Composites Part B 138 (2018) 77–86

Contents lists available at ScienceDirect

Composites Part B

journal homepage: www.elsevier.com/locate/compositesb

Specimen size effect on compressive and flexural strength of high-strength fibre-reinforced concrete containing coarse aggregate

Josef Fládr, Petr Bílý*

Czech Technical University in Prague, Faculty of Civil Engineering, Department of Concrete and Masonry Structures, Thákurova 7, 16629 Prague, Czech Republic

ARTICLE INFO

Keywords:
Size effect
High-strength concrete
Compressive strength
Flexural strength
Modified size effect law

ABSTRACT

It is a well-known fact that the size of the sample influences values of mechanical properties of concrete measured during the tests. However, the comparison of results of various researchers clearly shows that the importance of this effect varies for different types of concrete. The paper presents outcomes of extensive experimental study focused on determination of relations between the size of the specimen and results of mechanical tests of high-strength fibre-reinforced concrete (HSFRC) with coarse aggregate (maximum aggregate size 16 mm). The main observed parameter was compressive strength. Six different HSFRC mixes having the expected compressive strength between 100 and 175 MPa were investigated. Cube samples of four sizes – 40, 100, 150 and 200 mm – were examined. The results proved that the size dependence of compressive strength diminishes with increasing strength of concrete. For very high strength materials (more than 130 MPa), the results were almost size independent. Additionally, flexural strength of two high-strength concrete mixes was measured on prismatic specimens of two different sizes. The results indicated that flexural strength of HSFRC with coarse aggregate is size dependent without regard to expected compressive strength. Conversion factors for the tested type of material were proposed for both compressive and flexural strength measurements.

1. Introduction

Generally, there are two main types of specimens used for testing of compressive strength of concrete around the world – cylinders and cubes. Specimens of varying shapes and sizes are preferred in various countries. In the states using European standards (EN), 150 mm cubes and 150/300 mm (diameter/height) cylinders are the most commonly used types. In connection with the advancement of concrete technology and considering wider use of high-strength fibre-reinforced concretes (HSFRC), these types of specimens are often replaced by smaller samples, mainly by 100 mm cubes. The reason why cubes are preferred over cylinders is elimination of bottom and top surface preparation. Cylinder end grinding equipment is expensive, it is difficult to find a capping material with suitable properties for testing of HSFRC. Smaller specimens are also advantageous because of easier handling of the samples and lower material consumption. The main reason why smaller cubes are preferred is the effort to reduce testing machine capacity requirements. According to the experience of the authors, capacity of common testing machines usually does not exceed 3 MN, which means that the maximum possible strength of 150 mm cubes to be tested is 130 MPa. Such value is sufficient for majority of purposes, but not for research and application of the most advanced HSFRC. If the 100 mm cubes are used, the required force is theoretically 2.25 times lower. This enables testing of concretes exceeding 250 MPa compressive strength with the use of the same machine.

The situation is similar concerning the flexural strength which is the second most important parameter of HSFRC. Both 150 × 150 × 700 mm and 100 × 100 × 400 mm prisms are exploited in the states where European standards (EN) are adopted. In this case, capacity of testing machine is not an issue. Easier production and handling of the samples made 100 × 100 × 400 mm prisms more common in the recent years (the weight of the sample is approximately 10 kg compared to 40 kg in case of the bigger one), but 150 × 150 × 700 mm prisms are still employed occasionally as some specialists consider them to provide better representation of flexural behaviour of the material in real structure.

There is a general agreement on the fact that the results of both compressive strength and flexural strength tests are affected by the size of the sample to some extent. However, opinions regarding the quantification of the size effect are ambiguous. As will be shown in chapter 2.2, various researchers have come to miscellaneous conclusions when studying different types of concrete. In this paper, the authors focused on HSFRC with maximum aggregate size of 16 mm which is the object of their long-term research. They attempted to derive conversion factors

* Corresponding author.
E-mail addresses: josef.fladr@fsv.cvut.cz (J. Fládr), petr.bily@fsv.cvut.cz (P. Bílý).

https://doi.org/10.1016/j.compositesb.2017.11.032
Received 22 August 2016; Received in revised form 23 November 2017; Accepted 24 November 2017
Available online 27 November 2017
1359-8368/

for compressive and flexural strengths measured on specimens of different sizes made of 6 concrete mixes.

