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Mechanical Properties of Hardened High Strength Concrete

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Abstract

With the development of new and efficient admixtures for concrete, the production of high strength concrete (HSC) is becoming available at competitive prices. The behavior and properties of HSC are being studied around the world, but one of the advantages of concrete, namely that it can be cast using local materials, when dealing with new concretes can be a disadvantage, because research conducted elsewhere does not necessarily apply to the materials available near the construction site. The HSC studied in this research was cast using commercially available materials that require no special investments to procure. Samples were cast according to current standard provisions and tested at different ages in order to determine the mechanical properties of the produced concrete that are of interest to structural engineers and construction professionals. The samples were cured in different conditions in order to study the influence this has on the properties of the concrete. Results obtained show that some properties of high strength concrete are influenced by curing conditions, these properties are highlighted in the paper.

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Keywords: high strength concrete; modulus of elasticity; compressive strength; tensile strength.

1. Introduction

With the development of new and efficient admixtures for concrete, for example silica fume and high quality additives like high range water reducers, the production of high strength concrete is becoming available at competitive prices to the construction industry, thus moving away from being a novelty product.

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The introduction into general use of high performance materials, such as HSC, is of great importance as the move towards sustainable design certainly requires that materials be utilized to their full potential, in order for this to happen a proper understanding of the behavior of these materials is required. Such understanding can only be achieved through research directed towards the introduction of innovative technology into general use in order to cut down unnecessary consumption.

Unfortunately currently available design standards for concrete structures contain provisions based on research conducted on concrete with lower grades than those available today [1]. With the increase in strength, the behavior of concrete under loading changes due to the concrete matrix having strengths close to the strength of the aggregate used in the mix. Micro cracks and cracks develop through aggregate rather than in the interface between concrete matrix and aggregate, leading to a change in stress distributions in elements [2]. This modification in behavior is represented in standards by means of coefficients that are not based on experimental research and thus need to be verified, and if necessary, modified, in order to be able to fully utilize the advantages of higher strength concrete.

The behavior of high strength concrete in different loading conditions and environments is being studied around the world [3, 4, 5, 6, 7], but one of the advantages of concrete, namely that it can be cast using local materials, in the case of new concretes can be a disadvantage because research conducted on a material cast with local materials does not necessarily apply to the materials available near the construction site. The high strength concrete studied in the presented research was cast using commercially available materials that require no special investments to procure in Romania but their use leads to obtaining HSC.

The current paper presents an experimental study conducted on high strength concrete having a mean compressive strength determined at the age of 28 days of 100 MPa [8, 9]. Tests were conducted in order to determine the main characteristics of hardened concrete necessary for design, such as compressive strength, tensile strength longitudinal modulus of elasticity, transverse modulus of elasticity or shear modulus and Poisson's ratio. All samples and tests were cast and tested according to provisions contained by current standards.

2. Experimental program

2.1. Concrete mix

The HSC studied in the paper had a designed concrete class of C80/95 in accordance to the strength classes for concrete given in Eurocode 2 [10]. The mix constituents and quantities are given in Table 1, and the particle size distribution curve is given in Fig. 1.

Table 1. Mix constituents and quantities for 1 cubic meter of HSC.

Constituent	Quantity	Unit
Cement (CEM I 52.5 R)	520.00	kg/m^3
River sand (0-4 mm)	686.40	kg/m^3
Crushed quarry stone aggregate (4-8 mm, dacite)	343.20	kg/m^3
Crushed quarry stone aggregate (8-16 mm, dacite)	686.40	kg/m^3
Silica fume (Elkem Microsilica Grade 940 U-S)	52.00	kg/m^3
Water	135.20	l/m^3
Superplasticizer (Glenium ACE 30)	15.60	l/m^3
Water/Cement ratio	0.31	-
Water/Binder ratio	0.29	-

