DETERMINATION OF CONVERSION FACTORS FOR COMPRESSIVE STRENGTH OF HPFRC MEASURED ON SPECIMENS OF DIFFERENT DIMENSIONS

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Abstract

Current development of high-strength concretes is aimed at using high-strength aggregate with maximum grain size of four or eight millimetres. Ultra-high-strength concretes with compressive strength higher than 150 MPa are commonly produced in laboratories nowadays. For such concretes, measuring compressive strength on classic cubes with dimensions 150 mm x 150 mm x 150 mm is not suitable, as for this size of specimen the applied load of compression testing machine must be several thousand kiloNewtons. Reaching such values of applied testing load is difficult. Utilisation of smaller specimens for concretes with lower grain size is possible and strengths determined in tests with these specimens can be adequately accurate. The main objective of this paper is to present the research that investigated relations of compressive strengths measured on differently sized specimens. Results obtained for standard specimens (150 mm x 150 mm x 150 mm) are compared to 100 mm x 100 mm x 100 mm cubes. The values of conversion factors were determined for different levels of compressive strength.

Résumé

Le développement actuel des bétons à hautes performances (BHP) intègre l'emploi d'agrégats de haute résistance de dimensions maximales comprises entre 4 et 8 mm. Des BHP dont la résistance est supérieure 150 MPa sont aujourd'hui communément fabriqués dans les laboratoires. La détermination de la résistance à la compression de ces béton sur des cubes classiques de 150 mm x150 mm x 150 mm convient mal. En effet, pour ces dimensions, les charges à appliquer sont de l'ordre de plusieurs milliers de kiloNewtons. Atteindre ces valeurs de charge peut être difficile. La réalisation d'essais sur des plus petites éprouvettes de béton fabriquées avec des agrégats de plus petites tailles est possible. Les résistances déterminées sur ces petites éprouvettes peuvent être suffisamment précises. L'objectif principal de cet article est de présenter les résultats de la recherche qui a visé la détermination du ratio entre la résistance déterminée sur des éprouvettes de petite taille et la résistance déterminée sur des éprouvettes de taille classique 150 mm x 150 mm x 150 mm. L'évolution de ce ratio avec la résistance en compression des BHP a été analysée.

1.   INTRODUCTION

Concretes with compressive strength higher than 60 MPa ($f_{ck,cube} \geq 60$ MPa) are classified as high-strength concretes (HSC). For production of concretes with strength higher than 100 MPa, the mixture composition and the mixing procedure must be changed substantially. This consequently leads to new physical properties of hardened concretes. Therefore, concretes with high compressive strength and other outstanding properties are referred to as high-performance concretes (HPC). For concretes of higher class, term „Ultra High Performance Concrete (UHPC)" is used. Their compressive strength is higher than 150 MPa ($f_{ck,cube} \geq 150$ MPa) and they provide other very high level properties. In case of fibre reinforcement ensuring a quasi-ductile behaviour, the designation „Ultra High Performance Fibre Reinforced Concrete" (UHPFRC) is usually preferred. The term UHPFRC shows that besides the high compressive strength, these concretes also have other enhanced properties compared to common concretes (compressive strength circa 30 MPa). Main benefits of UHPFRC are for instance high compressive and tensile strength, low water absorption, high resistance to freeze-and-thaw cyclic loading, long-term stability and durability and rapid reaching of final creep value.

The title HPFRC/UHPFRC comprises word "concrete". Nevertheless, the material must be understood as a new one and different than other concretes. The differences are given by components used in mixing (namely regarding additives), processing and above mentioned outstanding properties.

Designing of HPC structures is not properly covered by codes and standards so far. The code ČSN EN 1992-1-1 assumes utilisation of concrete with cube strength up to 105 MPa ($f_{ck,cube} = 105$ MPa). The strength is measured on cubes 150 mm x 150 mm x 150 mm.

ČSN EN 206-1 [6] mentions concrete with cube strength $f_{ck,cube} = 115$ MPa; some German codes DIN introduce concrete with cube strength $f_{ck,cube} = 120$ MPa. Concrete with strength over 160 MPa is not included in any present-day code. Guidelines for preparation of testing specimens for laboratory testing are not given either.

Testing of HPFRC/UHPFRC characteristics on classic cube 150 mm x 150 mm x 150 mm is not suitable, as for this size of specimen the applied load of compression testing machine must be several thousand kilonewtons. Reaching such values of applied testing load is difficult. Therefore, many laboratories test smaller specimens. Test cubes 100 mm x 100 mm x 100 mm are most frequently used. The disadvantage of testing the smaller specimens is inaccuracy of test results. If extremely small specimens are used, the laboratory tests can exhibit several times higher strengths. In our research, in both cases (150 mm and 100 mm cubes) aggregate with maximum grain size 16 millimetres was used. This meets the requirement of specimen size being more than three times the maximum grain size.

