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Performance of concrete exposed to natural carbonation: Use of the *k*-value concept

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HIGHLIGHTS

- The contribution of fly ash to the concrete carbonation resistance is very weak.
- Slag contributes to the concrete carbonation resistance.
- Compressive strength at 28 days is a reasonable indicator of carbonation resistance.
- *k*-values from EN 206 are not conservative, when carbonation resistance is concerned.
- There is a need to replace deemed-to-satisfy rules by performance testing approach.

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ABSTRACT

This work presents results of concrete carbonation after 10 years of exposure to a natural environment not sheltered from rain, and the values are utilized for the application of the *k*-value concept used within EN 206 for Type II additions to concrete. The concrete mixtures were prepared with Portland cement and different replacement levels of cement by fly ash (FA), ground granulated blast furnace slag (GGBFS), or both FA and GGBFS and using distinct water/binder ratios. The concrete performance is related with the binder constituents and dosages through the *k*-value concept. Thirty-three concrete mixtures were tested and the results show a consistent decrease of carbonation resistance when the water/clinker ratio increases, which is in accordance with the low *k*-values obtained for fly ash and slag. The analysis performed also shows that the mixtures with FA present lower carbonation resistance than those with GGBFS, for the same cement replacement level.

1. Introduction

The cement industry contributes with about 5–8% of the global CO_2 emissions [1]. Concrete, as a cementitious based material, must play an active role in reducing the rate of greenhouse gas emissions, since the majority of the cement production is used in concrete [2]. Fly ash (FA) and ground granulated blast furnace slag (GGBFS) are well-known by-products, respectively from coal-fired power plants and iron production, which are used in concrete, either as cement constituents [3] or type II additions [4].

The use of these by-products to lessen the CO_2 emissions of cementitious binders [1] is a natural trend for the concrete industry. This view is strengthened in consideration of the excellent performance of concretes with fly ash or slag, when subjected to the chloride attack [5], a major problem in reinforced concrete structures. However, in regard to carbonation resistance, a general decrease of the concrete behaviour is observed when cement clinker is replaced by type II additions.

A work by Sisomphon and Frank [6] shows that the pozzolanic mixtures studied have a lower carbonation resistance, therefore have also shorter induction period for carbonation. Leemann et al. [7] indicate that the parameter governing the carbonation coefficient of the mortar and concrete mixtures is the CO_2 buffer capacity per volume of cement paste. Rozière et al. [8] point out that from concrete mixtures made of the same aggregates with the same water/binder ratio a negative effect of fly ash may be deduced. As regard blast-furnace slag, Gruyaert et al. [9] conclude that the carbonation coefficients increase as the replacement of cement by slag in the concrete increases. Younsia et al. [10] also report huge differences in accelerated carbonation kinetics between water-cured and air-cured concretes, especially in the case of concretes with blast furnace slag.

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The standard EN 206 [4], at European level, and the Portuguese LNEC E464 specification [11], state that the structural concrete is deemed to satisfy the durability requirements for the intended use in specific environmental conditions, if its composition is in conformity with prescribed limiting values. In fact, the concrete requirements are given either in terms of limiting values and established concrete properties, although, as an alternative, the requirements may also be derived from performance-related methods.

In this context, Rozière et al. [8] present a study where an accelerated carbonation test is proposed as a performance test, as part of a project aimed at designing methods to implement the equivalent performance concept described in the standard EN 206 [4]. Younsia et al. [12] also describe a work that aims at studying the accelerated carbonation of concrete mixtures with high substitution rates of cement by fly ash or blast-furnace slag, as a part of a research program on low CO_2 emissions concrete. The work investigates the equivalence of performance of concrete with high contents of mineral additions and concrete made with Portland cement and blended cements, used as references (see also [10] for the effect of interactions between hydration and drying). Ribeiro et al. [13] present as well correlations between laboratory properties and in-situ performance intended to be used as a basis in defining performance-related design methods.

Concerning the use of these type II additions (FA and GGBFS) in the concrete mixtures, they can be taken into account in the limits established for minimum cement content and maximum water/cement ratio (*w/c*) by the *k*-value concept [4].

According to CEN/TR 16639 [14] the *k*-value is a prescriptive concept based on the comparison of the durability performance (or strength as a proxy-criterion for durability where appropriate) of a reference concrete with cement "A" against a test concrete, in which part of cement "A" is replaced by an addition.

In EN 206, a prescriptive *k*-value is given for fly ash (0.4) and a recommended one is suggested for GGBFS (0.6). These *k*-values allow the use of these additions without further testing, provided that some conditions are fulfilled in terms of their maximum amount.