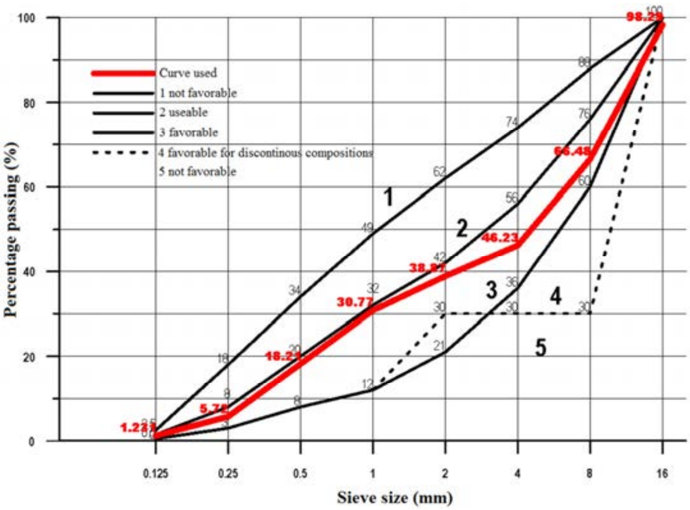

Fig. 1. Particle size distribution curve of the aggregates used based on NE 012-1:2007 [11].

2.2. Curing of concrete samples

The samples used to determine the properties of hardened HSC were produced during six separate concrete pours. After casting all samples were kept in their molds for 24 hours at a temperature of 22 °C ± 1°C and a relative humidity of 50%. After which they were cured up to 28 days either in the same conditions, referred to here after as laboratory conditions, or in water with a temperature of 20 °C ± 1°C, referred to here after as standard conditions. The standard conditions are those usually given in testing standards such as SR EN 12390-2:2009 [12] for curing of concrete specimens in order to determine physical and mechanical properties. The laboratory conditions were chosen in order to ascertain the differences in mechanical properties between samples which, due to their small size can be immersed in water for 28 days, and elements, such as precast reinforced concrete elements, which cannot be cured by immersion in water.

2.3. Properties of hardened HSC

The characteristics of the hardened HSC determined in the study were:

- $f_{c,cube}$ compressive strength, determined on cubes with sides of length 150mm;
- $f_{c,prism}$ compressive strength, determined on prisms 100mm x 100mm x 300mm;
- $f_{ct,sp}$ tensile strength determined by splitting, determined on cubes with sides of length 141mm;
- $f_{ct,fl}$ tensile strength determined by flexure, determined on prisms 100mm x 100mm x 550mm;
- E_c longitudinal modulus of elasticity, determined on prisms 100mm x 100mm x 300mm;
- G_c transverse modulus of elasticity, determined on prisms 100mm x 100mm x 300mm.

2.3.1. Compressive strength, f_c

The compressive strength of the studied concrete was determined in accordance with the testing procedures given by RILEM Technical recommendations for the testing and use of construction materials [13] and SR EN 12390-3:2003 Testing hardened concrete. Compressive strength of test specimens [14].

The tests were carried out using an automated hydraulic press with characteristics in accordance to SR EN 12390-4:2002 Testing hardened concrete. Compressive strength. Specification for testing machines [15].

During testing the load was applied perpendicular to the direction of casting and increased at a rate of 1 MPa/s up to failure of the specimen. Fig. 2 shows a test on a cube and it’s mode of failure.

Fig. 2. Compression test on HSC cube.

Based on the failure loads obtained the compressive strength of the concrete was calculated using equation (1) given by [13, 14]

$$f_c = \frac{F}{A_c}[N/mm^2] \tag{1}$$

in which:

F failure load, in Newtons;
A_c area of the specimen on which the load was applied, in mm^2.

A total of 35 cubic samples were tested at the age of 28 days, out of these, 12 were cured in standard conditions and the rest in laboratory conditions. The mean strength values, $f_{c,cube}$, obtained were:

- Mean strength value at 28 days determined on samples cured in standard conditions: **107.60** [N/mm^2]
- Mean strength value at 28 days determined on samples cured in laboratory conditions: **118.61** [N/mm^2]

A total of 44 prisms were tested at the age of 28 days, out of these, 22 were cured in standard conditions and the rest in laboratory conditions. The mean strength values, $f_{c,prism}$, obtained were:

- Mean strength value at 28 days determined on samples cured in standard conditions: **92.86** [N/mm^2]
- Mean strength value at 28 days determined on samples cured in laboratory conditions: **102.62** [N/mm^2]

Based on the results obtained mean strength values determined on cubes cured in standard conditions the actual strength class of the concrete was established using equation (2) contained by Eurocode 2 [10] and Fib Bulletin 42 [2].

$$\begin{aligned} f_{cm} &= f_{ck} - \Delta f [N/mm^2] \\ \Delta f &= 8[N/mm^2] \end{aligned} \tag{2}$$

The characteristic value of the compressive strength, $f_{ck}=99.60[N/mm^2]$, shows that the cast concrete achieved the strength class that the mix was designed for, C80/95.

