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Orginal Article

Size effect at testing strength properties of concrete

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Abstract: Various strength characteristics of concrete are considered as fracture parameters. The compressive strength of concrete is of paramount importance when designing concrete structures, whereas tensile strength of concrete is the basic property when estimating cracking resistance of a structure and analysing fracture processes in concrete. When testing the compressive strength of concrete, the results are dependent on the shape and dimensions of used specimens. Some findings reported in the literature suggest that size effect exists also when testing such fracture properties of concrete as tensile strength. Unfortunately this problem is much less recognized and described compared to size effect in compressive test results. In this paper, the experimental investigation is presented on how the length of cylindrical specimens influences the tensile splitting strength of concrete obtained by means of the Brazilian method. Additional variable parameters were: type of aggregate (natural gravel and crushed granite) and cement-water ratio (C/W = 1.8 and C/W = 2.6). In conducted laboratory experiments a higher splitting tensile strength of concrete was noted for all specimens with nominal dimensions of 150×150 mm, compared to specimens 150×300 mm in size, regardless of type of aggregate or cement-water ratio.

Keywords: concrete, size effect, tensile strength

1. Introduction

Concrete is a composite material which is produced by mixing cement, water, fine and coarse aggregates. Some additives, for example pozzolanas and superplasticizers can be added to improve the mechanical and physical properties of the concrete mixture as well as hardened concrete. The proportions of ingredients are calculated according to appropriate methods to obtain a required quality of hardened concrete, which is particularly important with regard to its compressive and tensile strength. When designing concrete structures, the compressive strength of concrete is of paramount importance, whereas when estimating cracking resistance of structure and analysing fracture processes the tensile strength of concrete is the basic property. The tensile strength of concrete is much lower than its compressive strength and in normal strength concretes it reaches about 10% of compressive strength. Therefore, concrete is rated among quasi-brittle materials.

The bulk of concrete is made up of fine and coarse aggregates which should be of proper granulation. The type of aggregate is also crucial. Both crushed and gravel aggregates can be used as a coarse aggregate in concrete production. The internal structure of hardened concrete causes that concrete is an heterogeneous material and therefore its properties, especially the compressive and tensile strength, should be tested experimentally. Tests should be performed at standard conditions and using standardized specimens according to the code [1]. Concrete compressive strength should be tested in uniaxial compression test on cylindrical or cubic specimens according to the procedure given in the code [2]. To determine the tensile strength of concrete, indirect methods are usually applied due to the difficulty of performing the direct tensile test. As the standard method, the Brazilian splitting tensile test is recommended in the code [3]. The splitting test can be performed using both cylindrical and cubic specimens. Specimens which are admitted for testing, the compressive strength and the splitting tensile strength of concrete are presented in Fig. 1.

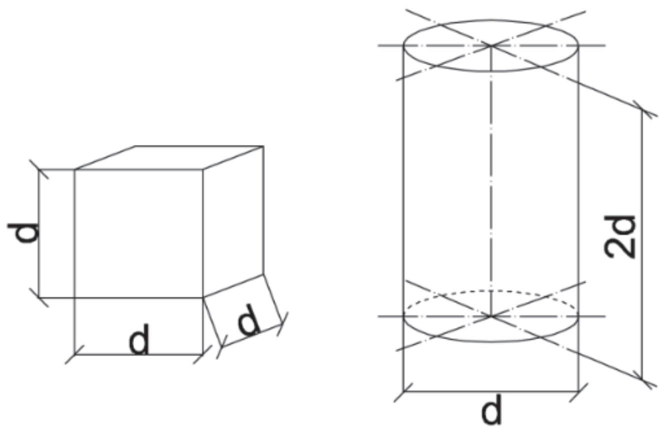

Fig. 1. Admissible types of specimens for testing concrete compressive and tensile strength. Nominal dimensions for cubes: d = 100, 150, 200, 250, 300 mm, and for cylinders: d = 100, 113, 150, 200, 250, 300 mm, with acceptable dimension discrepancy ± 10%

