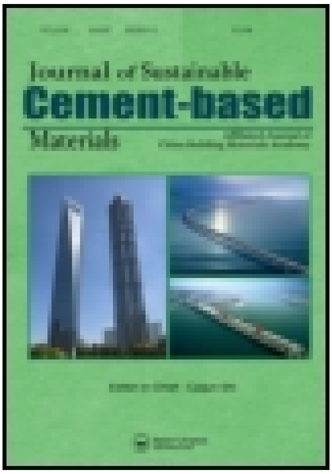
View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by Ghent University Academic Bibliography

On: 29 August 2014, At: 08:37
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK



Journal of Sustainable Cement-Based Materials

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tscm20

Degree of hydration-based creep modeling of concrete with blended binders: from concept to real applications

G. De Schutter[a], Y. Yuan[b], X. Liu[b] & W. Jiang[c]

[a] Magnel Laboratory for Concrete Research, Faculty of Engineering and Architecture, Department of Structural Engineering, Ghent University, Belgium

[b] State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, P.R. China

[c] School of Materials Science and Engineering, Tongji University, Shanghai 201804, P.R. China

Published online: 27 Aug 2014.

To cite this article: G. De Schutter, Y. Yuan, X. Liu & W. Jiang (2014): Degree of hydration-based creep modeling of concrete with blended binders: from concept to real applications, Journal of Sustainable Cement-Based Materials, DOI: 10.1080/21650373.2014.928808

To link to this article: http://dx.doi.org/10.1080/21650373.2014.928808

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

Journal of Sustainable Cement-Based Materials, 2014
http://dx.doi.org/10.1080/21650373.2014.928808

Degree of hydration-based creep modeling of concrete with blended binders: from concept to real applications

G. De Schutter[a]*, Y. Yuan[b], X. Liu[b] and W. Jiang[c]

[a]*Magnel Laboratory for Concrete Research, Faculty of Engineering and Architecture, Department of Structural Engineering, Ghent University, Belgium;* [b]*State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji University, Shanghai 200092, P.R. China;* [c]*School of Materials Science and Engineering, Tongji University, Shanghai 201804, P.R. China*

(*Received 3 January 2014; accepted 22 May 2014*)

The mechanical behavior of hardening concrete is to a large extent determined by the evolving microstructure as a result of the hydration process. For traditional binder systems, consisting of Portland cement or blast furnace slag cement, the degree of hydration is known to be a fundamental parameter in this respect, enabling a detailed study and accurate prediction of the early-age mechanical behavior, including basic creep. Nowadays, in view of improved sustainability of cementitious materials, binder systems tend to become more complex, consisting of a blend of different powders. As the hydration process and microstructure development are influenced by the inclusion of powders into the binder, the question is raised whether the degree of hydration concept is still applicable to concrete based on complex blended binder systems. In this paper, some experimental results are summarized and the application to real structures is illustrated. Basic creep of hardening concrete with complex blended binders can still be modeled following the degree of hydration concept.

Keywords: concrete; blended binders; degree of hydration; basic creep

Introduction

The macroscopic or engineering properties of a structural element made in concrete depend to a large extent on the microstructure at the material's level. The mechanical behavior of concrete is depending on the microstructure as a result of the hydration process. In case of hardening concrete, this microstructure is continuously evolving, due to the ongoing hydration reactions, with continuous formation of hydration products. As the geometry and the properties of the microstructure depend on the amount of hydration products formed, it can easily be understood that the degree of hydration, describing the relative amount of cement that has already reacted, is an important parameter. The degree of hydration can be practically approximated and calculated by considering the heat of hydration.[1] In previous research, in case of traditional binder systems consisting of Portland cement or blast furnace slag cement, the degree of hydration is shown to be a fundamental parameter, enabling a detailed study and accurate prediction of the early-age mechanical behavior, including basic creep.[2–9] Nowadays, in view of improved sustainability of cementitious materials, binder systems tend to become more complex, consisting

---

*Corresponding author. Email: Geert.DeSchutter@ugent.be

of a blend of different powders. Where initially, waste powders have been incorporated in cementitious materials mainly because of environmental reasons, nowadays the sustainability pressure on concrete technology is more and more leading to a complete rethinking of the concept of cementitious binders. Portland clinker, waste materials, and natural powders of different type and nature are being combined in order to benefit from synergetic effects. This is also particularly true in case of powder-type self-compacting concrete (SCC), where a higher powder content is needed to obtain stable mixes. As the hydration process and microstructure development are influenced by the inclusion of powders into the binder,[10–12] the question is raised whether the degree of hydration concept is still applicable to concrete based on complex blended binder systems. In this paper, some experimental results are summarized, and the application to real structures is illustrated.

Degree of hydration

The degree of hydration $\alpha(t)$ of a hardening cementitious material is giving information on the state of the hardening process, and can be defined as the fraction of cement $C(t)$ that has already hydrated, relative to the initial amount of cement C_0, as mathematically shown in Equation (1):

$$\alpha(t) = \frac{C(t)}{C_0} \tag{1}$$

In a practical approximation, the degree of hydration can be estimated as the fraction of the heat of hydration that has been released, following Equation (2):

$$\alpha(t) = \frac{Q(t)}{Q_{\text{tot}}} = \frac{1}{Q_{\text{tot}}} \int_0^t q(t)\mathrm{d}t \tag{2}$$

