EFFECT OF SPECIMEN SIZE ON THE COMPRESSIVE STRENGTH OF ULTRA-HIGH PERFORMANCE CONCRETE

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Abstract

Using test specimens with different shapes and sizes may result in different values of concrete compressive strength, as known for normal-strength concrete (NSC) and high-strength concrete (HSC). Thus, appropriate conversion factors have to be established in order to provide necessary input for classification of UHPC and conformity test. Since retaining standard specimen sizes for UHPC may cause problems due to the limited capacity of present testing machines, test specimens with reduced sizes seem to be favourable.

Within the present study, cubes and cylinders made with NSC, HSC, and UHPC with different maximum grain size are tested. Special preparation of test specimens was established in order to minimise falsifying effects and to obtain reliable test results. Standard deviation and coefficient of variation of compressive strength document high accurateness and validity especially for the UHPC mixtures. Compared with NSC and HSC, the effect of specimen size and slenderness on the compressive strength is very small for UHPC.

Résumé

L'utilisation d'éprouvettes ayant des formes et des tailles différentes peut aboutir à des valeurs variables de la résistance à la compression du béton, ce qui est connu pour les bétons ordinaires (BO) et les bétons à hautes performances (BHP). De ce fait, des facteurs de conversion appropriés doivent être établis pour permettre la classification des BFUP et tester leur conformité. Comme le maintien des tailles standards d'éprouvettes pour les BFUP peut poser problème en raison de la capacité limitée des machines d'essai actuelles, des éprouvettes de taille réduite semblent être préférables.

Dans la présente étude, des cubes et des cylindres constitués de BO, BHP et BFUP avec des tailles du plus gros granulat différentes ont été testés. Une préparation spéciale des éprouvettes a été définie afin de minimiser les artefacts et d'obtenir des résultats d'essais fiables. L'écart-type et le coefficient de variation de la résistance en compression attestent d'une grande précision et de la validité de la méthode, en particulier pour les BFUP. Par rapport aux BO et BHP, l'effet de la taille de l'échantillon et de son élancement sur la résistance en compression est très faible pour les BFUP.

1. INTRODUCTION

Concrete compressive strength is determined acc. to EN 12390-3 [1] using cubes or cylinders with a height/diameter ratio (slenderness) of h/d = 2. Cubes should have an edge length between 100 and 300 mm and cylinders a diameter between 100 and 300 mm [2]. The characteristic compression strength of cylinders with a diameter of 150 mm ($f_{ck,cyl}$) or the characteristic compression strength of cubes with an edge length of 150 mm ($f_{ck,cube}$) at the age of 28 days forms the basis for the classification of normal-strength concrete (NSC) and high-strength concrete (HSC) acc. to EN 206 [3]. Retaining these specimen sizes as standard for UHPC may cause problems due to the high ultimate loads and limited capacity of present testing machines. Thus, test specimens with reduced sizes, e.g., cylinders with h/d [mm] = 200/100 or cubes with an edge length a = 100 mm, are more favourable.

Using test specimens with different shapes and sizes may however lead to various values of concrete compressive strength. This is basically caused by different multi-axial compression stress-states depending on the slenderness of the test specimen [4]. But even changing the specimen dimensions without changing the slenderness may influence the compressive strength due to statistical effects. In this regard, specimens with smaller dimensions (e.g., cube with a = 100 mm) lean towards higher strength values than specimens with larger dimensions (e.g., cube with a = 150 mm).

2. BACKGROUND AND SCOPE OF RESEARCH

For NSC and HSC, appropriate conversion factors have been established [4-6] in order to relate results obtained from different specimen sizes to a reference (generally cylinder with h/d [mm] = 300/150), that forms the basis for structural design [7]. As depicted in Fig. 1, NSC cylinder with h/d [mm] = 300/150 typically reaches only about 82 % of the compressive strength of a cube with a = 150 mm and only about 75 % of the compressive strength of a cube with a = 100 mm. These factors increase for HSC, i.e. the difference of test results obtained from specimens with different slenderness is smaller than for NSC. This effect may be attributed to the basically minor increase of concrete compressive strength of HSC due to multi-axial compression stress state [8].

