TIME- AND LOAD-DEPENDENT BEHAVIOUR OF FLOWABLE CONCRETE: PROGRESS REPORT OF FIB TASK GROUP 4.3

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Abstract

Stress and strain interaction is of vital importance for concrete structures as it has an influence on cracking, deflection and prestressing loss. With the increased range of compressive strengths and flow characteristics, the mixture composition of nowadays concretes often differs considerably from Vibrated Concrete (VC) with regard to paste strength, paste composition and paste volume. As a result, the viscoelastic properties of concrete are altered as well and some of the established stress-strain-relations valid for VC have to be questioned or at least reconfirmed for new concrete types like Self-Compacting Concrete (SCC), Ultra High Performance Concrete (UHPC) and Engineered Cementitious Composites (ECC). This paper discusses time- and load-dependent characteristics of flowable concrete as an outcome of a workgroup within fib Task Group 4.3 that aims at facilitating the use of innovative flowable materials for the design of concrete structures.

Keywords: Autogenous shrinkage, Cracking sensitivity, Creep, Drying shrinkage, Flowable concrete

1 Introduction

With the trends to apply concrete of improved workability and to use new concrete components more options are available to design concrete. Concrete types like SCC, UHPC and ECC require different mix design approaches compared to VC and in case, a new engineering approach. Mixture compositions of different concrete types vary widely. For example, UHPC and ECC contain aggregates with a relatively small maximum grain size and fibres are added to obtain the required tensile strength and ductile behaviour. At specific points in a structure, strain caused by shrinkage and creep may add up or creep may lead to relaxation and reduce the stress caused by shrinkage strain. Because of different mixture compositions the ‘laws’ which are valid for shrinkage and creep of VC have to be carefully checked if they can be applied to these new types of concrete.

2 Creep

2.1 Creep in compression

(a) Influence of paste volume and w/p: Comparing creep strain and creep coefficients of VC and SCC of the same strength class, strength development and binder composition, the differences of creep coefficients are smaller than the ones of creep strain (Fig. 1).

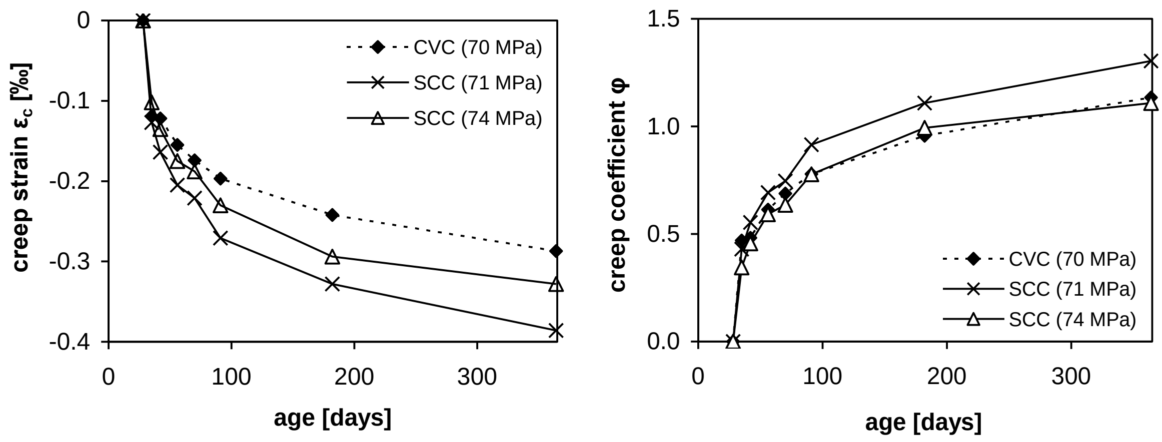

Fig. 1 a) Creep strain and b) creep coefficient of VC (CVC) and SCC produced with Ordinary Portland Cement versus time (applied load = 10 MPa / numbers in parentheses = compressive strength at 28 days / paste volume of SCC is 80 l/m3 higher than the one of VC) (Loser & Leemann 2006).

