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Influence of active crack width control on the chloride penetration resistance and global warming potential of slabs made with fly ash + silica fume concrete

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HIGHLIGHTS

- Uncracked fly ash + silica fume concrete is very resistant to chloride penetration.
- Uncracked fly ash + silica fume concrete has a long service life (>100 years).
- The seemingly uncracked condition only exists for crack widths below 0.1 mm.
- Limiting the maximum crack width allowed requires more reinforcing steel in concrete slabs.
- More reinforcing steel results in a substantial increase of the slab's global warming potential.

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ABSTRACT

Service life predictions for concrete exposed to chloride-induced corrosion usually result from durability tests performed on uncracked concrete. Chloride migration coefficients for uncracked concrete should only be used if the structure can be considered as uncracked. The seemingly uncracked condition requires crack widths below 0.1 mm. The extra reinforcing steel to achieve this in concrete slabs, results in a 30–43% increase of the global warming potential. Fly ash + silica fume concrete may be preferred because of its low 28 day migration coefficient (3.4×10^{-12} m^2/s), its long service life (>100 years) and its autogenous healing ability.

1. Introduction

Recent sustainability studies show that concrete's global warming potential (GWP) is mainly governed by its binder composition, strength and service life [1,2]. With respect to the latter, researchers are advised to implement data from durability tests into models that simulate the main deterioration mechanism of the environment to estimate the concrete's life span. When looking at chloride-induced corrosion, the end of service life is often equaled with steel depassivation. For this failure event the model of Fib Bulletin 34 [3] based on Fick's second law, looks straightforward. Experimental chloride migration coefficients can be used to estimate when the critical chloride concentration will reach the rebars and end service life. However, this approach does not take into account the unavoidable presence of cracks in concrete due to the mechanical loads applied. True, a structure should always be designed as such that the maximum allowed crack width (0.3 mm for a submerged marine environment according to Eurocode 2 [6]) is not exceeded. Nevertheless, even 0.3 mm wide cracks in the tensile zone of a concrete slab – the case study of this paper – can easily extend beyond the location of the rebars and therefore offer direct pathways for chlorides. As a consequence, it makes sense to limit the maximum crack width allowed even more. Of course, this design approach will have its implications on the amount of reinforcing steel needed and therefore on the environmental impact of the slab.

In this research, we conducted chloride migration tests on concrete representative mortar samples containing a crack of 0.3, 0.2 and 0.1 mm in width. This was done to see whether crack width reduction could decrease the chloride penetration around the crack significantly. If not, it may be necessary to aim for very fine crack widths that can heal autogenously. Jaroenratanapirom and Sahamitmongkol reported a fast and complete natural crack closing for crack widths ⩽0.05 mm in Ordinary Portland cement (OPC) mortars, OPC + 10% silica fume (SF) mortars and OPC + 30% fly ash (FA) mortars [7]. Since the binder of the mortar compositions studied in this paper consisted of a combination of the same

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materials (50% OPC, 40% FA and 10% SF), it is certainly relevant to consider the 0.05 mm crack width criterion here as well. In a next research phase, concrete slabs made with traditional concrete and fly ash + silica fume concrete were designed according to the most suitable crack width criterion. Then, a full probabilistic service life prediction cf. Fib Bulletin 34 [3] was performed in the Comrel software [4], followed by a life cycle assessment (LCA) in the SimaPro software [5]. These calculations were done to see the effect of crack width limitation on the GWP of the studied concrete slabs.

2. Materials and methods

2.1. Concrete representative mortar mixes

Two concrete compositions were studied (Table 1). Mix T(0.45) has a cement content and water-to-cement (W/C) ratio of 340 kg/m^3 and 0.45, respectively. It is seen as the appropriate OPC reference concrete for exposure class XS2 [8]. The exposure class corresponds with an environment where steel reinforced concrete is permanently submerged in sea water. As a consequence, the concrete is exposed to chlorides and this can induce steel corrosion. The other concrete mix is characterized by the same total binder content (340 kg/m^3) as the OPC reference. Only now it consisted of three different cementitious materials: 50% Portland cement, 40% FA and 10% SF. The water-to-binder ratio (W/B) equaled 0.35 to ensure a strength class at least equal to the strength class of the OPC reference (C50/60). By doing so, composition SF(0.35) was characterized by a strength just one strength class higher (C55/67). The environmental consequences associated with difference in strength between the two mixtures under investigation were taken into account by choosing a strength related functional unit for LCA (see Section 2.7.1). Because of its high cement replacement level, cement related greenhouse gas emissions could be reduced significantly with the latter concrete mix. Therefore, it is seen as a potentially 'green' concrete type.