where $Q(t)$ is the cumulated heat of hydration at time t, Q_{tot} is the cumulated heat of hydration at completion of the hydration process, and $q(t)$ is the heat production rate at time t. The total heat of hydration Q_{tot} liberated after complete hydration is determined by the cement composition. For Portland cement, it can be estimated from the chemical composition by Bogue's formulas. However, no equivalent of Bogue's formulas exists for blast furnace slag cement, nor for complex blends of cement and powders. The total cumulated heat in case of complex binder systems can be experimentally determined by means of hydration tests. In order to make clear that in this case not the theoretical total heat of hydration Q_{tot} after full hydration is considered, but rather the measured cumulated heat of hydration $Q_{\max}$ at the end of the hydration test, the term degree of reaction r is sometimes used instead of degree of hydration, as shown in Equation (3):

$$r(t) = \frac{Q(t)}{Q_{\max}} \tag{3}$$

The degree of hydration is a more fundamental parameter than the degree of reaction, which is an experimental approximation which does not correspond to full hydration. In this paper, the term degree of hydration will be further considered as well. However, the reader will understand that in case of complex binders for which no theoretical estimation of the total heat of hydration is available, a practical approximation through the degree of reaction could be needed.

It is further remarked that the degree of hydration of a blended cement is considered here as an overall degree of hydration. The degree of hydration of the individual powders (Portland, slag, fly ash, etc.) could be considered individually, as could be done also in Portland cement for the individual minerals (alite, belite, etc.). However, this level of detail is not needed when linking the overall state of the reaction process to the macroscopic engineering properties of the concrete.

Basic creep

The basic creep deformation is the time-dependent increase in deformation of a constantly loaded concrete element showing no moisture exchange with the environment. In hardening massive concrete elements, where the effect of drying is very limited in the first weeks and months, basic creep behavior is very important for an accurate estimation of early-age thermal stresses and cracking. Also in high-rise buildings, where massive concrete cores or mega columns are loaded at very early age, the basic creep deformations are primordial while estimating time-dependent (differential) deformations. In case of important moisture exchange with the environment, an additional drying creep component would have to be added, but this is not considered in this paper, as we are more focusing on early-age concrete.

Previously, based on fundamental physical observations, a degree of hydration-based Kelvin chain (Figure 1) has been defined for hardening concrete, for the simulation of instantaneous deformation and basic creep.[4] The Kelvin chain model, with properties depending on degree of hydration, was experimentally validated for constant and varying stress conditions, and a good accuracy was reported.[4]

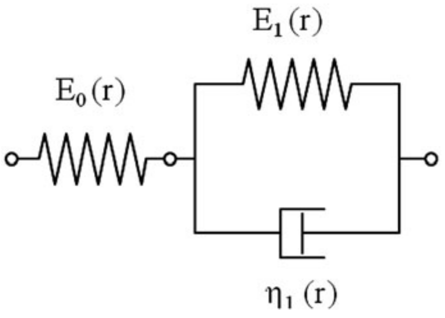


Figure 1. Degree of hydration based Kelvin chain for early age concrete.[4]

In an even more fundamental approach, the study of the effect of ongoing hydration as well as microcracking on the basic creep of hardening concrete has been entirely based on the degree of hydration. Following this approach, time is no longer an explicit model parameter, its role being taken over by the degree of hydration. The translation of the results into a real time frame is obtained through the link between degree of hydration and time. For basic creep under constant stresses, the non-linear model is given in Equations (4) and (5).[5]

$$\varepsilon_{cc}(r, r_b, a_b) = \varepsilon_{c0}(r_b, a_b) \,.\, \varphi_c(r, r_b) \quad (4)$$

$$\varphi_c(r, r_b) = c_1(r_b)\left(\frac{r - r_b}{1 - r_b}\right)^{c_1(r_b)} \quad (5)$$

In Equations (4) and (5), ε_{cc} is the basic creep strain, ε_{c0} the instantaneous deformation due to the stress level a_b at loading, r the degree of hydration, r_b the degree of hydration at loading, φ_c the creep coefficient, and c_1 and c_2 are the constants depending on r_b. In Equation (4), the non-linearity of the basic creep strain is perfectly correlated with the non-linearity of the instantaneous deformation at loading, showing the crucial role of microcracking for the time-dependent mechanical behavior of early-age concrete.

Other degree of hydration-based simulation models for the basic creep of early-age concrete have also been developed, while still considering time as an explicit parameter. According to Guenot et al. [13], the specific basic creep can be obtained with Equation (6):

$$C(t - t_b, r_b, a_b) = \mu_0(r_b, a_b)\left(\frac{t - t_b}{\mu_1(r_b) + t - t_b}\right)^{b} \quad (6)$$

In this equation, r_b is again the degree of hydration at the time of loading

t_b, a_b is the stress level, and b is an exponent. The parameter μ_1 depends on the degree of hydration r_b at the moment of loading t_b, while the parameter μ_0 also depends on the stress level ab at the moment of loading. The creep development is thus both influenced by r_b and by the stress level a_b. These parametric functions μ_0 and μ_1 are cement type dependent,[3] and can thus be different for different blended binder systems.

Fictitious degree of hydration method

Based on Equations (4) and (5), and inspired by the equivalent time method,[14] a new method for the situation of varying stresses was developed, called the fictitious degree of hydration method.[5] During loading, as long as the stress $\sigma(t_b)$ applied at the degree of hydration r_b remains constant, the basic creep evolution can be estimated following the creep curves given in Equations (4) and (5). Now consider the situation that at a certain degree of hydration r, when the basic creep reached the value $\varepsilon_{cc}(r)$, the stress is changed to a new value as shown in Figure 2. In the fictitious degree of hydration method, it is assumed that the further basic creep development can be estimated by means of the creep curve determined by a new value for the degree of hydration at loading r_{bf} obtained by Equation (7):

$$\varepsilon_{cc}(r_b) \quad = \quad \varepsilon_{c0}(r_{bf}, a_{bf}) \,.\, \varphi_c(r, r_{bf}) \tag{7}$$

