Concept for concrete production

Hybrid intensive conical mixer with integrated rheometer for high-performance concrete

This article presents a new comprehensive concept for concrete production. On the basis of the following illustrated relationships between mixture design, mixing technology and the rheological characteristics of the concrete in the mixer which have to be measured, the goal-orientated production of tailor-made concretes can be ensured, taking into account both ecological and economic aspects. With the help of the Bétonlab Pro software, indicative values were calculated for the mixture design with regard to the liquid limit and the viscosity of the fresh concrete. The effects of the different mixing regimes on the liquid limit, the viscosity and the thixotropy were evaluated by the additional use of the mixer as a rotary rheometer or the use of the mixer for oscillation measurements. In this way the mixing regime and the mixture design can be optimised with the software on the basis of the measured rheological characteristic values.
As a 'low-cost rheometer', the modified LCPC box also enables statements to be made about the viscosity of the fresh concrete in addition to the measurement of the liquid limit.

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Problem statement

The requirement profile for a modern concrete increasingly covers aspects of the durability and the preservation of resources in addition to the classic hardened concrete characteristics. The cement clinker portion is reduced as a concrete technology measure. In addition to the partial substitution of cement by substitutes, the packing density is increased by fines and the water/binder ratio is reduced. The use of high-performance superplasticisers is compulsory, since it is the only way to achieve a workable consistency extending to self-compaction.
The mixture design of special concretes, which is modified considerably in comparison with normal concretes, requires much longer mixing times and a higher consumption of electricity [1, 2]. The actual challenge here, according to [3], is to reduce the viscosity of the concrete, so that it becomes workable in practice. The rheological properties of the concrete also depend on the mixing technology employed and the mixing regime [4] and are determined after mixing is completed in fresh concrete tests on partial quantities of the mixture—usually outside the mixer. Despite the well-known interactions between the two, the mixture design and the mixing technology are often considered separately and an inadequate rheological characterisation of the fresh concrete takes place via fresh concrete tests.

State of the art

Mixing technology

In practice the mixing process is complete following the so-called stabilisation time. The power consumption of the driving motors thereby asymptotically approaches a minimum according to [5]. The fresh concrete characteristics obtained depend on the design and size of the mixer and the mixing regime. Large mixers [3] and mixers with higher tool speeds [1] enable lower values to be achieved for the liquid limit and in particular for the viscosity of the concretes manufactured in them. The higher tool speed shortens the mixing time by the faster homogenisation of the raw materials and brings about a better disintegration of the agglomerates. Although the electrical drive power of the mixing tool must be significantly increased due to raising the rotary speed, the power required to manufacture the batch is reduced due to the shorter mixing times [1]. Concretes to which superplasticiser is added, and which are manufactured in a two-stage process, achieve 8-17% higher compressive strengths [6]. The mortar, consisting of sand, cement, water and superplasticiser, is initially manufactured in a suspension mixer and subsequently mixed with the coarse aggregate in a second conventional mixer. In [2] it was possible to significantly increase the slump-flow and improve the

Table 1: Investigated mixing regime of test series 1 to 8 and selected fresh concrete and hardened concrete results

	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8
Mixing energy kWh/m³	8,75	5,25	3,45	5,25	5,25	3,45	3,45	2
Superplasticiser kg/m³	6	6	6	4,5	4,5	4,5	4,5	4,5
Addition of 40% superplasticiser at kWh/m	5,55	1,85	1,4	1,65	3,25	1,75	1,15	1
Stage I	Concrete 100 rpm	Mortar 600 rpm	Mortar 600 rpm	Mortar 1000 rpm	Concrete 250 rpm	Concrete 250 rpm	Mortar 1000 rpm	Paste 1000 rpm
up to kWh/m³	-	3,7	2,1	3,7	-	-	2,3	
Stage II	-	Concrete 150 rpm	Concrete 150 rpm	Concrete 150 rpm	-	-	Concrete 150 rpm	Concrete external
plastic viscosity ICAR [Pa]	163	86,6	150	181	316	471	210	348
LCPC T_{700} [s]	29	25	34	29	43	51	37	43
LCPC slump-flow [cm]	115 (13,8 Pa)	107 (17,2 Pa)	104 (18,4 Pa)	111,5 (15,4 Pa)	111 (15,6 Pa)	110 (16 Pa)	106 (17,6 Pa)	105 (18 Pa)
$f_{cm,cube\ 100,\ 1d}$ [N/mm²]	15,8	5,1	3,5	11,6	14,2	12,3	10,4	13,5

consistency retention of an SCC by means of a two-stage mixing process using a suspension mixer.

