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Rate effect on the mechanical properties of eight types of high-strength concrete and comparison with FIB MC2010

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ABSTRACT

This paper reports recent experimental results on the rate sensitivity of mechanical properties for eight types of performance-designed high-strength concrete. In particular, compressive tests were conducted using a hydraulic servo-controlled testing machine at strain rates from $2.1 \times 10^{-7}\ s^{-1}$ to $2.1 \times 10^{-4}\ s^{-1}$. The experimental results show that the compressive strength and the elastic modulus increase with an increase in the strain rate. Moreover, the empirical formulas showing the variation between the compressive strength, the elastic modulus and the strain rate for each type of concrete are presented, respectively. Compared with the empirical formulas of the FIB Model Code 2010 (MC2010), it is clear that the predictions from the Code are in a good agreement with the experimental results, and the lowest limit of the empirical formulas for strain rate can be extended to $10^{-7}\ s^{-1}$ instead of originally proposed $10^{-5}\ s^{-1}$ in the order of magnitude. However, for predicting quasi-static mechanical properties, the Code is not appropriate since the relative error would reach 90%.

1. Introduction

High-strength concrete (HSC) is very often used in modern complicated structures of considerable height and span, such as skyscrapers, high towers, tunnels and large bridges. It is important to fully understand the mechanical characteristics of HSC to predict the structure response. The compressive strength is the principal property considered in the design of reinforced and pre-stressed concrete elements. For this reason, a number of research activities have provided valuable information regarding the mechanical properties of HSC in compression [1–7]. However, compared with extensive research into the quasi-static compressive behavior of HSC, much less information is available on its rate-dependent compressive behavior [8,9]. For instance, Krauthammer et al. [10] have studied the size and strain rate effect on a high-strength concrete using a type of drop-weight impact machine, the strain rate was around $10^{-1}\ s^{-1}$ in the order of magnitude. The results show that the size effect was time-dependent. Wu et al. [11] have used a SHPB (Split Hopkinson Pressure Bar) system to investigate the rate effect on the mechanical properties of copper-slag-reinforced concrete (high-performance concrete), the dynamic compressive strength was observed to improve up to 20%, at strain rate approximately 10^2 in the order of magnitude. Nevertheless, the experimental data on the rate sensitivity of the compressive behavior of HSC are scant, specially, when the strain rate is lower than $10^{-5}\ s^{-1}$, such as $10^{-7}\ s^{-1}$, only partial information can be obtained on normal strength concrete (NSC) [8], this is also evidenced by Müller in a recently published state-of-the-art on constitutive modeling of HSC [9].

It is well known that it is not appropriate to transfer knowledge of the fracture properties of NSC directly to HSC. Thus, in order to get additional insights into the strain rate effect on the mechanical behavior of HSC, particularly, from very low strain rate ($10^{-7}\ s^{-1}$), we performed compressive tests of eight types of HSC with six different types of coarse aggregates, using a hydraulic servo-controlled testing machine at strain rates from $2.1 \times 10^{-7}\ s^{-1}$ to $2.1 \times 10^{-4}\ s^{-1}$, corresponding to a type of traffic loading [12]. The results show that both the elastic modulus and the compressive strength increase with increases in the strain rates. Moreover, some empirical formulas describing such rate effect were proposed. Finally, the comparison of mechanical properties was conducted between the experimental data and the formulas given in the FIB Model Code (MC 2010) [13].

Regarding the rate effect on the fracture energy of HSC, which is also one of the most important mechanical properties of concrete, the experimental data available in scientific literature is, again, scant [14]. A need is felt for obtaining experimental evidence on the rate effects on fracture properties of HSC and on their relation with other mechanical properties.

The rest of this paper is structured as follows: the experimental procedure is given in Section 2, in Section 3 the results are presented and discussed in Section 4. Finally, relevant conclusions are drawn in Section 5.

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2. Experimental procedure

2.1. High-strength concretes

The eight types of concrete under study were engineered for performance in a factory close to Madrid, Spain. The provision of design and nomenclature adopted for each of them are shown in Table 1, note that H04 was planned but not fabricated in the end, we nevertheless respected the initial nomenclature. From a mechanical point of view, the concrete can be characterized by the type of coarse aggregate used, its maximum size and compressive strength [15], this information is also included in Table 1.

2.2. Experimental tests

Independent compressive, splitting and three-point bending tests were performed to characterize these eight types of concrete under different loading rates (strain rates).

2.2.1. Compressive tests

Compressive tests were carried out following the recommendations of ASTM C39 (which is analogous to EN 12390-3), cylinders of 75 × 150 mm (diameter × height) were used as shown in Fig. 1. The displacement between two steel platens was measured through two LVDTs (Linear Variable Differential Transformer). Two clip gauges, with a span of 50 mm, were installed centrally around the specimen to determine the elastic modulus. Thus, the local constriction caused by the friction between the steel platens and the specimen surfaces was not influencing the measurement of the elastic modulus [16].