with:

$$a_{bf} = \sigma(r)/f_c(r_{bf}) \tag{8}$$

in which $f_c(r_{bf})$ is the concrete strength at degree of hydration r_{bf} . In case of (partial) unloading, the recovery creep can be obtained by combining the superposition principle and the fictitious degree of hydration method, as illustrated in the right part of Figure 2. Assume that at a certain degree of hydration r_2, when the basic creep reached the value $\varepsilon_{cc}(r)$, the stress is changed from $\sigma(r_1)$ to a lower value $\sigma(r_2)$. It is assumed that a tensile force, which is equal to $\sigma(r_1)$–$\sigma(r_2)$, is added on the specimen and the total creep is obtained by superposition of the compressive creep, obtained by the fictitious degree of hydration method, and the tensile creep. In case further unloading steps are considered, the creep recovery part can also be calculated following the fictitious degree of hydration method, applied to the tensile creep part. A more detailed background and explanation of the fictitious degree of hydration method can be found in literature.[5]

Blended binders

While decades ago mainly Portland cement and blast furnace slag cement were applied in daily concrete practice, the situation now has significantly changed. Because of several reasons, binder systems are becoming more and more complex, consisting of a combination of different powders in combination with Portland clinker.

One reason for the increased application of different powders is the development of SCC.[15] In several parts of the world, e.g. Europe, the stability of the SCC mix is typically obtained by the application of a high powder content, resulting in the so-called powder-type SCC. In order to avoid problems with increased heat of hydration and increased shrinkage, the high powder contents are obtained by combining cement with other powders like e.g. limestone filler. It has been previously concluded that the addition of mainly inert limestone filler can influence the hydration process and microstructure development of the cementitious materials.[10–12] Due to the high specific surface and the nature of the limestone filler, the hydration of the Portland clinker is accelerated due to

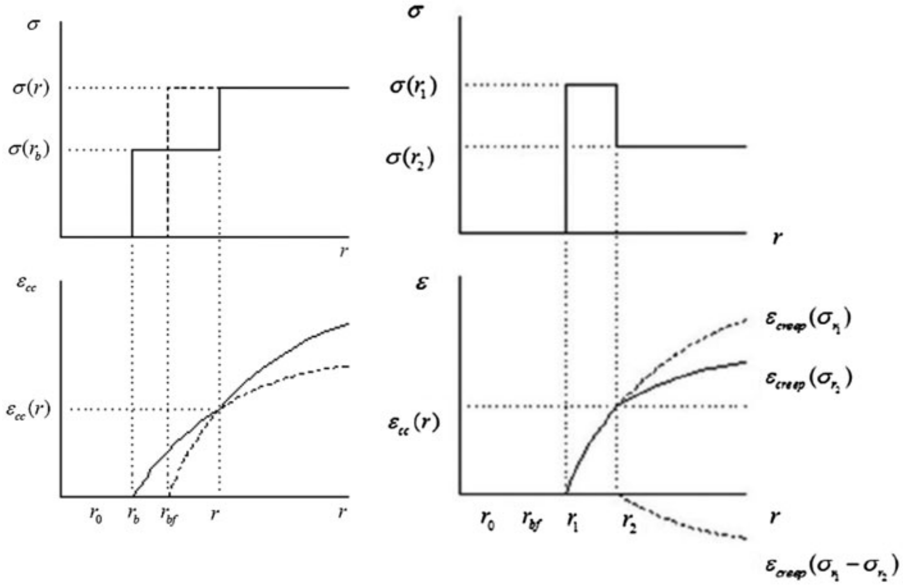


Figure 2. Fictitious degree of hydration method (left figure for increasing stress, right figure for decreasing stress).[5]

improved nucleation. Furthermore, the interaction of the limestone filler with the aluminate phase in the Portland clinker is leading to a modified reaction scheme, inducing the formation of monocarbonate which in case of limestone filler addition is more stable than monosulfate.

Another reason for the increased application of blended binder systems is the search for more sustainable concrete solutions, with reduced carbon dioxide footprint. The production of Portland clinker is inducing the production of almost equal masses of carbon dioxide (typically 0.8 kg of CO_2 per kg Portland clinker). In order to reduce the carbon footprint of concrete, due attention is given to the replacement of Portland clinker by alternative materials, in many cases waste materials like fly ash, rice husk ash, municipal waste ash, etc. The hydration process of these kind of blended systems is also investigated in detail, and many reports can be found in literature, e.g. [16,17].

Based on the increasing insight of the effect of different powders on the hydration process and microstructure development, new developments can be expected in near future, relying on so-called synergetic effects between different powders [18]. A promising new approach seems to combine a minimum amount of Portland clinker with limestone filler and a third (possibly puzzolanic) powder containing aluminate phases. Different synergetic effects occur in this kind of system. The limestone filler is accelerating the Portland reaction due to improved nucleation, the Portland reaction is initiating the puzzolanic reaction, and the limestone filler is interacting with the aluminate phase of Portland clinker and third puzzolanic powder. Other combinations of powders of course are possible, even leading to binders with more than three different powders.

In the sequel of this paper, some basic creep studies on a ternary blended cement in laboratory conditions will be summarized, and the applicability of the degree of hydration concept will be illustrated. Furthermore, the application of this concept in case of some important large-scale structures in China will be illustrated.

Basic creep studies on ternary blends

An experimental program has been set up in order to examine the applicability of the fictitious degree of hydration method for the modeling of early-age basic creep and creep recovery behavior of concrete based on a ternary blend consisting of ordinary Portland cement, blast furnace slag, and fly ash. An overview of the concrete composition is given in Table 1. An ordinary Portland cement of strength class 42.5 MPa was used in combination with blast furnace slag and fly ash.