Even when results of different studies are not consistent, there seems to be a general agreement that the creep coefficient and the specific creep are normally slightly higher for SCC compared to VC (Vieira & Bettencourt 2003; Loser & Leemann 2006). When an identical w/c and an identical grain size distribution of the aggregates but a difference in paste volume of 150 L/m^3 are applied, higher creep strain and higher creep coefficients of SCC compared to VC are observed (Leemann, Lura & Loser 2011). Although UHPC contains a considerable volume of paste, its creep behaviour is not significantly different compared to both SCC and VC. Specific creep of UHPC is in the range of 0.01-0.035 ‰/MPa, while the creep coefficient is in the range of 0.5-1.2 (Mazloom, Ramezanianpour & Brooks 2004; Tue, Ma & Orgass 2006; Flietstra & al. 2012). In general, these values are slightly lower than for VC and SCC. Heat curing within the first days decreases creep of UHPC (AFGC 2002; Garas & al. 2012). Because of a high paste volume ECC show large creep deformations, but due to a low E-modulus creep coefficients can be even smaller than the ones of VC (JSCE 2008).

(b) Influence of binder composition: An investigation of basic and drying creep of SCC shows that both increase when cement is replaced with limestone powder at a constant water-to-powder ratio (w/p) and volume of paste (Fig. 2). When the specific creep is calculated though, there are only insignificant differences between the four different SCC mixtures, as the compressive strength decreases with increasing limestone content.

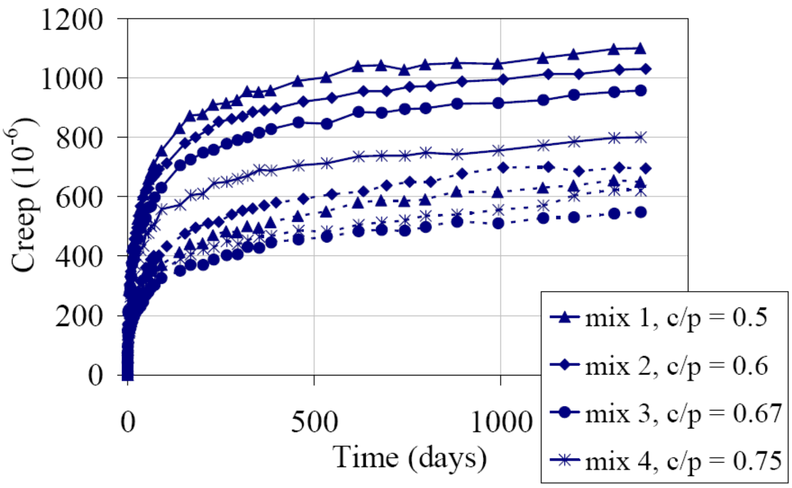

Fig 2 Basic (dotted lines) and drying creep of SCC at constant paste volume and water-powder-ratio (0.28) with varying limestone powder content (Poppe & DeSchutter 2005).

A variation of the grain size distribution of the aggregates, w/c, paste volume and binder composition did not cause significant differences in creep of VC and SCC (Persson 2001). Assessing the influence of the binder composition on creep, the hydration kinetics of the binder after loading has to be considered. SCC produced with Ordinary Portland Cement (OPC) or a combination of OPC with limestone powder has a lower strength increase after loading than SCC with fly ash or slag. Therefore, the creep coefficient of systems with fly ash or blast furnace slag increases less compared to SCC produced with OPC or OPC with non-reactive additions. In High Performance Concrete (HPC) basic creep decreases replacing cement with silica fume or blast furnace slag (Li & Yao 2001; Mazloom, Ramezanianpour & Brooks 2004). The only component in UHPC contributing to creep seems to be the C-S-H phase (Acker 2004). The creep deformation of ECC can be reduced by approximately 50% replacing 50% of the cement with inert fines (grain size of 0.15-0.30 mm) (Billington & Rouse 2003). In Flietstra & al. (2012) the influence of applied load and temperature on UHPC were investigated. Two different load levels of 19 and 58 MPa were applied after demoulding. The creep deformation was measured for about 60 hours at ambient temperature, for 60 hours during a heat treatment at 90 °C and afterwards again at ambient temperature until 28 days. The creep deformation at both load levels was similar during the first two periods while it was higher by a factor of two during the third period.

