

*Daniel Walach **, *Andrzej Szumiński **, *Piotr Dybel **

THE INFLUENCE OF SPECIMENS SIZE ON THE DEFORMATIONAL PROPERTIES OF HIGH-PERFORMANCE CONCRETES

1. Introduction

Due to the increasingly wider uses and capabilities of high-performance concrete (HPC), both in civil and underground construction, and the use of numeric methods in the process of designing, it seems appropriate to determine the exact deformational properties of the HPC. The stress-strain relations in concrete are of great significance in the design process and the method of determination depends on many factors, such as: the rate of stress, number of load cycles, the age of concrete since the moment of its production, load duration temperature and environment humidity changes. Another significant factor seems to be the size of the specimens, used to determine these relations. Those specification particularly concern HPC which, due to its modified formulas, may behave in a different way to regular concretes.

Strength tests of HPC specimens in the standard size i.e. $\phi 150 \times 300$ mm, may present a problem, because the maximum specimen load may reach up to 4000 kN. Many research units do not possess testing machines of such capability and usually the pressure allowed should not exceed 80% of the machine's permissible load. It seems thus appropriate to determine the possibility of conducting strength tests using smaller specimens and to determine the influence of specimen size on the strength and deformation parameters obtained. According to Neville [11], as far as HPC is concerned, $\phi 100 \times 200$ mm cylindrical specimens, or a 100 mm regular cube would be fully satisfactory, assuming that in HPC, the maximum aggregate size does not usually exceed 12.0 mm. The authors of the following paper have assessed the strength and deformation parameters of HPC using even smaller specimens, i.e. $\phi 55 \times 110$ mm.

High performance concretes are produced using traditional methods both by manufacturing companies, as well as directly at the building site. Their production involves traditional

* AGH University of Science and Technology, Faculty of Mining and Geoengineering, Kraków

ingredients (cement and aggregate) and mineral admixtures, such as silica fume, fly ash, ground granulated blastfurnace slag (ggbs), as well as mineral admixtures i.e. superplasticizers and fluidifiers.

The properties of HPC result directly from its composition and microstructure. High performance concretes are characterised by a dense matrix of high strength and are well set with the coarse grain surface. High material homogeneity, no local weakenings, such as cracks or air-pores left after the excess water has evaporated, will fundamentally change the behavior of HPC as compared to that of regular concretes (Fig.1).

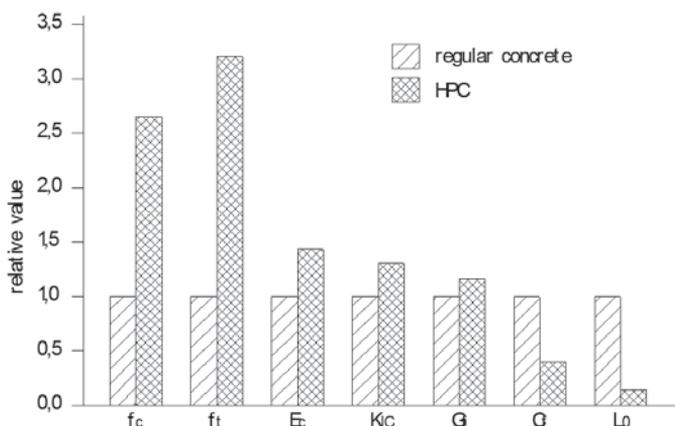


Fig. 1. Comparison of selected mechanical properties of regular concrete and HPC (f_c — compressive strength, f_t — tensile strength, E — modulus of elasticity, K_{IC} — stress intensity factor, G_f — fracture toughness, C_f and L_0 — parameters determining the distribution of microcracks near the crack tip) [10]

What has the greatest influence on the characteristics of HPC, is its low water-cement (w/c) ratio, paired with the presence of silica fume. Lower w/c ratios cause the pozzolanic reaction which help the products to combine more effectively. It should be noted, that the effectiveness of silica fume use in concrete increases together with the w/c ratio decrease. The above mentioned properties of silica fume will thus impact directly on the mechanical properties of the concrete. The presence of silica fume and superplasticizers changes the structure of HPC, which results in a material with significantly improved properties. The excellent mechanical properties of HPC result in their failure mechanism proceeding in a manner different from that of regular concretes. This is why in newer generations of concrete one shouldn't assume the same relation between basic mechanical properties as may occur in regular concretes.

The comparison of deformational properties of various concretes is shown in Figure 2.