Results show that strengths developed by curing in laboratory conditions are approximately 10% higher than those obtained by curing in standard conditions; these results are in accordance with information available in current scientific literature on the subject [16].

2.3.2. Tensile strength, $f_{ct,sp}$ and $f_{ct,fl}$

The tensile strength of the HSC studied was determined indirectly with two different tests, splitting and flexure. The splitting tests were performed in accordance with provisions given by SR EN 12390-6:2002 Testing hardened concrete. Part 6: Tensile splitting of test specimens [17], while flexure test were conducted according to SR EN 12390-5:2009 Testing hardened concrete. Part 5: Flexural strength of test specimens [18].

During splitting tests the load was applied perpendicular to the direction of casting using two circular dowels with standard strips between them and the sample. The load was increased at a rate of 0.1 MPa/s up to failure of the specimen. Fig. 3 shows a test on a cube and it's mode of failure.

Fig. 3. Splitting test on HSC cube.

A total of 24 cubic samples were tested in splitting, 12 of them having been cured in standard conditions and 12 in laboratory conditions up to testing. The tests were carried out using an automated hydraulic press with characteristics in accordance with [15].

The tensile strength, $f_{ct,sp}$, was determined using equation (3) given in [15].

$$f_{ct} = \frac{2 \cdot F}{\pi \cdot L \cdot d} [N / mm^2] \tag{3}$$

in which:

F failure load, in Newtons;

L length of the specimen on which the load was applied, in mm;

d height of the specimen on which the load was applied, in mm.

The mean strength values, $f_{ct,sp}$, obtained were:

- Mean tensile splitting strength value at 28 days determined on samples cured in standard conditions: **8.23** [N/mm^2]
- Mean tensile splitting strength value at 28 days determined on samples cured in laboratory conditions: **5.27** [N/mm^2]

Flexural tests were performed using 4 point bending tests, the load was applied perpendicular to the direction of casting using two circular dowels while the sample was supported on a set of circular supports. The load was increased at a rate of 0.1 MPa/s up to failure of the specimen. Fig. 4 shows a test on a prism and it's mode of failure.

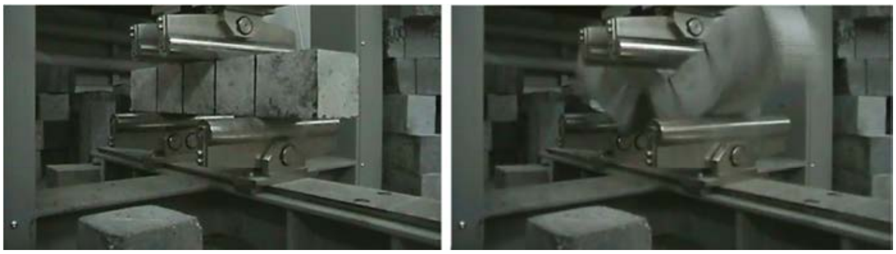

Fig. 4. Flexural 4 point bending test on HSC prism.

A total of 12 prisms were tested in flexure, 6 of them having been cured in standard conditions and 6 in laboratory conditions up to testing. The tests were carried out using an automated hydraulic press with characteristics in accordance with [15].

The tensile flexure strength, $f_{ct,fl}$, was determined using equation (4) given in [18].

$$f_{ct} = \frac{F \cdot l}{d_1 \cdot d_2^2} [N / mm^2] \tag{4}$$

in which:

F failure load, in Newtons;

l distance between supports, in mm;

d_1, d_2 sides of the samples cross section, in mm.

The mean strength values, $f_{ct,fl}$, obtained were:

- Mean tensile flexure strength value at 28 days determined on samples cured in standard conditions: **13.66** [N/mm^2]
- Mean tensile flexure strength value at 28 days determined on samples cured in laboratory conditions: **9.65** [N/mm^2]

The results obtained for the tensile strength of the HSC on samples cured in standard conditions, which are the tests required by standards for the designed class, are superior to the requirements for concrete class C80/95, however, the results obtained on samples cured in laboratory conditions, which are similar to conditions in which structural elements will cure, are approximately 44% lower than those obtained in standard conditions. This decrease of tensile strength due to curing conditions should be kept in mind when using HSC.