An equivalent mortar mix was designed for the two concrete compositions in accordance with the Concrete Equivalent Mortar (MBE) method [9]. Within a MBE mortar mix, the gravel mass fractions of the corresponding concrete mix – in this case $f_{\text{gravel 2/8}}$ and $f_{\text{gravel 8/16}}$ – are replaced with the amount of sand $\Delta f_{\text{sand 0/4}}$ that has the same specific surface. This sand fraction can be calculated by means of Eq. (1) in which $S_{\text{gravel 2/8}}$, $S_{\text{gravel 8/16}}$ and $S_{\text{sand 0/4}}$ represent the specific surface areas of the applied coarse aggregates and sand used in the studied concrete mixes. The ratios 2/8, 8/16 and 0/4 refer to the minimum and maximum aggregate sizes in mm. The first figure of the ratio represents the lower sieve size, while the second figure is the upper sieve size.

$$\Delta f_{\text{sand 0/4}} = \frac{f_{\text{gravel 2/8}} \cdot S_{\text{gravel 2/8}} + f_{\text{gravel 8/16}} \cdot S_{\text{gravel 8/16}}}{S_{\text{sand 0/4}}} \tag{1}$$

Table 1
Concrete compositions, specific surface areas and water absorption coefficients of the sand and aggregates and MBE mortar mix proportions.

Concrete composition	T(0.45)	SF(0.35)	
Sand 0/4 (kg/m^3)	778	791	
Gravel 2/8 (kg/m^3)	676	687	
Gravel 8/16 (kg/m^3)	447	454	
CEM I 52.5 N (kg/m^3)	340	170	
Fly ash (kg/m^3)	0	136	
Silica fume (kg/m^3)	0	34	
Water (kg/m^3)	153	119	
W/B	0.45	0.35	
FA/B (%)	0	40	
SF/B (%)	0	10	
Sand/aggregate properties	Sand 0/4	Gravel 2/8	Gravel 8/16
Specific surface area (m^2/kg)	4.889	0.398	0.194
Absorption coefficient	0.008	0.018	0.011
MBE composition	MBE T(0.45)	MBE SF(0.35)	
Sand 0/4 (kg/m^3)	850.8	864.9	
CEM I 52.5 N (kg/m^3)	340	170	
Fly ash (kg/m^3)	0	136	
Silica fume (kg/m^3)	0	34	
Water (kg/m^3)	136.5	102.2	
Superplasticizer (ml/kg B)	3.0	14.0	
W/B	0.40	0.30	
FA/B (%)	0	40	
SF/B (%)	0	10	
Strength class	C50/60	C55/67	

Replacing the gravel 2/8 and gravel 8/16 by the much finer sand 0/4 obviously affects the water demand of the mortar. As a result, its required water amount needs to be adjusted in accordance with the difference in water absorption between the gravels and the sand. This can be done with Eq. (2):

$$\Delta f_{\text{water}} = -f_{\text{gravel 2/8}} \cdot A_{\text{gravel 2/8}} - f_{\text{gravel 8/16}} \cdot A_{\text{gravel 8/16}} + \Delta f_{\text{sand 0/4}} \cdot A_{\text{sand 0/4}} \tag{2}$$

with $A_{\text{gravel 2/8}}$, $A_{\text{gravel 8/16}}$ and $A_{\text{sand 0/4}}$ the water absorption coefficients of the coarse aggregates and the sand. The measured water absorption coefficient and the specific surface areas are shown in Table 1. The resulting two MBE mortar compositions can be found there as well. By following this method the workability of the MBE mortars should be identical to the workability of the corresponding concrete mixtures. The use of MBE mortar instead of concrete normally reduces the material cost and effort [9].

