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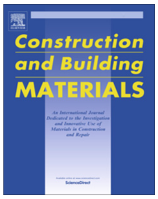

Stochastic fracture-mechanical characteristics of concrete based on experiments and inverse analysis

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HIGHLIGHTS

- It incorporates testing on concrete with different slump values and hardening time.
- Characterization of fracture-mechanical parameters with different testing methods.
- Material parameters were also identified by using inverse analysis technique.
- It provide statistical parameters and stochastic models for numerical assessment.

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ABSTRACT

The use of stochastic nonlinear computational mechanics in real-world applications faces a fundamental obstacle – the lack of detailed information about the stochastic properties of material parameters involved in the problem. The current paper describes the results of an extensive experimental program which focused on determining fracture-mechanical parameters and their stochastic models of concrete C25/30. The testing program consisted of compression tests on cubic specimens, three-point bending tests on beams with notch and wedge-splitting tests on cubic specimens with notch. In the case of the three-point bending tests, along with the standard evaluation of fracture-mechanical properties according to code specifications material parameter identification, artificial neural network based inverse analyses were carried out. In order to quantify the influence of the consistency of freshly mixed concrete on its fracture-mechanical properties, two concrete mixtures of the same strength class were tested: (i) mixture with a slump value of 45 mm and (ii) mixture with a slump value of 70 mm. In addition, the time development of fracture-mechanical parameters and their variability was studied. All results obtained from individual tests are presented, compared and discussed here. Stochastic models of selected parameters of the analyzed concrete for stochastic nonlinear FE-model analysis will be recommended.

1. Introduction

Design, computation and construction of engineering structures are generally based on linear static analyses and on linear or multilinear material models [1]. In the new generation of design specifications, all design associated uncertainties, e.g., in material properties, are covered in the so-called semi-probabilistic safety concept (SPSC) [2]. The SPSC guarantees desired reliability levels over the entire life cycle of a structure by a careful selection of (a) suitable safety factors for the resistance and for the action of the load side, and (b) of load combination factors. The SPSC, using fractiles of material properties and loads as inputs, provides the means for a standardized verification of the usability and the static safety [3] for engineering structures. The required general validity of the SPSC for a wide range of types of structures gives rise to reliability levels that may turn out to be even higher than originally intended [4]. Unbalanced levels of reliability exist (e.g. some existing structures possess high reliability levels (e.g. $\beta \geqslant 6$) while others are on the lower level (e.g. $\beta = 3.8$) as a result of their being constructed for their respective planned design life) beyond the codes of design. Even the design specifications are established as a result of sophisticated calibration procedures. SPSC can also result in a lower level of reliability. For instance, jointless concrete structures or abutment bridges generally require a higher production quality (e.g. due to the high sensitivity of internal forces with

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respect to the structural stiffness and the soil structure interaction [5–7]) than what is given in the code specific standards.

These uncertainties can be captured by probabilistic methods which allow the integration of previously mentioned existing geometrical as well as material uncertainties both at the time of construction and during the entire life cycle of a structure in form of probability density functions (PDFs) [8–10]. Probabilistic methods are frequently based on advanced Monte Carlo simulation techniques [11], where e.g. multiple evaluations of a problem are carried out with different input values. These input values are extracted from aforementioned PDFs of the properties under investigation. This makes it possible to calculate the failure probability p_f and the reliability index β [9].

Such advanced Monte Carlo simulation techniques, but also approximation techniques such as the First Order Reliability Method (FORM) or the Second Order Reliability Method (SORM) [12–14] provide the means for the probabilistic reliability assessment (PRA) and life cycle analysis of new and existing structures with acceptable computing complexity and therefore within a reasonable computing time [8]. The random inputs (e.g. concrete compressive strength f_c or tensile strength f_t) for PRA must be defined based on literature (e.g. [15,16]) or on experimental tests (e.g. [17–21]). However, the random fracture relevant properties (e.g. specific fracture energy G_f) of numerous materials within the new code specifications have in most cases not yet found their way into the literature [2]. The properties are frequently derived from historical experiments (e.g. [22]) and specified material development is usually disregarded [23].

Nevertheless, the effective application and acceptance of PRA as a module for design and development depends considerably upon the accessibility of information about the random properties. Hence, the practical implementation of PRA and thereby of an integrative approach in design calls for a stochastic database system that enables the systematic storage and retrieval of the random properties of continuously evolving materials [19]. Such a stochastic database which contains a multitude of materials with their properties would support the performance assessment of existing structures and serve for the characterization of the variables for the Design by Testing Concept as it is incorporated in the EN 1990 [24], which enables the development and adaptation of design based on experimental data.

2. Research significance

A database can serve as valuable source of information for fully probabilistic analyses. In this respect, the current paper is focused on determining the fracture-mechanical parameters of concrete C25/30 with the aim of establishing a first step towards such a database for several types of concrete. The research was also indirectly stimulated by the urgent need for the statistical parameters of fracture-mechanical parameters of concrete when using software tools for the probabilistic assessment of concrete structures [10,25–28].