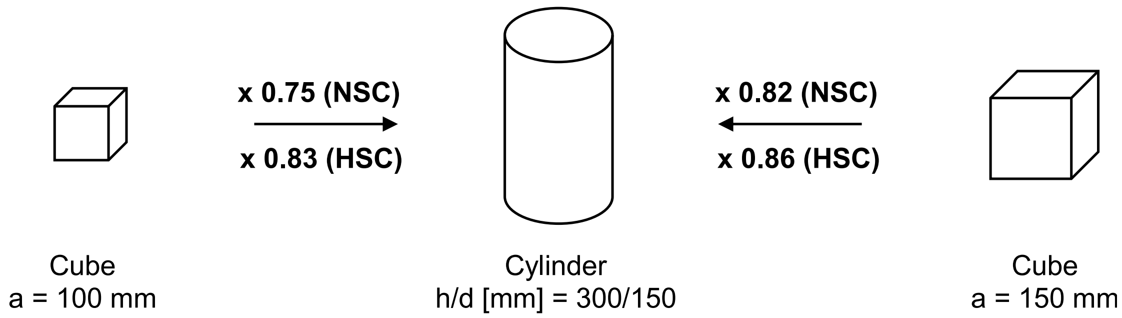

Figure 1: Conversion factors for NSC and HSC compressive strength obtained from different specimen shapes and sizes (results from [4-6])

More than two decades ago, introducing HSC required checking the applicability of preparation and test methods well established for NSC [9-11]. De Larrard et al. [11] point out that preparation of HSC test specimens requires special accurateness in order to limit the scattering of test results. Amongst other things, they recommend grinding the faces of cube specimens and determining the relation between cylinder and cube for each particular HSC mix since scattering of test results does not allow a general proposal.

Graybeal and Davis [12] evaluated 14 series of compression tests on HSC and UHPC mixtures using premixes without coarse aggregate with compressive strengths in the range between 80 and 200 MPa. Methods of producing, curing, preparing, and testing UHPC are based on findings of a large-scaled research programme investigating commercially available UHPC premixes [13]. Each series included three sizes of cylinders (d = 51, 76, and 102 mm) with a slenderness of h/d = 2 and three sizes of cubes (a = 51, 70.7, and 100 mm). Most of the series were heat-treated, some were cured in air. The cube specimens were tested with unground loaded faces. Comparison of mean compressive strengths obtained from cylinders with d = 102 mm ($f_{c,cyl}$) and cubes with a = 100 mm ($f_{c,cube}$) resulted in conversion factors $f_{c,cyl}/f_{c,cube}$ between 0.97 and 1.10 for the UHPC mixtures, i.e. in most cases the compressive strength obtained from cylinders was higher than the compressive strength obtained from cubes. Especially the UHPC mixtures without fibres showed high standard deviation of up to 15 MPa so that scattering of test results superimposed the impact of the different shapes and sizes.

Fládr et al. [14] investigated the relation of compressive strengths of different sized cubes made with fibre reinforced HSC and UHPC using mixtures with coarse aggregate. Cubes with a = 100 mm and 150 mm with compressive strengths in the range between 100 and 180 MPa were tested in 7 series. Conversation factors $f_{c,cube150}/f_{c,cube100}$ between 0.85 and 0.99 were obtained by comparing mean compressive strengths. However, standard deviations of test results of up to 12 MPa might have falsified the impact of specimen size.

Within the German Priority Programme 'Sustainable Building with Ultra-High Performance Concrete', an inter-laboratory test was performed to study the influence of different methods of production, curing, preparation, and testing on the test results obtained for UHPC. Based on statistical evaluation, Fröhlich and Schmidt [15] emphasise the necessity of standardised procedures, e.g. water-curing, precision-grinding etc., in order to avoid possible falsifying effects on the test results especially in case of compression tests. Unevenness of only few µm may influence the test results significantly so that compressive strength of the same mixture can differ up to 20 MPa. Due to the large scattering of results (standard deviations of up to 16 MPa within a test series), reliable conversion factors for the compressive strength obtained from different specimen sizes could not be derived.

