of creep deformation in different creep models, the creep coefficient is used as a simple and practical parameter. The creep coefficient is usually determined in the codes as the function of several parameters such as ambient humidity, composition of the concrete mix, age at loading and member dimensions. When a structure requires more detailed time-dependent analysis, the total stress-produced strain is calculated using creep function $J(t,t_0)$.

4. CREEP MODELS FOR NORMAL AND HIGH STRENGTH CONCRETE

For the comparison of creep, three conventional models are selected which represent a simplified approach for design purposes. The ACI 209 model, the Eurocode 2 model and *fib* Model Code 2010 are compared using the same parameters as the initial data. The models are a compromise between accuracy and simplicity. Two of the models consider that basic creep and drying creep may be calculated as independent, in Eurocode 2 partially for high strength concretes. In the ACI 209 model and the general section of Eurocode 2, creep is dependent and calculated using a product type formula. In the models an effort was made to represent varying characteristics of high strength concretes. The creep models are presented and compared in terms of better calibration. They are physically consistent at the time when they were elaborated and they try to avoid some shortcomings in the former models by taking into consideration concrete technology development, but they can still be used for conventional concrete with some exceptions.

The oldest model is the ACI 209 model which was devised in 1971, modified in 1982, developed by ACI in 1992 and reapproved in 2008 (without any corrections). Its main advantage is simplicity and long-time of use with minimal background knowledge. For creep-sensitive structures, more advanced models and methods of structural time-dependent analysis are suggested in the ACI guide [8]. Eurocode 2 model is based on improved series of CEB-FIB models, i.e. MC90 and MC90-99. The strength grades are covered up to C90. In general part, for practical purposes, EC2 gives a graphical method for establishing the final value of creep coefficients which may be used for creep non-sensitive structures. When knowledge of creep development over time is necessary EC2 gives formulas for numerical calculation of creep coeffi-

