Determination of the Uniaxial Tensile Strength of Concrete with a Modified Test Setup

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Abstract. While the testing of the compressive strength of cement-bound materials is regulated by norms and only differentiates in the dimensions and shapes of the specimens to be tested (cube, cylinder, prism), such standards are missing for the determination of the uniaxial tensile strength. The test methods known from literature which can be used to determine the uniaxial tensile strength, are partly associated with a high test effort, cannot ensure introducing the tensile force centrically or determine the tensile strength only indirectly via a conversion, e.g. from the flexural strength or the splitting tensile strength.

In the evaluation of uniaxial tensile tests on textile reinforced concretes and fiber reinforced concretes, the tensile strength of the concrete and the interaction of the concrete with the textile is currently not or only indirectly taken into account. This is partly due to difficulties in ensuring that the specimen is tested centrically or due to time-intensive test methods for determining the centric tensile strength of the non-reinforced concrete. Based on the ASTM C307-03, a test device was developed which, reproducibly and time-reliably, allows measuring the maximum centric tensile load of concrete. It is also possible to use coarse-grained concrete with a maximum grain size of up to 16 mm. With the help of the new test setup, the test specimens can be examined immediately after the curing. A lengthy preparation time, such as the grinding of test specimens or the hardening time of an adhesive, is no longer necessary.

During initial investigations with the developed test setup, standard concretes and an ultra-high-performance concrete (UHPC) with and without steel micro-fibers were examined.

Keywords: Tensile strength · Concrete · Test setup · UHPC · SFRC

1 Introduction

As the architecture in concrete construction asks progressively for slimmer components, deepened knowledge about the tensile behavior of concrete is essential. Moreover, a dependency between the compressive strength, flexural tensile strength and the tensile strength of concrete exists, which is why the tensile strength should be known for the precise description of the properties of the used concrete according to Duda (1991) and Grossmann (1987).

In general, a distinction is made between a sudden, brittle failure without prior indication and a ductile failure according to Blaschke (1993). The failure type of

concrete may be described as a brittle failure, which can be explained by the slow propagation of several small (micro) cracks according to Leutbecher (2007). The tensile strength is thus closely related to the crack formation in the concrete, since the separation of a concrete body is based on the propagation of these (micro) cracks according to Leutbecher (2007) and Grossmann (1987). The ductility can be increased e.g. by the addition of steel fibers, but the load bearing capacity of steel fiber reinforced concrete (SFRC) depends highly on the fiber distribution, fiber orientation, number of fibers, fiber type and the concrete composition according to DAfStb (2013) and Lee and Barr (2002).

2   Determination of the Tensile Strength of Concrete

To determine the tensile strength of concrete, direct and indirect tensile test methods are available. The direct examination is carried out by means of a centric load introduction into the concrete specimen. For the indirect determination of the tensile strength, the flexural tensile test as well as the splitting tensile test are used. The indirect test methods are often used to circumvent the uniaxial tests, since a centric introduction of the load is technically difficult to achieve. Due to the resulting eccentricity, the non-uniform stress distribution across the cross-section causes a high variance of the test results according to Blaschke (1993) and Heilmann (1969). Following to the investigations of Zamorowski (1990) relating to the tensile strength of concrete and the associated deformation behavior, however, the determination with a centric load introduction has the highest significance. An overview of possible test setups can be found in Krähe (1989). In Helbing and Brühwiler (1987) a summary of the varying types of mounting devices for these test setups is displayed.

In order to evaluate the general suitability of the newly developed test setup (see Sect. 3.1). Table 1 shows the threshold values of the coefficient of variation of the tensile strength $V_{X,fctm}$ as a function of the compressive strength f_{ck} according to Fischer (2001).

Table 1. Overview of the coefficients of variation of the tensile strength of concrete as a function of its compressive strength according to Fischer (2001).

f_{ck}	N/mm^2	8	12	16	20	25	30	35	40	45	50
f_{cm}	N/mm^2	16	20	24	28	33	38	43	48	53	58
f_{ctm}	N/mm^2	1,2	1,6	1,9	2,2	2,6	2,9	3,2	3,5	3,8	4,1
$V_{x,fctm}$	%	21,0	22,0	22,0	22,0	21,0	22,0	22,0	20,0	20,0	20,0

Since the UHPC, which is used in the present study, belongs to a higher strength class than those presented in the table, the threshold value can only be assumed. According to Six (2001), the coefficient of variation of the tensile strength also depends on the compressive strength and assumes values of approximately 30% to 40%, while according to Hansen (2004), it lies between 17% and 20%.

