DESIGN OF CONCRETE FOR HIGH FLOWABILITY: PROGRESS REPORT OF *FIB* TASK GROUP 4.3

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Abstract

Flowable concretes can differ significantly from traditional vibrated concrete. Concrete types like self-compacting concrete (SCC), ultra-high performance concrete (UHPC) and high performance fibre reinforced cementitious composites (HPFRCCs) require novel mix design approaches. This has consequences for the production and the performance in the hardened state. Mix designs for flowable concretes can incorporate a wide variety of innovative admixtures or components: e.g. superplasticisers increase the flowability and allow for significant reduction of the water content, shrinkage compensating admixtures or superabsorbent polymers support sound and damage free curing processes, viscosity modifying admixtures enhance the robustness, and new fibre types allow for sophisticated and tailored structural performance.

The new Model Code has limitations regarding the application of flowable concrete, e.g. thresholds for the minimum aggregate size and the maximum strength. Provisions are added to include fibres for structural design. *fib* Task Group 4.3 aims at facilitating the use of innovative flowable materials for designing concrete structures and considers three aspects of flowable concrete: material properties, production effects and structural boundary conditions and performance. This paper reports about the progress of *fib* TG 4.3 related to the mix design of flowable concrete and discusses the present state-of-the art concerning admixtures and robustness.

Keywords: Admixtures, *fib* Model Code, Fibres, Flowable concrete, Mix design, Robustness

1 Introduction

1.1 General aspects of modern concrete technology

Over the course of the last three decades concrete has evolved from a rather simple mass construction material based on only the three components cement, water, and aggregates towards a high performance material. Modern concrete can be tailored for high performance applications and according to individual user specifications. For many decades the water-cement ratio (w/c) was a limiting factor. It had to be sufficiently low to guarantee a satisfying strength but high enough to allow for a reliable casting process. The reason for the rapid evolvement of concrete technology in the last three decades was the increasing awareness about how the workability of concrete and particularly the rheology or flowability of concrete can be manipulated without compromising the hardened state properties. The incorporation of superplasticisers in concrete eventually enhanced the workability without the need to increase the water-cement ratio or alternatively it became possible to significantly reduce the w/c ratio without loss of workability. This finally resulted in concrete with higher performance and with specified properties. With superplasticisers in conjunction with additions (e.g. inert or reactive mineral fines that add up to the powder content in the binder system) cement can be reduced in concrete and the particle packing of cementitious systems can be optimised, which in return helps to enhance the flow properties. Additions modify the water demand and may interact with superplasticisers as well. Therefore, today it is possible to cast a wide range of concrete types, which exhibit more or less flowable properties. Examples of flowable concrete types are given in Table 1.