When testing the strength properties of concrete, the shape and dimensions of tested specimens are crucially important. The influence of a specimen's size on concrete compressive strength has been described in depth ([4]-[7]). The specimens which are the most often used in testing compressive strength of concrete are 150 mm, 100 mm and 200 mm cubes, and cylinders 150 mm in diameter and 300 mm long. The relations among concrete compressive strengths tested on different specimens are presented below (Eq. 1).

$$f_{c,cube15} = 0.9 f_{c,cube10} = 1.05 f_{c,cube20} = 1.25 f_{c,cyl15/30} \quad (1)$$

where: $f_{c,cube15}$ – compressive strength tested on cubes 150 mm, $f_{c,cube10}$ – compressive strength tested on cubes 100 mm, $f_{c,cube20}$ – compressive strength tested on cubes 200 mm $f_{c,cyl15/30}$ – compressive strength tested on cylinders 150mm in diameter and 300 mm in length.

Some findings reported in the literature suggest that size effect also plays an important role when testing fracture properties of concrete such as tensile strength ([8]-[10])and fracture energy ([11]-[12]). Unfortunately, this problem is much less recognized and described. Furthermore, specimens of different shapes and dimensions are used when testing tensile strength of concrete. The schematic diagrams of examples of control specimens under loading for the measurement of tensile strength of concrete are shown in Fig. 2.

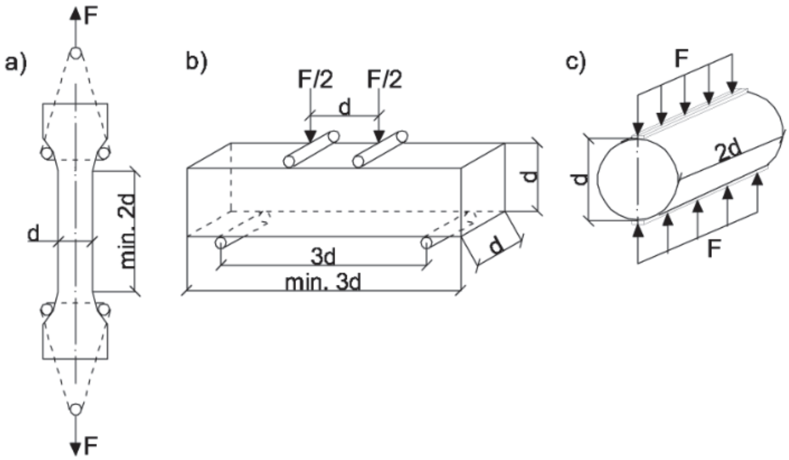

Fig. 2. Test methods of tensile strength of concrete (with examples of admissible control specimens): a) uniaxial tensile test, b) flexural test, c) split cylinder test

The uniaxial tensile test is conducted on rectangular prisms of a cross section 100×100 mm or 150×150 mm and the length equals two times the specimen's width. The specimen is fixed in the load frame of the testing machine by wider ends of the specimens. In case of cylindrical specimens (which are also acceptable) grip handles or stiff plates glued to the face of the specimens are used for fixing. In the uniaxial test, the maximum axial load is measured when the failure of the specimen appears in the middle part of the specimen's length and the tensile strength is calculated from Eq. 2.

$$f_{ct,dir} = \frac{F}{A} \tag{2}$$

where: F – failure load, A – cross section area in a damaged place. When performing the flexural tensile test two static schemes are possible: a three point bending test and a four point bending test. As a standard method a simple plain concrete beam loaded at one-third span point is recommended. The span of the beam should be three times its depth. The typical arrangement for the test is presented in Fig. 2b. The flexural tensile strength is computed as a maximum tensile stress from the standard flexural formulas: Eq. 3 in case of two point loading and Eq. 4 in case of one point loading.

$$f_{ct,fl} = \frac{M}{W_c} = \frac{F \cdot l}{d_1 \cdot d_2^2} \tag{3}$$

$$f_{ct,fl} = \frac{M}{W_c} = \frac{3 \cdot F \cdot l}{2 \cdot d_1 \cdot d_2^2} \tag{4}$$

where: F – failure load, l –span of the beam, d_1 and d_2 – dimensions of beam's cross section.