2.2 Creep in tension

While similar creep coefficients of VC in tension and compression were observed (Gutsch 2002), differences can occur in HPC (Atrushi 2003). The initial creep compliance in tension is lower but increases more with time, leading to an intersection of creep compliance in tension and compression few days after loading (Atrushi 2003). On the other hand, the specific tensile creep of VC was measured being approximately four times higher than the specific compressive creep (Li, Wee & Wong 2002). The increase in creep of ECC after cracking is likely caused by fibre creep or time-dependent fibre pull-out (Boshoff & Van Zijl 2007).

3 Shrinkage

3.1 Autogenous shrinkage

a) Influence of paste volume: At a constant w/p, the autogenous shrinkage of SCC increases with increasing paste volume (Rozière & al. 2007). As a result, VC shrinks less than SCC when the binder composition and strength class are the same. Autogenous shrinkage of UHPC is considerably larger than the one of VC (Loukili, Khelidj & Richard 1999; Graybeal 2006). However, this cannot only be attributed to the high paste volume of UHPC, but is a combined effect of paste volume and low w/p. In ECC a decrease in paste volume by the addition of fine-grained aggregates (grain size of 0.15-0.30 mm) can significantly reduce autogenous shrinkage (Billington & Rouse 2003).

(b) Influence of binder composition: Autogenous shrinkage is usually significantly lower than drying shrinkage in ECC and normal strength SCC. When the amount of limestone powder is increased at a constant w/p and constant paste volume, autogenous shrinkage decreases (Fig. 3) (Poppe & DeSchutter 2005; Rozière & al. 2007; Pons, Proust & Assié 2003). Increasing only the content of limestone powder but keeping cement and water contents constant has only a minor effect on autogenous shrinkage (Vieira & Bettencourt 2003). Increasing the fineness of the limestone filler leads to an increase of autogenous shrinkage in the first day (Esping 2008). Replacing cement with silica fume leads to an increase of autogenous shrinkage (Zhang & al. 2009; Mazloom, Ramezanianpour & Brooks 2004; Eppers & Müller 2008).

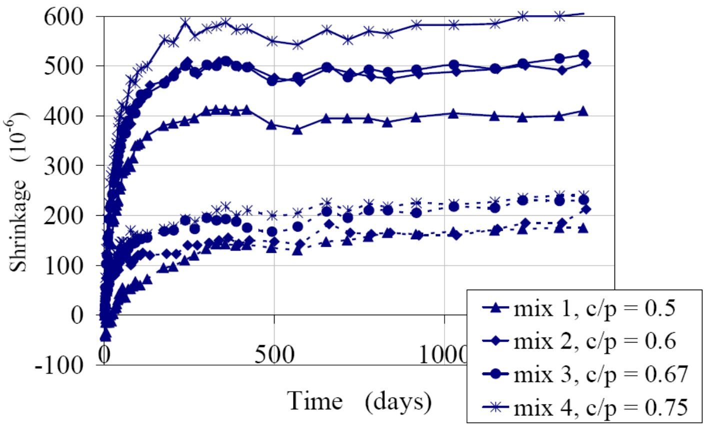

Fig 3 Autogenous (dotted lines) and total shrinkage of SCC with varying limestone powder content, constant w/p (0.28) and constant volume of paste (Poppe & DeSchutter 2005).