Table 1
Flowable concrete types

Self-compacting concrete	Comprises all concrete types which exhibit slightly or significantly higher paste volumes than normal concrete. The flowability is typically generated by the combination of powders in interaction with high amounts of superplasticiser. Depending on the paste volume, the water volume, the superplasticiser type and dosage, yield stresses and plastic viscosities can vary in a wide range.
High performance concrete (HPC)	Concrete with strengths higher than standard strengths (approximately 50 MPa to 120 MPa). The high cement contents and the dense particle packing makes flowable consistency favourable.
High performance fibre reinforced concrete (HPFRC)	Like HPC but including supplementary fibres. In addition, a flowable consistency supports a good distribution of the incorporated fibres.
Ultra-high performance concrete (UHPC)	Concrete with significantly higher strength than normal design strength (approximately 120 MPa up to 200 MPa). Typically used for very thin structures and special applications. Flowable consistencies are required in order to guarantee a good dispersion of the finest components as well as to provide workability. Due to the high powder content and the dense particle packing, the viscosity is high, which has to be compensated by decreasing the yield stress as much as possible.
Ultra-high performance fibre reinforced concrete (UHPFRC)	Like UHPC but including fibres. Fibres can be metallic or synthetic. In order to ensure a good distribution of the fibres, a flowable consistency is inevitable.
Sprayed mortar or concrete	Mortar or concrete which is sprayed through a jet nozzle to adhere immediately to the structure. Typically used for repair or in tunnel construction. The fresh material has to be flowable during pumping and the spraying process. After placement, the concrete must not sag and rebound has to be reduced to a minimum. Therefore, the yield stress needs to be high but typically a low viscosity is required.
Grout	Mortar, which is typically used to fill structural gaps or to connect structural elements (e.g. for machine foundations or to connect steel piles). Dependent on the strength, the viscosity can be very high. In order to provide for sufficient workability, the yield stress needs to be adjusted by superplasticiser.
Floor screeds	Mortar, which exhibits a very high flowability. The technical requirements are typically not too challenging, but the flowability is essential for a reasonable casting process. Challenges can be found in segregation and poor bond.
Injection grout	Binder pastes that are used to fill cracks or to connect structural elements. They typically have to be filled in areas, which are difficult to observe. Therefore, flowability is required to guarantee complete filling.
Strain hardening cement based composites (SHCC)	Binder paste systems containing high volumes of fibres (typically PVA, PP or PE). The fibre-paste system has to be adjusted in a way that first cracks do not widen up significantly; the fibres transmit stresses to other areas for the next crack to occur. As a result, these concrete types are extremely ductile and can be deformed without occurrence of wide single cracks.

1.2 Towards flowable systems

The prototypes of what is understood today as self-compacting concretes were invented in Japan in the mid-eighties of the last century in order to compensate for the observed lack of skill of construction workers in Japan (Okamura & Ouchi 2003). SCC was originally named high performance concrete (Ozawa & al. 1989). As of 1983, it was observed in Japan that with decreasing skill level of the construction workers, the construction quality decreased proportionally (Okamura & Ouchi 1999). SCC, hence, was the suggested method to ensure durable concrete constructions which was largely independent of the qualification of the casting staff.

Though flowable cementitious systems were well-known from special mortar applications before, they became increasingly interesting for concrete applications. The final trend to more flowable consistencies was significantly fostered by the invention of modern superplasticisers. When SCC was developed, super flowable concrete was not particularly new in the world. Flowable consistencies were already achieved about 1980 in Germany using anti-washout admixtures that increase the adhesion and viscosity of the suspension (Ohama 1997; Nagataki 1998; Hunger 2010). Also

Collepardi reports about the application of concrete mixtures with so-called rheoplastic consistencies in the beginning of the seventies from Italy and Hong Kong (Collepardi 2001). However, the invention of what is called SCC today could only be achieved with the invention of superplasticisers based on polycarboxylates, which were more efficient and much more versatile than the products available on the market before. Steady innovations in this field finally fostered further developments like UHPC or SHCC and also accompanied a world-wide trend towards more and more plastic to flowable consistencies. Today, self-compacting concrete types have only little similarities with the traditional SCC according to the so called general purpose approach as recommended by Okamura, yielding a low yield stress system with high viscosity.

1.3 Modern flowable concrete types

Today, flowable systems can provide a wide range of yield stresses and plastic viscosities, depending on the application as well as on individual and national preferences and concrete components. In order to describe the workability, EN 206:2014 provides so called consistence classes amended by classes for additional properties of SCC. The consistency classes define ranges of fresh concrete properties depending upon the test methods that can be used to describe the performance of concrete. For flowable concrete, consistencies are typically described by the flow diameter (F1 to F6 measured on the flow table) or by slump-flow classes (SF1 to SF3 measured with the Abrams cone). The classes for additional properties of SCC are the t_{500}-time (VS1 and VS2 measured during the slump flow test), the viscosity classes t_V (VF1 and VF2 measured in the V-funnel), the passing ability classes (PL1 and PL2 measured with the L-box), the passing ability classes (PJ1 and PJ2 measured with the J-ring), and the sieve segregation resistance classes (SR1 and SR2 measured in the sieve segregation resistance test).