Rheological measurements in the mixer

In practice the current or power consumption of the drive motors has proven to be suitable for evaluating the consistency of concretes of the usual consistency classes. In addition, the individual mixing phases and thus also the end of the mixing process can be derived from the power consumption curve over the mixing time [7]. According to [8] this procedure is unsuitable for the rheological evaluation of SCC. Alternatively the speed is lowered by a frequency converter in 5 steps during the last mixing phase in this procedure. The value pairs of speed/torque in the individual steps are used by means of linear regression for the calculation of the relative Bingham parameters, from which the slump-flow is derived. The Viscoprobe™ sold by Skako Concrete measures the resistance to movement of a steel ball immersed in concrete, which is fastened to a torque sensor via a rod. Two value pairs (speed and the associated torque) are necessary in order to be able to calculate the relative Bingham parameters. The data acquisition and evaluation take place in real-time in parallel to the mixing process and therefore do not lead to extended mixing times.

Procedure

Using inexpensive raw materials with a low greenhouse potential, the Bétonlab Pro software was used to develop the recipe for a concrete of strength class C60/75 with excellent durability. The manufacture of the concrete took place in a single stage and in two stages in a modified conical mixer. Whereas the water was added after the submission of all dry materials in the single-stage process, in the two-stage process the mortar or paste was manufactured first followed by the addition of the aggregate inside the same mixer. In both processes the electricity consumed by the mixer drives, the tool speed and the time of the addition of the superplasticiser were varied, see table 1.

The rheological characteristic values were measured using the mixing tool, a concrete rheometer and the modified LCPC box.

The mixing tool of the conical mixer, which rotates or oscillates at a very low speed, allows the evaluation of the complete batch with regard to its liquid limit, viscosity and thixotropy. The effects of a changed mixing regime on the rheology thus become identifiable and can be optimised purposefully for the respective application in an integral process by the adaptation of the recipe using the Bétonlab Pro software. Since the mixing tool has no defined shear requirements with regard to shear area and shear gap, the values determined have a relative character. In order to calibrate the mixing tool as a result of wear and to determine the liquid limit and the viscosity, the LCPC box was modified for highly viscous concretes.

Mixture design

The concrete design is based on the concept of [9] and is called High Volume Fly Ash (HVFA) Concrete in the English-speaking world. In addition to the concrete described in Table 2 with a maximum grain size of 16 mm, high-strength fine-grained

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concretes and high-strength lightweight concretes characterised by a very low tendency to shrink have been developed at the Institute of Materials in the Construction Industry at the TU Darmstadt.

Table 2: HVFA recipe used

	HVFA kg/m³
CEM I 52,5 N HS/NA	180
Fly ash KM/C	309
Superplasticiser Sika 20 HE	4.5 - 6
Water	112
Sand 0/2	640
Gravel 2/8	746
Gravel 8/16	391

Table 3: Stabilisation times calculated using Bétonlab Pro for different mixture compositions

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
CEM I 52,5 N HS/NA	x	x	x	x	x	x
Fly ash KM/C	x	x	x	x	x	-
Superplasticiser Sika 20 HE	x	x	x	x	x	x
Water	x	x	x	x	x	x
Sand 0/2	x	x	50%	-	-	x
Gravel 2/8	x	-	-	x	-	x
Gravel 8/16	x	-	-	-	x	-
Stabilisation time [s]	210	166	143	122	178	235

Although the use of cement with a high effective alkali content appears to be sensible on account of the high proportion of pozzolans, two cements with a low effective alkali content were used. Their low water and superplasticiser requirement enabled a further reduction in the water/binder ratio in conjunction with suitable high-performance superplasticisers. Hence, strength classes up to C60/75 and considerably higher early strengths are possible. Due to pronounced post-hardening, cube compressive strengths of over 120 N/mm² can be reliably achieved after 90 days. Contrary to the design of the superplasticiser, which is aimed at maximum liquefaction with a short duration of effectiveness, the concrete consistency can be maintained for several hours.

Bétonlab Pro

The software for mixture development, which was developed at the Laboratoire central des ponts et chaussées (LCPC), enables the stabilisation time to be calculated. A low relative concentration of solids is thereby accompanied by a short stabilisation time [5]. In order to be able to identify in advance which dosing sequences of the individual raw materials make sense, calculations were performed with Bétonlab Pro. The stabilisation times for the complete HVFA recipe and for mixtures without individual raw materials are given in Table 3. In the two-stage process (case 2), the mortar is manufactured by a significantly higher tool speed in the first phase and the stabilisation time is shortened further. A lengthening of the mixing time in comparison with the classic procedure (case 1) is therefore not to be expected.