3   Developed Test Setup and Specimens

3.1   Test Setup

In previous investigations at the Institute of Building Materials Research (ibac), the tensile test method based on ASTM C307-03 (2003) on small "bone-shaped specimens" yielded a low scattering of the tensile strength of cement based mortars with a high ratio of evaluable results. On the basis of these examinations the test apparatus according to ASTM (2003) was adapted for the determination of the centric tensile strength of concrete in order to check the suitability and reproducibility of the test method for concrete instead of mortar. The dimensions of the test specimens were thereby tripled in comparison to the original geometry in order to allow the use of coarse grains with a maximum grain size of up to 8 mm. A drawing of the used specimen including the associated dimensions is shown in Fig. 1, right. On the basis of the adapted geometry of these bone-shaped specimens, a corresponding fixture for the specimens, which is shown in Fig. 1, left, was developed.
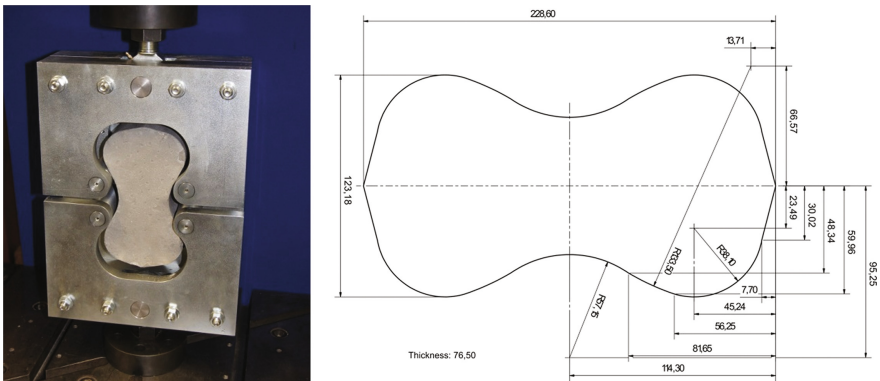
Fig. 1. Left: test setup for determining the tensile strength. Right: geometry and dimensions of the "bone-shaped" specimens in mm.

The tensile load is initiated via form closure between four symmetrically arranged roller bearings and the specimen. The bearings are fixed in pairs in two solid steel jaws that ensure a sufficiently high stiffness of the construction and at the same time are hinged to a universal testing machine. The device is thus freely movable between the load transmission points of the testing machine and allows the centrical introduction of the load as far as possible, due to the self-alignment of the specimen.

The test specimens are inserted into the device and loaded at a variable speed depending on the tensile strength. The test should last for about 45 ± 5 s until the failure of the concrete to limit the propagation of the cracks. In difference to the ASTM (2003) the test is carried out force-controlled and the peak load is recorded by using the analogue measuring signal of the testing machine.

   Due to the small free length of the test specimen and the small elongation of UHPC, the strain has not been recorded. A recording of the tensile load across the traversal path in the force-displacement diagram is, moreover, not useful since the measurements would not provide any evaluable results because of the large slippage and settlements in the device and the simultaneously small expansions of the specimen. However, in the scope of this preliminary investigation the level of the tensile strength was more relevant than the tensile strain of the concrete. But for strain-hardening concretes, the strain could be recorded to determine the elongation at the fracture and the modulus of elasticity under tensile stress by using a video extensometer.

3.2   Concrete Mix Design

Within the scope of the preliminary tests for the developed test setup, a reference-concrete was tested (M1a). During the subsequent main investigations a reference-concrete with and without steel fibers (M1b), as well as a UHPC with and without steel fibers (M2) were tested. An overview of the used concrete mixes is given in Table 2. The added amount of steel fibers was kept constant for both concretes.