It should be noted that a static scheme in flexural tensile test also influences the obtained results. Tensile strength is 13% higher when performing the test in three point bending compared to four point bending. Therefore, loading arrangement by two concentrated forces is recommended in the code [13].

During the splitting test, a specimen is placed in the compression testing machine (cylinders in a horizontal position) and the load is applied through plywood strips situated under and over the specimen in a central position. The specimen fails in tension into two halves (see Fig. 3). The concrete splitting tensile strength is calculated from Eq. 5.

$$f_{ct,sp} = \frac{2 \cdot F}{\pi \cdot L \cdot d} \tag{5}$$

where: F – failure load, L – specimen's length, d – dimension of a specimen's cross section.

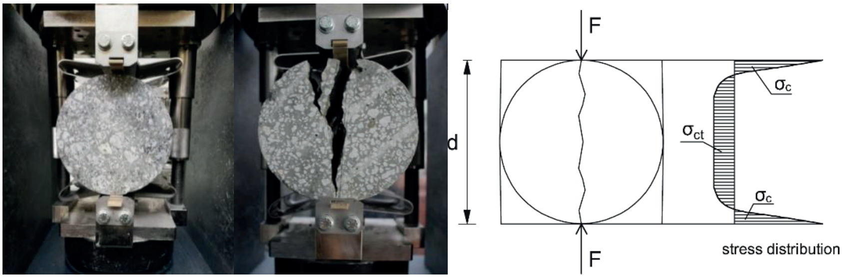

Fig. 3. The Brazilian splitting test: specimen in the test stand before and after the failure (left); stress distribution in cross section σ_{ct} – tensile stress, σ_c – compressive stress (right)

It can be suspected that the shape and size of specimens have a certain influence on tensile concrete strength tested in the Brazilian test. In the code [3] we can find only a short comment on the shape and dimensions of specimens used during the splitting tensile concrete strength saying that the tensile strength tested on cubic specimens is approximately 10% higher than on cylindrical specimens, and that the higher tensile strength is obtained using smaller cubic specimens. There is no information on how the size of cylindrical specimens influence the tensile splitting strength of concrete.

In the paper the experimental investigation is presented on how the size of cylindrical specimens influences the tensile splitting strength of concrete.

2. Laboratory experiments

Experiments were performed to evaluate the impact of a cylinder's length on tensile concrete strength received in the Brazilian method. Cylindrical specimens with a diameter of 150 mm and varied length equalling to 300 mm and 150 mm respectively were used. Additionally, four different concrete mixtures were designed for forming the specimens. The variable experiment parameters were: two types of aggregate (natural gravel and crushed granite) and two cement-water ratios (C/W = 1.8 and C/W = 2.6). Each concrete mixture was based on the maximum aggregate size 16 mm.

The laboratory tests were performed in two stages. The first one included a pilot study involving fewer test specimens. The second one comprised of more specimens. During both stages the same conditions concerning the aggregate type and a C/W ratio were kept.

On this account it was possible to gather more results in a larger testing group and to carry out a statistical analysis in a wider spectrum. In the size effect analysis concerning the tensile splitting tests, the results from both stages were taken into account together, due to identical recipes for concrete mixtures and the same types of aggregates.

The composition of the aggregate grading curve played a significant role in the concrete mixture design. The proportion of aggregate granulation was very similar in concrete mixtures with gravel and granite aggregates. A second key point was to fit the grading curves in the recommended area [14], between the upper and lower limit curves (Fig. 4 and Fig. 5).

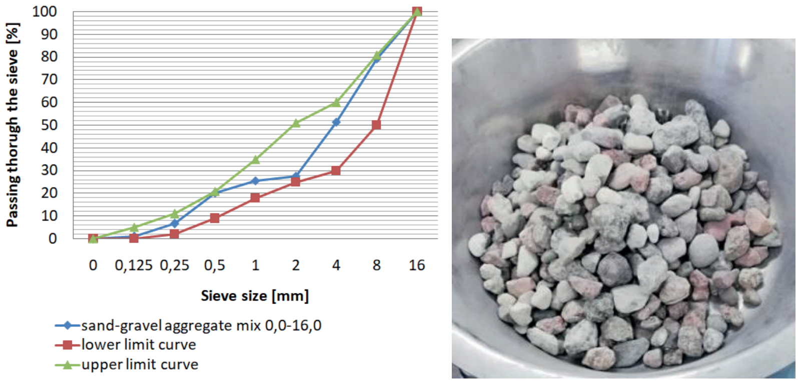

Fig. 4. Grading curve for sand and natural aggregate mixture (on the left); natural aggregate – fraction 8-16 (on the right)

