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Easy assessment of durability indicators for service life prediction or quality control of concretes with high volumes of supplementary cementitious materials

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ABSTRACT

This paper investigates whether durability indicators (DIs), more specifically transport properties, can be assessed by simple methods, e.g. direct experimental methods or indirect methods based on analytical formulas, for every type of concrete. First the results of electrical resistivity and *apparent* chloride diffusion coefficient obtained by direct measurement on a broad range of materials, particularly on high-volume supplementary cementitious materials (SCM) mixtures, are discussed. Then, various methods, in particular methods based on these last parameters, are compared for the assessment of *effective* chloride diffusion coefficient and "intrinsic" liquid water permeability, including for the latter a sophisticated method based on numerical inverse analysis. The good agreement observed between the various methods points out that simple methods can allow DI assessment with sufficient accuracy. Moreover, the available values of electrical resistivity, *effective*/*apparent* chloride diffusion coefficients and "intrinsic" liquid water permeability can be included in a database. Throughout the paper, the specificities of high-volume SCM mixtures are highlighted.

1. Introduction

In recent years, sustainable development has become a major concern, in particular in the construction field [1,2]. In this context, a global approach is needed, in order to meet technical, economical, environmental and societal requirements in an optimized way for the whole life cycle of a concrete structure [3,4]. The task of designers, engineers and infrastructure owners is therefore now more complex. In particular, they need to combine improved durability and environmentally friendly materials and structures. From a (concrete) material point of view, they are thus interested, on the one hand in relevant parameters, which can characterize durability, and on the other hand in the use of wastes, by-products or recycled materials, which are, at least at present time, regarded as zero-CO_2 emission constituents. As a consequence and in order to make this task easier, there is an increasing demand to include in current concrete or design standards (e.g. EN 206-1 [5]) the advanced concepts of durability and service life (SL) prediction, including performance-based and/or probabilistic approaches (see e.g. [6]), in particular with respect to the prevention of steel corrosion in reinforced concrete (RC) structures.

In this context, a general approach based on so-called *durability indicators* (DIs), which are key material properties with regard to durability (e.g. porosity, permeability or diffusion coefficient), has been developed [3,7–9]. Note that other similar concepts can be found in the literature [10–13]. A system of classes of "potential" durability with respect to reinforcement corrosion has been proposed for each DI. These five classes – very low (VL), low (L), medium (M), high (H) and very high (VH) "potential" durability – can be used for example for mixture comparison or quality control. The evaluation of the "potential" durability of a given RC will consist of comparing the values of the measured DIs to the threshold values of the associated classes. Another purpose of this approach is to design concrete mixtures capable of protecting structures against degradation for given target SL and environmental conditions, using performance-based criteria (specifications) related to the DIs. Furthermore, a multi-level modelling concept has been developed for SL prediction [8,14]. It can be applied to predict the SL of a new structure at the design stage or the "residual" lifetime of an existing and possibly deteriorated structure. Since concrete composition, which is often lacking for existing structures, is not needed, this approach can be very easily applied to them, in view of monitoring, diagnosis, maintenance and support to serviceability extension or repair decisions. Note that this is the same DI set, which is involved in the "potential" durability

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classes, in the specifications and as input data for the models of SL prediction [7,9,14,15].

Hence, it is important to:

- investigate whether DIs can be assessed by simple and rapid methods, in order to easily include them in a more general set of (sustainability) indicators and in harmonized standard methodologies,
- focus on "green" materials, which incorporate local aggregates or high volumes of supplementary cementitious materials (SCMs) such as fly ash (FA) or ground granulated blast furnace slag (GGBS).

With regard to the second item, it is well known that a complete characterization of SCMs can be very complex [16]. In addition, some properties of one FA for example cannot be generalized to all FAs, since the properties of a given type of SCM can be very variable (e.g. effects of the specific surface area, alkalinity and glass content). However, it is possible to benefit from the numerous researches carried out worldwide over a long period in particular in North America on these materials (see e.g. [17–20]). For example the effect of pozzolanic constituents on pore structure and thus on transport properties has been clearly described in the literature. It is not only a filler effect, but also the result of chemical reactions. The presence of fine particles can also induce acceleration of hydration reactions of the cement (potential nucleation sites for $Ca(OH)_2$ and C–S–H precipitation) and therefore induce earlier densification of the microstructure [21]. These effects are more significant with silica fume (SF), which has a 100-time smaller size than FA. $Ca(OH)_2$ crystals are consumed by the pozzolanic reaction, while finely divided C–S–H hydrate gel is formed, thus yielding a denser microstructure. In addition, when the FA content increases, fibril-type C–S–H are progressively replaced by foil-type C–S–H, which are more efficient to fill capillary pores [22]. Moreover, additional C–S–H (or other gel-type hydrates) form mainly far from the initial cement grains covered by pseudoform C–S–H [23]. These additional C–S–H thus create solid "islands", between partially reacted grains or pre-existing hydrate clusters, which increase the pore network tortuosity. However, this physical effect induced by chemical reactions will be efficient only once the pozzolanic reaction has significantly progressed, which means in the case of FA long after hydration (or pozzolanic reaction with SF [21]) has started (e.g. several months [3,24]). In addition, this effect depends on the initially available $Ca(OH)_2$ amount. Yet, $Ca(OH)_2$ is formed by portland cement hydration and can be affected by early-age drying or carbonation [3,24]. Further, SCMs are known to change the concentration and the mobility of the ions in the pore solution (e.g. as a result of modifications of the electrical double-layer at the solid–liquid interface [23,25–27]). For example, the presence of SF induces a significant decrease in alkali and hydroxyl ion concentrations in the pore solution [28,29], and according to [30] when 30% of the cement is replaced by FA the hydroxyl concentration is also reduced (see also [23]).