Kniele conical mixer

The mixing technology requirements encompass a variable-speed drive with a significantly higher speed and drive power as well as modifications to the mixing tool. While the mixing technology requirements can also be implemented with a frequency converter of the simplest design, the rheological evaluation demands maximum performance from the frequency converter. The direct torque control method meets this requirement, since it can accelerate the motor from a standstill in a controlled manner and enables operation at the lowest speeds. A further advantage exists in the possibility of torque-controlled operation, as is usual for rheological measurements [10]. By resorting to the frequency converter data, additional components such as torque sensors in or directly adjacent to the mixer can be dispensed with. In order to be able to dispense with a reduction gearbox and the associated disadvantages, and in order to achieve high speed accuracy, a high-torque permanent magnet synchronous motor (see fig. 1) was installed, which directly drives the internal mixing tool. The rigidity of the drive train attained in this way enables oscillating measurements to be made in the mixer. In addition to the determination of the liquid limit and viscosity, oscillation measurements enable statements to be made about the structure of a material.

Figure 1: Conical mixer (Kniele) with dosing equipment for laboratory use

Flow curve and liquid limit in the mixer

In order to determine the flow curve, the concrete is pre-sheared for 10 seconds. The mixing tool then rotates in 9 steps at speeds from 21.8 rpm to 1.7 rpm for 4 seconds in each case. The data from the pre-shearing phase and from the first second of each step are not taken into account for the evaluation. The actual speed and the associated torque are measured at intervals of 100 ms during the individual measuring phases with specified constant speeds; see figure 2. In turn, value pairs are determined from the measured values for the individual speed steps and are output. The relative liquid limit and the relative plastic viscosity are calculated in the mixer's programmable logic controller according to the least-squares error method. In order to determine the relative static liquid limit, the torque is continuously increased until the mixing tool begins to rotate.

LCPC box in combination with the discharge cone

In order to be able to accept the unimpaired flow process of a homogeneous material, a sampling height of at least five times the largest grain diameter of the sample is necessary at the outside edge [11]. While maintaining a manageable sample quantity, therefore, the LCPC box was developed as an alternative to the slump-flow. This consists of a 120 cm long, 20 cm wide and 15 cm high formwork, into which 6 litres of concrete are filled at one end. The slow manual filling of the concrete sample into the LCPC box is difficult to reproduce and therefore allows no statements to be made about the viscosity. In order to

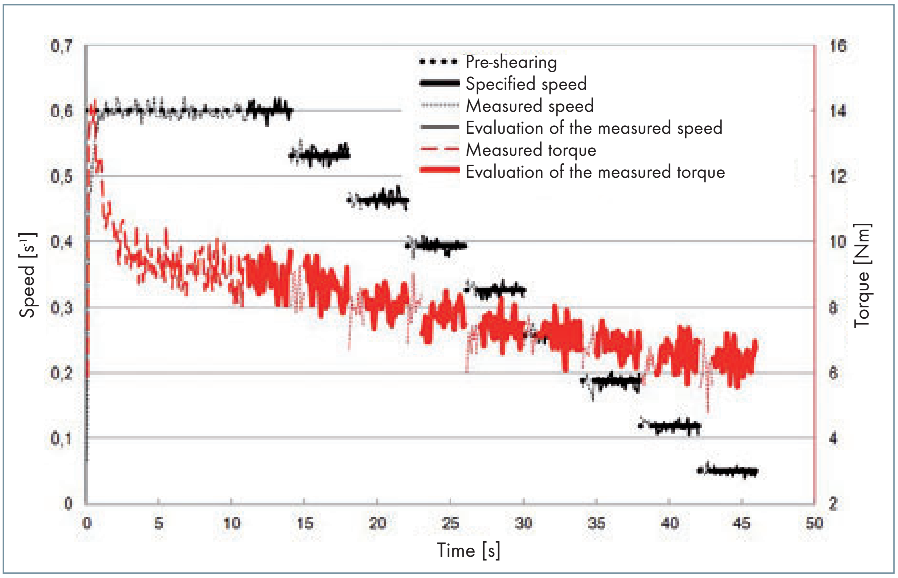

Figure 2: Measurement profile and values determined for the determination of the flow curve in the conical mixer

