Construction and Building Materials 175 (2018) 402–410

Contents lists available at ScienceDirect

Construction and Building Materials

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

Effect of age on the compressive strength of ultra-high-performance fiber-reinforced concrete

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HIGHLIGHTS

- Effects of fiber dosage and concrete age on UHPC were investigated.
- At least 112 specimens were tested.
- Test results were compared with relevant models.

ARTICLE INFO

Article history:
Received 4 January 2018
Received in revised form 8 April 2018
Accepted 24 April 2018

Keywords:
Compressive strength
Concrete age
Modulus of elasticity
Steel fibers
Ultra-high-performance fiber-reinforced concrete (UHPFRC)

ABSTRACT

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is a new type of concrete with excellent mechanical and durability characteristics. This study describes the influence of age on the compressive strength of UHPFRC. At least, 112 cubic specimens with dimensions of 100 × 100 × 100 mm were prepared. Steel fiber content, ranging from 0 to 6 percent by weight, was used as another variable in this study. Uniaxial compression tests were carried out on specimens at different ages varying from 2 to 42 days. Additionally, experimental studies were conducted on cylindrical specimens to determine the modulus of elasticity of UHPFRC specimens according to ASTM C469/C469M-14. Results showed that the increase of fiber content leads to an increase in the compressive strength of specimens. Moreover, on average, 90% of the ultimate compressive strength was achieved after only 18 days. Finally, a good correlation was demonstrated between the test data and the relevant equations proposed in literature for modulus of elasticity and compressive strength of UHPFRC.

1. Introduction

There is a clear trend in structural engineering towards the use of high-strength materials to achieve more lightweight and slender structures. This trend is also fueled by advancements in the construction industry. UHPFRC, characterized by its excellent mechanical and durability properties perfectly fits this trend [1–6]. According to EN 206 [7], UHPFRC has a compressive strength in excess of 100 MPa. The high compressive strength of UHPFRC results in a remarkable reduction in the weight of structures made from this material. Generally, the overall weight of structures made from UHPFRC is only one-third to one-half the weight of typical reinforced concrete (RC) structures under the same load [8].

Undoubtedly, compressive strength is one of the primary features of both conventional and advanced concrete. The main principle in the production of UHPFRC is to achieve a high-density material by preventing the formation of fine cracks. Numerous studies [8–13] have shown that steel fibers can be used to overcome the brittle nature of high-strength and high-performance concrete and help improve its ductility and tensile strength.

Modulus of elasticity is perhaps the second most important property of concrete. A number of models and equations have been proposed in the literature for the elastic modulus of both normal-strength and high-strength concrete [14–19]. However, there is not a consensus on the elastic modulus of UHPFRC as it strongly depends on the types of materials used in practice. Besides, most of the proposed equations for the modulus of elasticity, especially those proposed by codes of practice [14–16] do not cover the range specified in the definition of UHPFRC, i.e., compressive strengths above 100 MPa.

Ma et al. [18] proposed equations for the modulus of elasticity of UHPC without coarse aggregates and with basalt coarse aggregates; the proposed equations covered the compressive strength range between 150 MPa and 180 MPa; Association Française de

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https://doi.org/10.1016/j.conbuildmat.2018.04.203
0950-0618/Published by Elsevier Ltd.

Génie Civil (AFGC) [20] has proposed an equation for the modulus of elasticity of heat-cured UHPC with compressive strengths in excess of 140 MPa; the equation proposed by Sritharan et al. [21] requires compressive strengths above 177 MPa on average and Ma and Schneider [17] proposed an equation for the modulus of elasticity for UHPC with compressive strength of 140 MPa; In Section 5.2, experimental moduli of elasticity are compared with other available equations of modulus of elasticity in literature which cover the compressive strength range obtained in this study. Regarding the effect of age and modulus of elasticity, numerous studies are available in literature.

Habel et al. [22] conducted a series of experiments on UHPFRC specimens with the aim of investigating the hydration related indexes of UHPFRC and their association with mechanical properties of UHPFRC; mechanical properties of UHPFRCs were determined at several ages between 8, 15, 28, 90 and 365 days. Compression tests were undertaken on 110 × 220 mm cylindrical specimens; compressive strengths of up to 140 MPa were reported which amounted to 81% of the ultimate compressive strength of UHPFRC. Furthermore, the rate of development was highest for the secant modulus, which reached to 84% of its final modulus of elasticity (i.e. 51 GPa), followed by the compressive and tensile strengths of UHPFRC. The difference in the rate of development was attributed to the mix compositions.

Graybeal and Tanesi [23] carried out a series of standard experiments to evaluate the durability of UHPFRC with 2% volumetric fiber content. Significantly enhanced durability properties to freeze-thaw cycles, scaling deterioration, ion penetration and alkali–silica reaction compared to normal-strength concrete was reported. The effect of four different regimes, steam treated, untreated, tempered stem treated and delayed steam was also investigated on different ages; it was concluded that steam treatment improves the mechanical properties of UHPFRC due to the increased degree of hydration which improves the microstructure of the concrete and reduces its permeability.