This paper will focus on the assessment of DIs, more specifically of the transport properties *effective* chloride diffusion coefficient and "intrinsic" liquid water permeability, by various methods, on a broad range of materials including mortars or concretes with FA, as well as CEM-III concretes. The range of SCM contents has been selected to be relevant from a practical point of view or to be that commonly used in concretes. The purpose is to validate the use of simple and rapid methods (e.g. direct experimental methods or indirect methods based on analytical formulas) and to check their applicability particularly to high-volume SCM mixtures. Comparison with a more theoretical and sophisticated method based on numerical inverse analysis will be carried out in the case of the "intrinsic" liquid water permeability. Another aim is to contribute to the constitution of a database, at least for the concretes most likely to be used in practice, for *apparent*/*effective* chloride diffusion coefficients, "intrinsic" liquid water permeability and electrical resistivity. This will provide in particular an estimate of the values expected for DIs and their corresponding classes, within the framework of the associated performance-based approach. This aspect is very important for future recommendations/standardisation on this topic. Moreover, the specificities of high-volume SCM mixtures will be pointed out.

2. Materials and experiments

2.1. Materials

A broad range of concretes, ranging from low-grade materials (average 28-day cylinder compressive strength, c.s., approx. 20 MPa) up to very-high-performance concretes (28-day c.s. > 90MPa), has been tested in lab conditions at $T = 21 \pm 1$ °C. Since it is difficult to report in the paper the detailed mix-compositions of all the concretes tested (30), only the mix-composition and the average 28-day cylinder c.s. of the concretes most involved in the discussion and displayed in figures are reported in Table 1. Various CEM I and CEM III (mixtures denoted "-III") were used and the water-to-binder ratio by mass (W/B) ranged from 0.23 to 0.84. The composition of cement #3, which is the CEM I used for the "M" concrete series (see Table 1) and for several other concretes, is given in [31]. With regard to CEM III/A, the GGBS content was 43% (LR59-1-III) or 62% (e.g. BO-III and LR77-3-III) by mass of binder. In order to complement the data, one CEM III/C concrete with 85% GGBS has been tested (denoted B30-III/C [32]). Air-entraining admixture (AEA), FA or SF were incorporated in some of the mixtures (denoted "-EA", "FA" or "SF", respectively). In AEA-mixtures, the air content of the fresh concrete ranged from 2% to 8%. The SF content ranged from 6% to 11% by mass of binder. In the FA-concretes, the FA content was 20% (M25FA, M25FA-EA, M50FA and M50FA-EA [33]), 30% (M30FA), 35% (CFA) or 39% (B50FA) by mass of binder. The same FA was used for the various materials (its composition is given in [31] and its specific surface area is 1.73 $m^2\ g^{-1}$), except for concretes CFA [7] and B50FA. Not only lab mixtures, but also mixtures commonly used in bridges in various locations in France and in neighbouring countries (which include in particular local aggregates) have been studied (e.g. mixtures denoted "LR", such as LR77-3-III which is considered as suitable for exposure class XA2, or LR59-2 for exposure class XS3, according to the European concrete standard EN 206-1 [5]).

Moreover, in order to understand more precisely the FA effect in mixtures of practical interest, mortars with various FA contents (0%, 10%, 20% and 30% by mass of binder = C + FA), denoted FA-0, FA-10, FA-20 and FA-30 respectively, and with limestone filler (60% by mass of binder = C + FA) mainly used to improve the properties of the fresh material, have also been studied. Note that possible synergistic effects between FA and limestone filler are likely to enhance mechanical strength and durability (e.g. acceleration of early hydration, see section 1, formation of carboaluminate by limestone, as well as later strength development and microstructure densification by FA pozzolanicity). The content of binder B = C + FA or of powder materials, as well as W/B, were the same for all the mortars ($B = 511\ kg\ m^{-3}$, W/powder = 0.28, and W/B = 0.45). The same ingredients (cement, FA, and sand) as for the "M" concrete series were used. The amount of admixtures was selected to comply with the proper rheological properties of high-fluidity mortars [34]. FA-30 is regarded in Japan, within the framework of underground disposal facilities (for radioactive wastes) with multicomplex artificial barriers, as a basic mortar