The reasons for the use of flowable concrete types may have been changed significantly. Apart from the original idea to create a high durability despite the reduced skill level of the construction workers, today the list of reasons to utilise mixtures with a very high flowability is significantly wider. Flowable concrete types are used to

- create durable concrete despite generally unfavourable casting conditions
- cast concrete in sophisticated scaffolding and/or with smooth fair face quality
- create a high dispersion of the finest particles, e.g. when a high strength is required
- cast concrete with extreme reinforcement, where poker compaction would not be possible
- support a purposeful fibre distribution.

Despite the new possibilities related to its application, the use of flowable concrete also comes along with the need for a more complicated mixture design. Since all mixture components interact mutually with each other, the selective manipulation of the properties of flowable concrete can cause unwanted effects, e.g. the enhancement of the flowability by use of superplasticiser can cause unwanted segregation, or the minimisation of influences of the aggregates by increasing the paste volume can result in unwanted high plastic viscosity. The strong mutual effect of the individual mixture constituents is often put on a level with lack of robustness. In order to apply flowable concrete at high technological level, accurate and error-free as well as economically efficient a high level of expertise is required. Unfortunately, most application guidelines or standards cannot cope with the demand for a safe and sound application of flowable concrete technologies. The negative effect of the lack of applicable codes of practice often outweighs the benefits of the application of the technology, and this clearly antagonises a wider use of flowable concrete types. The aim of the work of the *fib* Task Group 4.3 'Structural design with flowable concrete' is to provide a comprehensive overview of the technology of flowable concrete types and thus provide background knowledge to increase the safety of producing with flowable concrete also for engineers and architects.

2 The scope of work of *fib* TG 4.3 'Structural design with flowable concrete'

Since flowable concrete (FC) is evolving from a special concrete type to a more and more commonly applied building material, *fib* TG 4.3 aims at promoting the application of flowable concrete, improving and adapting the concrete design and the production technology and its implementation in guidelines and codes. *fib* TG 4.3 considers three aspects of flowable concrete for structural design:

material properties, production effects and structural boundary conditions. The definition of flowable concrete comprises not only fully self-levelling concrete types but any type of concrete that shows high flow, may it be induced only by gravity force or by some vibration. The technical work of *fib* TG 4.3 considers the following aspects:

- mechanical /structural characteristics
- local effects
- effects of orientation/segregation due to the flow/vibration
- mixture composition
- production technique.

fib TG 4.3 compiles and analyses recent research findings in order to provide guidance for designers and users of concrete structures with flowable concrete by clearly identifying those areas of structural design, where FC distinguishes from traditional vibrated concrete (TC). There is a strong collaboration with RILEM TC MPS (Mechanical Properties of Self-Compacting Concrete) and ACI Committee 544 'FRC' (Fiber Reinforced Concrete).

3 Mix design differences and influences of the constituents

Depending upon the mixture composition different influences on the flow properties have to be considered. The main parameters that describe the flow properties of concrete are the yield stress and the plastic viscosity. The yield stress is the minimum shear stress of the fresh concrete that has to be exceeded in order to induce a plastic deformation. The yield stress is commonly described by the word ‘flowability’, and correlates well with the slump flow value. It is the principal parameter determining the shape of flowable concrete when it comes to rest, but it is also the most important factor for the assessment of the stability against static segregation. The plastic viscosity is the parameter that describes the resistance of a flowable system against a shear deformation. The viscosity is often determined qualitatively by efflux test methods, and it is the main determining parameter for the flow velocity but also for the de-aeration and segregation tendency during the casting process.