The following paper presents results of tests conducted using cylindrical specimens of high performance concrete. Tests involved specimens of significantly differing dimensions, although all sharing the same aspect ratio (height/diameter). Based on the tests conducted, the influence was determined of specimen size on the thus obtained values of the modulus

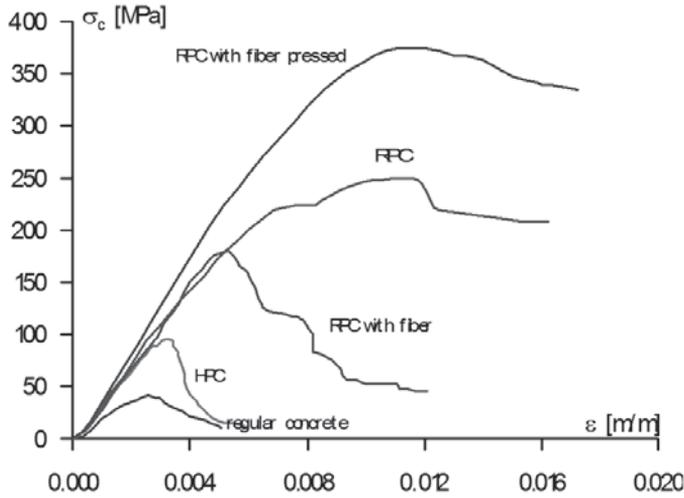


Fig. 2. Comparison of stress-strain relations of particular concretes [2]

of elasticity. The comparison was made both for the tangent, as well as the secant modulus of elasticity.

2. Relations illustrating the deformational properties of HPC

The elastic deformation of HPC is of particular interest, because the difference between the modulus of elasticity of the matrix and that of the aggregate is smaller than it is in regular concretes. The higher strength of the contact layer and smaller porosity than that found in regular concretes, reduces the number of microcracks in this layer. In HPC, first signs of microcracks appear only within the limits of 70–80% of failure stresses [10]. This is why the linear part of the stress-strain curve rises until it reaches a stress equaling as much as 85% of the failure stress. Specimens subjected to compression will rupture and the slope of the post-failure part of the stress-strain curve becomes steeper, as the concrete's strength increases (Fig. 3).

According to ACI 363R-92 (1994) [1], the value of the modulus of elasticity of HPC may be related with the 28-day compressive strength of concrete by means of the following equation:

$$E_{cm} = 3320 \cdot \sqrt{f_{cm}} + 6900 \quad (1)$$

where f_{cm} , E_{cm} are shown in MPa.

This relationship is correct in the case of concretes, the strength of which does not exceed 85 MPa. On average, in very high strengths the modulus of elasticity is lower than that which may be expected from the extrapolation of the equation above [11].

According to French specialists, the modulus of elasticity in HPC may be calculated from the following relation [6]:

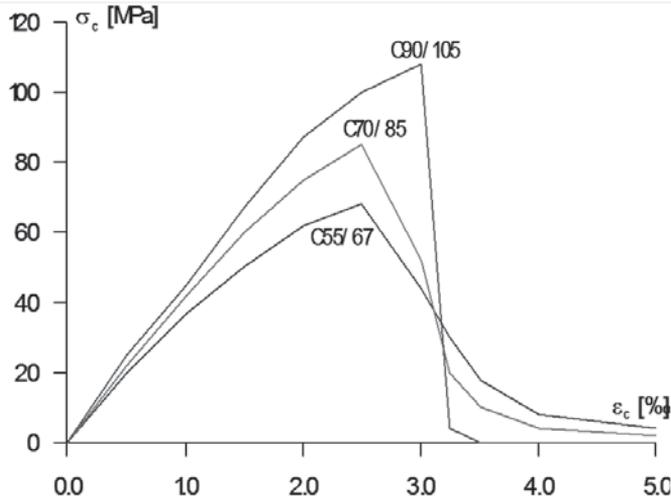


Fig. 3. Stress-strain relations in concretes of various strength [4]

$$E_{cm} = k \cdot \sqrt[3]{f_{ck}} \quad (2)$$

where:

f_{ck}, E_{cm} — are shown in MPa

k — coefficient depending on the type of aggregate (one assumes values from within the range between 9500–12 500).

