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Strength development of GGBS and fly ash concretes and applicability of fib model code's maturity function – A critical review

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HIGHLIGHTS

- Strength prediction according to the fib Model Code is improved using a new approach for the s-value.
- The factors determining the s-value are: SCM content, w/b-ratio and strength class of cement.
- With the new s-value strength development of GGBS and FA concretes can be predicted up to an age of 91 d.
- Late strength predictions tend to overestimate the strength of GGBS concretes and underestimate the strength of FA concretes.
- With the new s-value and the fib model code's maturity function, strength can be predicted for different curing temperatures.

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ABSTRACT

This paper is the joint work of working group 4 of the RILEM TC 238-SCM and the fib Task Group 4.6. It was the aim of this literature study to quantify the effect of ground granulated blast furnace slag (GGBS) and silicious fly ash (sFA) on strength development of concrete. For the strength development the approach of the *fib* Model Code was chosen, which is based on an e-function that can be adapted to the strength development of an individual binder by selecting the so-called s-value based on the strength class of the Portland cement used. No guidance is provided for s-values for supplementary cementitious materials (SCMs). In order to determine the s-values for mixes with SCMs, a database was set up with results of material testing from literature. A relationship between s-values and w/b plus SCM/b ratios has been determined. This has been tested on laboratory cast specimens with 50 and 30% cement replacement with GGBS and FA respectively. These were cured at 20 °C. The s-values from this relationship were compared to those obtained from regression analysis and they were found to be satisfactory. This increased confidence in their use for predicting the strength development of other curing regimes, i.e. adiabatically cured concrete cubes, using the maturity function in the *fib* Model Code. Predictions of the effect of curing temperature, i.e. the adiabatic temperature history, on the strength development were again satisfactory. These were not significantly affected by the fib model code's use of one value of "apparent" activation energy.

1. Introduction

There has been a significant change in the types of cements used in the last decade. Whilst before the norm was a neat Portland cement, nowadays referred to as CEM I, environmental considerations, i.e. carbon footprint, has led to CEM II and CEM III cements becoming popular. Many of these cements contain fly ash (FA) or ground granulated blast-furnace slag (GGBS) which alter the compressive strength-time relationship. The designers usually use the 28-day characteristic compressive strength for structural calculations. Whilst SCMs may be used to design concretes of equivalent 28-day strength as neat Portland cement (CEM I) their early age strength development is not only significantly different but it is also affected to a greater extent by curing temperature.

High early age strength, e.g. 15 N/mm^2 at 16 h, are needed by precast concrete factories for lifting operations in order to maintain their daily production of structural and non-structural elements. The factors affecting strength at early ages must therefore be considered. These factors include the composition of the concrete mixture, such as cement type and SCM addition and the use of retarding or accelerating admixtures. The strength development

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of the concrete is also influenced by temperature. Strength gain is more rapid at higher temperatures and slower at lower temperatures and if the temperature is too low then strength gain will cease altogether.

The need to understand and quantify the effect of temperature on the early age strength development of concrete mixes has been recognised for a long time. This was mainly for:

(a) determining elevated curing temperature needed to achieve the required early strengths for safely lifting precast concrete elements as early as sixteen hours after casting [1] and
(b) predicting the in-situ strengths especially during cold weather concreting, to allow stripping of formwork and removal of props without a collapse like the one that occurred in Willow Island in 1978 which resulted in 51 deaths [2,3].

This can be achieved with maturity methods which account for the combined effect of binder composition and temperature on the strength development of concrete [4–9].

2. Strength development

2.1. General

The replacement of Portland cement by GGBS or fly ash usually results in a reduced early strength, often coupled with an increase in late strength. According to the fib Model code [10] the strength of concrete at a certain point in time can be calculated from the strength at 28 days according to the following equation:

$$\mathrm{f}_{\mathrm{cm}}(\mathrm{t}) = \beta_{\mathrm{cc}}(\mathrm{t}) \cdot \mathrm{f}_{\mathrm{cm,28d}} \text{ with } \beta_{\mathrm{cc}}(t) = e^{s\cdot\left(1-\sqrt{\frac{28d}{t}}\right)} \quad (1)$$

where

$\mathrm{f}_{\mathrm{cm}}(\mathrm{t})$ is the mean compressive strength in $\mathrm{N/mm^2}$ at an age t in days,
$\mathrm{f}_{\mathrm{cm,28d}}$ is the average compressive strength in $\mathrm{N/mm^2}$ at an age of 28 days,
$\beta_{\mathrm{cc}}(\mathrm{t})$ is a function to describe the strength development with time,
t is the concrete age in days,
s is a coefficient, which depends on the strength class of the cement.