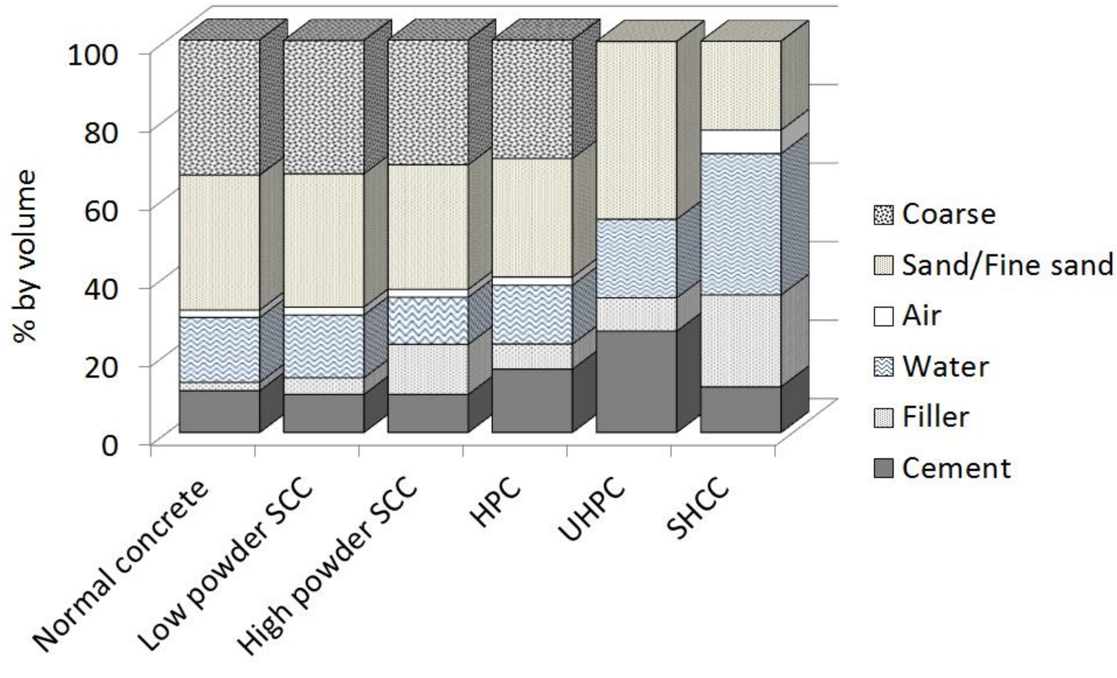

Fig. 1 Examples of different mineral mixture compositions for flowable concrete types in % by volume. Fibre contents are not shown and can be between 1.0 to 2.5 % by volume depending upon the application.

As shown in Table 1, flowable concrete types can vary greatly with regard to their application, performance specification, and specific flow properties. The increasing use of admixtures and additions in concrete technology allows the generation of flowable concrete types that do not inevitably need to have a significantly increased paste volume compared to normal concrete. SCC can be stabilised with a very low water to powder volumetric ratio, which in return demands for high amounts of superplasticiser. Figure 1 provides a number of examples of different flowable concrete types. The figure also shows the wide variety of possibilities to adjust flowable concrete types, only some of the mixtures contain coarse aggregates. Despite the often significant differences in the mix design and properties of these concrete types, the similarity of these concrete types is the relatively low yield stress, which is condition for flowability. Some basic rules for the achievement of the high flowability properties have to be followed. These are summarised in Table 2.