2.   THEORY OF SIZE EFFECT

It is well known that values of mechanical properties measured on different specimens made of absolutely the same material vary according to size of the specimen. This phenomenon, usually referred to as size effect, was mentioned already in 16th century by Leonardo da Vinci in association with strength of ropes. However, deeper examination did not take place until 1921, when Griffith measured significant increase in nominal strength of glass fibres after he decreased diameter of the fibres. Theory of size effect was later worked out in detail mainly by Weibull and Bažant [4].

2.1   Statistical size effect

Brittle materials like concrete follow weakest-link model – macro-fracture initiation from one representative volume element (RVE) causes the whole sample to fail. Since the material strength is random, the strength of the weakest element in a sample is likely to decrease with increasing size of the sample.

Statistical size effect can be intuitively best described by chain-link representation. In a chain, failure of one link causes failure of the whole chain. The more links we have in a chain, the higher the probability that one of the links will be defective. Similarly, with increasing size of the specimen, i.e. with increasing number of RVEs it contains, possibility of failure rises.

Until 1980s, statistical size effect was considered to be the only one with practical influence on real structures. The reason was that in neither elastic nor plastic classical material theories the nominal stress depends on size of the sample. Nevertheless, later investigations have proved that size effect can have its origin also in material mechanics.

2.2   Deterministic (energetic) size effect

If a body is subjected to effects of stress, the most of deformation is concentrated in an area called localization band or fracture process zone (FPZ). The size of this area depends on the type of material, for concrete the width of FPZ w_c can be estimated as 3 to 3.5 times the diameter of maximum aggregate size according to Bažant. For small-scale samples, width of FPZ is significant compared to the dimensions of the whole specimen, while for large-scale samples relative size of the zone is negligible.
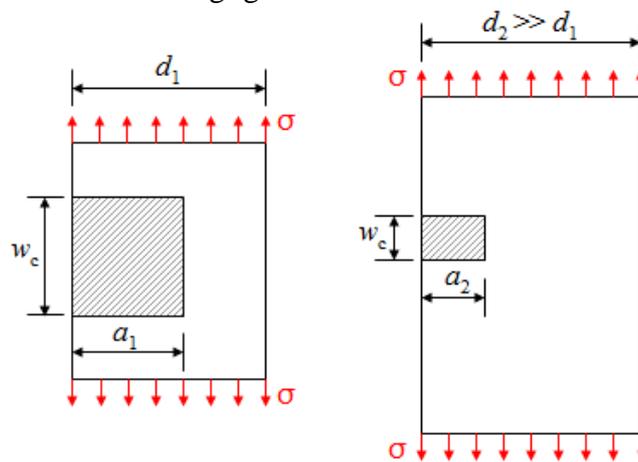

Figure 1: Fracture process zone (FPZ) in small-scale (left) and large-scale (right) samples.
Width of FPZ w_c is a material constant, i.e. w_c is the same in both cases.

In FPZ, material exhibits plastic behaviour. When the size of FPZ is significant compared to the specimen size, stress redistribution in the sample due to damage in FPZ can be observed. On the other hand, if FPZ size is negligible, stress redistribution has no important effect on global behaviour of the sample. As a result, small specimens tend to behave according to laws of plasticity and therefore are able to absorb relatively higher fracture energy than larger ones. For large-scale samples, linear elastic fracture mechanics (LEFM) is more apposite.

Taking into consideration deterministic size effect, nominal strength σ_N for a specimen loaded by tensile stress can be calculated from Bažant's size-effect law (SEL):

$$\sigma_N = Bf_t \frac{1}{\sqrt{1 + \dfrac{d}{d_0}}} \tag{1}$$

in which B is a constant expressing shape of the specimen, f_t is tensile strength, d is characteristic dimension of the sample and d_0 is dimension of RVE. Proceeding strictly according to this law, calculated strengths should be close to zero for large samples, which is in contradiction with experimental results. Tests conducted on large-scale specimens (e.g. [3]) showed that nominal strength tends to a non-zero constant value related to uniaxial tensile strength. Therefore, Bažant proposed modification of size effect law (MSEL) introducing size independent strength $\sigma_0 = \alpha f_t$:

$$\sigma_N = Bf_t \frac{1}{\sqrt{1 + \dfrac{d}{d_0}}} + \alpha f_t \tag{2}$$

in which α is an empirical constant less than unity. Relation between size of the specimen compared to RVE and nominal strength of concrete is usually being expressed in logarithmic scale, as shown in figure 2.
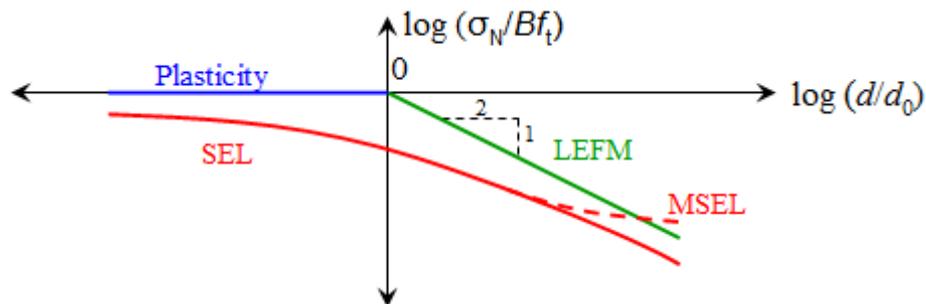

Figure 2: Dependence of nominal strength of concrete on relative size of the specimen.

Abovementioned theory was originally derived for concrete in tension. However, Kim and Yi [5] proved that with properly defined parameters of the model, it can be considered as valid also for compressed concrete samples.

3.   EXPERIMENTAL PROGRAM

Cubes 100 mm x 100 mm x 100 mm are used for testing of compressive strength in the HPFRC research program at Faculty of Civil Engineering, Czech Technical University in Prague. Commonly accepted compressive strengths are those measured on specimens with size 150 mm x 150 mm x 150 mm. Keeping in mind the consequences of size effect described in previous paragraph, the effect of specimen size on compressive strength had to be verified for correct interpretation of tests conducted on smaller specimens at different levels of compressive strength. The objective was to determine possible relation between specimen size and compressive strength.

3.1 Preparation of test specimens

The aim of the experiments was to determine the relation between compressive strengths measured on specimens of different sizes. The composition of the mixture was adjusted to obtain different values of compressive strength. Overview of ranges of mixtures compositions is presented in table 1.

3.2 Curing

Various methods of curing are used in HPFRC production. To reach compressive strength over 180 MPa, thermal curing of concrete together with moisture or water curing is applied. The test specimens in this experimental program were cured in a water container with temperature of 20º C during 26 days.

Table 1: Composition of mixtures

Compound	Type	Amount	Unit
Cement	CEM I - 42,5	600 – 900	kg/m^3
Water/Binder ratio	-	0.2 – 0.25	-
Aggregate	Quartz 4/8	500 – 1000	kg/m^3
	Quartz 2/4	200 – 400	kg/m^3
	Quartz 0/2	150 – 600	kg/m^3
Plasticizer	Polycarboxylate	10 – 30	kg/m^3
Microfiller	-	20 – 50	kg/m^3
Fibres	Steel	100 – 200	kg/m^3

3.3 Testing

All test specimens were subjected to destructive testing in hydraulic compression testing machine at the age of 28 days. The tests were performed according to ČSN EN 12390-3 [7]. The bulk density was determined before compressive strength tests.

4. RESEARCH RESULTS

The aim of the research was to determine the relation between strength measured on cubes 150 mm x 150 mm x 150 mm and strength measured on cubes 100 mm x 100 mm x 100 mm. The main objective of the study was the reduction of costs of HPFRC research. Testing of smaller specimens decreases the amount of consumed materials. For preparation of the same number of specimens, smaller batch volume has to be mixed.

Another important benefit is the decrease of demands on the testing machine. The HPFRC specimens achieve high compressive strengths. Bigger test specimens require compression testing machine with higher rated load. Destructive testing of smaller specimens is less demanding concerning the compressive load of the testing machine.

Table 2 shows values of compressive strength measured on cubes with size 150 mm x 150 mm x 150 mm and values measured on cubes 100 mm x 100 mm x 100 mm. Both sets with different specimen sizes were manufactured based on the same composition

and from the same batch. Seven batches (A – G) were mixed. The adjacent columns show compressive strengths of specimens manufactured from the same batch and measured on bigger and smaller test specimens. In the last row, coefficients calculated as ratio of average compressive strengths measured on specimens with size 150 mm x 150 mm x 150 mm and specimens with size 100 mm x 100 mm x 100 mm are presented.