The creep test apparatus principally consists of a self-balanced frame, which can apply constant compressive force for a certain duration. The concrete specimen is placed between the two plates of the frame. Load is applied to the top plate of the frame by increasing jack pressure with a pump. Once the desired loading level is obtained, the pump is disconnected and the constant pressure on the specimen will be maintained by the springs below the bottom plate of the frame. Overviews of the measuring device and of the shrinkage specimens are given in Figure 3

Readings of the applied force on the creep specimen are taken with a portable force transducer. Two gages of LVDT are placed on opposite surfaces to measure the displacement of specimens under creep load with time. The scale distance is 300 mm in the middle part of the specimen. All the sensors are connected to a computer system for data acquisition.

Concrete specimens used for the creep tests are prisms $100 \times 100 \times 515$ mm^3. All specimens were cast and stored in a curing chamber at 20 ± 2 °C and >90% R.H. for one day. Afterwards, they were removed from their molds and sealed by means of self-adhesive aluminum sheets in order to prevent moisture exchange with the environment. After being equipped with the measuring devices, the specimen is placed in the creep apparatus immediately, in controlled atmosphere at 20 ± 2 °C and 60 ± 5% R.H. In order to study the basic creep behavior at early age, creep tests are carried out for a loading age varying from 1 day to 14 days. The detailed loading program is explained in the following section. At all ages, the basic shrinkage of the concrete specimens has been measured on sealed companion specimens. These shrinkage results on the one hand served as reference information obtained on unloaded specimens, in order to exclude shrinkage deformation from the resulting creep deformation on the loaded specimens. On the other hand, the obtained basic shrinkage information was further applied as input in the modeling of the structural applications.

A series of concrete compressive basic creep tests were conducted at different ages of loading at early age under constant stress level and varying stress level. The stress/strength ratio was reduced from 40 to 20% when partial unloading was considered, in order to study creep recovery.

(1) Experiment 1: Creep under Constant Stress

Table 1. High strength concrete composition in kg/m^3.

W/*B*	Cement (P.O. 42.5)	Water	Sand	Gravel (5–25 mm)	Fly ash	Slag	Superplasticizer
0.35	350	170	720	1020	70	70	4.20

Figure 3. Shrinkage (left) and creep (right) test setup.

Four groups of concrete compressive creep tests are conducted at different ages of loading (1, 2, 3 and 7d) and lasted for 28 days. The stress/strength ratio at the age of loading is 40%.

(2) Experiment 2: Creep under Varying Stress

A stepwise increasing stress is considered in the first load program, whereas some stress decreases are included in the second to fourth load program. The first case of loading is as follows: the specimen is loaded at the age of 1d, and the stress/strength ratio at that time is 40%. The load will be increased accordingly at the ages of 2, 3, 7, and 14d to keep the stress/strength ratio 40%.

Different loading and unloading time are considered in the second, third, and fourth case. The loading programs can be found in Figure 4.

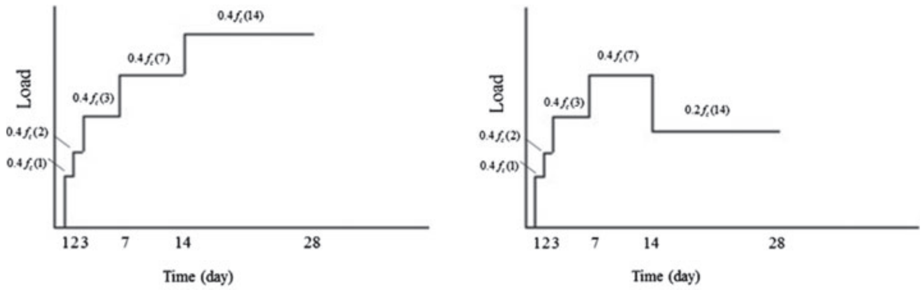
The experimental results of the laboratory creep tests and the simulation results by means of the degree of hydration-based model, including the basic creep strain combined with the instantaneous strain, are shown in Figures 5–8.

Based on the experimental results, it can be concluded that the fictitious degree of hydration method for creep and creep recovery modeling can be applied to ternary blends, even simplifying the hydration process to one general hydration reaction, considering only a single degree of hydration. The model illustrates the fundamental influence of the hydration process on the early-age basic creep and creep recovery behavior, even in the case of complex ternary blends.

Structural applications

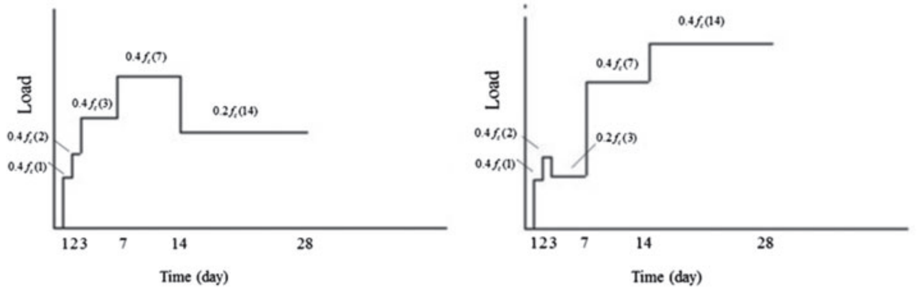
The degree of hydration-based creep model has been applied to real structures, including high-rise buildings for the prediction of the vertical deformation, and massive concrete structures for the estimation of tensile stresses at early age. Two representative cases are briefly illustrated hereafter, one is the Shanghai World Financial Center tower (492 m, Shanghai, 2008) and the other one is the precast segments of the Hong Kong – Macau – Zhuhai tunnel (under construction).