A HPC with a replacement level of 25% cement with fly ash shows approximately the same level of autogenous shrinkage as a concrete with the same paste volume but 100% OPC as binder. However, autogenous shrinkage is considerably decreased when the replacement level of cement with fly ash is increased to 50% (Termkhajornkit & al. 2005). This relation should be also applicable for SCC. The use of slag cement may lead to an initial expansion of SCC (Piérard, Dieryck & Desmyter 2005). If the paste volume is increased by mineral additions, the result can be less autogenous shrinkage, since some constituents contribute to expansion (Lura, van Breugel & Maruyama 2001). However, the effect of different mineral additions on autogenous shrinkage seems to be mainly an effect of the resulting pore size distribution. The long term autogenous shrinkage is not much influenced by supplementary materials as long as the critical pore diameter remains unchanged, even if the early age autogenous shrinkage varies considerably (Craye & al. 2010). Results on pastes confirm the latter in that a linear relationship was found between autogenous shrinkage and the amount of pores between 5 and 50 nm (Li, Bao & Guo 2010). Due to the change in pore size distribution coarse fly ash decreases autogenous shrinkage, silica fume increases it and blast furnace slag seems to have only a minor influence (Li, Bao & Guo 2010). The addition of steel fibres in UHPC may lead to a reduction in shrinkage (Eppers & Müller 2008; Loukili, Khelidj & Richard 1999). Generally, the cement content and w/p are the most influential parameters governing autogenous shrinkage. Shrinkage reducing agents (SRA), shrinkage compensating agents (SCA) and internal curing with saturated lightweight aggregates or superabsorbent polymer (SAP) permit a reduction of autogenous shrinkage (Mechtcherine & al. 2006; Koh & al. 2011; Park & al. 2011; Park & al. 2012).

(c) Influence of w/p: In general, autogenous shrinkage represents a substantial part of total shrinkage at a w/c below about 0.40. In the case of UHPC autogenous shrinkage is considerably larger than drying shrinkage. This applies for both a w/p-decrease by decreasing the water content at constant cement content or by increasing the cement content at constant water content (Eppers & Müller 2008). Autogenous shrinkage typically proceeds relatively fast during the first days of hydration and it is less afterwards. However, the binder used has an important influence as well.

(d) Influence of internal curing: Autogenous shrinkage can be decreased by internal curing. Usually, materials with physically bound water are used for this purpose. One possibility for internal curing is the use of super-absorbent polymers. With ongoing hydration the internal relative humidity in the cement paste decreases. This causes a gradient in water activity between the water in the SAP and the pore fluid (Lura & Jensen 2007). The SAPs are desorbed and provide water to the pore system of the cement paste resulting in a lower degree of self-desiccation and with it less autogenous shrinkage (Fig. 4). SAPs have been successfully applied in UHPC (Mechtcherine, Dudziak & Hempel 2009); the effect of SAPs depends on their size and content: at a dosage of 0.3% large particles seem to be more efficient for internal curing than smaller ones (Lura, Durand & Jensen 2006). Doubling the dosage to 0.6% the differences between large and small particles disappeared. SAP can have a beneficial effect on plastic and drying shrinkage as well (Mechtcherine & Dudziak 2012). Combining SAP with partially hydrated cementitious materials (PHCM) further reduces autogenous shrinkage

(Soliman & Nehdi 2013). However, the effectiveness of SAP to decrease shrinkage seems to be worse under field conditions compared to laboratory conditions (Soliman & Nehdi 2012). Lightweight aggregates have also successfully been applied for internal curing (Bentur, Igarashib, Kovler 2001).

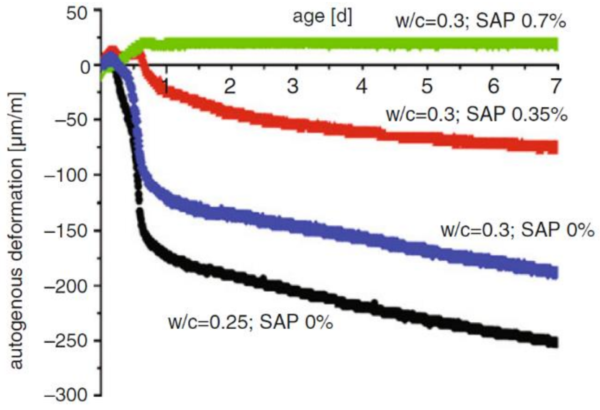

Fig 4 Autogenous shrinkage of concrete reduced by the use of SAP (Igarashi & Watanabe, 2006).