Table 2. Used concrete mixes.

| Component		Unit	Standard concrete			UHPC	
			M1a	M1b		M2	
			woSF	woSF	wSF	woSF	wSF
CEM III/A 52,5 R		kg/m³	–	365.0	500.0	–	
CEM I 52,5 R			365.0	–		832.0	
Water			146.0	146.0	200.0	188.5	
Aggregates	Millisil W12		–	–		218.8	207.3
	0,1–0,5 mm		375.0	375.0	306.6	1029.5	975.4
	0,5–1,0 mm		211.4	211.4	162.9	–	
	1,0–2,0 mm		277.0	277.0	222.2	–	
	2,0–4,0 mm		491.6	491.6	393.9	–	
	4,0–8,0 mm		528.7	528.7	423.6	–	
	Sum		1883.8	1883.8	1509.2	1248.4	1182.7
Silica fume			–	–		135.0	
Steel fibers			–	–	195.1	–	195.1
Super-plasticizer		M.-%/cem	0.426	0.426	0.222	3.534	
w/b-ratio		–	0.40	0.40		0.19	

woSF/wSF: without/with Steel fibers. M.-%/cem: percent by mass of cement content. w/b-ratio: water-binder ratio.

4   Test Results and Discussion

4.1   Preliminary Tests

In order to investigate the general suitability of the new test setup for determining the tensile strength of concrete and to examine the reproducibility of the results, the reference-concrete M1a without steel fibers (see Table 2) was tested. Tests were performed on three series of this reference-concrete, each series with 7 test specimens at an age of 14 days. In order to prevent an influence by possibly occurring cracks due to shrinkage, the test specimens were stored under water until shortly before the test. The cross-section of the fracture zone was measured after each test, to determine the tensile strength.

The test results showed a good reproducibility (see Fig. 2). The coefficient of variation of the first series is 4.4%, the one of the second series is 3.1% and of the third series only 2.5%. The coefficient of variation of all 21 specimens is 4.5%. Thus the variation coefficient of the test results is far below the limits of the coefficients of variation for determining the tensile strength as a function of the compressive strength (Table 1).
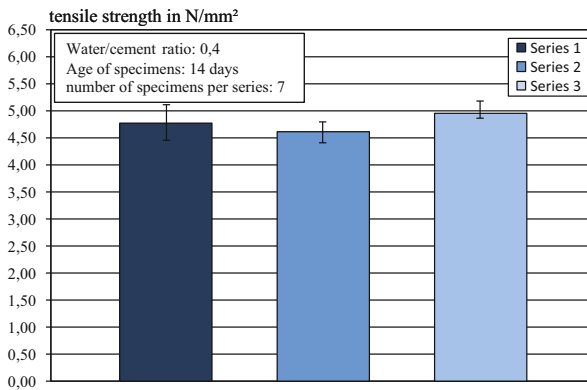
Fig. 2.   First results of determination of the tensile strength with the new test setup; Mixture M1a.

4.2   Main Investigation

Following the promising preliminary investigations, the centric tensile strength of additional concretes was examined. Each series consisted of 6 specimens, which were tested at an age of 28 days and were cured 7 days subsequent to their production in water and afterwards at a temperature of 20 °C and 65% relative humidity (L7). The type of compaction method was dependent on the type of concrete. The standard concretes were compacted on a vibrating table and the UHPC with an internal vibrator. In addition to the investigations with the new setup, tests on cylinders with a diameter of D = 100 mm and a height of h = 300 mm were carried out, to enable a possible connection to prior investigations. These cylinders were grounded plane-parallel and glued onto steel plates to introduce the load.

Table 3 shows the tensile strength determined by means of the new test device ("bone-shaped"), those determined by glued cylinders and the compressive strength. In addition, the corresponding standard deviation and the coefficient of variation of the respective series are presented. The scatterings are below the values assumed by Fischer (see Table 1). The coefficients of variation of the determined tensile strengths are, with the exception of the mixture M2 wSF, less than or equal to 8.1%. They are therefore considerably below the limits stated in the literature (Sect. 2). The increased variance of the test specimens of the mixture M2 wSF is presumably due to an unfavorable fiber distribution and/or fiber orientation in the concrete (Sect. 1).

Table 3. Overview of the test results.