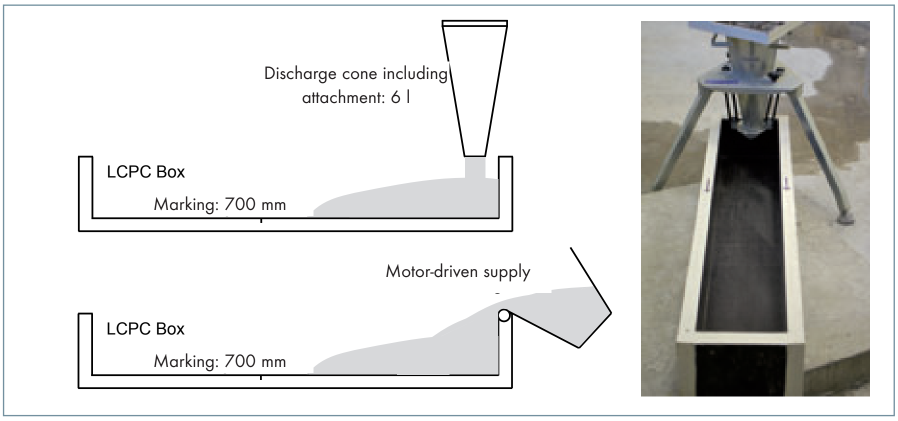

Figure 3: LCPC box with discharge cone including attachment (left) and with a motor-driven supply (right)

obtain measured values both for the actual liquid limit and for the viscosity, the LCPC box process was modified for these examinations in accordance with fig. 3. In this case filling takes place reproducibly at one end of the LCPC box with the discharge cone. The time between opening the closure of the discharge cone and the concrete flowing over the 700 mm mark in the box is taken for the evaluation of the viscosity (T_{700}-time in [s]).

Results

Flow curve and liquid limit in the mixer

Figure 4 illustrates the very good correlation of the flow curves measured with the ICAR rheometer and with the conical mixer. To this end the measuring body of the rheometer was fastened to the mixing shaft using an adaptor. The rheometer measurement took place in a cone with the dimensions of the conical mixer (fig. 5).
Figure 6 illustrates the good correlation between the plastic viscosity determined using the rheometer and the motor torque of the mixer at a mixing tool speed of 11 rpm for various mixing regimes. The relative static liquid limits measured at different times in the mixer (Table 4) enable the structure of the fresh concrete to be evaluated in relation to the mixing regime.

Amplitude sweep in the mixer

With a specified torque, this is increased continuously while at the same time maintaining the frequency. The measurement results determined in the amplitude test enable the visco-elastic material behaviour to be characterised in relation to the load. If the specified torques REL′ and REL′′ are represented as in the graph below, statements can be made about the character of the structure. The test is non-destructive as long as REL′ and REL′′ remain constant, since the structure is not irreversibly disturbed (linear visco-elastic range). The limit value of the torque My,relativ (yield point),

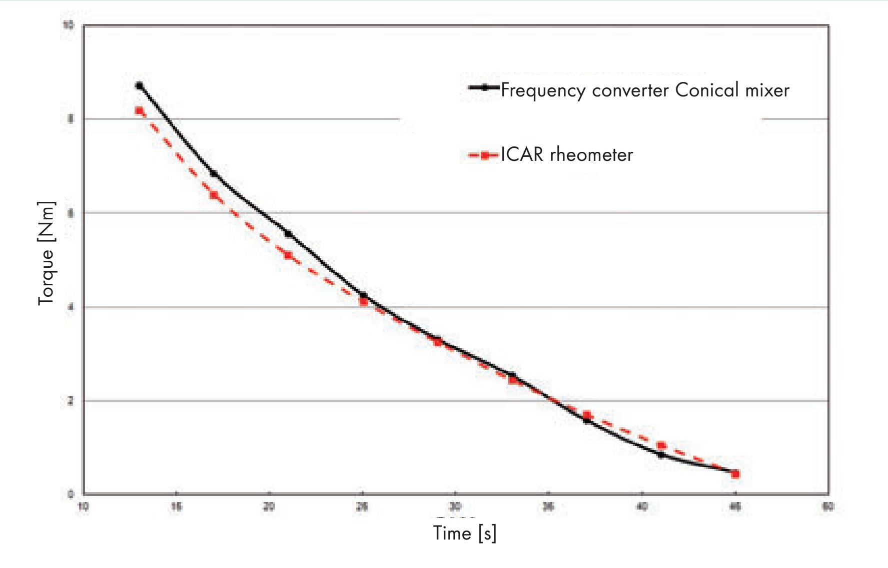

Figure 4: Flow curves, measured with conical mixer and ICAR rheometer

Figure 5: Adaptor for rotary impeller in the mixer (left) and ICAR rheometer in a replica cone with identical dimensions to the conical mixer (right)

which leads to the linear viscous range being exceeded, is called the yield limit. REL´ and thus the elastic part continue to dominate the viscous portion R". A change to the liquid character takes place only at the intersection of REL' with REL"; see figure 7. This point specifies the liquid limit $M_{f,relativ}$ which is usual in the rheology of concrete. According to [10], the values of M_y and M_f deviate significantly from each other and can influence the associated shear rate by a factor of more than 10.