3. Experimental investigation

In general, the properties of concrete are characterized via the compressive strength according to EN 206-1 [29], the exposure classes and the slump value. Nevertheless, any realistic modeling of structures requires the consideration of (a) nonlinear effects in the analysis and material properties of concrete (usually referred to as fracture-mechanical parameters), which can be captured e.g. by a variable modulus of elasticity E_c, tensile strength f_t, and specific fracture energy G_f, and (b) of aleatoric uncertainties in material and geometrical properties caused (among others) by natural effects, manufacturing processes and curing [9]. These requirements together with the newly characterized concrete classes in the Eurocode concept gave rise to the experimental investigations with the concrete type C25/30 according to EN 206-1 or ÖNORM B 4710-1 [30]. In particular, the standardized compression test (EN 12390-3 [31]), the standardized three-point bending test of notched specimens (EN 14651 [32]) and the wedge-splitting test (ÖNORM B 3592 [33–35]) were applied in the course of the investigations.

Table 1
Concrete mixture of series 1 and 2 corresponding to concrete strength class C25/30.

Concrete properties[a]	Density (kg/m^3)	Dry amount (m^3)	(kg)
Aggregate 0–4 mm	2650	0.296	785.00
Aggregate 4–16 mm	2670	0.198	528.44
Aggregate 16–32 mm	2670	0.165	439.47
Water content	1000	0.175	175.00
Superplasticizer LZF[b]	1080	0.001–0.002	0.93–2.64
Stone meal Ca(OH)$_2$	2700	0.018	49.58
Fly ash Fluamix C	2900	0.026	74.86
Cement CEM I 42.5R	3100	0.097	299.76

[a] Consistence series 1 – slump value $F = 45.3$ mm; consistence series 2 – slump value $F = 70.1$ mm; (water/cement + ($k \cdot$ addition) ratio or k-factor = 0.80 according to EN 206-1; water–cement ratio w/c = 0.58; water–binder ratio w/b = 0.49) seven days water immersion and twenty-one days air exposure; air-content of series 1:1.1% and of series 2:0.5%.

[b] The amount of superplasticizer was varied between the two series in order to achieve a slump value of F45 and F70 respectively.

The experiments enabled a partially redundant identification of the above mentioned material properties and consequently an effective comparison and a verification of testing procedures. These investigations were divided into four parts: (a) concrete C25/30 with a slump value of 45 mm (F45) tested after 28 days of curing (series 1, set 1), (b) concrete C25/30 with a slump value of 70 mm (F70) tested after 28 days of curing (series 2, set 1), and both series tested after a long term curing period (176 days), indicated as set 2 (see also Table 1).

Slump values indicate the workability of freshly mixed concrete and can be evaluated by slump tests according to EN 12350-2 [36]. Slump depends on many factors, such as the properties of concrete ingredients or aggregates and others. Also, temperature has its effect on the slump value. For the investigated concrete mix design, chemical ingredients (superplasticizers) were used to adjust the slump value. Beyond determining the random mechanical parameters of concrete as sketched above, and prior to the validation of testing procedures, the effect of the considered slump values on the scattering properties was of high interest to our industrial partners.

3.1. Compression test

In order to determine the compressive strength according to EN 12390-3, test cubes of the investigated concrete type C25/30 with the dimensions 150 × 150 × 150 mm were loaded with a gradual increase of the stress level start-

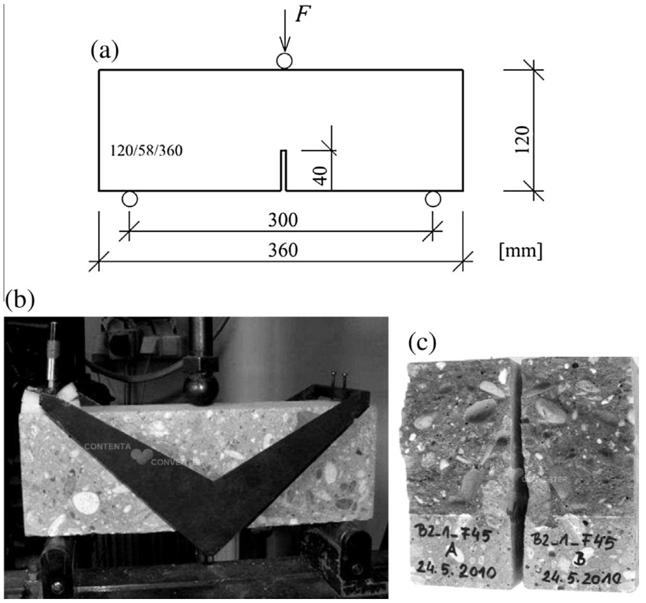

Fig. 1. Three-point bending fracture test: (a) testing configuration, (b) laboratory test set-up and (c) example of fractured surface.