Shanghai World Financial Center (SWFC) is a super tall skyscraper, one of the highest in mainland China, with a height of 492 meters (Figure 9). The main building contains 101 floors above ground, and three floors underground.



(a) The first case

(b) the second case



(c) The third case

(d) the fourth case

Figure 4. Load programs.

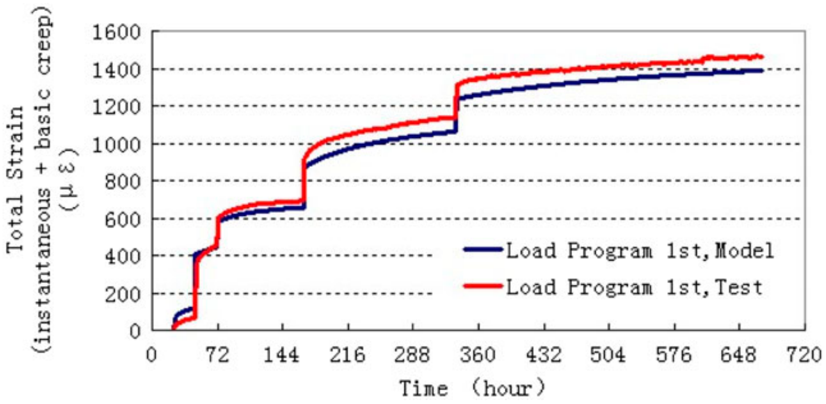


Figure 5. Results for load program 1 of varying stress.

The vertical and especially the differential deformations of concrete core and concrete mega columns are very important for the construction and for the service performance of the super high-rise building.[19]

Embedded vibrating wire strain gages EM-5 have been used to monitor the vertical deformation. Monitoring sections have been installed at the 6th, 18th, 30th, and 42nd floor in the mega-structure column and at the 12th, 27th, 42nd, and 60th floor in the reinforced concrete core. The monitoring results of both the 12th floor of the concrete core and the sixth floor of the mega-structure column are shown in Figure 10 as an illustration. The simulated deformations, obtained with the

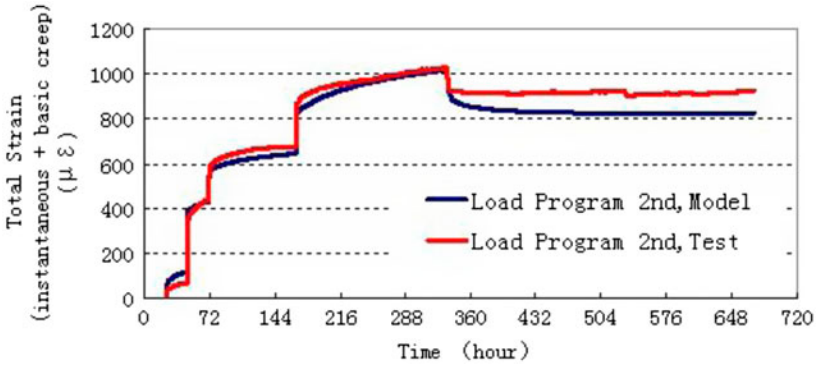


Figure 6. Results for second load program of varying stress.

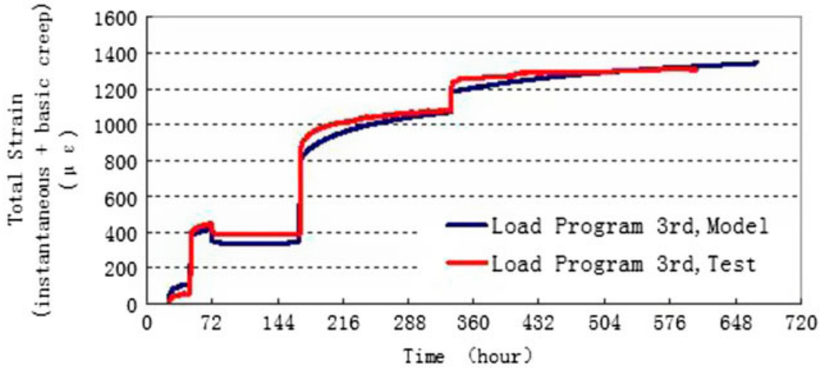


Figure 7. Results for third load program of varying stress.

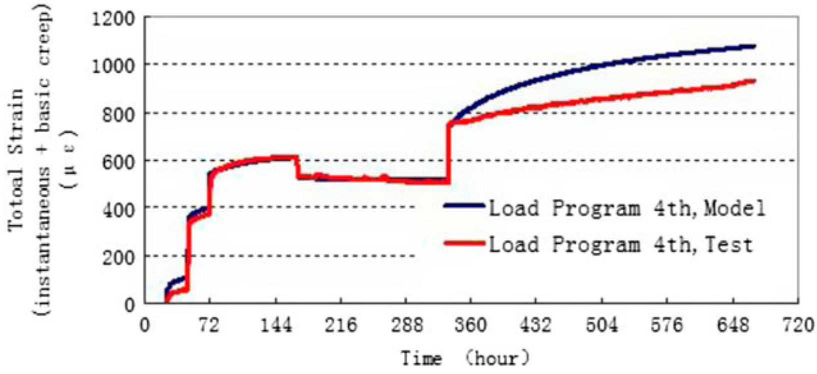
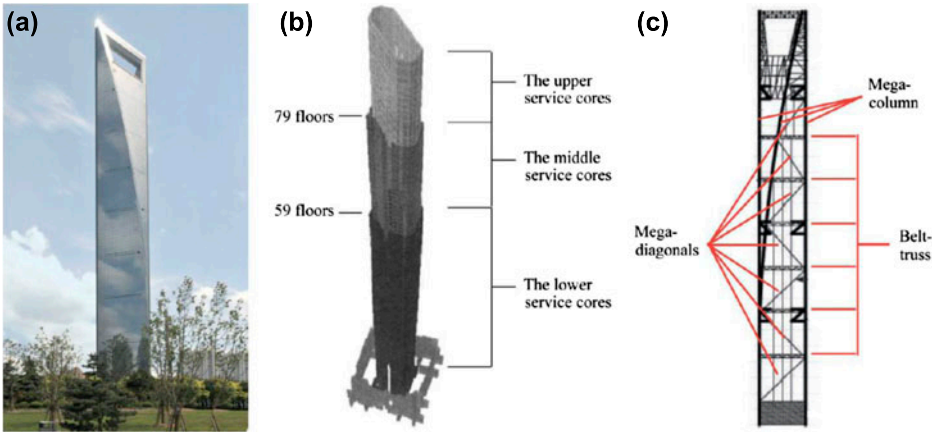