(e) Influence of heat treatment: As in the case of creep, shrinkage measurements on UHPC usually start after heat curing, typically 5-7 days after concrete production. The results reported on the effect of heat treatment on autogenous shrinkage are inconsistent. While some studies report a decrease of autogenous shrinkage strain with increasing temperature (Garas, Kurtis & Kahn 2012), other studies report the opposite (Matsuda & al. 2011; Graybeal 2006). The shrinkage was measured for about 60 hours at ambient temperature, for 60 hours during a heat treatment at 90 °C and afterwards again at ambient temperature until 28 days (Flietstra & al. 2012). Shrinkage before and after heat treatment was in the same range (252 versus 305 µm/m) while it was about 5 times lower during the heat treatment. The influence of heat with respect to hydration and heat treatment can to some degree compensate for the occurrence of autogenous shrinkage in an early phase. The influence of heat treatment most likely depends on its start compared to the progress of cement hydration.

3.2 Drying shrinkage

a) Influence of paste volume and w/p: The total shrinkage increases with increasing paste volume (Loser & Leemann 2009). When w/p is kept constant, the relation between shrinkage and paste volume is approximately linear and can be regarded as the dominating parameter in drying shrinkage (Fig. 5). With constant paste volume but increasing water content, the total shrinkage may increase as well (Pons, Proust & Assié 2003). As a result, shrinkage is increased considerably when the increase of paste volume goes together with an increase in water content (Rozière & al. 2007). Drying shrinkage in UHPC is very low (in the range of 0.1‰) compared to autogenous shrinkage (Fig. 5) (Garas & al. 2009; Koh & al. 2011). The total shrinkage reaches values in the range of 0.50-1.00 ‰ (Loukili, Khelidj & Richard 1999; Koh & al. 2011). Although the shrinkage of ECC is high (range of 1‰ at a RH of 60%), its tensile strain capacity seems to be higher than the drying shrinkage deformation (Weimann & Li 2003); the tensile strain capacity depends on the composition and tensile characteristics of the ECC under consideration.

The shrinkage of SCC can be decreased using shrinkage compensating cement (Zhang & al. 2009). Drying shrinkage of High Performance Fibre Reinforced Cementitious Composites (HPFRCCs) can be reduced to the level of VC by adding shrinkage reducing/compensating admixtures (JSCE 2008).

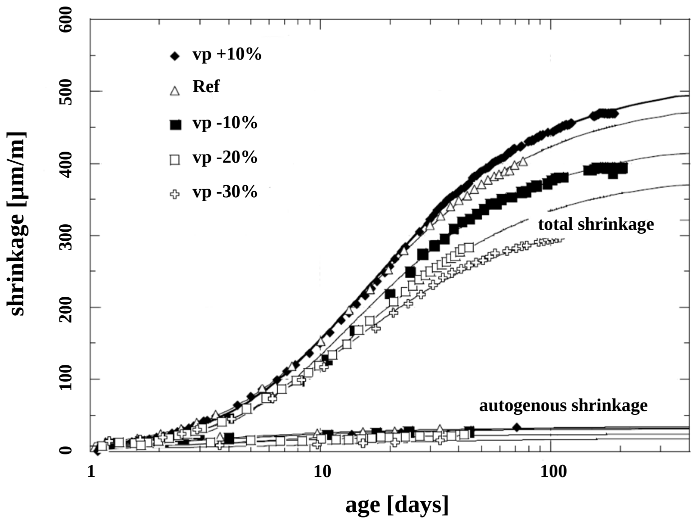

Fig 5 Shrinkage of SCC with varying paste volume (paste volume vp: 291-457 l/m^3) and constant w/p (w/p = 0.32, w/c = 0.54) (Rozière & al., 2007).