Right before the tests, the bases of the cylinders were polished with a wet diamond disc to ensure perfectly-plane and parallel surfaces. The tests were performed by controlling the average of the signals coming from the two LVDTs previously described, i.e. the reduction in height of the specimen, such record divided by the total height gives the average strain along the cylinder. Consequently, we were actually controlling the average strain rate by setting the LVDTs average velocity. Three strain rates were set as, $2.1 \times 10^{-7}\ \mathrm{s}^{-1}$, $6.7 \times 10^{-6}\ \mathrm{s}^{-1}$ and $2.1 \times 10^{-4}\ \mathrm{s}^{-1}$, respectively. In general, the middle one $6.7 \times 10^{-6}\ \mathrm{s}^{-1}$ fits the requirement of ASTM C39 (approximately from $5 \times 10^{-6}\ \mathrm{s}^{-1}$ to $1.7 \times 10^{-5}\ \mathrm{s}^{-1}$). It is worth to noting that the test at the lowest strain rate $2.1 \times 10^{-7}\ \mathrm{s}^{-1}$ took around 8 h. Four specimens were tested at each strain rate for each type of concrete to obtain the compressive strength and the elastic modulus.

2.2.2. Splitting tests

Quasi-static splitting tests (Brazilian tests) were conducted using the same dimensional cylinders following the procedures recommended by ASTM C496 (which is analogous to EN 12390-6), to determine the splitting tensile strength (f_{tSP}). More information on dynamic splitting tests can be found in [17–22].

2.2.3. Three-point bending tests

The fracture energy, G_F, was measured through three-point bending tests following the procedures devised by Elices et al. [23–25]. All of the beams were 100 mm in thickness, 100 mm in depth and 400 mm in length. The initial notch-depth ratio was approximately 0.5, the span was 380 mm. Four tests for each type of concrete were performed in position control at five loading rates: 17.4 mm/s, 0.55 mm/s, 1.74×10^{-2} mm/s, 5.5×10^{-4} mm/s and 1.74×10^{-5} mm/s. More detailed information can be seen in Ref. [14]. For the following analysis, we take the experimental results at 5.5×10^{-4} mm/s as the quasi-static state.

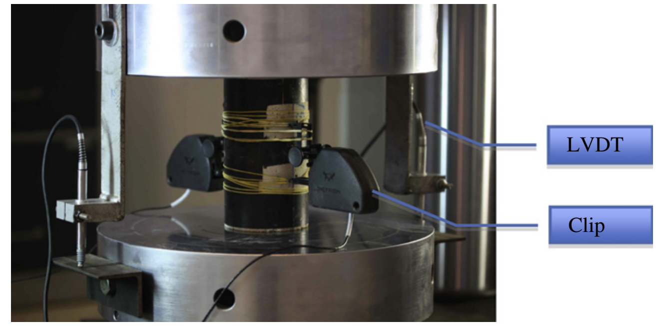

Fig. 1. Experimental setup for compressive tests.

3. Experimental results

3.1. Rate effect on compressive behavior

Fig. 2 shows typical stress–strain curves (σ–ε) at three different strain rates for each concrete. The compressive strength f_c and the elastic modulus E_c are obtained from these curves. It is clear that the compressive strength increases with an increase in the strain rate, while the strain rate effect on the elastic modulus is far less pronounced. Similar tendency was found in Ref. [26]. In Table 2, the average values of the compressive strength and the elastic modulus are listed, the standard deviation of each measurement is shown in parenthesis.

Various relations have been proposed for the characterization of the rate-sensitivity of the compressive strength of concretes [8,27–30]. Logarithm functions as shown in Eqs. (1) and (2) are adopted to represent the rate effect on the compressive strength and the elastic modulus.

$$\frac{f_c}{f_{c0}} = f_0 + m \log \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \tag{1}$$

$$\frac{E_c}{E_{c0}} = E_0 + n \log \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \tag{2}$$

where f_0, E_0, m, n are adjustment parameters. $f_{c0}, \dot{\varepsilon}_0$ and E_{c0} are set as 1 MPa, $1\ \mathrm{s}^{-1}$ and 1 GPa, respectively. Thus, those adjustment parameters are without units.

Figs. 3 and 4 represent the strain rate effect on the compressive strength and the elastic modulus, respectively. Table 3 lists the adjustment parameters and also the correlation coefficient for the experimental results using Eqs. (1) and (2). As mentioned before, compared with the pronounced strain rate effect on the compressive strength, the rate effect on the elastic modulus is minor, and for concrete H02, it is almost constant while the strain rate changes three orders of magnitude. Nevertheless, taking the results of H02 as an exception, Eq. (2) can describe the rate effect on the elastic modulus reasonably. Regarding the rate effect on the compressive strength, except H01, the coefficient relation is only 0.64, the fitting curves and the experimental results are in a good agreement.

Fig. 5 describes the relation between the concrete mechanical properties and the compressive strength of coarse aggregates under quasi-static loading conditions, the values of the compressive strength and the elastic modulus were measured at the strain stain

Table 1
Performance of design, type and category of aggregate used in HSC.

Features	Nomenclature	Coarse aggregate	Category of aggregate	d_{max} (mm)	f_c aggregate (MPa)
Conventional	H01	Siliceous	Quartzite	20	130
Pumpable to elevated height	H02	Andesite	Basalt, dense limestone	12	250
Reduced shrinkage	H03	Andesite	Basalt, dense limestone	12	250
Elevated high strength	H05	Porphyry	Basalt, dense limestone	12	200
High early strength	H06	Mylonite	Sandstone	6	150
Low heat of hydration	H07	Andesite	Basalt, dense limestone	12	250
Lightweight	H08	Arlite	Sandstone	10	10
Heavyweight	H09	Barite	Basalt, dense limestone	10	12