2.3.3. Longitudinal and shear modulus of elasticity, E_c and G_c, and Poisson's ratio, ν

In order to determine the static moduli of elasticity, and the Poisson's ratio of the studied HSC in compression, a total of 44 prismatic samples were tested at the age of 28 days, 22 of them were cured in standard conditions and 22 in laboratory conditions. The tests were performed in accordance to RILEM Technical recommendations for the testing and use of construction materials [13], using an automated hydraulic press with characteristics in accordance with [15] and digital displacement transducers in order to measure the strains, longitudinal and transversal, induced in the samples by the applied load. The placement of the transducers on the sample can be seen in Fig. 5.

Fig. 5. Determination of HSC moduli of elasticity.

Equation (5) was used in order to determine the longitudinal modulus of elasticity:

$$E_c = \frac{\Delta f}{\Delta \varepsilon} = \frac{f_a - f_b}{\varepsilon_a - \varepsilon_b} [N / mm^2] \tag{5}$$

in which:

f_a compressive efforts $f_a=0.4f_{c,pr}$, $f_{c,pr}$:strength of the concrete determined on samples identical to those tested.

f_b compressive efforts $f_b=0.05f_a$;

ε_a, ε_b longitudinal deformations corresponding to compressive efforts f_a and f_b.

The mean values for the longitudinal modulus of elasticity, E_c, were:

- Mean value for the E_c determined on prisms cured in standard conditions: **44,6** [GPa]
- Mean value for the E_c determined on prisms cured in laboratory conditions: **44,5** [GPa]

Poisson's ratio was determined based on the measurements performed using equation (6).

$$\nu = \frac{\Delta \varepsilon_t}{\Delta \varepsilon} = \frac{\varepsilon_{t2} - \varepsilon_{t1}}{\varepsilon_2 - \varepsilon_1} \tag{6}$$

in which:

ε_{t1}, ε_{t2} transverse deformation measured at mid-height of the samples, corresponding to compressive efforts: $f_a=0.4f_{c,pr}$, $f_b=0.05f_a$; $f_{c,pr}$ – strength of the concrete determined on samples identical to those tested.

ε_1, ε_2 longitudinal deformations corresponding to compressive efforts f_a and f_b.

The mean values for Poisson's ratio, ν, were:

- Mean value of Poisson's ratio, ν, determined on prisms cured in standard conditions: **0,20**
- Mean value of Poisson's ratio, ν, determined on prisms cured in laboratory conditions: **0,22**

By using the values obtained for the modulus of elasticity and Poisson's ratio, the value for the transversal or shear modulus of elasticity, G_c, was determined using equation (7).

$$G_c = \frac{E_c}{2 \cdot (1+\nu)} [N / mm^2] \tag{7}$$

The mean values for the shear or transversal modulus of elasticity, G_c, were:

- Mean value for the modulus of elasticity determined on prisms cured in standard conditions: **24,1** [GPa]
- Mean value for the modulus of elasticity determined on prisms cured in laboratory conditions: **24,4** [GPa]

The mean values obtained for the moduli of elasticity are in accordance with standard provisions for concrete class C80/95 as given by Eurocode 2, thus proving that HSC can be successfully obtained using local materials available in Romania.

The values of the moduli of elasticity show that they are not influenced by curing conditions, in the case of HSC.

The values of Poisson's ratio are the same as those given by design standards for all concrete classes.

3. Conclusions

The research performed shows that while most of the mechanical properties of HSC are similar to those of normal strength concrete and current standard provisions can be successfully applied to its design, other properties are differ and application of current standards can have, in the least, the effect of inefficient use of material leading to unjustified consumption of resources, and in the extreme lead to unforeseen behavior of structures and structural elements. The failure modes observed during testing mean that any structural designer using this material must take special care to ensure that failure is warned. Also, the development of tensile strength being greatly affected by curing conditions means that any structural elements that require crack control need to be designed with great care.

The presented study on the properties of HSC obtained using local materials from Romania shows that the price of this new high performance material can be economically viable. This means that, in the context of sustainable design, HSC can play a major role helping to reduce the amount of concrete needed for reinforced concrete structures, cutting down on initial costs and maintenance costs.

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