The model code gives the following benchmarks for the different strength classes defined in the European standard EN 197-1:

$$32.5\ \mathrm{N}: \quad \mathrm{s} = 0.38$$

$$32.5\ \mathrm{R} \text{ and } 42.5\ \mathrm{N}: \quad \mathrm{s} = 0.25$$

$$42.5\ \mathrm{R},\ 52.5\ \mathrm{N} \text{ and } 52.5\ \mathrm{R}: \quad \mathrm{s} = 0.20$$

These values are valid for 20 °C and water storage.

For concretes with high GGBS or fly ash contents strength development is slower, which leads to higher s-values. In order to quantify that effect, data on strength development of concretes with GGBS and/or fly ash were collected from research reports and literature [11–78] and internal reports of material testing at the Institute of Building Materials Research, RWTH Aachen University, (ibac) [65]. For comparison concretes with CEM I of different strength classes were also included in this study. The compressive strength of each concrete was tested at least at three points in time, always including 28 days. The average number of testing ages was 4.5. The s-value of every binder was fitted using Eq. (1). Since all experimental data show some scatter, the measured 28 day strength was not taken as a fixed value. Instead a fitting was carried out, allowing a variation of the 28 d strength in the range of ± half a strength class compared to the measured value in order to get the most appropriate s-value for the strength development. Fig. 1 shows two examples of the fitting, a typical and a bad example. The bad example shows that in a few cases the experimental data could not be described adequately with Eq. (1). 18 out of 1017 data sets were not considered, because the average discrepancy between measured and calculated strength was more than 2.0 $\mathrm{N/mm^2}$. Results for very early ages (<24 h) should not be considered in the fitting of the s-value because high discrepancies at later ages were found in this study. That means on the other hand that the strength at t < 24 h cannot be predicted by Eq. (1).

The database includes only concrete samples with a minimum dimension of 100 mm. The curing temperature was 20 ± 3 °C. The humidity storage conditions of the samples varied. Some samples were stored under water or in a fog room and others were stored under water for 7 days and at 65% relative humidity afterwards. An overview of the available data is given in the Annex, Tables A1–A4. The tables give information on binder composition, strength class of the cement, the water/cement ratios (w/c) and the storage conditions.

Quite often the strength class of the cements is not specified in non-European literature, but in many cases results of mortar compressive strength tested according to ASTM C 109 are included in the papers. These results were used to classify the cements according to EN 197-1 (assuming a size factor of $\mathrm{f}_{\mathrm{cm,51mm}}/\mathrm{f}_{\mathrm{cm,40mm}} = 0.95$). Most of these cements were assigned to strength class 32.5 R or 42.5 N.

2.2. Influence of curing conditions, binder composition and w/b ratio

As mentioned above all concretes were cured at 20 ± 3 °C but at different humidity conditions. The humidity may influence the subsequent hardening of concrete. Exemplarily Fig. 2 shows the s-values of concretes with different binders and similar w/b-ratios prepared with cements of strength class 32.5 R. The s-values show a large scatter, but nevertheless it can be seen that there is no systematic difference between 7 days of curing and water storage. There are a few results with only one or two days of curing in the data base and they show lower s-values indicating

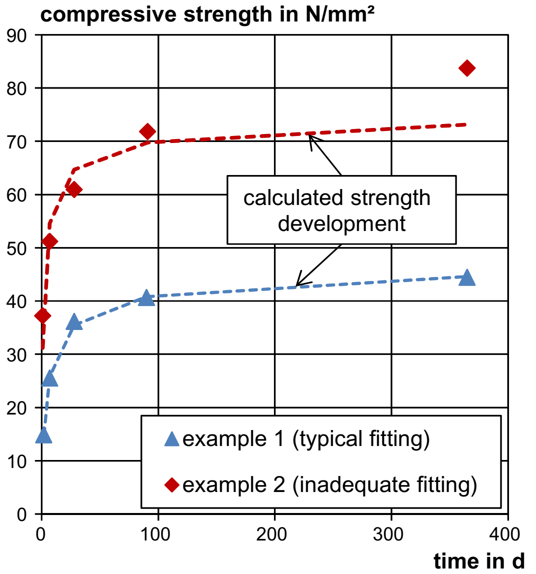

Fig. 1. Fitting of experimental data on strength development (example 1: B13, [25], example 2: No. 12, [15]); dots: experimental data, dotted lines: fitted curves.