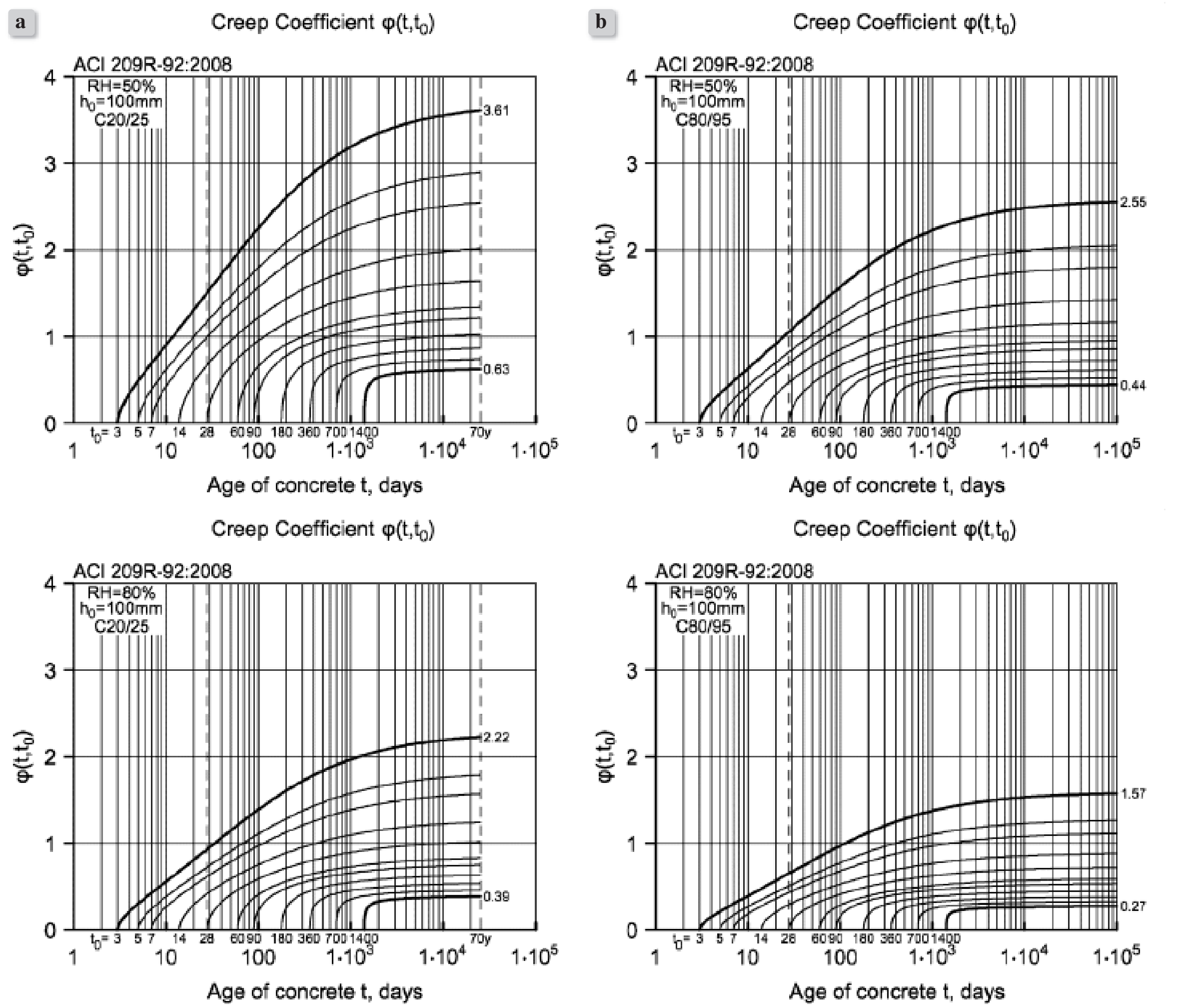

Figure 1.
Creep coefficient of concrete $\varphi(t,t_0)$ according ACI 209 for concretes: a) C20 and b) C80, at relative humidity RH = 50 and 80%

cients. For structures sensitive to creep deformations, in EC2 – Part 2 (for concrete bridges) there are presented structural methods for time dependent analysis. Additionally, a creep model for high strength concretes is included in part 2 as the model in the general part of the code may not give adequate results for such concretes. This model should be used for strength greater than C50 with or without silica fume, made with high strength cements (R).

The new *fib* Model Code 2010 has recently been approved and introduces new formulas for creep description returning to the well-established basic creep concept. The range of applicability is enlarged up to concrete strength grade C120. The creep formulas for ordinary normal weight concrete are applicable to both normal strength (NSC) and high strength (HSC) concretes. MC2010 has new and improved formulas for describing the time-dependent behaviour of structural concrete to better represent the real performance of concrete.

5. COMPARISON FOR CREEP

The comparison investigates the differences between the creep results for different but improved models. For consistency, the results are presented for selected parameters which are the same for the concretes used for comparison. Creep coefficients are presented for concrete loaded at t_0 = 3, 5, 7, 14, 28, 60, 90, 180, 360, 700 and 1400 days after casting for C20 and C80 concrete grades, at relative humidity 50 and 80%, and for notional member size h_0 = 100 mm. Two different concrete mixes are used in estimations of creep in normal and high strength concretes, C20