A similar concept of calculating the modulus of elasticity was suggested in Model Code 90 [3], where the following relations was illustrated:

$$E_{cm} = 10^4 \cdot \sqrt[3]{f_{ck}} \quad (3)$$

where:

$$f_{cm} = f_{ck} + 8 \quad (4)$$

In the strength scope between 80.0 MPa and 140.0 MPa Kakizaki et al. [8] have stated that the modulus of elasticity is approximately related with the average compressive strength through the following relation:

$$E_{cm} = 3650 \cdot \sqrt{f_{cm}} \quad (5)$$

where: f_{cm}, E_{cm} are shown in MPa.

According to Eurocode 2 [5] the value of the E_{cm} modulus may be calculated from the following relation:

$$E_{cm} = 22 \cdot \left(\frac{f_{cm}}{10} \right)^{0,3} \quad (6)$$

where: f_{cm} is shown in MPa and E_{cm} in GPa.

HPC is a material characterized by small values of critical strain during compression. According to CEB-FIP MC 90 [3], in concretes of classes under C80, the critical strain value — corresponding to the compressive strength f_{cm} — should be assumed as:

$$\varepsilon_c = - 0.0022 \quad (7)$$

In recommendations for CEB-FIP MC 90 [4], also contained in Eurocode 2 [5], the critical strain denotation has been revised according to the following formula:

$$\varepsilon_c = \frac{-0.7 \cdot f_{cm}^{0.31}}{1000} \quad (8)$$

where: f_{cm} is shown in MPa.

One must, however, remember, that lab tested specimens of HPC will deform in a different manner to that of ready-made elements. Research by Kaminska [9] have shown that in beam elements made of HPC, critical strain in the zone of compressive stresses falls between 4,2–6,5‰. These values are twice that of the critical strains observed in the lab-tested HPC specimens. Both in the case of specimens as well as ready-made elements, failure would proceed in the manner of rupture.

3. Testing the deformational properties of HPC

Tests were conducted on cylindrical specimens made of HPC, in a uniaxial stress state. The specimens subjected to tests were of significantly different dimensions, but with a similar aspect ratio (height/diameter) i.e. $\phi 150 \times 300$ mm and $\phi 55 \times 110$ mm. All specimens were made of the same concrete mix and prepared according to the formula shown in Table 1.

The cylindrical specimens to be tested were made according to the PN-EN 12390-2:2000 standard instructions [12]. Concrete, placed in molds, was compacted on a vibrating table. Until test time, specimens were subjected to care in water at 20°C. Tests were conducted according to the regulations of the PN-EN 12390-3:2001 standard [13], using a „Walter+bei” testing machine with a load capacity of 3000 kN.

The testing method of the modulus of elasticity is not normalized. Regulations concerning the method of determining the modulus may be found in the ITB manual no 194 [7]. Tests of the tangent modulus were conducted on cylindrical $\phi 150 \times 300$ mm and $\phi 55 \times 110$ mm specimens. Deformations were measured using a strain gauge extensometer. The value of the tangent modulus was determined for a lineal deformation range of the specimens tested, i.e.

TABLE 1
HPG concrete mix formula

Content of individual ingredients per m ³ of the mix	
Cement CEM I 42.5	500.0 kg
Water	160.0 dm ³
0/2 mm river sand	575.0 kg
2/8 diabase aggregate	1 224.0 kg
Silica fume	51.6 kg
Superplasticizer	7.5 kg

0,25–0,60 f_{cm} . Analogically, tests of the secant modulus were conducted on $\phi 150 \times 300$ mm and $\phi 55 \times 110$ mm cylindrical specimens. Each specimen was subjected to a load, until the initial stress of $\sigma_d = 0,1 f_{cm}$ was reached. The specimen strain (ε_d) was then recorded. The stress was then increased to $\sigma_g = 0,3 f_{cm}$, the specimen strain ε_g recorded, and the specimen unloaded, until the return to the initial stress. The load-unload cycles were repeated until an average value of specimen strain was reached. Usually, the number is ca. 5 load-unload cycles.

The value of the secant modulus, according to the regulations in the ITB manual no 194 [7] was determined for the last load cycle, ranging between 0,1–0,40 f_{cm} . Additionally, for specimens subjected to load-unload cycles, the value of the tangent modulus of elasticity was also determined, for a rectilinear deformation range of the specimens tested, i.e. 0,25–0,60 f_{cm} .

The σ – ε characteristics of the tests conducted is shown in figures 4–7 and the obtained values of the modulus of elasticity were presented in Table 2.