Figure 8. Results for fourth load program of varying stress.

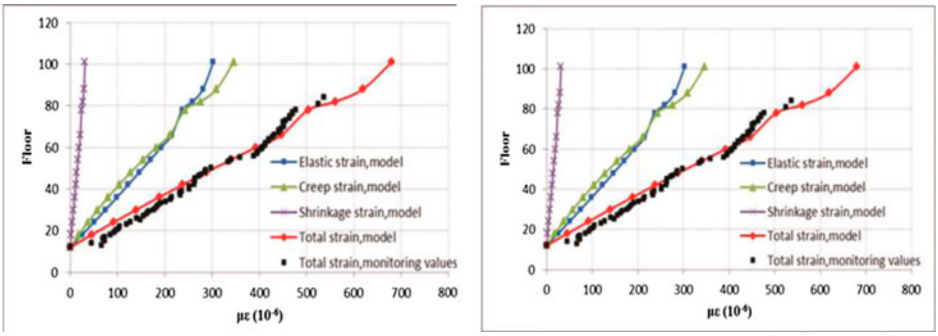


(a) Exterior (b) RC core (c) External structure

Figure 9. Shanghai World Financial Centre (SWFC).

time-dependent numerical analysis applying the degree of hydration-based creep model, are also shown in Figure 10. A good agreement is noticed for the mega-structure column and the concrete core, showing results which are fully in line with the numerically predicted results.

The Hong Kong – Macau – Zhuhai (GZM) Link is a major infrastructure project currently under construction in China. The project links three regions including Hong Kong, Zhuhai, and Macao. The main structures of the project consist of one cable stayed bridge, two artificial islands and an immersed tunnel, and are the largest of its kind in the world with a total length of 49.968 km. The GZM immersed tunnel consists of 33 elements, varying from 112.5 to 180 m in length, resulting in a total immersed tunnel length of 5664 m. Each standard element consists of eight segments of 22.5 m long, 37.96 m wide, and 11.4 m high (Figure 11).



(a) 12th floor of concrete core

(b) 6th floor of mega structure column

Figure 10. Deformation and deformation decomposition of concrete core and structure column. The deformations (horizontal axis) are given during the construction stage depending on the number of floors constructed (vertical axis).

The accurate description of creep behavior is quite important for the calculation of performance of early-age concrete and the control of early-age cracking.[20] The constitutive model for early-age concrete is used for the numerical calculation in which the previously described creep model is included. To get insight in the early-age behavior of the tested segment, a numerical model was employed to reproduce the whole experimental period. At the same time, measurements have been performed on real tunnel segments (Figure 12).

The comparison between the calculated values and the monitored strain data is carried out hereafter. Three typical locations are selected, which include the inner face of the top slab, the center of an external side wall, and the center of the base slab. The strains in both base slab and top slab are horizontal in direction along the transversal direction of the segment, while the strain in the side wall is also horizontal however in longitudinal direction of the tunnel segment. The detailed position of each point is shown in Figure 12.

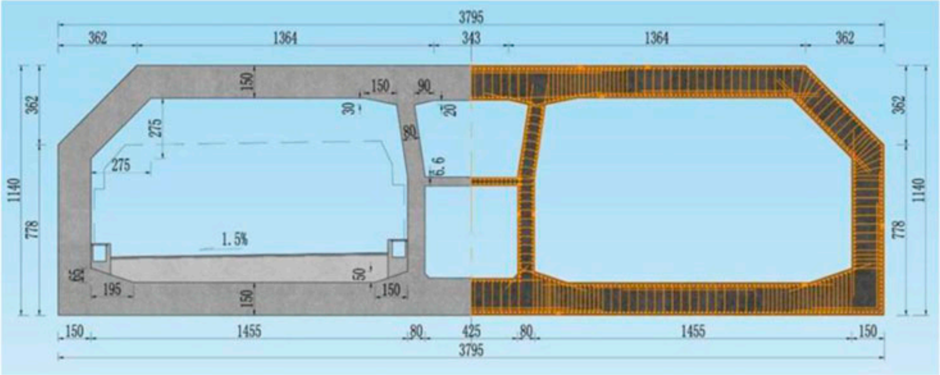


Figure 11. Basic cross-section of the immersed tunnel.