Conclusion / prospects

Two-stage mixing regimes significantly lower the viscosity of the fresh concrete with the use of less energy; see table 1. In two-stage processes the delayed addition of 40% of the superplasticiser also led to better results than the addition of the entire quantity at the start of mixing. Although the liquid limit is slightly raised in comparison with single-stage processes, this is associated with a lower segregation tendency. In test 8 the paste was manufactured for three individual concrete batches with one mixer batch at a higher tool speed. Subsequently, in order to simulate a truck mixer, the paste was mixed with the aggregate in a single-shaft mixer at 2 rpm for 20 minutes. Although only 38% of the mixing energy from test 5 was used for the production of the paste, the fresh concrete characteristic values were equivalent. If concrete mixer vehicles with built-in consistency monitoring and control are used, it is possible to considerably increase the yield and to lower the energy consumption.

Since the end of setting of a concrete manufactured in two-stages is reached later due to the improved consistency retention, its early strength is reduced. This can be compensated by decreasing the quantity of superplasticiser. According to figure 8, however, specifying a cement is decisive for the development of strength.

The rheological characteristics are reproducibly identified both by the conical mixer and with the modified LCPC box – see figure 9 – and enable further optimisation of the mixture using Bétonlab Pro. In addition, the oscillating measurements allow the concrete to be characterised more extensively.

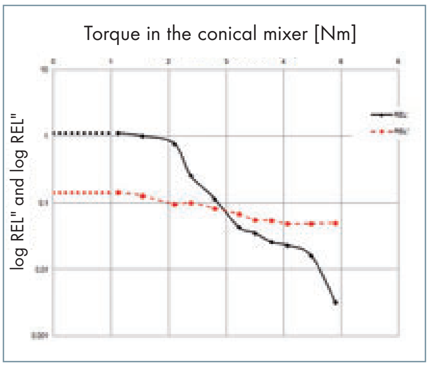

Figure 7: REL' and REL" curves determined by means of the amplitude test in the conical mixer

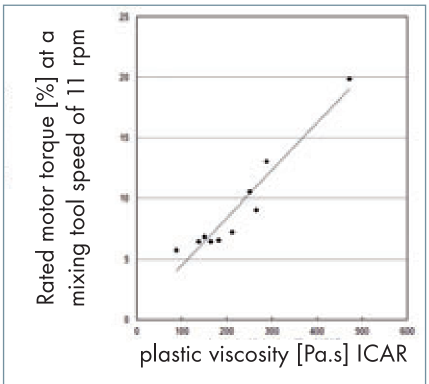

Figure 6: Comparison of the motor torque and the plastic viscosity determined using the ICAR rheometer

Table 4: Motor torques measured at different times

	Test 4	Test 5	Test 6	Test 7
	[Rated motor torque in %]			
End of mixing	1,45	1,98	6,41	1,48
30 min after end of mixing	4,63	11,78	28,61	6,35
30 min after end of mixing and after a pre-shearing time of 30 seconds	1,78	1,69	4,1	1,38

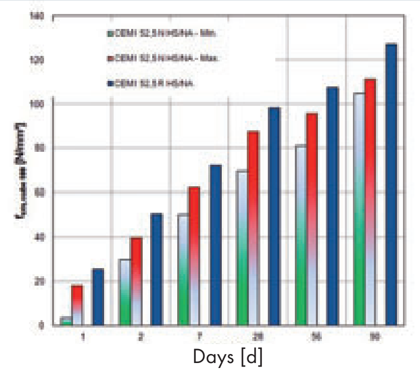

Figure 8: Strength development of different cements; the lower and upper average values are indicated for CEM I 52.5 N HS/NA for different mixing regimes

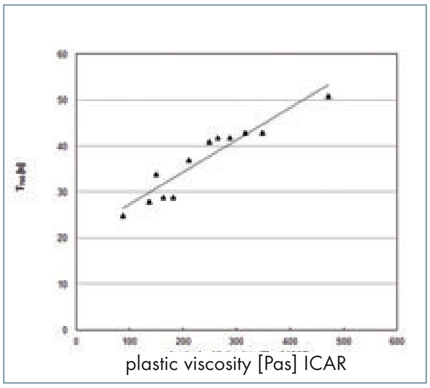

Figure 9: Comparison of the T_{700} time and the plastic viscosity

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FURTHER INFORMATION

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