Table 2
Effects of different concrete constituents on the flow performance

Parameter	Effect
Grading curve of sand and aggregates	The distribution of coarse aggregates in the system has a strong effect on the flow properties. The sand content has a higher contribution to the plastic viscosity than to the yield stress. The richer a concrete is of sand, the higher the plastic viscosity.
Aggregate to powder ratio	The higher the paste content the lesser the properties of the aggregates affect the rheology.
Particle shape	The surface properties and the particle shape of mixture constituents have a strong effect on the rheology by absorbing water as well as by hindrance of particle motion. The more water is absorbed, the higher the plastic viscosity and the yield stress. The more the deviation from a rounded shape, the higher the plastic viscosity and the yield stress.
Water to powder ratio	The higher the water to powder ratio, the lower the plastic viscosity and the yield stress become. However, changes in water to powder ratio have a significantly stronger effect on the plastic viscosity than on the yield stress.
Mineral additions and mineral stabilizing agents	The use of mineral additions is closely linked to a modification of the water to powder ratio but also modifies the particle packing density. A denser particle packing and a lower water to powder ratio result into higher yield stress and plastic viscosity. However, since the yield stress can be effectively controlled by the superplasticiser, the major effect of mineral additions is an increase of the plastic viscosity.
Polymeric stabilising agents	Stabilising agents for flowable concrete types are typically based on polysaccharides. Without the presence of superplasticisers their mode of operation depends much on the polymeric architecture. However, since in flowable systems they are typically combined with superplasticisers that avoid strong interactions with particles by adsorption, they typically have a very strong influence on the plastic viscosity whereas the effect on the yield stress is moderate.
Superplasticisers	Superplasticisers need to be adsorbed on the surfaces of positively charged cement and cement hydration phases or mineral particles in the paste. They mainly affect the yield stress without significant effect on the plastic viscosity. The higher the charge density of superplasticisers, the more they tend to adsorb on surfaces and the higher is the efficiency. However, the lower the charge density, the lower is the workability loss as a consequence of retarded adsorption.
Air-entraining agents	Air entraining agents have a stabilising effect that causes an increase of the yield stress at rest. At the same time, air pores increase the paste volume and reduce its density, which in return reduces the plastic viscosity.
Shrinkage reducing agents	Shrinkage reducing agents have a complex effect. Often they are sprayed on nano silica particles, which can increase both, yield stress and plastic viscosity. Fluid stabilizing agents have a de-airing effect, which often significantly increases the yield stress and reduces the plastic viscosity, especially when the paste volume is high.
Fibres	Due to their high surface areas, fibres can significantly increase the water demand, causing an increase of the yield stress and plastic viscosity. At the same fibre dosage, the effect of synthetic fibres is more pronounced compared to steel fibres. Often synthetic fibres also introduce high volumes of air particularly at the interface between fibre and paste. This can have a positive effect on the flow properties, but may compromise the hardened concrete properties. Therefore, typically de-airing agents are used in addition.

4 Effects of fine particles

Flowable concrete types often contain high amounts of fines. In addition, particular for HPC and UHPC very fine powders like silica fume are used in order to improve the packing density. These cause a rapid thixotropic structural build-up. Thixotropic behaviour means that a fluid shows decreasing viscosities at a constantly applied shear rate, which increases again as soon as the shear stress is stopped. The thixotropic build-up is related to particles interacting with each other due to charged surfaces, and must not be confused with the structural build-up due to the hydration. Thixotropic effects are overlapped with effects of cement hydration (particularly ettringite formation) and interactions with superplasticisers. According to Roussel (Roussel 2006), three categories of thixotropy can be distinguished for SCC (Table 3). After the first initial hydration upon contact of cement with water, thixotropic build-up is a major effect observed in flowable concrete types.

Table 3
SCC thixotropy classification (Roussel 2006)

Flocculation rate A_{thix}* (Pa/s)	SCC type
Less than 0.1	Non-thixotropic SCC
Between 0.1 and 0.5	Thixotropic SCC
Higher than 0.5	Highly thixotropic SCC
*A_{thix} is a term that adds up to the yield stress equation over the course of time. It is defined as the yield stress (τ_0) divided by the flocculation characteristic time (T)	

Thixotropic build-up can cause problems related to the formation of distinct casting layers, incomplete filling, and concrete aesthetics. However, the structural build-up also can have beneficial effects, for example to improve the production efficiency like in the case of slip-cast paving (Shah & al. 2007) or for the production of panels with a flexible mould (Schipper & al. 2014). When casting self–levelling concrete that rapidly builds up strength, the mould can be removed (or deformed) quickly. This can save considerable production time. Furthermore a rapid thixotropic build-up releases the stress from the scaffolding.