Table 2: Compressive strength in MPa as measured on cubes 150 mm x 150 mm x 150 mm and 100 mm x 100 mm x 100 mm. Overview of all seven different batches.

| Batch	A		B		C		D		E		F		G	
Specimen size [mm]	150	100	150	100	150	100	150	100	150	100	150	100	150	100
Specimen 1	101	115	106	121	109	120	133	139	139	146	144	130	178	168
Specimen 2	98	116	102	118	106	124	132	138	144	143	145	152	177	173
Specimen 3	98	115	103	121	118	127	132	137	140	143	129	142	170	191
Specimen 4									143	143				
Specimen 5									143	148				
Specimen 6									143	142				
Average compressive strength	99	116	104	120	111	124	133	138	142	145	139	141	175	177
Coefficient	**0,852**		**0,867**		**0,897**		**0,960**		**0,981**		**0,985**		**0,987**	
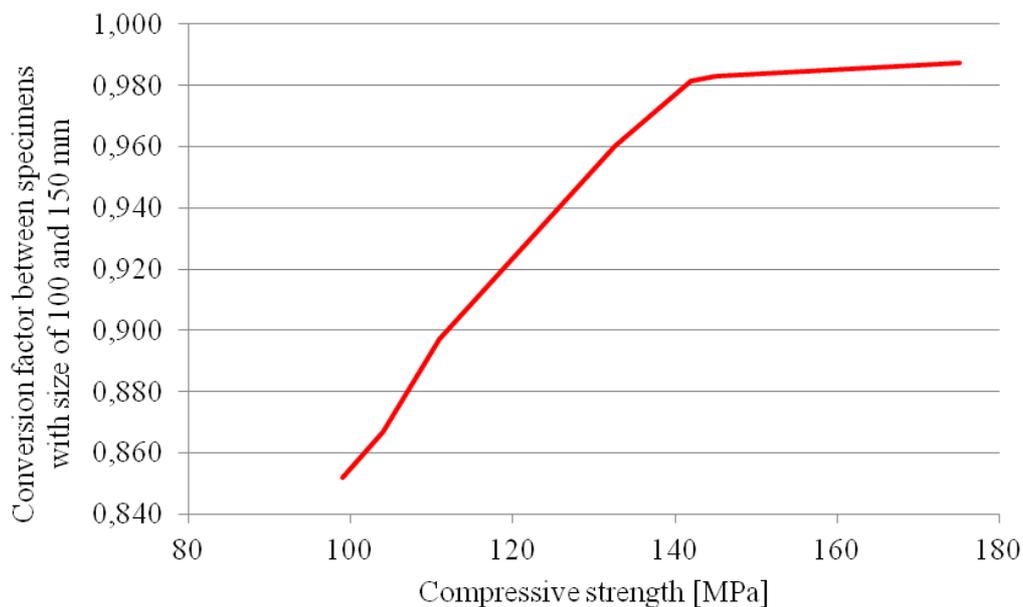
Figure 3: Relation of compressive strength and conversion factor between compressive strength measured on cubes 150 mm x 150 mm x 150 mm and cubes 100 mm x 100 mm x 100 mm

The graph (figure 3) shows relation of compressive strength and ratio of compressive strengths measured on cubes 150 mm x 150 mm x 150 mm and cubes 100 mm x 100 mm x 100 mm. Increase of the ratio with increasing compressive strength is evident. Using coefficients form the presented plot, the investigation of compressive strength of HPFRC can be performed with cubes 100 mm x 100 mm x 100 mm, the results can be easily converted and compared with results for commonly used 150 mm x 150 mm x 150 mm cubes.

Presented results should be considered as informative, as for different concretes (with different grain-size distribution or different sizes of aggregate) the conversion factors can vary.

5. CONCLUSIONS

The paper presents effect of the size of cube specimen on cube compressive strength. Two specimen sizes were compared – cubes 100 mm x 100 mm x 100 mm and cubes 150 mm x 150 mm x 150 mm. The presented graph indicates that the size effect decreases with increasing strength. This corresponds to findings of Kim and Yi [8], who observed that FPZ of high-strength concretes is smaller that for normal-strength concretes and therefore size independent strength σ_0 becomes more important as compressive strength rises.

For compressive strengths higher than 140 MPa, the graph also shows a value of conversion factor 0.98 for the relation between strength determined on cubes 100 mm x 100 mm x 100 mm and cubes 150 mm x 150 mm x 150 mm. This value was determined from relatively small set of experimental results. For objective analysis of compressive strengths of various concrete samples, it should be reduced with respect to reliability and uncertainties in composition of mixtures different from tested ones.

Conclusions of this paper are important for testing of HPRFC and UHPFRC specimens, as they indicate that by using appropriate conversion factors, standard cubes 150 mm x 150 mm x 150 mm can be replaced by smaller cubes 100 mm x 100 mm x 100 mm without unwanted effect on the results.

In further work, authors would like to focus on theoretical explanation of size effect impacts on testing of UHPFRC properties. This will probably require some additional experimental work to obtain more representative set of data.

Within the scope of research program, cubes with dimensions smaller than 100 mm were tested. The results had high scatter, the accuracy was not sufficient. Therefore, the authors do not recommend using smaller specimens for HPFRC and UHPFRC compressive strengths testing.

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