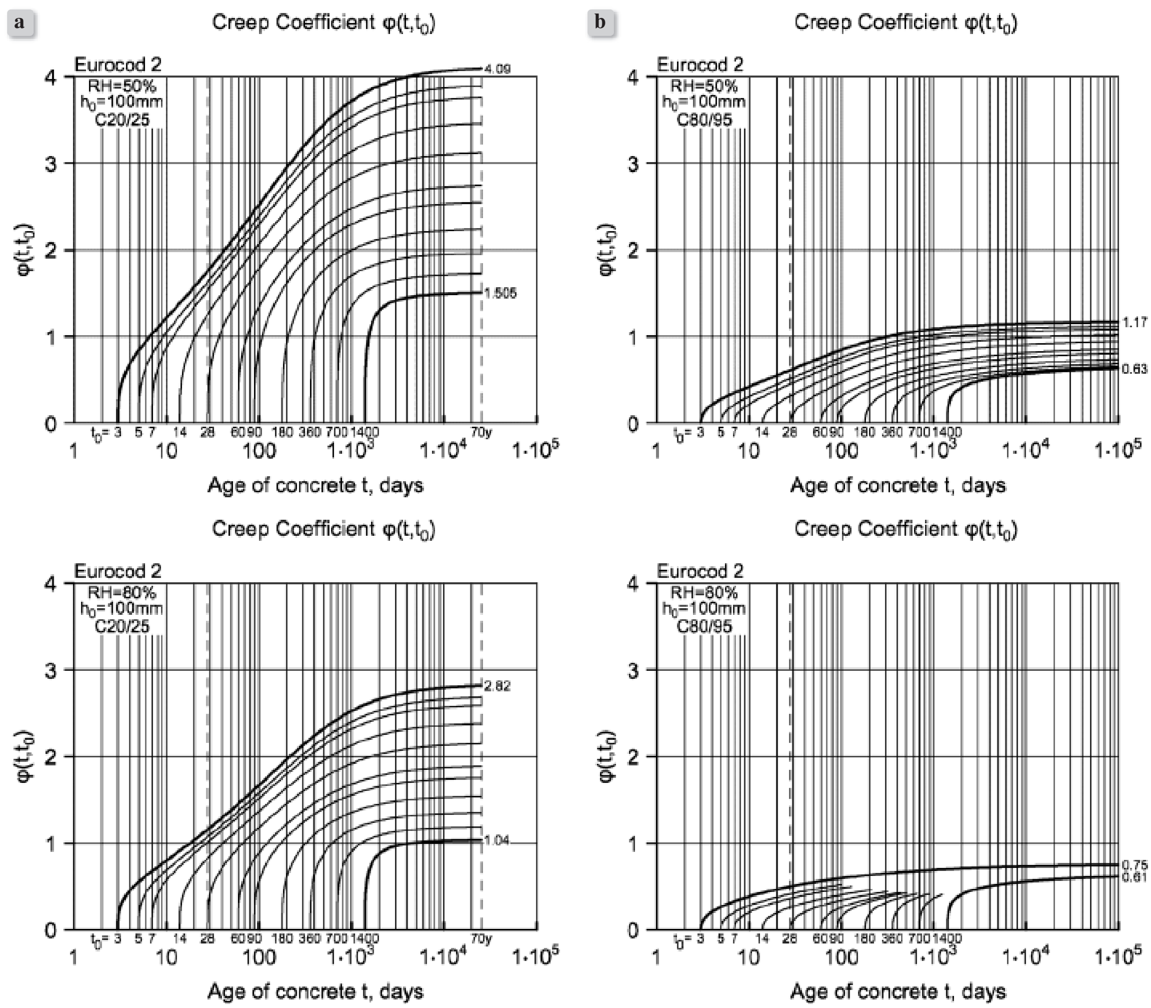

Figure 2.
Creep coefficient of concrete $\varphi(t,t_0)$ according Eurocode 2 for concretes: a) C20 and b) C80, at relative humidity RH = 50 and 80%

and C80, respectively. Stress range is assumed to be lower than $0.4f_{cm}$ and the ambient temperature within normal range. For concrete grade of C20, normal hardening cement and for C80, rapid hardening high-strength cement are used. The creep coefficients are calculated versus time, giving the development and magnitude of creep deformations. The time development of creep predicted by the ACI 209 model for two concrete grades and the initial data are presented in Fig. 1. For normal strength concrete, the final creep coefficient values are established at age t = 70 years as for Eurocode 2 and $t = 10^5$ days for high strength concretes. Concrete creep according to Eurocode 2 for the same initial parameter is presented in Fig. 2.

For high strength concrete the results are presented for time $t = 10^5$ days, as some scientists expect that the durability of such concretes may reach a few hundred years. However, the increase in the magnitude of concrete creep over a longer period of time is not significant. In MC2010 basic creep modelled using a logarithm function is infinite on-going deformation, while drying creep approaches a finite value (hyperbolic function). The time development of creep predicted by the MC2010 model for two concrete grades and the established initial data are shown in Fig. 3.