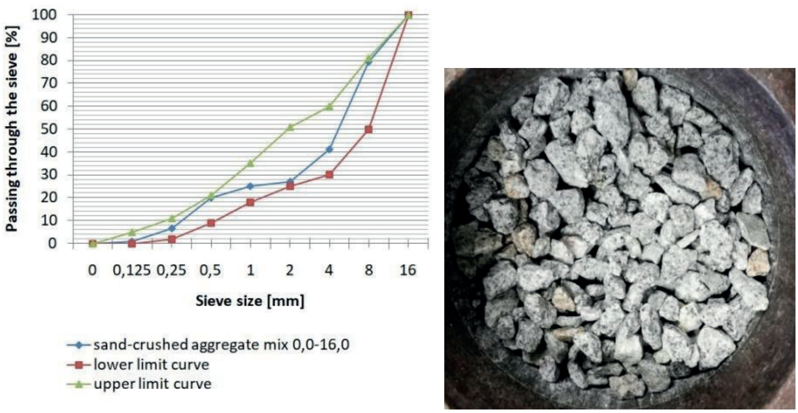

Fig. 5. Grading curve for sand and crushed aggregate mixture (on the left); crushed aggregate – fraction 8-16 (on the right)

Two types of aggregates were used for preparing various concretes: one with a lower strength matrix (C/W = 1.8) and the other with a higher strength matrix (C/W = 2.6). Apart from the aggregate granulation, the cement matrix is one of the fundamental elements of the heterogenic structure of hardened concrete which influences the fracture processes ([15]-[19]). Therefore, the cement matrix was considered as an important strength parameter during laboratory investigations and it was tested in the flexural strength test of hardened cement mortar. The tests were carried out in accordance with the code [20], on beams 40 mm × 40 mm × 160 mm in size, in a three-point bending test (Fig. 6). The proportions of water, cement and sand in the mortars were modified to obtain a proper consistency of the concrete mixtures comparing to requirements given the code PN-EN 196-1.

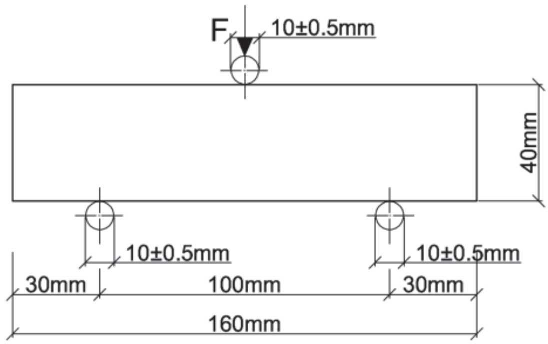

Fig. 6. A loading arrangement for testing flexural strength of cement mortar on a prism specimen according to PN-EN 196-1

Table 1. Composition of concrete mixtures

	Aggregate type	C/W	Cement [kg/m³]	Water [kg/m³]	Sand0.0-2.0 [kg/m³]	Coarse aggregate 2.0-16.0 [kg/m³]
1	Granite	1.8	375.6	206.6	481.0	1300.5
2	Granite	2.6	580.7	223.4	421.6	1140.0
3	Gravel	1.8	349.8	192.4	497.1	1344.0
4	Gravel	2.6	533.6	205.2	445.5	1204.5

The compositions of concrete mixtures are shown in Table 1. The flexural strength of the weaker cement matrix (C/W = 1.8) was 6.80 MPa and the flexural strength of the stronger matrix (C/W = 2.6) was 8.78 MPa.

Test results of tensile splitting strength are presented in Table 2.