Mixture	CC	Age	Tensile strength						Compressive strength		
			Bone shaped			Cylinders					
			$f_{ct,b}$	s_x	v_x	$f_{ct,cyl}$	s_x	v_x	$f_{c,cu100}$	s_x	v_x
		d	N/mm^2	%		N/mm^2		%	N/mm^2		%
M1b woSF	L7	28	**3.8**	0.14	3.7	**3.3**	0.19	5.8	103.6	8.19	5.1
M1b wSF			**4.8**	0.25	5.2	**4.0**	0.25	6.3	111.6	1.62	0.9
M2 woSF			**4.5**	0.36	8.1	**3.5**	0.15	4.3	159.5	1.29	1.2
M2 wSF			**7.2**	1.01	14.0	**4.1**	0.33	8.0	171.4	2.32	2.1

woSF/wSF: without/with Steel fibers. CC: Curing Condition. L7: 7 d water, afterwards 20 °C and 65% relative humidity. s_x: standard deviation of 6 specimens, v_x: coefficient of variation.

The results show that the tensile strength determined with the new test setup for all tested concrete mixes is significantly greater than the tensile strength determined by means of cylinders. This could be due to the smaller cross-section of the "bone-shaped" specimens, which reduces the probability of defects in the specimen (size effect). This leads to higher, but also more realistic test results for slim structural elements. The proven influence of the addition of short fibers on the uniaxial tensile strength is also of significance. In the case of the standard concrete (M1b), the tensile strength was increased by approx. 26.3%. In the investigations of the UHPC (M2) an increase of the centric tensile strength by 60% was documented.

As a further indication of the suitability of the test setup, in addition to the small coefficients of variation, the places of the fractures of the "bone-shaped" specimens can be used. An exemplary fractured specimen is shown in Fig. 3, where the point of failure is positioned in the region of the smallest cross-section.

In the course of further suitability investigations, a total amount of 330 specimens were tested. A failure in the area of the bearing points occurred only in 5% of the specimens and can be attributed to stress peaks from the roller bearing or local imperfections in the cross-section due to entrapped air or unhydrated cement particles. The results of these tests were not taken into account for the evaluation of the tensile strength, but a quantity of 7 specimens per series is therefore sufficient for such a rate of not evaluable test results. By means of the ball joints on both ends of the device, the
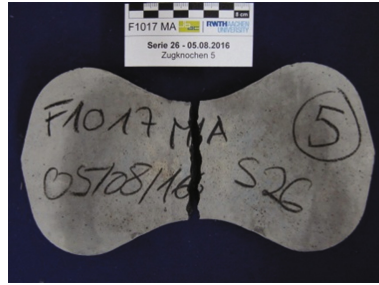
Fig. 3. Exemplary fracture of a tested "bone-shaped" specimen.

centric load introduction is ensured as far as possible. The risk of eccentricity of the tested specimens is largely reduced by the flexible coupling of the steel jaws.

Another substantial advantage over other test setups is the considerably lower time required for the preparation of the test specimens. For example, the grinding of the test specimens or the double-sided adhesion of the plates, to introduce the load, can be omitted. Furthermore the specimens can be taken, for example, directly out of the water basin after water storage and mounted into the setup, to investigate the effect of different curing conditions, while this is not possible with other test methods.

In general, however, the geometry has the disadvantage that, due to the small free measuring length, the recording of the strain with strain gauges is only possible to a limited extent and at the same time is uneconomical. In order to determine the tensile strengths on a large scale, however, the test setup is well suited, since the tests provides valid results with an considerably lower amount of time and effort and furthermore provides low variances of the test results for concretes with a maximum grain size of 8 mm.

5   Conclusions

The study has shown that the newly developed test setup can be used to determine the uniaxial tensile strength of concretes in a well reproducible manner. The tests can be performed time-reliably and allow the determination of the influence resulting from different curing conditions. The maximum tensions are higher than in other experimental setups, which also determine the uniaxial tensile strength. This, in combination with the low coefficient of variation, suggests a lower defect probability and thus a more realistic measurement of the properties of the building material for slim structural elements.

In future investigations, the age of the specimens and the type of subsequent treatment (heat treatment, autoclaving, water storage and storage at standard climate) will be varied. At the same time, the flexural tensile strength will be examined by means of prisms and the uniaxial tensile strength of cylinders, to make a possible connection. Furthermore, a numerical analysis of the stress distribution at the central cross-section will be carried out.

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