The CEN/TR 16639 provides a procedure for calculating *k*-values, which is based on the *w/c* versus strength relationship of concretes with the same content of addition. In the present study, the same principles are followed, but considering the carbonation resistance instead of the compressive strength. Here, the *k-value*, a cementing efficiency factor, is used with regards to durability.

This type of approach was also adopted in others works. In a study published more than 20 years ago, Vandewalle [15] concluded that replacement of 20% cement by fly ash, for concrete produced with Portland cement or Portland blast furnace slag cement, using a *k-value* of 0.3, results in a lower carbonation rate. Branca et al. [16] reported that, at a given water/(cement + fly ash) ratio, the addition of fly ash to replace cement accelerates the carbonation process (*k-value* = 1).

More recently, Lollini et al. [17] suggest that strength was appropriate as a proxy-criterion for carbonation resistance and that *k-values* estimated for compressive strength could be considered valid also for the resistance to carbonation. In tests with metakaolin, Badogiannis et al. [18] obtained very high *k-values* for strength (close to 3.0 at 28 days), but durability-related properties were not included in the study.

With a different perspective, Sanjuán et al. [19] indicate that setting up only a general *k-value* for GGBFS is complex and risky and national practice rules must be prudent and established according to a safety criterion. With comparable meaning, Gruyaert et al. [20] indicate that application of the *k-value* concept for BFS, with respect to durability, seems to be ambiguous and laborious.

Carbonation in natural conditions is a slow process, requiring several years to obtain significantly different values between distinct mixtures. In laboratory conditions, the accelerated tests are useful to distinguish different behaviours, but the testing environment is quite different from the natural one. In fact, the CO_2 in the atmosphere and the cycles of temperature and humidity cannot be efficiently reproduced in a climatic chamber. When compared with accelerated tests, long term carbonation tests in natural environments decrease the uncertainty associated with the influence of fly ash and slag on concrete behaviour.

The results presented in this paper are only part of an ongoing LNEC research project on concrete durability, namely on the concrete properties related with reinforcement corrosion, in the framework of pre-standardization of concrete durability. The results will support proposals for *k*-values to be included in Portuguese standards.

The main objective of this study is to evaluate the efficiency of information usually available in the concrete industry, compressive strength and water/binder ratio, as proxy-criterion for carbonation. It is outside the scope of this work the research on the physical-chemical phenomena responsible for the observed trends.

2. Materials and methods

2.1. Materials

Thirty-three concrete mixtures were prepared using 11 different binders. The constituents of the binders were two Portland cements, according to EN 197-1 [3], CEM I 42,5R and CEM II/A-L 42,5R (supplied by CIMPOR), and two mineral additions, type II according to EN 206-1, fly ash and ground granulated blast furnace slag. Table 1 shows the composition of the binders, and the properties of each constituent. The binder is designated by a character (A-K) and, inside parentheses, there is information about the cement with similar composition in EN 197-1, using the notation of the cements presented in the standard. Table 2 indicates the physical characteristics of the binders.

The concrete mixtures were formulated with three different water/binder ratios (*w/b*): 0.65 ± 0.01; 0.45 ± 0.01; and 0.35 ± 0.01. The correspondent binder dosages were: 255 ± 4 kg/m^3, 340 ± 4 kg/m^3 and 435 ± 5 kg/m^3. The aggregates used were: natural siliceous sand (fineness modulus 1.76, density 2.61, absorption 0.2%) and limestone crushed aggregates in 3 different granular ranges (2/6.3, 4/12.5 and 12.5/25 mm), designated as crushed 0 (fineness modulus 4.99, density 2.66, absorption 2.3%), crushed 1 (fineness modulus 6.48, density 2.59, absorption 1.2%), and crushed 2 (fineness modulus 7.32, density 2.66, absorption 0.5%), respectively.

The selected values of water/binder ratio and binder dosage cover a range that contains the majority of concrete used in structures. The content of each aggregate was computed using the Faury method [27]. The use of different water content and variable materials leads to a large range of consistency values, as expected. However, it was established that results within the consistency classes S2 to S5 [4] would be acceptable.

With the 11 binders (A-K), 33 concrete mixtures were prepared (3 mixtures per binder). The concrete formulations are presented in Table 3. The mixtures were designated with the correspondent character (identifying the binder used), and with a number (1, 2, or 3) related to the *w/b*. As examples, mixture B1 is the concrete prepared with the binder B (Table 1) and *w/b* = 0.65 (number 1), and mixture C3 is the concrete prepared with the binder C and *w/b* = 0.35 (number 3). The superplasticizer was added in a sufficient amount to obtain a workable and easily mouldable concrete, in order to achieve an acceptable consistency with the selected values of water/binder ratio and binder dosage.