5 Robustness improvement

Robustness is understood as the stability against variations in the conditions of concrete production related to either quality or quantity of the constituents, or to human or process-technological uncertainties (bibm & al. 2005; Terpstra 2005; Hamada & al. 2006; Nunes & al. 2006; Wallevik & al. 2007). According to the glossary of the State of the Art Report of the RILEM Technical Committee 228 (Mechanical properties of self-compacting concrete) (Khayat & al. 2014), robustness is defined as "The characteristic of a mixture that encompasses its tolerance to variations in constituent characteristics and quantities, variations during concrete mixing, transport, and placement, as well as environmental conditions". However, in practice, the robustness is often studied as the tolerance against influences of varying water contents. In this conjunction, mineral and polymeric stabilising agents were found to have a capacity to improve the robustness effectively (Grünewald & Walraven 2005; Khayat & Hwang 2006; Sonebi 2006; Wallevik & al. 2007; Lowke 2010; Lowke & al. 2010; Schmidt & al. 2010; Schmidt & al. 2013a).

Grünewald and Walraven proposed an evaluation scheme for the robustness of SCC mixtures, in which SCC is categorised in three classes (Table 4) according to its performance in slump flow, sieve segregation resistance test, and L-box ratio (Grünewald & Walraven 2009). The resulting robustness class is determined by testing the fresh concrete properties with water content variations from the reference water content and observing the performance change. The larger the change at a given water deflection, the lower is the robustness class of the SCC. This method can help assessing different mixture compositions in terms of their robustness with regard to variations of the total water content; in some cases viscosity modifying admixtures are recommended to enhance the robustness.

The strong influence of the water content on the performance scatter was also emphasised by Nunes & al. (Nunes & al. 2006). The authors evaluated the robustness of concrete by varying different interacting parameters in parallel. The observed parameters were the volumetric water to powder ratio, the addition to cement ratio, the superplasticiser to powder ratio, the sand to mortar ratio, and the solid volume fraction. They found that the volumetric water to powder ratio was the most affecting factor. However, strong interactions were also found between addition to cement ratio and sand to mortar ratio as well as between superplasticiser to powder ratio and solid volume.

Table 4
Robustness class: response change per water variation (Grünewald & Walraven 2009)

Test method	Unit	Robustness class		
		C1	C2	C3
Slump flow	[mm/l]	< 6.2	6.2 to 10.0	> 10.0
Sieve stability	[%/l]	< 0.62	0.62 to 1.0	> 1.0
L-box ratio	[-/l]	< 0.012	0.012 to 0.02	> 0.02

The latter observation shows that robustness is not limited to variations in the water content of the total mixture. The influences of various raw material variations on the robustness was studied by different authors (Ramge & Lohaus 2010; Ramge & al. 2010), unfavourable equipment or unsteady supply chains (Kordts & Grube 2002; RILEM-TC-188 2006), or climatic influences (Berhane 1992; Yamada & al. 1999; Aiad & al. 2002; Schmidt & al. 2007; Schmidt & al. 2008; Schmidt & al. 2009; Schmidt & al. 2011; Schmidt & al. 2012; Schmidt & al. 2013a; Schmidt & al. 2013b; Schmidt 2014) as well.

The robustness against temperature-induced performance variations of concrete types incorporating high amounts of polycarboxylate ether based superplasticisers (PCE) can be strongly influenced by the modification of the PCE and the mixture composition (Schmidt & al. 2010; Schmidt & al. 2013a; Schmidt 2014). The reason is that PCE interacts with the hydration phases of the reactive components in the binder paste, which induces a time-dependent effect.

It was found that low powder SCCs are more prone to deviation in rheological properties than powder rich SCCs at low temperatures. At low temperatures the binder cannot produce sufficient new hydration phases, which would attract PCE to stabilise the flow. However, the use of high charge density PCE as usually used in pre-cast concrete could compensate for these negative effects. At high temperatures, the situation was found to be exactly inverted. SCC with low powder content may be more robust against influences induced by PCE than powder rich SCC, since a powder rich SCC tends to rapid stiffening due to the dense particle packing, which is aggravated by the temperature accelerated hydration. This high temperature effect can be compensated by using low charge density PCE, which is adsorbed over a longer period of time compared to high charge density PCE. Table 5 provides an overview of which types of SCC are more prone to failure in a particular climate.