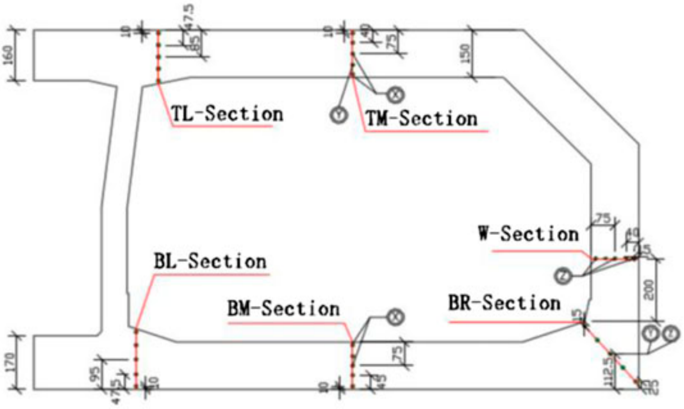


Figure 12. Instrumentation layout.

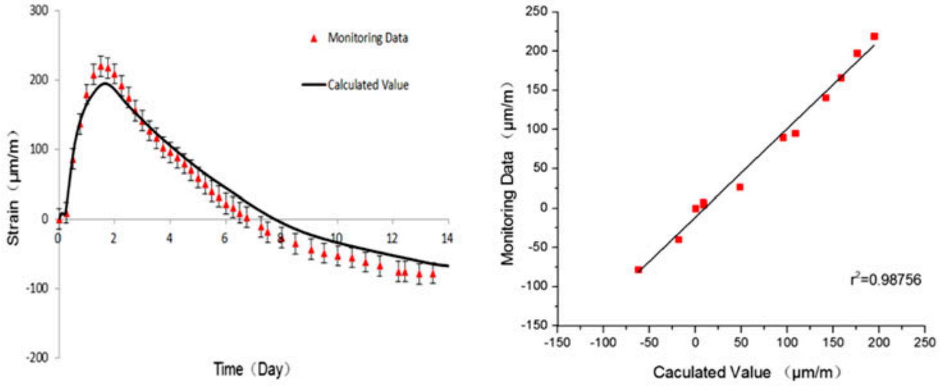


Figure 13. Comparison of monitoring data and simulated strain values at the base slab.

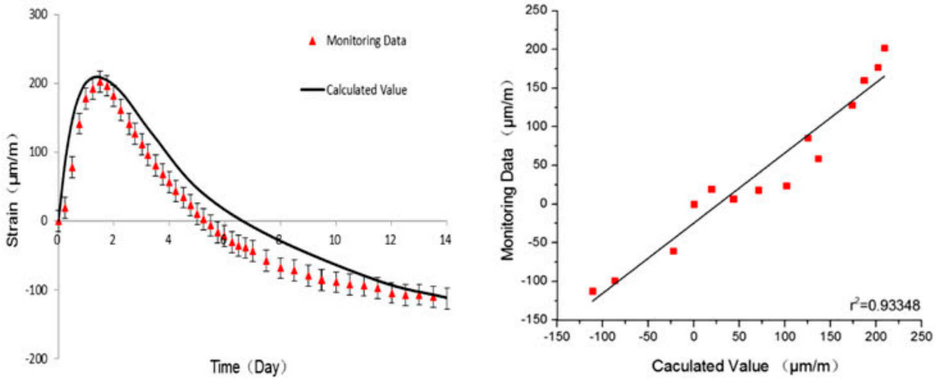


Figure 14. Comparison of monitoring data and simulated strain values at the center of external side wall.

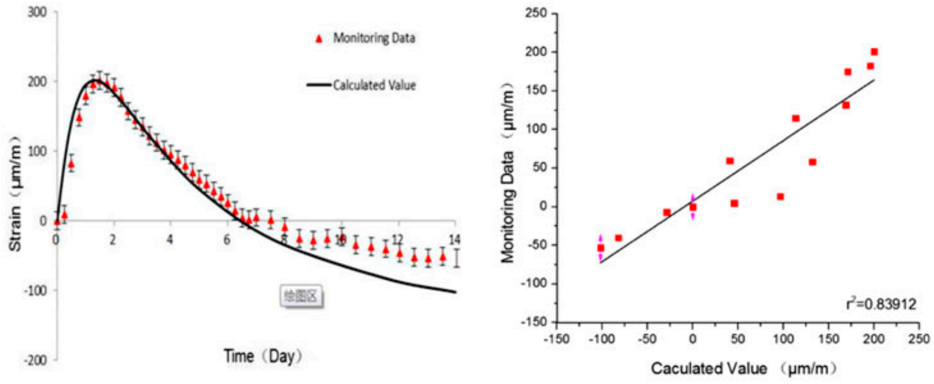


Figure 15. Comparison of monitoring data and simulated strain values at the center of top slab.

Three locations from the tested tube are selected to compare the strain development between the monitoring data and the simulated strain values, as shown in Figures 13–15. The duration from casting to 14th day is shown as the horizontal ordinate. A 5% error bar on the monitored data is also shown in the figures.

A good agreement between monitored strain values and simulation results is noticed. This is also true for the value and timing of the strain peak. The R^2 values of the center of base slab and external wall are 0.987 and 0.933, respectively. However, at the center of the top slab, a slightly lower R^2 value is obtained, equal to 0.839. Nevertheless, the validity of the numerical model is still nicely illustrated by the comparison of the calculated values with the monitoring results. Similar findings are noticed when checking the simulated and monitored stress fields; however this is not shown in this paper.

Discussion

The hydration process and microstructure development of blended systems, containing three or more different powders, are very complex, and involve a multitude of aspects: chemical aspects, physical aspects, dilution effect, and filling or compaction effect. For the purpose of predicting early-age mechanical properties in a practical way, it is not realistic to properly consider all these effects in detail. The previously developed fictitious degree of hydration-based general hydration model [1] considered the twofold character of binary systems consisting of Portland cement and Blast furnace slag, considering the individual degrees of hydration of slag and Portland cement. This approach can also be applied for other binary systems, e.g. consisting of Portland cement and fly ash. Considering different sub-reactions in the system, linked to the different clicker minerals present in the blend, a more detailed approach can even be followed.[21] This kind of detailed fundamental modeling, however, is too complicated in case of practical early-age creep studies.