(b) Influence of binder composition: The replacement of cement with siliceous mineral additions or with limestone powder generally leads to a reduction of total shrinkage (Poppe & DeSchutter 2005). The only exception is silica fume which increases the total shrinkage. In general, an increased fineness of the cement increases shrinkage (Vikan, Hammer & Kjellsen 2010). When concretes produced with different binders are compared, the absolute values of shrinkage strain and mass loss do not show the same relation (Leemann, Lura & Loser 2011; Vikan, Hammer & Kjellsen 2010). Binary, ternary and quaternary blends of cement were investigated by Güneyisi (2010), and it was observed that fly ash, blast furnace slag and metakaolin relatively decreased shrinkage, and that silica fume contributed to more shrinkage in SCC. Generally, a replacement of cement with additions leads to a higher mass loss during the first days even when the shrinkage strain is the same or lower than the one of mixtures produced with plain OPC (Vikan et al. 2010). However, the relative change of these two parameters are the same and appear to be unaffected by binder type or volume of paste, when the values of shrinkage strain and mass loss at an age of 91 days are used as a reference. This leads to the suggestion that the mechanisms leading to shrinkage are the same for different types of concrete, even when the absolute values differ. The ranking of cements with respect to shrinkage can change depending on the initial curing (Hammer 2009). Concrete with rapid hardening cement (having a high fineness) has considerably higher shrinkage than concrete with standard cement (lower fineness and with 20% fly ash), when initially water cured (during 6 days after demoulding). When initially cured in 90% RH in the same period, there was no significant difference between the two. Drying shrinkage can be decreased considerably by the use of SRA (See & Attiogbe 2005; Loser & Leemann 2009).

4 Cracking sensitivity

4.1 Shrinkage-induced cracking

(a) Plastic and early hardening state: Plastic shrinkage of SCC has been found to be higher than for VC of the same w/c ratio (Gram & Pentti, 1999). At a high evaporation rate, both plastic shrinkage and the cracking risk of SCC and VC of the same strength class are comparable (Turcy & Loukili 2006). At a low evaporation rate, the lack of bleeding of SCC produced a higher plastic shrinkage, most likely increasing the susceptibility to plastic shrinkage cracking. On the other hand, horizontal plastic shrinkage of VC starts earlier and is higher than that of SCC of comparable compressive strength but different paste volume and w/c (Holt & Schodet 2002). Besides the w/b, the fineness of the binder increases the cracking risk. The addition of a SRA and a paraffin-oil based admixture were able to efficiently prevent cracking (Leemann, Nygaard & Lura 2014). The first succeeded by reducing surface tension and with it capillary underpressure. The second worked because the paraffin-oil was transported to the concrete surface where it formed a continuous impermeable film deceasing water evaporation. Due to a reduced w/p, finer cements, and a higher volume of filler, SCC should be more susceptible to plastic shrinkage cracking than VC and accordingly special care should be taken to reduce evaporation in the first hours after casting (Hammer 2003). These considerations seem to be partially contradicted by experiments on SCC with limestone filler with different fineness, where it was observed that a high fineness reduced both the evaporation rate and the risk of cracking (Esping 2008). Concretes having an equal water/powder-ratio (cement plus fines, w/p=0.35) but different cement/fines-ratio were studied by Hammer (2007b); the fines had approximately the same fineness as the cement. The results, with respect to deformations in the plastic stage, confirm that w/p is the important factor rather than w/c. In general, the inconsistent results in the literature indicate that shrinkage-induced cracking of SCC in the plastic state is highly dependent on the materials used, the mix design and the experimental set-up.

