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Compressive behavior of UHPFRC under quasi-static and seismic strain rates considering the effect of fiber content

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HIGHLIGHTS

- DIF values for mechanical properties of UHPFRC under seismic strain rates are presented.
- Dynamic modulus of elasticity measured from three different technics are presented.
- Stress-strain equations for static and dynamic compressive behaviors are presented.

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ABSTRACT

The high ductility and toughness of ultra-high performance fiber-reinforced concrete (UHPFRC) make the composite a promising material to be applied in earthquake-resistant structures. For this reason, the knowledge of its constitutive behavior on seismic strain rates (10^{-2} s^{-1}) becomes of great importance, which was not reported for compressive loading yet. Thus, the purpose of this paper is present experimental results and propose a uniaxial stress-strain equation that predicts the behavior of UHPFRC under compression at seismic strain rate considering different fiber contents. The experimental tests were performed with cylindrical specimens in a servo-hydraulic machine under seismic and quasi-static strain rates for comparison and to determine the dynamic increase factor (DIF). Also, nondestructive tests were performed to determine the dynamic modulus of elasticity. From experiments, UHPFRC was rate sensitive mainly for peak stress and toughness. The DIF observed for peak strength were 1.12 and 1.11 for UHPFRC with 1% and 2.5% of fibers. For toughness, the DIF was 1.21 for the composite with 1.0% of fibers. Peak strain and modulus of elasticity instead were not rate sensitive. Also, high standard deviations characterized the test results. From the analytical study, the proposed constitutive model predicted the dynamic experimental results accurately for different fiber contents.

1. Introduction

Ultra-high performance fiber reinforced concrete (UHPFRC) has a high capacity of energy absorption under severe loading due to the optimal combination of a well graded matrix with surface treated steel fibers. The excellent interaction between matrix and fibers makes UHPFRC a ductile composite with high toughness. The superior mechanical performance compared to other concretes attracted the attention of researchers to apply UHPFRC under seismic conditions of loading, [1–6].

As is well accepted, the mechanical properties of cement-based materials are sensitive to strain rates higher than quasi-static [7,8]. Also, the sensibility is not the same for tensile and compressive loading [9], and the volume of fibers can present an essential role in the behavior [9,10]. For UHPFRC under compression, most of the researches have been developed for high strain rates, for example, tests with split-Hopkinson pressure bar (SHPB) [11,12]. No results were found for UHPFRC under compression at seismic strain rates, which are comprised in the range between 5×10^{-3} and 5×10^{-1} s^{-1} [10,13]. Consequently, besides the tests results, the constitutive modeling for this material is also required for further applications of UHPFRC in research and construction at seismic areas.

Recently, some of the major finds for UHPFRC under compressive dynamic loading were reported and deeply discussed [9]. In short, UHPFRC is less rate-sensitive than normal-strength concrete, but the compressive strength, strain capacity, and toughness are all improved by the increase in strain rate. Furthermore, it is worth highlighting that the effect of fiber content on the dynamic behavior of UHPFRC is more significant on toughness than on the other

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mechanical properties [11]. Also, several researches have been raised hypothesis about the possible physical mechanisms that make cement-based materials rate-sensitive, but there is no a universally accepted explanation for the phenomena [10]. Lu et al. [14] presented a detailed discussion, from a macroscopic view, about the rate sensitivity, and in brief, they attributed the improvement of mechanical properties to changes in the nature of fracture process due to high strain rates, also to the viscous behavior and inertial effects.

In the field of constitutive modeling, a conventional approach to take into account the dynamical effects is through the dynamic increase factor (DIF) [15]. The DIF is the ratio between the dynamic and quasi-static properties. Su et al. [16] determined DIF values for UHPFRC under compressive and tensile stress states. For UHPFRC with 3% of fibers submitted to a strain rate of 90 s^{-1}, DIF was 1.54 for compression strength, when 3% of nano-$CaCO_3$ was added to the mix. The authors emphasized the need for experimental results in the range of 0 to 40 s^{-1}, which concern the seismic strain rate.

Furthermore, the research on constitutive modeling of UHPFRC is in current development. Few studies were reported even for compressive quasi-static response [17–20] and no studies for seismic strain rates. The fib Model Code [15] recommends that the same constitutive model utilized for quasi-static case can be used to simulate the dynamic behavior. The changes to be made are on the model parameters that must be calculated considering the DIF values correspondent to the strain rate. For quasi-static conditions, there exists many analytical models to describe the compressive behavior of fiber-reinforced concrete, [21–23]. Besides, some studies for UHPFRC under high rates of loading utilized the continuum damage mechanics framework where the damage variable is described by a Weibull function [23,24]. In this methodology, experimental results are required to calibrate the parameters of the function that describes the damage variable. Thus, both of the mentioned methodologies have a statistical base to determine the dynamical response.