2. State of the art

2.1. Theory of size effect

The values of mechanical properties measured on different specimens made of 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 [3].

2.1.1. 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 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 the size of the sample. Nevertheless, later investigations have proved that size effect can have its origin also in material mechanics.

2.1.2. 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 2 to 3 times the diameter of maximum aggregate size [4,5]. 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 (Fig. 1).

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.

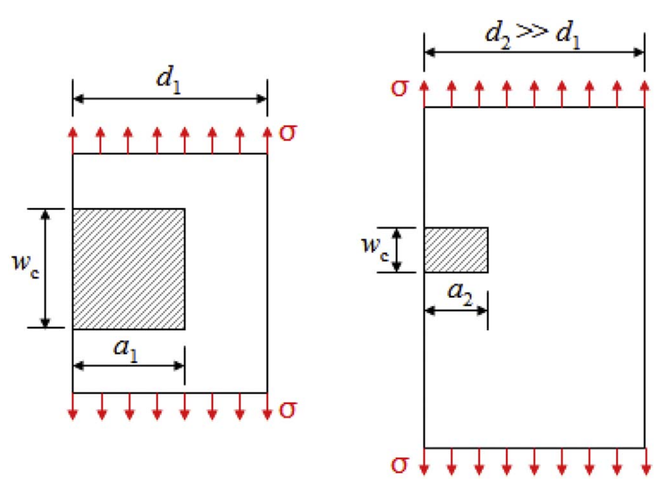

Fig. 1. Fracture process zone (FPZ) in small-scale (left) and large-scale (right) samples. Width of FPZ w_c is a material constant, i.e. w_c is the same in both cases.

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) [4]:

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

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. Ref. [18]) showed that nominal strength tends to a non-zero constant value related to uniaxial tensile strength. Therefore, Bažant [4] proposed modification of size effect law (MSEL) introducing size independent strength $\sigma_0 = \alpha f_t$:

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

in which α is an empirical constant less than unity. Abovementioned theory was originally derived for concrete in tension. Kim and Yi [13] proved that with properly defined parameters B and α, it can be considered valid also for concrete samples in compression, passing to a form of (f_c is compressive strength of the sample):

$$\sigma_N = Bf_c \frac{1}{\sqrt{1 + \frac{d}{d_0}}} + \alpha f_c \tag{3}$$

2.2. Size effect in concrete strength measurements in practice

2.2.1. Compressive strength

The theory of size effect described in the previous chapter clearly explains why different results are obtained when strength of a material on specimens of different size is measured. It also provides a mathematical model that can be used for prediction of strength measured on any size of the specimen, provided that sufficient set of experimental data is available for calibration of the model. In this chapter, results of various authors dealing with practical investigation of cube size effect on compressive strength of concrete are summarized in order to enable comparison and discussion of own results presented later. Studies from the past 20 years are cited as they are considered to be more relevant for currently used concretes, although the research of size effect on concrete strength dates back to the study conducted by Gonnermann as early as in 1925 [11]. The focus is solely on studies dealing with cube samples as cylinders were not tested in own experimental program.

In European standards, a correction factor is not used and 100, 150 or 200 mm cubes can be used without correction to the compressive strength obtained from the test when checking for strength class conformity [19].

Xincheng [21] gives a set of conversion factors to transform the strength measured on 100 mm cube $f_{c,100}$ to the strength of 150 mm cube $f_{c,150}$ (Table 1). The factors are taken from the Chinese codes. The value of the factor depends on the compressive strength, the difference is increasing with increasing strength.

Zhang [24] states that the results obtained on 100 mm cube should be multiplied by 0.95 and the results obtained on 200 mm by 1.05 to get $f_{c,150}$. The coefficients are valid for normal-strength concrete.

A comprehensive study on compressive strength on HSFRC was