Nevertheless, the use of UHPC in structural applications requires defining concrete strength classes and appropriate criterions in order to decide about conformity. In this regard, the French Standard NF P 18-470 [16] classifies UHPC using six strength classes, which are defined by means of the characteristic compressive strength obtained from cylinders with h/d = 220/110 mm or cubes with a = 100 mm assuming a difference of 15 MPa between cylinder and cube strength as indicative value. This results in ratios between cylinder compressive strength and cube compressive strength of 0.90 ($f_{ck,cyl}/f_{ck,cube}$ = 130/145 MPa) up to about 0.94 ($f_{ck,cyl}/f_{ck,cube}$ = 250/265 MPa).

In Germany, the DAfStb-Guideline for Ultra-High Performance Concrete [17], which will extend the scope of EN 1992-1-1 [7] by three strength classes, is in progress. The classification is adopted from NF P 18-470, however the characteristic strength values of 130, 150, and 175 MPa are defined by cylinders with a diameter of 150 mm in accordance with

EN 206. In default of verified conversion factors for deviating specimen geometries, a test programme has been set-up and supported by the German Committee for Structural Concrete (Deutscher Ausschuss für Stahlbeton – DAfStb) in order to provide necessary input for classification and conformity test of UHPC.

3. EXPERIMENTAL INVESTIGATIONS

3.1 Test programme

The test programme consists of seven test series in total including NSC, HSC, and UHPC mixtures with compressive strengths ranging from about 25 MPa to 180 MPa (mean value of compressive strength f_{cm} of cylinders with h/d [mm] = 300/150). Five of the test series are performed at the University of Siegen. For validation purposes and in order to exclude systematic falsifying effects, the University of Kassel and the Rhein-Main University of Applied Sciences carry out one test series each. In this respect, also NSC and HSC mixtures have been included in order to form a link with results from literature. Within the study, cubes with an edge length a = 100 mm (Cube100) and a = 150 mm (Cube150) as well as cylinders with h/d [mm] = 200/100 (Cyl100) and h/d [mm] = 300/150 (Cyl150) are tested. Thus, conversion from all common types of specimen to the reference cylinder Cyl150 can be made. Table 1 gives a survey of the complete test programme. The following explanations focus on the experimental work done at the University of Siegen (Series 1 to 5), that has been completed so far.

Table 1: Test programme

Series	Type of concrete	f_{cm} [MPa]	d_g [mm]	Type of specimen	Number of specimens
1	NSC	≈ 25	16	Cube100, Cube150, Cyl100, Cyl150	4 x 6 = 24
2	HSC	≈ 75	16	Cube100, Cube150, Cyl100, Cyl150	4 x 6 = 24
3	UHPC	≈ 150	3	Cube100, Cube150, Cyl100, Cyl150	4 x 6 = 24
4	UHPC	≈ 160	0.5	Cube100, Cyl100, Cyl150	3 x 6 = 18
5	UHPC	≈ 160	8	Cube100, Cyl100, Cyl150	3 x 6 = 18
6	UHPC	≈ 130	8	Cube100, Cube150, Cyl100, Cyl150	4 x 6 = 24
7	UHPC	≈ 180	0.5	Cube100, Cube150, Cyl100, Cyl150	4 x 6 = 24

Series 1 and 2 consist of 24 specimens each (6 of each type of specimen). Both mixtures were fabricated with coarse aggregates (round gravel with maximum grain size d_g = 16 mm).

In Series 3, 4 and 5 three different mixtures of UHPC were examined. Both fine grained and coarse grained mixtures with comparable strengths and – based on the field of practical application – with maximum grain size d_g of 0.5 mm (quartz sand 0.125/0.500 mm), 3 mm (crushed basalt 1/3 mm), and 8 mm (crushed basalt, fractions 2/5 mm and 5/8 mm) were used. Series 3 consists of 24 specimens (6 of each type of specimen). In series 4 and 5, cubes with an edge length a = 150 mm (Cube150) were omitted considering the limited capacity of the available testing machine (4.0 MN).

