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Suitability of the damage-plasticity modelling concept for concrete at elevated temperatures: Experimental validation with uniaxial cyclic compression tests

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ABSTRACT

Strain-rate controlled cyclic compression tests enable us to explore the softening behaviour and the elastic stiffness evolution with increasing plastic straining of concrete in uniaxial compression. From such tests at ambient temperature, it is known that concrete exhibits the phenomenon of elastic stiffness degradation upon unloading—a macroscopic behaviour that can be captured by damage-plasticity models. However, the damage-plasticity concept has been implemented in some available finiteelement method codes as temperature-dependent concrete models which are often used today in structural fire engineering, despite the lack of experiment-based calibration data. This paper presents the results of an experimental study on the uniaxial behaviour of concrete at elevated temperatures under cyclic compressive loading. The experimentally derived evolutions of the elastic stiffness with increasing plastic straining (1) confirm the suitability of the damage-plasticity modelling concept for concrete in uniaxial compression at elevated temperatures and (2) provide novel temperature-dependent calibration data for damage-plasticity models.

1. Introduction

In structural fire engineering, the failure analysis of concrete structures or steel–concrete composite structures has become increasingly important to achieve safe and economic fire design solutions. In this framework, the nonlinear finite element method allows a numerical analysis of the structural fire behaviour and the partial replacement of costly large-scale fire tests by numerical simulations, since some of the available nonlinear codes, such as ABAQUS Standard, permit to consider the implemented concrete models as temperature dependent. However, these models were developed on the basis of phenomena observed in concrete fracture experiments at ambient temperature.

Plasticity -based concrete models can capture on a macroscopic level the strain softening behaviour of concrete, consisting of decreasing stress with increasing straining, accompanied by irreversible strains and inelastic volumetric expansion (depending on the confining pressure). However, they cannot account for the stiffness degradation observed in uniaxial cyclic tests in compression [1–5] and tension [6]. Therefore, damage-plasticity models were developed that could reproduce the observed stiffness degradation. A brief overview of this research development is given in ref. [7]. A damage-plasticity model type, combining stress-based plasticity in terms of effective stresses with isotropic damage, is implemented in ABAQUS Standard. This implementation is based on the models of refs. [8,9], which were validated at ambient temperature with data from uniaxial monotonic and cyclic tests in compression [2] and tension [6], amongst other validation data. Such a model requires an entire set of input data to fully deploy its features in the inelastic regime. Besides the parameters governing the yield function, the input data consist of: (1) stress-hardening and strain-softening data in compression, (2) strain-softening data in tension, (3) elastic stiffness degradation data in compression and (4) elastic stiffness degradation data in tension. As implemented in ABAQUS Standard, the model can be temperature-dependent when this input data is provided at different temperature levels.

A considerable amount of data is available in the literature from load-controlled compression strength tests of concrete at elevated temperatures, dating as far back as 1950. But it was only in the mid 1970s that the first strain-rate controlled compression tests at elevated temperatures were performed, giving insight into the post-peak behaviour of concrete in compression at high temperatures. Ongoing research in this area lead during the second half of the 1990s and the early 2000s to the Eurocode model for the stress–strain curves of siliceous and calcareous concretes at elevated temperatures [10] and to the RILEM recommendations for test methods for the mechanical properties of

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concrete at high temperatures [11]. There are many extensive literature reviews giving a detailed survey of the development of this research area, e.g. refs. [12–14].

However, to date, no strain-rate controlled cyclic compression tests at elevated temperatures have been published, providing data that would allow, (1) to validate experimentally at elevated temperatures the suitability of the damage-plasticity modelling concept for concrete in uniaxial compression, and (2) to calibrate finite element method implementations of damage-plasticity models for concrete in compression at elevated temperatures. Therefore, in the scope of a larger research project on the structural fire behaviour of concrete-filled circular hollow section columns with a solid steel core [15], a series of strain-rate controlled cyclic compression tests at elevated temperatures were performed.

This paper is divided into in three parts, dealing with (1) the experimental program, (2) the results of the testing series and their evaluation within the framework of damage-plasticity and (3) the comparison of the results with available data in the literature.

In the first part, discussed in Section 2, relevant details about the test specimens are given, including the concrete mixture proportions. Then, the design of the test apparatus is presented, which consisted of a furnace combined with a universal testing machine. Afterwards, the preliminary tests are outlined, which consisted of benchmark tests for the elastic modulus assessment and of temperature regime control tests. Finally, the fully automated test sequence used is described in detail. In the second part, presented in Section 3, the evaluation of the raw data for a discussion within the framework of damage-plasticity is illustrated and the experimental validation of the applicability of the damage-plasticity modelling concept for concrete in uniaxial compression at elevated temperatures is presented. Then, the influence of the temperature exposure on the concrete properties is discussed. Aspects taken into account include the characteristics of the stress–strain curves (peak strength, ultimate strain, softening behaviour), the failure mode of the specimens, the fracture mode in the fracture surfaces and the degradation of the elastic stiffness. Furthermore, the influence of a sustained pre-load during heating on the characteristics of the stress–strain curves and on the degradation of the elastic stiffness are reviewed. In the third part, detailed in Section 4, the reduction factor–temperature curves of the compressive strength and the initial elastic modulus are compared to test results available in the literature. Additionally, the potential influence of measurement techniques on the reduction factor–temperature curve of the initial elastic modulus is outlined.