From the discussion above, the current research focused on present experimental results for UHPFRC under compressive seismic strain rates. From the stress-strain curves, peak stress, peak strain, modulus of elasticity, toughness are reported. Quasi-static results are also reported for comparison and the determination of the DIFs. Furthermore, analytical stress-strain models are proposed for both cases of strain rate. Also, measurements of dynamic modulus of elasticity are determined through standardized acoustic and ultrasonic tests.

2. Experimental program

2.1. Materials, mix proportions and procedure, casting and curing process

The materials used to produce a self-compacting UHPFRC were 768 kg/m^3 of type III Portland cement, 192 kg/m^3 of silica fume (specific surface of 20000 m^2/kg and density of 2220 kg/m^3), 844 kg/m^3 of fine sand with grain size less than 0.42 mm, 384 kg/m^3 of quartz powder (density of 2670 kg/m^3), 69 kg/m^3 of polycarboxylate-based superplasticizer (density of 1060 kg/m^3) and 154 kg/m^3 of water. UHPFRC with five different fiber volumes (1%, 1.5%, 2%, 2.5% and 3%) were casted with copper-coated steel fibers with 13 mm of length and 0.2 mm of diameter. The fibers had tensile strength of 2850 MPa and modulus of elasticity of 200 GPa. Fig. 1 presents the particle size distribution of the mix constituents.

High shear pan mixer for mixing UHPC was utilized. Firstly, all dry components, excepting fibers, were mixed for 5 min until a homogeneous mixture was obtained. Then, water and superplasticizer were added, and concrete was mixed during additional 10 min to get the desired workability. Finally, steel fibers were included, and concrete was mixed for more 5 min to obtain a homogeneous distribution of fibers. Concrete was then molded on a vibrating table to improve densification. Following the casting process, all samples were stored in a moist chamber for 28 days. After this, the samples were submerged in water for heat treatment for seven days at 70 °C. Nine specimens were cast for each fiber content in which six were tested in quasi-static strain rate and three in dynamic strain rate.

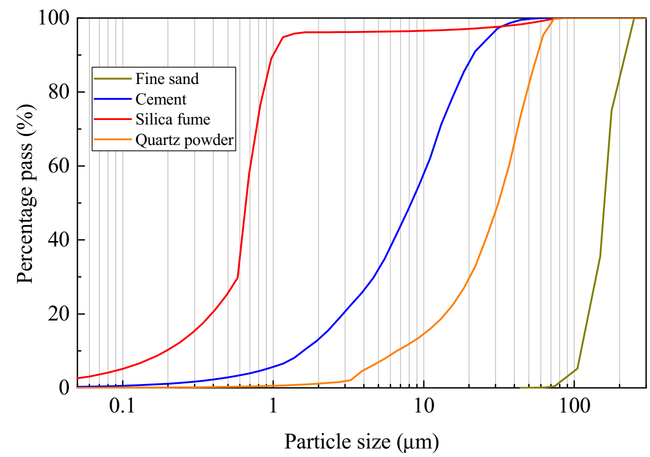

Fig. 1. Particle size distribution of the UHPFRC constituents.

2.2. Test setup and loading procedure

The compression tests were performed on cylindrical specimens of 50 mm in diameter and 100 mm in length. The test was carried out under displacement control in a universal servo-hydraulic testing machine with a maximum load capacity of 1500 kN. Besides, an axial hinge was installed on the top of the specimen. Two clip gages were attached to the UHPFRC samples to measure axial displacement with a gauge lenght of 50 mm, as presented in Fig. 2. Also, two axial LVDTs (Linear Variable Differential Transformer) were fixed between the steel plates of the test machine. The LVDTs allow to register the post-peak stress versus

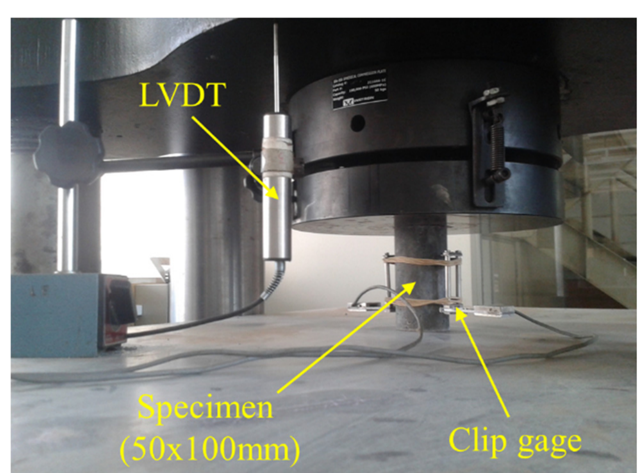

Fig. 2. Compression test set-up.