In order to become independent of varying fibre type and fibre content, that might reduce the influence of specimen shape and size, plain UHPC was investigated. Knowing that this could increase the scattering of test results, preliminary tests on appropriate procedures in production, curing, preparation, and testing were carried out in order to improve reliability of test results. Especially the evenness of loaded specimen faces was analysed by means of testing the compressive strength of 12 cubes overall with an edge length of a = 100 mm, which were cast in steel moulds using a single batch of the UHPC mixture. Forms were stripped after 24 hours and specimens were stored under laboratory environmental conditions. Six of the cubes were tested without preparing the specimen faces. The other six cubes were prepared by grinding the cast faces before testing. All specimens were tested on the same day.

Two main results could be obtained within this study:

1. The cubes with ground faces showed a 12.3 MPa higher mean value of compressive strength than the untreated cubes. Thus, compressive strength may be underestimated by testing untreated cubes even if steel moulds are used. Results are then conservative but however disadvantageous for practice. With regard to derivate conversion factors, comparing compressive strength of cylinders with ground faces and compressive strength of untreated cubes, may lead to misinterpretation.
2. The results of the untreated cubes showed a standard deviation of 7.9 MPa compared to 4.6 MPa of the cubes with ground faces. Thus, using cubes with ground faces provides higher significance and reliability for the present study.

Based on these findings, it was decided to use specimens with ground faces (cubes and cylinders) in case of HSC and UHPC only and to improve the grinding procedure due to its relevance. A precision-grinding regime as well as equal curing conditions (water storage for all UHPC mixtures) was established for the main investigation in order to minimise the scattering of test results. Only in case of NSC specimens, loaded faces of cubes stayed untreated.

3.2 Production and storage of specimens

The specimens were fabricated in single batches of 75 litres (Series 1, 2 and 3) and 55 litres (Series 4 and 5) fresh concrete mixed in a high-performance compulsory mixer. Table 2 presents the details of the mix design of the concrete mixes used in Series 1 to 5 as well as some basic characteristics of fresh concrete.

Table 2: NSC, HSC and UHPC mix design and fresh concrete characteristics of Series 1 to 5

Series	1	2	3	4	5
Type of concrete	NSC d_g = 16 mm	HSC d_g = 16 mm	UHPC d_g = 3 mm	UHPC d_g = 0.5 mm	UHPC d_g = 8 mm
Cement [kg/m^3] CEM I 52.5R HS-NA	264	505	392	791	668
Silica fume [kg/m^3]	-	-	98	167	167
Quartz powder [kg/m^3]	-	-	323	200	250
Quartz sand [kg/m^3]	-	-	647	982	501
Coarse aggregate [kg/m^3]	1870	1628	906	-	701
Superplasticiser [kg/m^3]	-	2	12	23	20
Water [kg/m^3]	198	185	146	186	170
Water-cement ratio [-]	0.75	0.37	0.37	0.26	0.25
Water-binder-ratio [-]	0.75	0.37	0.32	0.21	0.22
Slump [mm]	495	534	185	215	220
Temperature t_0/t_1 [°C]	-	-	23.7/25.6	21.9/26.5	21.5/26.7

Depending on the type of concrete, different mix regimes were applied for production. For UHPC mixtures, at first silica fume, quartz sand and coarse aggregate were mixed in dry state for about 1 minute. Afterwards quartz powder and cement were added and mixed again for 1 minute in dry state to ensure the uniformity of the mix. Water and superplasticiser were premixed and added simultaneously. All contents were then mixed for 10 minutes. The temperature of fresh concrete was measured at the beginning (t_0) and at the end (t_1) of the mixing procedure. The consistency of fresh concrete was measured by a conventional slump test acc. to [18] for NSC as well as for HSC and for UHPC by a spread-flow test using a Hägermann cone generally used for mortar acc. to [19] without shocking.

After finishing the mixing procedure the concrete was cast into plastic (cylinders) and steel moulds (cubes). The same moulds were used in all series. Each mould was numbered consecutively and charged in ascending order to be able to relate to a potential time-depending degradation of concrete quality during manufacturing process. For compaction of concrete a vibrating table was used. All moulds were adequately fixed to ensure uniform compaction. All specimens were capped with plastic foil and stored at 20 ± 2 °C before being demoulded after 24 h. The specimens of Series 1 (NSC) and Series 2 (HSC) were cured in water for 7 days (20 ± 2 °C) and then stored in moist climate until testing (20 ± 2 °C and 65 ± 5 % RH). The specimens of Series 3 to 5 (UHPC) were stored in water (20 ± 2 °C) until testing.