A comparison of the time development of creep $\varphi(t,t_0)$ which is described by three models: ACI 209, Eurocode 2 and MC2010 at relative humidity RH = 50 and 80%, for time of loading t_0 = 7 and 28 days, and two classes of concrete grade C20 and C80 are presented in Figure 4. The same initial parameters are used in comparison. Higher values of creep coefficients predicted by MC10 than Eurocode 2 are

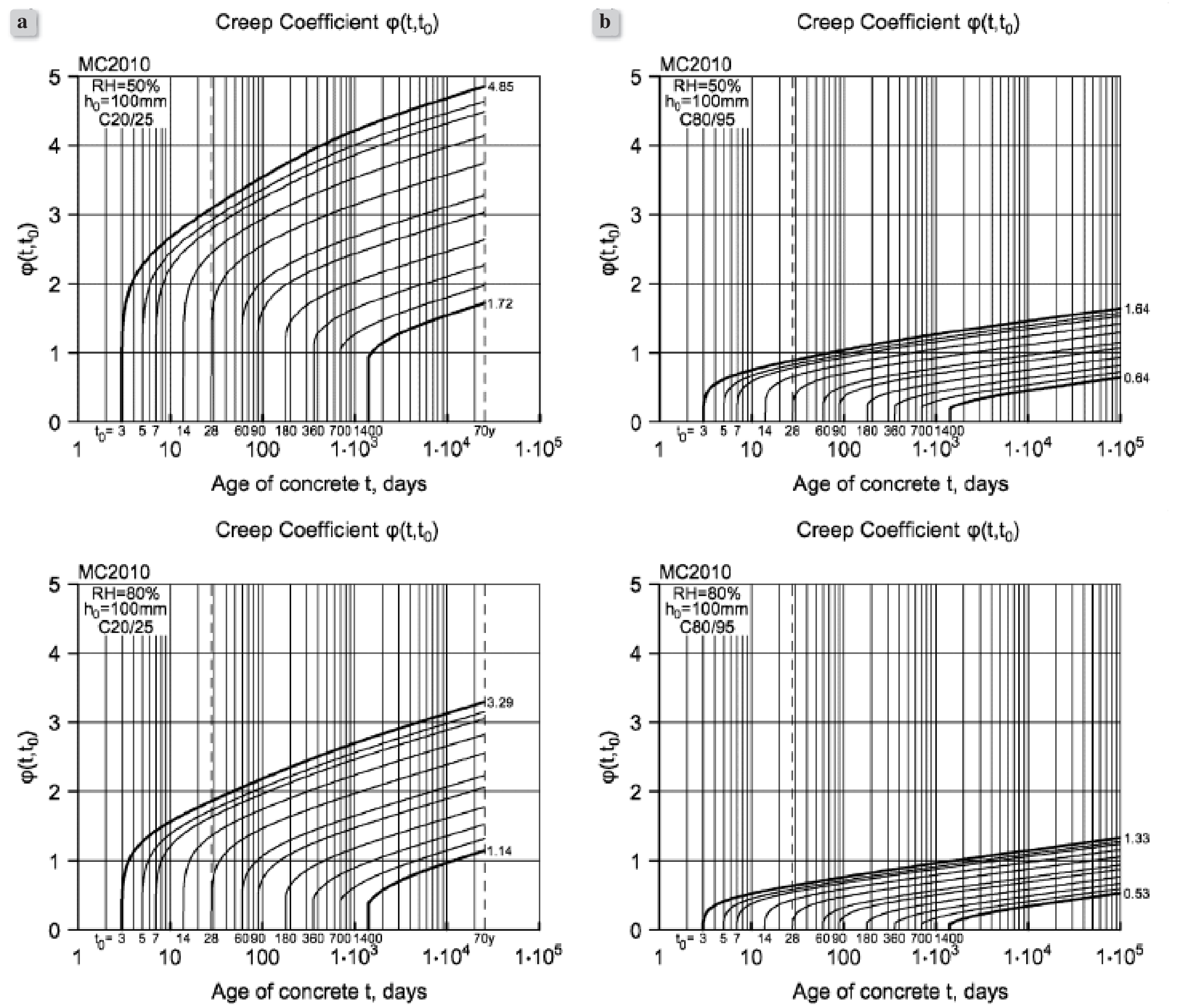

Figure 3.
Creep coefficient of concrete $\varphi(t,t_0)$ according *fib* Model Code 2010 for concretes: a) C20 and b) C80, at relative humidity *RH* = 50 and 80%

remarkable for this comparison. In all models, the creep in high strength concrete is significantly lower. The ACI 209 model is very sensitive to concrete mix composition, and for different mixes and the same concrete grade different values of creep coefficient are obtained. Models in the Eurocode 2 and MC2010 are independent of concrete mixes.