Graybeal [24] carried out an experimental study to specify the uniaxial compressive behavior of UHPFRCs with 2% volumetric fiber content; results obtained from 138 steam-treated and 88 untreated cylindrical specimens varying between 1 and 57 days in age were used to determine the modulus of elasticity, overall stress-strain behavior, strength, and strain capacity of UHPFRC. It was found that regardless of the concrete age, the overall shape of the ascending branch of the stress-strain curve under steam treatment remains unchanged. Furthermore, examining the stress-strain behavior of the specimens revealed that as stiffness and strength increase, the nonlinearity prior to fail becomes less pronounced. Additionally, based on experimental observations, a relationship was proposed for the modulus elasticity of UHPFRC. What's more, based on the deviation of the actual stress-strain behavior from the elastic response an experimental equation was established between the stress and strain of UHPFRC; difficulties in obtaining the stress-strain curve stemming from inherent nonlinear behavior of concrete, various concrete compositions and different experimental techniques to capture stress and strain values were highlighted.

Prem et al. [25] detailed the mixing process required to obtain UHPFRCs with a compressive strength of 150 MPa after 28 days; five mix designs with varying fiber contents were investigated. Moreover, mechanical properties of the UHPFRC with 2% and 2.5% volumetric fiber content were evaluated by means of compression tests on 100 × 100 × 100 mm cubic specimens; compressive strength of the specimens was determined after 7, 14, 21 and 28 days; 90% of the 28 day compressive strength was achieved after 14 days. Furthermore, elastic moduli varying between 39 GPa and 44 GPa were reported. Finally, the significant effect of fiber content on the ductile post-peak behavior of the stress-strain curve which gives steep descending branch for low fiber contents and gradually sloping for higher fiber contents was highlighted.

The effect of concrete age and curing conditions on mechanical properties of UHPC was conducted by Magureanu et al. [26]. The primary objective of the study was to develop UHPC with local materials and to eliminate the quartz powder because of expensive shipping costs; early-age (6 days) and long-term (371 days) behavior of specimens were investigated; cubic specimens with different sizes with and without fiber were tested and size-dependent compressive strengths up to 180 MPa and 157 MPa were reported for specimens with and without 2.55% hybrid fiber, respectively. Besides, an increase of modulus of elasticity was reported with the addition of fibers.

Yoo et al. [27] investigated the effect of steel micro fibers with ratios varying between 1% and 4% volumetric content on interfacial and bond properties of UHPFRC. Compression and modulus of elasticity tests were carried out to determine the strength and stiffness of the cylindrical specimens based on international standards; values ranged between 183.1 MPa and 215.2 MPa for f'_c and between 46.2 GPa and 56.2 GPa for E_c increasing with the fiber content except for the 4% volumetric fiber content. The best result in terms of all the mechanical properties was reported for the 3% volumetric content case; reduced mechanical properties were reported for the 4% case due to poor dispersion of fibers.

The effect of fibers varying in length (8, 12 and 16 mm) and dosage (1, 3 and 6% by volume) were investigated by Abbas et al. [28]; different mechanical properties were assessed and an increased mechanical properties were reported with the increase in fiber dosage; specimens were tested in different ages varying between 7 and 56 days; less than 2% increase was reported for UHPFRC with different fiber length and dosages in terms of f'_c and E_c. The insignificant changes were reported for compressive strengths and moduli of elasticity UHPFRCs after 28 days.

Ahmad et al. [29] investigated the effect of fiber content (1%–3% by volume) and different curing regimes at 7, 14 and 28 days. Improved mechanical properties were reported for the water-cured case compared to air-cured case at low fiber dosages; the difference became negligible at high fiber dosages; increasing the fiber content and concrete age increased both f'_c and E_c of UHPFRC to a certain extend beyond which the effects were not noticeable.

Sobuz et al. [30] investigated 40 mix designs, 16 without coarse aggregate and 24 with. Four types of fine aggregates were examined to examine the effect of natural grading on the attributes of fresh and hardened UHPC and therefore to provide an insight to the optimal water-to-cement and superplasticizer-to-cement ratios. In the meanwhile, cylindrical compressive strength of UHPC without coarse aggregates were determined after 7, 28, 56 and 90 days; compressive strengths up to 150 MPa were achieved and it was reported that the specimens reached 80% of their 90 day compressive strength after 7 days and minimal strength gain was observed after 28 days. In some cases reduction of strength between 56 and 90 days was also reported which was attributed to the formation of shrinkage-induced micro cracks.

Alsalman et al. [31] measured the moduli of elasticity of 16 UHPC mixes in which fine sand was replaced with natural-gradation sand or fly ash to reduce both costs and time associated with the production of UHPFRC. Straight steel fibers with a diameter of 0.2 mm and a length of 12.7 mm were used; Arkansas River and fly ash class C were used as fine aggregates. Reduced modulus of elasticity of UHPFRC was reported with the replacement of natural-gradation sand or fly ash which reduce the stiffness by changing the microstructure of the UHPFRC. Nonetheless; compared to natural sand, use of fly ash had little effect on modulus of elasticity of UHPFRC at 28 days of age. Furthermore, based on