TABLE 2
Results of the conducted strength tests of HPC

Specimen size [mm]	Load type	Tangent modulus of elasticity E_{st} [MPa]	Secant modulus of elasticity E_s [MPa]	Compressive strength f_c [MPa]	Critical strain ε_c [m/m]
$\phi 55 \times 110$	Direct	30 868,82	—	71,13	0,0047
$\phi 150 \times 300$	Direct	35 589,77	—	82,62	0,0032
$\phi 55 \times 110$	Load-unload	34 417,58	40 527,77	69,56	0,0034
$\phi 150 \times 300$	Load-unload	44 144,62	43 718,64	74,86	0,0028

Basing on the tests conducted, one should state that in reference to the tangent modulus of elasticity, one may notice the influence of both specimen size, as well as the type of load used on them. It may be generally noticed, that for $\phi 55 \times 110$ mm specimens, one will obtain smaller values of the tangent modulus of elasticity than in the case of $\phi 150 \times 300$ mm ones. Cyclic loading and unloading will also cause the increase of the tangent modulus of elasticity, both in case of standard sized $\phi 150 \times 300$ mm specimens and smaller ones. It may be caused by the ‘setting’ of the specimens tested and the elimination of creeping. Generally, in case of the tangent modulus, significant differences were found in the values obtained, which

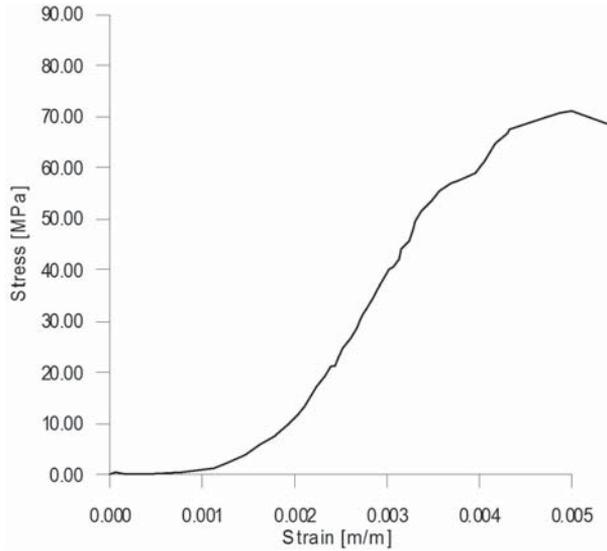


Fig. 4. The stress-strain relations of HPC, determined on a $\phi 55 \times 110$ mm specimen — tangent modulus of elasticity

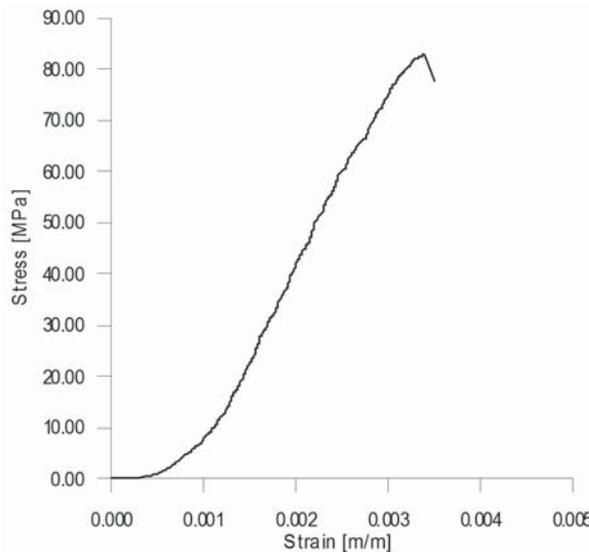


Fig. 5. The stress-strain relations of HPC, determined on a $\phi 150 \times 300$ mm specimen — tangent modulus of elasticity

reached as much as 30,0%, depending on the specimen size and loading type. One must however emphasize that the tangent modulus of elasticity is of little practical use [11].

As for the secant modulus of elasticity, determined for the last load cycle between $0,1-0,40 f_{cm}$, the values obtained differed only by 7,3%, depending on the specimen size. In case of $\phi 150 \times 300$ mm specimens, one may notice also the lack of any significant influence of the