A comparison of the final values of creep coefficient $\varphi(\infty,t_0)$ versus concrete strength is shown in Fig. 5. The graph clearly shows that the amount of creep is dependent on the concrete grade. Higher grade concretes may be used not only to increase durability but also to control creep.

6. CONCLUSIONS

The paper outlines concrete creep models for ordinary normal weight concrete with normal strength (NSC) and high strength concrete (HSC). The majority of such concretes are now in use for typical concrete structures. Conventional concrete range was enlarged and now includes also high strength concrete. Creep behaviour of concrete and concrete structures is still very uncertain as it is influenced by many nano-, micro- and macro-processes in concrete whose mechanisms and correlations are not clearly discovered until now.

The paper shortly outlines and compares the models for creep in cement concrete included in the ACI 209R-92 report, Eurocode 2 and *fib* Model Code 2010.

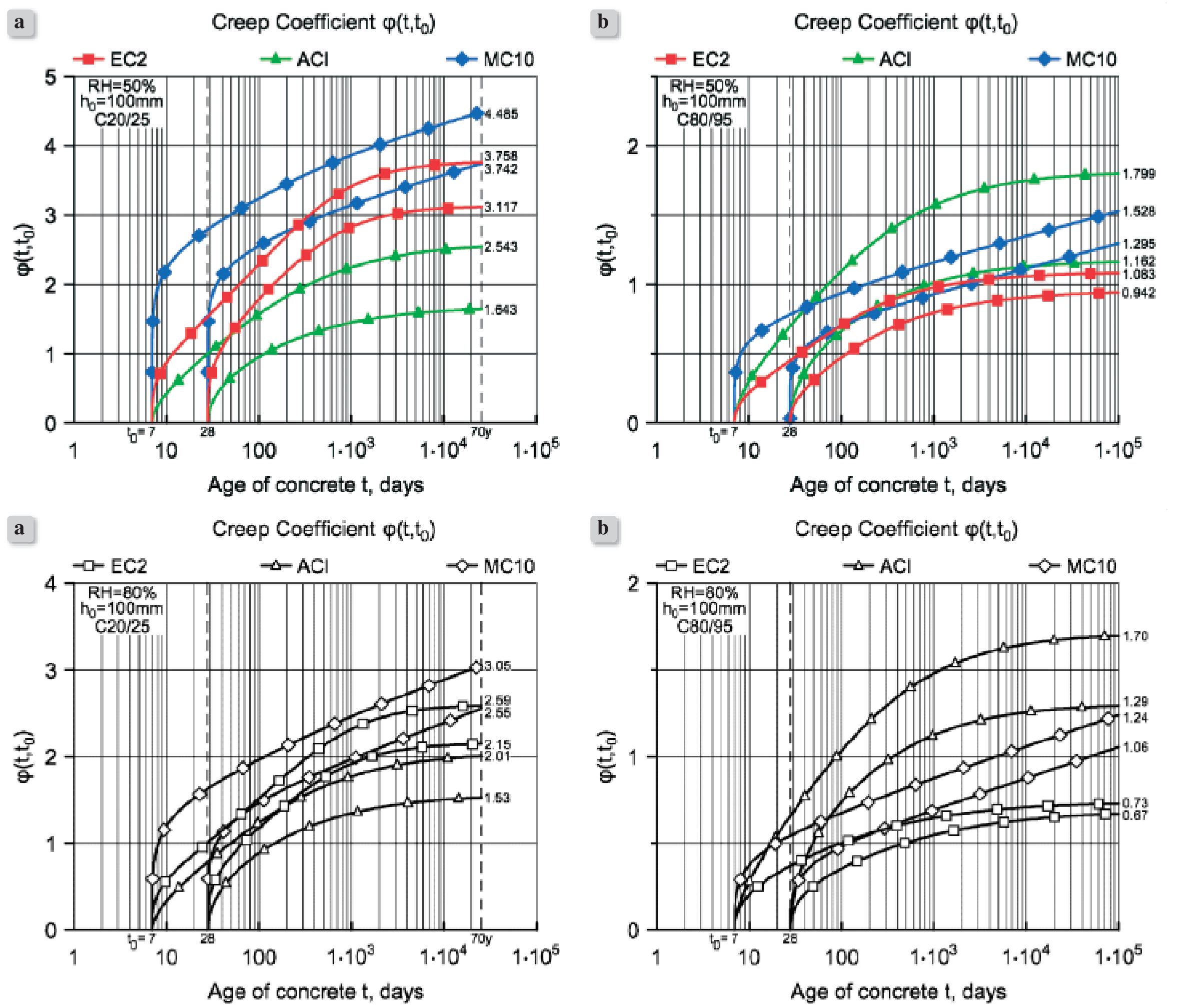

Figure 4.
Comparison of creep coefficient $\varphi(t,t_0)$ according ACI 209, Eurocode 2, MC2010 for concretes: a) C20 and b) C80 loaded at t_0 = 7 and 14 days, at relative humidity RH = 50 and 80%