A more simplified approach, only considering one degree of hydration linked to the overall hydration process of the entire (ternary) blend, is followed in this research. Even while simplifying the hydration process in a significant way, neglecting the individual hydration reactions of the different powder materials, a good prediction of deformation and stresses in early-age concrete elements can be obtained. In this way, the fundamental degree of hydration-based models for the description of mechanical properties during hardening, including basic creep behavior, can be successfully applied to real structures made with complex binder blends.

Conclusions

An overview is given of the degree of hydration concept for the description of mechanical properties of hardening concrete. The application of the degree of hydration concept to complex binders, consisting of three or more different powders, is verified with laboratory test. The experimentally obtained results show that the followed approach, based on one degree of hydration describing the overall hydration process, is leading to acceptable results. The fictitious degree of hydration model for creep and creep recovery can be applied to complex binder systems by simplifying the hydration process to one general hydration reaction. The model has been successfully applied to some important concrete structures as illustrated in the paper.

Acknowledgment

The development of the degree of hydration concept for early-age concrete was financially supported by the Fund for Scientific Research (FWO), Flanders, Belgium. Further research was supported by NSFC (51308405) awarded to Dr Jiang Wei as Principal Investigator. The authors also appreciate the financial support by LiSUM, which is an Erasmus Mundus External Cooperation Windows partnership of European and Chinese scholars.

Notes on contributor

Full professor at Ghent University, Belgium, in the field of Concrete Technology. Author of numerous articles and books, among which 'Self-Compacting Concrete', Whittles Publishing, Caithness, UK, CRC Press, Taylor & Francis Group, Boca Raton, USA, ISBN 978-1904445-30-2, USA ISBN 978-1-4200-6833-7, 2008, pp. 296.

References

[1] De Schutter G, Taerwe L. General hydration model for portland cement and blast furnace slag cement. Cem. Concr. Res. 1995;25:593–604.

[2] De Schutter G, Taerwe L. Degree of hydration based description of mechanical properties of early age concrete. Mater. Struct. 1996;29:335–344.

[3] De Schutter G, Taerwe L. Towards a more fundamental non-linear basic creep model for early age concrete. Mag. Concr. Res. 1997;49:195–200.

[4] De Schutter G. Degree of hydration based Kelvin model for the basic creep of early age concrete. Mater. Struct. 1999;32:260–265.

[5] De Schutter G, Taerwe L. Fictitious degree of hydration method for the basic creep of early age concrete. Mater. Struct. 2000;33:370–380.

[6] De Schutter G. Fundamental study of early age concrete behaviour as a basis for durable concrete structures. Mater. Struct. 2002;35:15–21.

[7] De Schutter G. Influence of hydration reaction on engineering properties of hardening concrete. Mater. Struct. 2002;35:447–452.

[8] De Schutter G. Finite element simulation of thermal cracking in massive hardening concrete elements using degree of hydration based material laws. Comput. Struct. 2002;80:2035–2042.

[9] De Schutter G. Applicability of degree of hydration concept and maturity method for thermo-visco-elastic behaviour of early age concrete. Cem. Concr. Compos. 2004;26:437–443.

[10] Poppe A-M, De Schutter G. Cement hydration in the presence of high filler contents. Cem. Concr. Res. 2005;35:2290–2299.

[11] Ye G, Liu X, Poppe A-M, Taerwe L. Influence of limestone powder used as filler in SCC on hydration and microstructure of cement pastes. Cem. Concr. Compos. 2007;29:94–102.

[12] Liu X, Ye G, De Schutter G, Yuan Y. Simulation of the microstructure formation in hardening self-compacting cement paste containing limestone powder as filler via computer-based model. Mater. Struct. 2013;46:1861–1879.

[13] Guenot L, Torrenti JM, Laplante P. Stresses in early-age concrete: comparison of different creep models. Mater. J. 1996;93:246–253.

[14] Acker P, Lau MY. Creep Behavior of Concrete: Experimental Validation of the Equivalent Time Method. Bull. Liaison LCPC. 1989;163:31–39.

[15] De Schutter G, Bartos PJM, Domone P, Gibbs J. Self-compacting concrete. Caithness: Whittles, Boca Raton, FL: CRC Press, Taylor & Francis Group; 2008, ISBN 978-1904445-30-2, ISBN 978-1-4200-6833-7, p. 296.

[16] Baert G, Hoste S, De Schutter G, De Belie N. Reactivity of fly ash in cement paste studied by means of thermogravimetry and isothermal calorimetry. J. Therm. Anal. Calorim. 2008;94:845–492.

[17] Baert G, Debelie N, Deschutter G. Multicompound model for the hydration of Portland cement – fly ash binders. J. Mater. Civ. Eng. 2011;23:761–766.

[18] De Weerdt K, Blended cement with reduced CO_2 emission – utilizing the fly ash-limestone synergy, Doctoral thesis, Norwegian University of Science and Technology, Trondheim, Norway, 2010.

[19] Jiang W, Gong J, De Schutter G, Huang Y, Yuan Y. Time-dependent analysis during construction of concrete-tube for tower high-rise building. Struct. Concr. 2012;13:236–247.

[20] Liu X, Jiang W, De Schutter G, Yuan Y, Su Q. Early-age behavior of precast concrete immersed tunnel based on degree of hydration concept. Structural Concrete, 15, 2014, 66–80. doi:10.1002/suco.201300027.

[21] Baert G, De Belie N, De Schutter G. Multicompound model for the hydration of Portland cement – fly ash binders. J. Mater. Civ. Eng. 2011;23:761–766.