3.3 Preparation of specimens and test execution

As mentioned before, the loaded faces of all HSC and UHPC specimens were prepared by precision-grinding using a parallel grinding and cutting machine. For that purpose, the UHPC specimens where temporarily removed from water and kept in damp cloth.

Grinding followed a specific procedure, which was developed and optimised as a result of preliminary tests (see chapter 3.1). In case of cylinders, the side from which the concrete was poured into the forms was smoothed in a first step. Since cubes were turned aside for testing, this step could be omitted for such kind of specimens. Then, cylinders and cubes passed through four cycles of parallel grinding with average removal of 0.5 mm, 0.5 mm, 0.3 mm, and finally 0.15 mm from each loading face. After that procedure, evenness of all specimens was checked by one particular person moving the specimen upon the loading plate of the machine which was subsequently applied for compression loading. As a result of trying different methods for defining and checking evenness it turned out that 'human sense' was the most precise and appropriate measuring device. If specimens passed this test, they were restored to water-curing, if not, the final steps of grinding were repeated.

Compression test was executed force controlled with a loading rate of 0.4 MPa/s using a hydraulic controlled testing machine (class 1 acc. to [20], maximum load 4.0 MN). After removal from water, UHPC specimens were stored in damp cloth until shortly before testing but ground faces were fully dried for load application. Specific dimensions, mass, and maximum load was logged for each specimen. A complete test series was conducted subsequently within one day.

4. TEST RESULTS AND ANALYSIS

Table 3 gives information about the mean value f_{cm}, the standard deviation σ, and the coefficient of variation c_v of the compressive strength of each type of specimen (6 samples of each type of specimen) of Series 1 to 5.

Table 3: Test data of Series 1 to 5

Series	Type of concrete	Type of specimen	Compressive strength		
			f_{cm} [MPa]	σ [MPa]	c_V [%]
1	NSC d_g = 16 mm	Cube100	35.7	1.8	5.1
		Cube150	33.9	1.7	4.9
		Cyl100	27.9	0.9	3.3
		Cyl150	26.8	1.6	6.0
2	HSC d_g = 16 mm	Cube100	94.9	3.2	3.4
		Cube150	93.7	3.1	3.3
		Cyl100	79.3	3.3	4.2
		Cyl150	78.5	1.9	2.4
3	UHPC d_g = 3 mm	Cube100	169.0	2.7	1.6
		Cube150	161.3	3.6	2.2
		Cyl100	158.1	4.2	2.7
		Cyl150	151.9	3.5	2.6
4	UHPC d_g = 0.5 mm	Cube100	167.9	3.3	2.0
		Cyl100	164.5	3.6	2.2
		Cyl150	165.2	1.8	1.1
5	UHPC d_g = 8 mm	Cube100	165.1	2.2	1.3
		Cyl100	161.8	2.0	1.2
		Cyl150	161.7	3.8	2.3

Depending on the type of specimen, the mean value of compressive strength is between 26.8 and 35.7 MPa for NSC, between 78.5 and 94.9 MPa for HSC and ranges from 151.9 to 169.0 MPa (Series 3), from 164.5 to 167.9 MPa (Series 4), and from 161.7 to 165.1 MPa (Series 5) for UHPC. Margins of 8.9 MPa for NSC, 16.4 MPa for HSC, and 3.4 MPa for UHPC (Series 4 and 5) reveal that size and slenderness of specimens tend to have less influence on the compressive strength for UHPC than for NSC or HSC. Considering the coefficient of variation shows that accurateness and validity is very high especially for the UHPC mixtures, where c_V is between 1.1 and 2.7 %. For all types of specimen and test series standard deviation σ is below 4 MPa except for one.

