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# DO MODERN CONCRETES EXHIBIT SIMILAR EARLY-AGE STIFFNESS AND STRENGTH DEVELOPMENTS AS THEIR PREDECESSORS?

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## 1. Introduction

Some 5 % of global anthropogenic $CO_2$ emissions result from the production of cement-based materials [1]. Therefore, the cement and concrete industry is challenged to produce less $CO_2$-intensive binders. The currently implemented strategy is to replace traditional Portland cement clinker partly by Supplementary Cementitious Materials, resulting in so-called *blended cements*.

Supplementary Cementitious Materials (SCMs) are typically waste products of other industrial sectors, e.g., fly ashes from combustion power plants or blast furnace slags from steel production. SCMs exhibit a hydraulic reaction when mixed with water, but the reaction kinetics are slower compared to the hardening reaction between traditional Portland cement clinker and water.

Concretes produced with blended cements are known to exhibit a reliable and durable field performance at mature ages (> 28 days), but a comparably slow development of mechanical properties such as stiffness and strength, particularly during the first week after production. Suitably well-developed early-age mechanical properties, in turn, are required, such that (i) formworks may be removed, or (ii) prestress may be applied without damaging the concrete.

This antagonism is setting the scene for the present contribution that aims at characterizing the early-age evolutions of stiffness and strength of twelve different concrete mixes, typically used for bridge construction.

## 2. Standard formulas for early-age strength and stiffness development of concrete

The most important material property of concrete is its uniaxial compressive strength at an age of 28 days. It can be quantified by means of a simple-to-perform destructive cube compression test. The pre-standard, “Model Code 2010”, see [2], provides many formulas that relate other material properties of interest to the uniaxial compressive strength at 28 days, $f_{cm}$. In more detail the Model Code provides (i) a mathematical function for quantifying the early-age increase of strength with increasing material age, up to the strength value at 28 days, with coefficient $s$ accounting for the strength class of cement [2],

$$f_{cm}(t) = f_{cm} \cdot \exp\left\{s \cdot \left[1 - \sqrt{\frac{28\text{ days}}{t}}\right]\right\}, \qquad (1)$$

(ii) a function for estimation of the Young’s modulus of concrete at 28 days, with coefficient $\alpha_E$ accounting for different types of aggregates [2],

$$E_{ci} = 21.5\text{ GPa} \cdot \alpha_E \cdot \sqrt[3]{\frac{f_{cm}}{10\text{ MPa}}}, \qquad (2)$$

and (iii) a function for quantifying the early-age increase of Young’s modulus with increasing material age, up to the stiffness value at 28 days

$$E_{ci}(t) = E_{ci} \cdot \sqrt{\exp\left\{s \cdot \left[1 - \sqrt{\frac{28\text{ days}}{t}}\right]\right\}}. \qquad (3)$$

These mathematical relations were historically developed based on many experimental data obtained from early-age testing of concretes made with traditional Portland cements. The applicability of Eqs. (1) – (3) is, thus, questionable when it comes to modern concretes produced with blended cements.

## 3. Testing campaigns

A comprehensive experimental campaign is carried out in order to check the reliability of

Model Code functions (1) – (3) for the early-age development of uniaxial compressive strength and Young's modulus. It involves 12 different concrete mixes. They are referring to three different compressive strength classes, they are made of three different types of cement and two types of aggregates, and they are targeting at two different air contents.

Standard experiments refer to the determination of the uniaxial compressive strength and the unloading modulus at material ages amounting to 1, 3, 7, 14, and 28 days after production. Non-standard experiments follow the experimental protocol developed in [3]. This test protocol includes hourly repeated loading-unloading cycles under uniaxial compression. The first test is carried out 24 hours after production. Hourly testing is repeated until the tested concrete specimen reaches an age of 8 days. Therefore, each specimen undergoes some 170 loading-unloading cycles during the first week after production. In order to ensure that the specimens remain undamaged, the maximum forces are selected such that the loading does not exceed 20 % of the strength of the specimen at the time of testing. In addition, a few loading-unloading cycles are carried out 28 days after production. From these tests, the unloading modulus is determined.

The standard strength values, determined at the material age amounting to 28 days, are used as input for Eqs. (1) – (3). Corresponding outputs are compared with the experimental data. This is shown exemplarily for one of the tested concretes in Figs. 1 and 2.

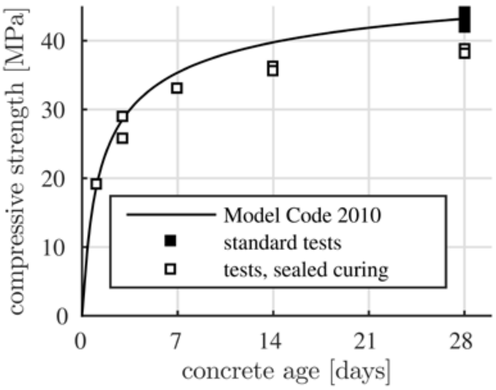

**Fig. 1.** Uniaxial compressive strength as a function of material age of one of the tested concretes: test data from testing, see squares, and expectations of Model Code 2010 [2], see the solid line and Eq. (1)

Figs. 1 and 2 underline exemplarily (i) that Eqs. (1) to (3) are qualitatively quite satisfactory, (ii) that quantitative aspects deserve improvement, (iii) that the early-age strength development of concrete strongly depends on the curing condition, and (iv) that Eqs. (2) and (3) significantly underestimate the early-age stiffness evolution.

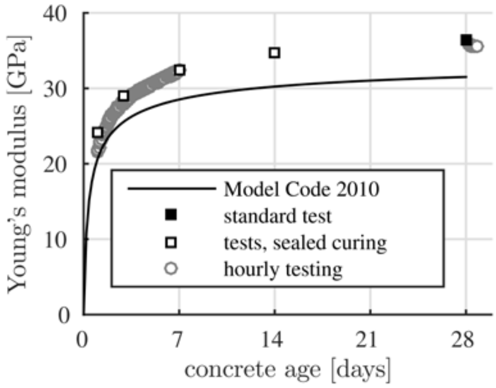

**Fig. 2.** Young's modulus as a function of material age of one of the tested concretes: test data from standard tests, see squares, test data from hourly testing, see circles, and expectations of Model Code 2010 [2], see the solid line as well as Eqs. (2) and (3)

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