Table 5
Examples for influencing factors for the robustness of SCC against temperature influences after (Schmidt & al. 2013a)

		Charge density of PCE		Problem field	Solution
		low	high		
Stabilising agent type	5 °C	Poor flow, low strength	Good flow retention	PCE dependency	High charge density PCE
	20 °C	Good flow retention	Good flow retention	-	-
	30 °C	Good flow retention	Medium flow retention	-	-
Powder type	5 °C	Good flow retention	Good flow retention	-	-
	20 °C	Good flow retention	Medium flow retention	-	-
	30 °C	Good flow retention	Poor flow retention, low strength	PCE dependency	Low charge density PCE

SCC is typically considered to be inherently less robust than vibrated concrete. This impression often limits the use of SCC and flowable concrete types in ready-mix concrete applications (Grünewald & Walraven 2009; Schmidt 2014). As mentioned before, the initial idea behind SCC was to enhance the robustness of the concrete production and to improve the concrete durability despite the low skill level of the construction workers (Ozawa & al. 1989; Okamura & Ouchi 1999). This aspect is often forgotten, since in most industrial nations the concrete casting process and all related supply chains are well adjusted to produce with a robust process. However, in many less industrialised nations, the concreting process of normal concrete is also not very robust due to lacking supply chains and sets of standards or application guidelines or unsatisfactory equipment. Based on this consideration, the use of flowable concrete was recommended in particular for challenging concreting environments where the process chains are not optimised with the result that large performance scatter also occurs in traditional concrete technology (Schmidt & al. 2013b). Here, the use of flowable concrete itself helps improving the robustness against influences of unfavourable construction site conditions.

6 Supplementary topics covered by TG 4.3 and way forward

The present paper focuses on mixture components' effects and the robustness improvement of flowable concrete types. The scope of *fib* TG 4.3, however, goes far beyond this. Research findings from the entire designing and production process with flowable concrete will be compiled and analysed in order to provide guidance for designers and users of concrete structures with flowable concrete. Besides material-related aspects the focus is also on design-related topics and the structural behaviour of concrete that was cast with a flowable consistency. Table 6 provides an overview of the topics that are covered by the task group and that will be published in the state of the art report.

Table 6
Summary of topics covered by the work of *fib* TG 4.3

Topics	Description
Flowable concrete	General overview about flowable concrete types
Components and mixture composition	Introduction of mixture constituents and their peculiarities
Fresh state	Influences of mixture constituents and methods to control the rheology
Local effects	Effects of segregation, blocking and fibre orientation on structure
Mechanical characteristics	Hardened state behaviour of flowable concrete types
Creep and shrinkage	Time and load dependent behaviour at hardened state
Bond and anchorage	Interactions with other structural components
Durability	Peculiarities of flowable mix design concepts with regard to durability
Production influences/methods	Considerations about the casting processes and supply chains
Applications	Examples of structures built with flowable concrete types

7 Conclusions

This paper provided a concise overview of the work of *fib* TG 4.3 'Structural design with flowable concrete'. After a description of different types of flowable concrete, the aspect 'mix design' was discussed. Pronounced differences are possible concerning mixture composition, of which the consequences are discussed related to the thixotropy and the robustness of flowable concrete. For more information and specific results on the behaviour of flowable concrete in the fresh and hardened state as well as production influences, the reader is referred to the state-of-the-art report prepared by *fib* Task Group 4.3.

Acknowledgements

Contributions to the work of the *fib* Task Group 4.3 were made by J. Barros, M. Behloul, H. Beitzel, G. Bertram, P. Billberg, F. Dehn, P. Domone, L. Ferrara, B. Freytag, R. Gettu, T.A. Hammer, T. Kanstad, F. Laranjeira, L. Martinie, S. Nunes, M. di Prisco, Y. Sato, W. Schmidt, M. Sonebi, P. Stähli, H. Stang, J. den Uijl, L. Vandewalle, J.C. Walraven, K. Zilch, J. Spangenberg, A. Leemann, B. Obladen, S. Taylor, N. Roussel, M. Geiker, B. Barragan, J. Cairns, G. Fischer, S. Grünewald

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