(b) Hardened state: The proneness to cracking of a particular concrete is not only determined by the shrinkage strain but by the interaction of the time-dependent viscoelastic properties, the tensile strength and the E-modulus. When the w/p is constant and the tensile strength is similar, the tensile stress of SCC developing in the ring test and in a shrinkage frame with passive restraint increases with paste volume (Leemann, Lura & Loser 2011; Rozière & al. 2007). The time of cracking follows the same pattern (See & Attiogbe 2005). The relaxation of VC and SCC having a considerable higher paste volume differs; VC shows a lower degree of relaxation, which is the result of the generally lower creep of VC. In a passive restrained shrinkage frame the replacement of cement with either limestone powder or fly ash leads to a decrease of shrinkage and the time of cracking is increased. For two SCC's with identical paste volume and composition but different water contents, the one with the lower w/c cracks first (Tongaroonsri & Tangtermsirikul 2009). This is caused by the higher E-modulus and resulting higher stress rate directly after the 7 day curing period. When the gravel content of SCC with identical paste volume, binder composition and w/p is increased, the time of cracking increases as well (See & Attiogbe 2005). Cracking occurs earlier when crushed aggregates are used instead of rounded aggregates (See&Attiogbe, 2005). As SRA's decrease the total shrinkage, they are able to delay the time of cracking (Loser & Leemann 2009; See & Attiogbe 2005). The cracking risk can be further decreased by the combination of SRA with fibres (Hammer 2007a).

The use of polycarboxylate-based superplasticizer (SP) seems to result in a higher cracking risk than the use of poly-naphthalene sulfonate-based SP (Hammer 2002). UHPC can develop stress before setting causing a risk of first crack development at a very early stage (Kim & al. 2012). Stress measurements in a rigid cracking frame show that the stress increase during the first 20 hours is larger for HPC and UHPC produced with OPC than for HPC and UHPC produced with slag cement (Lura, van Breugel & Maruyama 2001; Schachinger & al. 2002). Afterwards, stresses of UHPC with slag cement are considerably higher because UHPC with OPC shows higher relaxation (Schachinger & al. 2002). UHPC reaches higher stress levels than VC and SCC before it cracks in the ring test and in case of additional fibre reinforcement no cracking occurred. Shrinkage-induced cracking of UHPC is a special case as the high fibre content leads to a ductile behaviour (Habel 2004). Curing has a significant influence on the cracking risk due to restrained shrinkage for all types of concrete. Longer water curing leads to a decrease of the time of cracking after the end of curing, as creep is reduced and the E-Modulus increased with time (Loser & Leemann 2009; See & Attiogbe 2005). As a result, the low degree of relaxation leads to relatively fast cracking. Due to its generally higher creep and consequently higher degree of relaxation, SCC can crack at the same time or even later than VC despite the higher shrinkage rate (Loser & Leemann 2009). However, when drying occurs fast, the influence of stress relaxation due to creep is low and the time of cracking mainly depends on shrinkage.

4.2 Thermal dilation and thermal cracking

Thermal dilation is the product of the temperature change, ΔT, and the coefficient of thermal expansion (CTE). ΔT is determined by the maximum temperature, which is mainly dependent on the amount and type of binder, geometry of the component and environmental conditions. Consequently, designing SCC and UHPC by the use of increased binder content will contribute to an increased susceptibility to thermal cracking. Thermal dilation increases with decreasing w/b (Bjøntegaard 1999). The influence of fly ash addition on early age cracking of SCC was investigated by Utsi & Jonasson (2001); even if the fly ash addition resulted in higher heat evolution, a numerical stress analysis showed that the risk for early age cracking for a typical civil engineering structure is significantly decreased in the mixes containing fly ash. It has been shown that the use of SAP can significantly reduce the risk of thermal cracking by decreasing the CTE (Wyrzykowski & Lura 2013). As the CTE not only depends on temperature but also on the internal relative humidity, it can be reduced by 60-70% during the first days of hydration by maintaining a high internal relative humidity.

5 Conclusions

This paper reviewed the effect of the mixture composition of flowable concrete, which often contains fibres, on creep, shrinkage and the risk of cracking. As pointed out, the mix design varies considerably not only between different concrete types but for one type of flowable concrete as well. This paper showed tendencies without providing guidelines for specific creep and shrinkage behaviour. The behaviour can be modelled and simulated; tests always deliver more accurate results than assessments or modelling. For specific results and more details about the time-dependent behaviour of flowable concrete, the reader is referred to the state-of-the-art report prepared by fib Task Group 4.3.

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