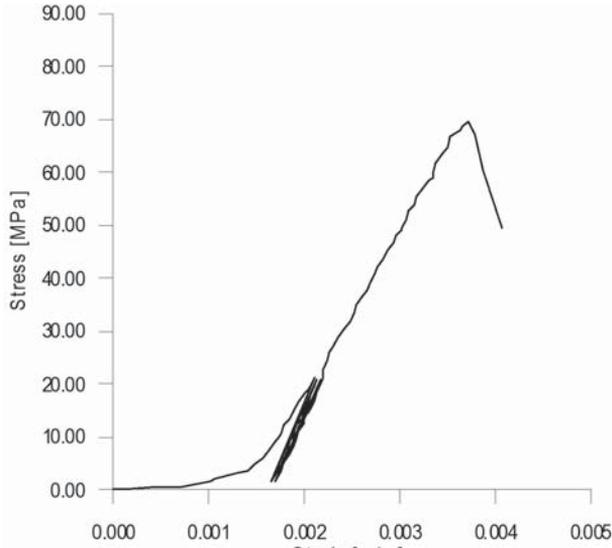


Fig. 6. The stress-strain relations of HPC, determined on a $\phi 55 \times 110$ mm specimen — secant modulus of elasticity

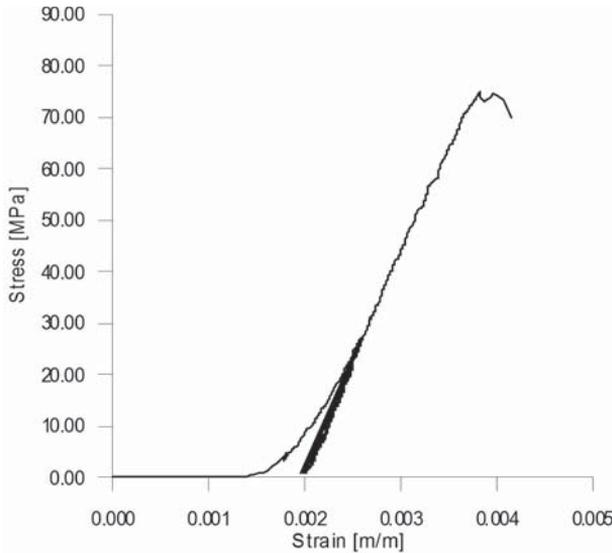


Fig. 7. The stress-strain relations of HPC, determined on a $\phi 150 \times 300$ mm specimen — secant modulus of elasticity

load type. For these specimens, the obtained values of the tangent and secant modulus of elasticity differed only by 1,0%. However, in case of $\phi 55 \times 110$ mm specimens, the difference reached as much as 15,0%.

When comparing the secant modulus of elasticity values obtained during the tests to the calculated ones, one should state that both the formula (3) from Model Code 90 [3] and the

expression from Eurocode 2 [5] best describe the relation. The calculated modulus values were respectively:

$$E_{cm} = 10^4 \cdot \sqrt[3]{f_{cm}} = 43\,539.97 \text{ [MPa]} \quad (9)$$

$$E_{cm} = 22 \cdot \left(\frac{f_{cm}}{10}\right)^{0.3} = 41\,440.22 \text{ [MPa]} \quad (10)$$

One must however emphasize, that the relations (10) concerns concretes with quartzite aggregates. When employing other aggregates, the values obtained need to be increased or reduced accordingly.

The strain values obtained from the tests, corresponding to the largest stress, are slightly higher than the values universally used in Eurocode 2 [5].

Compressive strength tests have shown that the $\phi 55 \times 110$ mm specimen were labeled as lower strength than $\phi 150 \times 300$ mm ones, which diverged from the generally observed tendencies. The results obtained may have been influenced by the scale effect, through the employment of aggregate up to 8 mm in the specimens tested.

4. Summary

As a result of the tests conducted, the following observations and conclusions were reached:

- 1) Due to the strength and durability demands required from modern constructions, HPC will be employed increasingly more often. However due to the small load capacity of the testing machine, difficulties may arise in testing specimens.
- 2) In case of the tangent modulus of elasticity, determined using HPC specimens, significant differences were determined in the values obtained, even reaching up to 30,0% depending on specimen size and load type.
- 3) Multiple loading and unloading causes the tangent modulus value to increase, both in $\phi 55 \times 110$ mm specimens and in standard sized $\phi 150 \times 300$ mm specimens.
- 4) In reference to the secant modulus of elasticity, the values obtained differed by a mere 7,3% depending on specimen size. In case of $\phi 150 \times 300$ mm specimens, one may also notice the lack of significant influence of the load type. For these specimens the obtained values of the tangent and secant modulus differed by a mere 1,0%.
- 5) Due to the fact that the tangent modulus is of little practical use and the obtained differences in the secant modulus determined on specimens were of significantly different dimensions, but also considering that the slenderness ratio did not exceed 1.0%, one may state that specimen size has little influence on obtained values of the modulus of elasticity.

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