2.2. Manufacture of MBE mortar with an artificial crack

15 Cylindrical specimens (diameter: 110 mm, height: 53 mm) were made for each of the two MBE mortar mixes in PVC tube moulds: 3 samples without crack plus 3 × 4 samples containing an artificial crack as a result of putting thin metal plates with a nominal thickness of 0.1, 0.2 and 0.3 mm at a depth of 15 mm in the cylindrical moulds just before casting. Fig. 1a shows a schematic of the mould setup with the metal plate fixed at the desired crack depth cf. Mu [10].

Note that artificial cracks created by means of thin metal plates are different from more naturally induced cracks induced by mechanical loading. Both techniques are in use and have their advantages and disadvantages. By means of thin metal plates it is indeed not possible to reproduce a concrete crack which is realistic in all its properies. However, it is seen as a very convenient way to study the effect of one crack property in particular, being the crack width (which is the main crack property considered in crack controlled slab design). The reproducibility of cracks created as such is high. On the other hand, displacement steered mechanical loading to create more natural cracks does not always guarantee the same predefined crack width. Moreover, with the latter method it is difficult to ensure that the crack does not go all the way through the specimen. This condition is required to be able to conduct the chloride migration test. With thin metal plates fixed at a certain height in the sample mould the crack depth is rather easy to control. For this case study we therefore adopted the thin metal plate technique. Though, one should remain aware of the differences between these artificial cracks and naturally induced cracks. The walls of the voids created with thin metal plates should be considered as cast surfaces. These surfaces are subject to the so-called wall effect which means that the more fine (usually cementitious) materials will be present in the vicinity of the crack walls. Its unhydrated fraction can still react later on and initiate autogenous healing. However, this may be the only effect that favors this mechanism for the artificial cracks. It is also unknown if the fraction of unhydrated materials near the crack walls is sufficient to induce full closure of the crack. For naturally induced cracks on the other hand, there can be several beneficial effects. There, the crack width can seriously vary length of a crack. The crack tortuosity and crack wall roughness will evidently be higher [11]. Moreover, cracks will contain more concrete particles broken from the surface due to cracking [12]. All these conditions contribute to a partial blocking of the crack followed by the autogenous healing phenomenon. These favorable conditions are not present in the artifical cracks. Given these differences, a more detailed comparison between artifically and naturally cracked specimens in relation to their autogenous healing capacity would certainly be relevant. This investigation is for the moment still ongoing.

After casting, the specimens were kept at a constant temperature and relative humidity (RH) of 20 °C and 95%, respectively. The metal plates were carefully removed from the samples after approximately 12 h whereupon the cylinders were demoulded. From then on, they were stored again under the same conditions until the age of 28 days.

2.3. Microscopic crack width measurements

After 28 days, the obtained crack widths were measured after mechanical flattening of the cylinders' troweled surfaces and on the saw cut perpendicular to the crack of the fourth cylinder of each cracked series. The latter samples were only used for the evaluation of the cross-sectional crack width and not exposed to chlorides. All crack width measurements were done on micrographs taken with a Leica S8 APO stereo microscope (SM) (magnification: 20×) while using the LAS 3.7 software.

After the cross-sectional crack width evaluation with the stereo microscope, the cracked area of the non-exposed MBE mortar SF(0.35) with the 0.1 mm wide crack was also subjected to scanning electron microscope (SEM) analysis to study the partial closing of the crack more in detail (see Section 3.1). By then, the sample was 196 days old. Three 20 × 20 × 10 mm^3 prisms containing a cross-section of the crack, were cut from one cylinder halve and then put in an ultrasonic bath with isopropanol to remove all loose particles inside the crack. Afterwards, the samples were vacuum dried for one week and gold coated by means of a Baltec SCD030 Sputter Coater before being examined in a FEI QUANTA 200F SEM at an accelerating voltage of 20 kV. Secondary electron imaging was used for electron micrography.