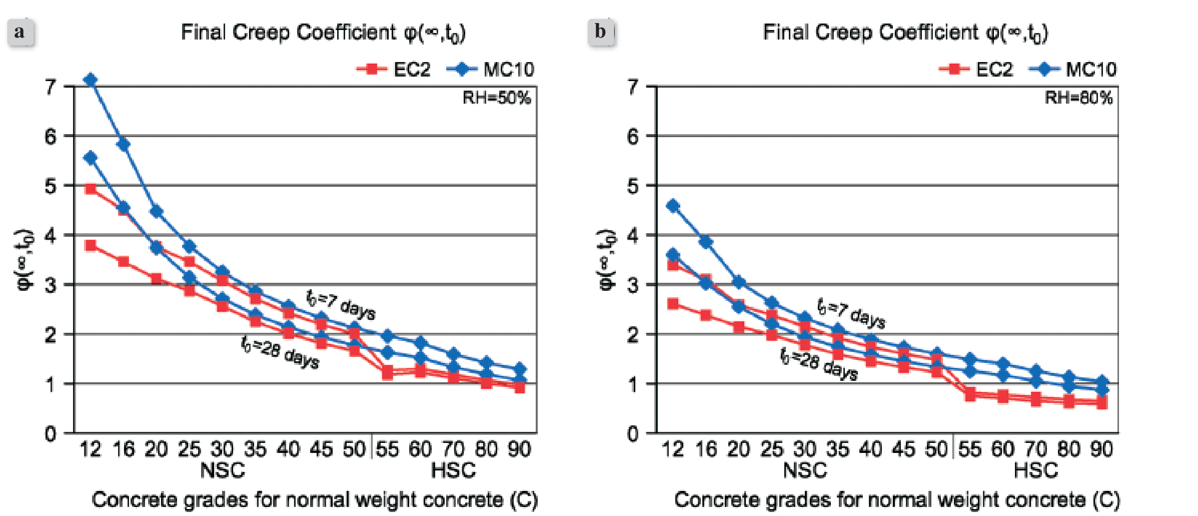

Figure 5.
Comparison of final creep coefficient $\varphi(\infty,t_0)$ versus concrete grades according Eurocode 2 and MC2010, at relative humidity RH = 50 and 80%

ACI 209 model is the oldest one but was positively verified for high strength concrete. In EC2 and *fib* MC10 models the code-type modelling for concrete behaviour is applied. EC2 presents different creep models for normal strength and high strength concrete. *fib* MC10 model for creep introduces new and improved formulas and some inconsistencies existing in older models had been removed.

The development and magnitude of creep deformations in the form of creep coefficients are presented and compared. The models for creep in current use are based on many years' research and experience in describing the long-term behaviour of concrete. The models enable a more accurate analysis and better assessment of the creep deformation of concrete structures at the design stage. Their complexity is significantly reduced and a range of influencing parameters are excluded from the models for simplicity and easy adaptation at the design stage.

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