2. Experimental program

2.1. Overview

Steady state, strain rate–controlled cyclic compression tests at elevated temperature levels were performed with constant strain rates in loading and unloading. The temperature levels examined were 300 °C, 400 °C, 500 °C, 600 °C, 700 °C and 800 °C, besides reference tests at ambient temperature. The specimens were heated to the target temperatures without a load applied (unstressed conditions). Additionally, specimens were tested at 600 °C and 700 °C that had sustained a load during heating (stressed conditions) of 40% of the actual compressive strength at ambient temperature. Preliminary temperature control tests were performed to assure uniform temperature distributions within the specimens during the cyclic compression tests. The target temperatures were attained with a constant heating rate of 5 °C/min within the specimens, and a subsequent conditioning time of one hour was observed, to comply with the RILEM recommendations [16]. Then, the elastic modulus was established at a target temperature with a series of load cycles. Subsequently, the specimens were loaded until complete softening with intermediate unloading–reloading cycles in the post-peak regime.

2.2. Mixture proportions, specimen preparation and instrumentation

The mixture proportions and properties of the concrete used to fabricate the test specimens are listed in Table 1. The cement was an unblended Portland cement classified as CEM I 42.5 R. The sand consisted of crushed limestone containing four different grain size fractions: (1) 0.2–0.6 mm (350 kg/m^3), (2) 0.6–1.1 mm (150 kg/m^3), (3) 1.1–2.0 mm (350 kg/m^3) and (4) 2.0–3.15 mm (430 kg/m^3). The filler was a limestone filler with grain sizes ranging from 0.0 to 0.2 mm. The wet properties of the concrete mixture were comparable to self-consolidating concrete, despite the lack of coarse aggregates in the design. This concrete can prove to be useful in the manufacturing of special composite members for applications in structural fire engineering like, e.g. concrete-filled circular hollow section columns with a solid steel core [15], where it is used as a robust infill of the designed void between the outer steel tube and the inner steel core, also providing thermal insulation of the steel core.

The specimens were casted in moulds prepared with segments of PVC tubes with a matching cap at the bottom as depicted in Fig. 1a. The PVC tubes featured a nominal inner diameter of 51.3 mm and rendered castings of 150 mm in height. After casting, the moulds were stored in a climatic chamber at 20 °C and 95% relative humidity. Ten days after casting, the specimens were demoulded. Thirty-one days after casting, they were cut wet to a length of 100 mm using a diamond saw. Due to the high precision of the saw cuts, both loading planes of the specimens met the perpendicularity requirements. For their planeness requirements, a minor additional finish on a high-precision grinding table was necessary. After 141 days in the climatic chamber, the specimens were dried in a furnace at 105 °C until the relative change in mass was less than 0.1% within 24 h (reached after four days). From the mass losses of three reference specimens, the mean value of the initial moisture content, given in Table 1, was calculated. The dried specimens were then stored at ambient temperature and 50% relative humidity for 555 days. Shortly before testing, the masses of all specimens were measured to give the mean value at the time of testing, listed in Table 2. By combining this mean value with the mean value of the reference specimens of the drying process, the moisture content at the testing time was assessed (Table 1).

All of the specimens used for compression tests at elevated temperatures were equipped with type K thermocouples at axial positions close to their top and bottom borders as indicated in Fig. 1e. Only those specimens which were used for the preliminary temperature tests featured an additional third thermocouple at the axial mid-position. Fig. 1b to d illustrate how the thermocouples were placed into 5 mm diameter drills, filled with an injectable cement paste and then held in position until hardening occurred.

2.3. Test setup and preliminary tests

2.3.1. Test apparatus

The steady-state cyclic compression tests at elevated temperatures were displacement controlled and conducted with a universal testing machine from manufacturer ZWICK. This testing machine features a movable solid crosshead in between two fixed solid tables at the top and bottom of a stiff loading frame. Propulsion of the crosshead is provided by an AC-servomotor within a control circuit with a cycle time of 500 Hz. For the specific compression test setup shown in Fig. 2, the machine's upper compartment was used, with the crosshead moving upwards, pressing against the upper fixed table. The relative displacement, u, between the lower and the upper table of the high-temperature loading rams was selected as the control variable. This displacement was measured with a high-temperature resisting compressometer from MAYTECH, featuring two ceramic spring-loaded rods that can transmit the displacement between two points inside the furnace to a high-precision LVDT located outside the furnace in the housing of the device. The compressometer was calibrated