Table 2. Test results

	Aggregate type	C/W	Cylinder's dimensions [mm]	Tensile strength – mean value [MPa]	Number of specimens [-]	Standard deviation, σ_s [MPa]	Coefficient of variation [%]
1	Granite	1.8	150x300	3.40	8	0.123	3.6
			150x150	3.49	8	0.295	8.5
2	Granite	2.6	150x300	3.78	8	0.415	11.0
			150x150	4.22	8	0.332	7.9
3	Gravel	1.8	150x300	2.68	8	0.227	8.5
			150x150	2.96	7	0.203	6.5
4	Gravel	2.6	150x300	3.54	8	0.197	5.6
			150x150	3.77	8	0.259	6.9

In the conducted laboratory experiments, a higher splitting tensile strength of concrete was noted for all specimens with nominal dimensions of 150×150 mm compared to specimens 150×300 mm in size. That tendency was observed in every series of tested cylinders, both for concrete containing natural gravel, and crushed granite. The increase of tensile strength was 6.6% for the gravel concrete with the ratio C/W = 2.6 (stronger concrete) and 15.9% for the gravel concrete with the ratio C/W = 1.8 (weaker concrete). In case of the granite concrete, the strength increase was 2.9% for the lower C/W and 11.7% for the higher C/W. However, this unique trend cannot be deduced from the obtained test results.

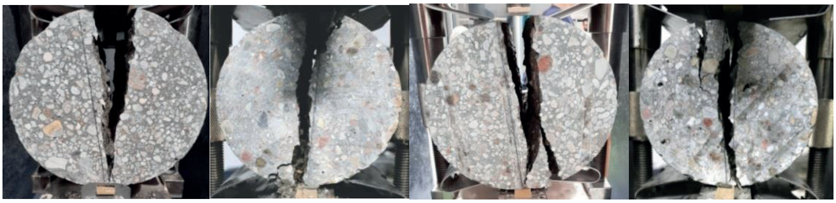

Fig. 7. Examples of the specimens' failure after the tensile splitting test, concrete with natural gravel aggregate (from the left): cylinder 150x300, C/W = 1.8; cylinder 150x150, C/W = 1.8; cylinder 150×300, C/W = 2.6 and cylinder 150×150, C/W = 2.6

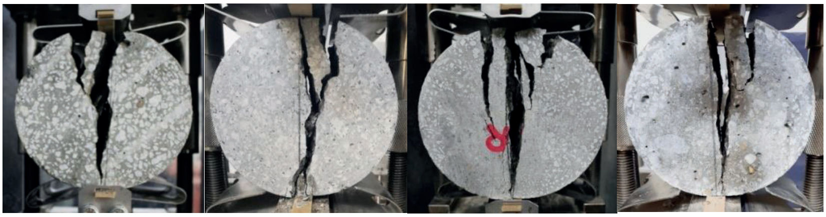

Fig. 8. Examples of the specimens' failure after the tensile splitting test, concrete with crushed granite aggregate (from the left): cylinder 150×300, C/W = 1.8; cylinder 150x150, C/W=1.8; cylinder 150×300, C/W=2.6 and cylinder 150×150, C/W=2.6

The mode of failure for the tested specimens was similar and independent of aggregate type, cement water ratio C/W and the specimen's length.

The failure of cylinders in the performed splitting tensile tests resulted from cracking in the plane of load application, usually together with wedges chipping off from the bulk concrete (Fig. 7 and 8). The more intensive destructive cracks observed at the points of contact of the specimen with the testing machine were caused by concrete crushing as a result of compressive stresses due to the stress distribution in failure cross section (as it is presented in Fig. 3).

3. Conclusions

The main conclusion from the performed experimental research is that the length of cylindrical specimens influences the tensile concrete strength when performing the Brazilian splitting test. Lower test results were obtained when using a longer cylindrical specimen – 300 mm long compared with tensile strength on a shorter one – 150 mm long. However, due to a relatively big scatter of test results, it was not possible to draw conclusions about the quantitative relations between tensile splitting test derived on cylinders 300 m long and cylinders 150 mm long. The type of aggregate, gravel or crushed granite, or the flexural strength of cement matrix did not affect the test results.

The observed size effect at testing tensile splitting strength of concrete requires further research on more samples. When planning the experimental investigation it would be valuable to differ the aggregate granulation, in particularly the maximum aggregate size.

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