Table 4 provides ratios of compressive strength between different specimen sizes. The ratios are obtained by dividing the mean values f_{cm} of the specimen types denoted in the fourth column of Table 3. While strength ratios (Cyl150/Cube150) and (Cyl100/Cube100) represent the influence of specimen slenderness, the strength ratios (Cyl150/Cyl100) and (Cube150/Cube100) account for the effect of different specimen size. For NSC and HSC, the strength ratios (Cyl150/Cube100) and (Cyl150/Cube150) range in the same order of magnitude as the conversion factors proposed in literature (see chapter 2). This underlines reliability of test results and appropriate execution of experimental work.

While the NSC cylinders with a slenderness h/d = 2 show only 79 % (and 78 % respectively) of the compressive strength obtained from cubes with the same edge length a = d, this relation increases to 84 % for HSC and up to 98 % for UHPC (Series 4 and 5). Variation of slenderness shows the same impact on specimens with smaller size (d = 100 mm and a = 100 mm respectively) and larger size (d = 150 mm and a = 150 mm respectively). Thus, strength ratios (Cyl100/Cube100) and (Cyl150/Cube150) are quasi-identical.

Table 4: Ratio of compressive strength between different specimen sizes

Series	1	2	3	4	5
Type of concrete	NSC d_g = 16 mm	HSC d_g = 16 mm	UHPC d_g = 3 mm	UHPC d_g = 0.5 mm	UHPC d_g = 8 mm
Ratio (Cyl150/Cube100) [-]	0.75	0.83	0.90	0.98	0.98
Ratio (Cyl150/Cube150) [-]	0.79	0.84	0.94	-	-
Ratio (Cyl100/Cube100) [-]	0.78	0.84	0.94	0.98	0.98
Ratio (Cyl150/Cyl100) [-]	0.96	0.99	0.96	1.00	1.00
Ratio (Cube150/Cube100) [-]	0.95	0.99	0.95	-	-

Increasing the specimens size from d = 100 mm (and a = 100 mm respectively) to d = 150 mm (and a = 150 mm respectively) without changing the slenderness tends towards a small decrease in compressive strength. The strength ratios obtained in the study range from 0.95 to 1.00 without showing dependency on the concrete strength.

Series 4 and 5 with equal strength but different maximum grain size (d_g = 0.5 mm and d_g = 8 mm) show exactly the same compressive strength ratios, i.e. strength ratio is determined by the concrete strength but not influenced by the mix design.

5. CONCLUSIONS AND OUTLOOK

Although examination of the effect of specimen size on the concrete compressive strength of UHPC is still ongoing, some conclusions may be drawn based on the results obtained so far:

1. In order to obtain reliable and economic results, precision-grinding of specimen faces is recommended in case of cylinders and cubes. Testing cubes without special preparation may underestimate the compressive strength significantly, especially for plain UHPC. High contents of fibres may help compensating lack of accurateness in specimen preparation. The apparent unevenness of the untreated specimen faces even in case of steel moulds may be caused by inhomogeneous shrinkage of concrete. The background should be examined further.
2. The influence of the specimen slenderness on the results obtained in compression tests decreases significantly with increasing concrete compressive strength. For UHPC, the ratio of compressive strength between cylinder and cube is close to 1. Maximum grain size does obviously not influence the ratio of compressive strength for UHPC.
3. When keeping the slenderness constant, compressive strength of NSC, HSC and UHPC changes only marginally for different specimen sizes. The by trend minor strength of the larger specimens (strength ratios between 0.95 and 1.00) may predominantly be caused by statistical effects. Based on weakest-link theory, scattering of concrete quality results in smaller compressive strength with increasing specimen size.
4. Within the present study, the difference between cylinder compressive strength and cube compressive strength was about 10 MPa for UHPC with lower cylinder compressive strength (Series 3) and less than 5 MPa for UHPC with higher cylinder compressive strength (Series 4 and 5) when comparing specimens with similar dimensions in diameter and edge length. These values may serve as a basis for defining UHPC strength classes.

The present study will be continued examining Series 6 (at the University of Kassel) and Series 7 (at the Rhein-Main University of Applied Sciences). After completing the experimental work, conversion factors for conformity test will be defined and validated by numerical analysis considering behaviour of concrete with different strengths in multi-axial stress state.

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