High filler concrete using fly ash - Chloride penetration and microstructure

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Most high filler concrete studies are based on relatively high contents of powder (cement + filler) (> 400 kg m^{-3}). This paper aims to increase the total fly ash content relative to the clinker content, while simultaneously minimizing the total powder content in the concrete to values lower than 300 kg m^{-3}. The motivation for decreasing the total powder content using fly ash as a cement replacement is based on the fact that concrete structures often have an 'overstrength' related to excess cement. Consequently, there is potential for using lower amounts of clinker and replacing it by filler, which can reduce the amount of primary raw materials used and CO_2 related to clinker production. However, the question arises if sufficient durability of this 'high filler' concrete is achieved. In this paper chloride penetration resistance is measured by rapid chloride migration and diffusion tests on both laboratory mixes and samples from pilot projects. Also, electrical resistivity and polarization-and-fluorescence microscopy (PFM) are used to evaluate the development of the microstructure in time. The results show possibilities and limitations of high filler concrete in achieving long service life.

1 Introduction

In most of the structural applications, there is an overstrength of concrete, i.e., the concrete is stronger (e.g. C28/32-C35/45) than what it was designed for and what is required to carry out its structural function. (e.g. C12/12-C20/25) [Fennis 2006, 2011]. Often, this overstrength is related to an excess amount of clinker. Lowering the amount of excess clinker will have a positive ecological impact in terms of the use of raw materials and the CO_2 output, of any concrete. This may be achieved by using higher filler contents (fly ash, limestone mill) than conventionally used in Portland fly ash cement (CEM II/B-V) or mixtures of ordinary Portland cement (CEM I) with typically 25-30% fly ash. Because fly ash partially can react, but often acts as filler, concretes containing a high relative amount of fly ash are called 'high filler' concretes. Most 'high filler' concrete studies are based on relatively high contents of powder (cement + filler) (> 400 kg m^{-3}) [e.g., Lammertijn & de Belie 2008, Baert et al. 2008] and even higher powder contents in self-compacting concretes (SCC) (> 500 kg m^{-3}) [e.g., Dinaker et al., 2008]. This paper aims to increase the total fly ash content relative to the clinker content, while simultaneously minimizing the total powder content in the concrete to values lower than 300 kg m^{-3}. The potential of decreasing the total powder content using fly ash as a clinker replacement is based on the fact that concrete applications do not always need the high strengths as in SCC concretes. Moreover, as fly ash can hydrate, it may partly fulfill the role of the clinker that it has replaced. However, the question arises how sufficient durability of HiFi concrete required for a specific application is to be achieved. Optimizing particle packing plays an important role in this aspect [Fennis et al. 2006, Fennis et al. 2008, Fennis 2011, Fennis & Walraven, 2012]. In this paper chloride penetration resistance by rapid chloride migration (RCM) [NT Build 492] and accelerated (immersion) diffusion tests [NT Build 443], electrical resistivity and microstructure using polarization-and-fluorescence microscopy (PFM) are reported on both laboratory mixes and samples from pilot projects.

2 Concrete mixtures

Laboratory concretes have been cast with 250 and 300 kg m^{-3} of total powder content (cement + fly ash). Cements used were ordinary Portland cement (CEM I 32.5 R) and blast furnace slag cement (CEM III/B 42.5 N LH HS) according to EN 197. The water/powder ratio (w/b) was fixed around 0.54 while maintaining workability using a superplasticizer (SP Cugla Cr.pl. SL-01). Fly ash percentages to total powder were 30, 50 and 70% by weight. Mix details are given in Table 1. The 250 kg m^{-3} total powder concrete series was cured at 20°C and 96% RH or at 20°C and 65% RH. The 300 kg m^{-3} total powder series was cured at three different conditions: (1) in a fog room for 7 days and then at 20°C and 96 %RH; (2) in a fog room for 7 days and then at 20°C and 65 %RH; (3) submerged in a saturated $Ca(OH)_2$ solution. Laboratory concretes are compared with cores obtained from two pilot projects: an industrial floor (IF) cast in situ using Portland fly ash cement (CEM II/B-V 32.5 R) with additional fly ash; and a cycling track (CT) cast in situ with Ordinary Portland cement (CEM I 32.5 R) with fly ash (Table 2). Both had a total powder content of about 350 kg per m³ with 50% fly ash. These concretes were 525 and 467 days old, respectively when sampled.

3 Test methods

3.1 Chloride penetration resistance

Accelerated chloride diffusion was performed by immersing concrete sample to a 3.5 % NaCl solution. The test is carried out according to CUR Recommendation 48, similar to NT Build 443. Normally, the test starts at an age of 90 days and lasts 35 days, after which slices are

Table 1: Concrete mixtures for the experiments

Concrete mix	P30	P50	P70	B30	B50	B70	300 P50	300 B50
Cement (kg m^{-3})								
CEM I 32.5 R	175	125	75				150	
CEM III/B 42.5 N LH HS				175	125	75		150
Fly ash (kg m^{-3})	75	125	175	75	125	175	150	150
Aggregate (kg m^{-3})								
River sand 0 – 4 mm	749	744	738	745	741	736	699	696
River gravel 4 -16 mm	1269	1261	2375	1264	1256	1248	1184	1181
Water (kg m^{-3})	133	134	135	134	134	135	161	161
Plasticizer (%)	2.00	0.85	0.85	1.30	1.30	0.85	1.0	0.6
Calculated density [1] (kg m^{-3})	2406	2391	2375	2397	2384	2371	2347	2340
Total powder (kg m^{-3})	250	250	250	250	250	250	300	300
Fly ash / total powder	0.3	0.5	0.7	0.3	0.5	0.7	0.5	0.5
Water / cement	0.78	1.09	1.84	0.78	1.09	1.81	1.08	1.08
Water / powder	0.53	0.54	0.54	0.54	0.54	0.54	0.54	0.54

[1] with 1% air

Table 2: Overview of the field concrete mixtures

Concrete mix		IF	CT
Cement			
CEM I 32.5 R	kg m^{-3}		175
CEM II/B-V 32.5 R [1]	kg m^{-3}	240	
Fly ash	kg m^{-3}	110	175
Aggregate			
River sand 0 – 4 mm	kg m^{-3}	880	
River gravel 4 -16 mm	kg m^{-3}	975	
Water	kg m^{-3}	123	
Plasticizer	%	1.38	
Total powder	kg m^{-3}	350	350
Fly ash / total powder		0.5	0.5
Water / powder		0.51	0.46

[1] with c. 27% fly ash

ground off and the chloride profile is determined. In this study, testing started at 28 days age. Chloride exposure was carried out for 28, 56 and 337 days, obtaining concrete ages at the end of the test of 56, 90 and 365 days. Subsequently chloride penetration profiles were determined by first indicatively determining the penetration depth by spraying with $AgNO_3$-solution and subsequently grinding 12 equal slices down to the penetration front. The chloride content of the dust was determined by dissolution in hot nitric acid and subsequent titration according to Volhard's method. From the profiles obtained, the surface chloride content (C_{surf}) and the diffusion coefficient (D) were determined by fitting the error function solution to Fick's second law of diffusion using least square methods. It should be realised that D's obtained in this way represent a time average over the exposure period, which may be called apparent diffusion coefficients, D_{app}.

Rapid Chloride Migration (RCM) was tested according to NT BUILD 492 by applying a potential difference of typically 30 V across a 50 mm slice of concrete for 24 hours on samples previously saturated with calcium hydroxide under vacuum. After the test, $AgNO_3$ is sprayed on a split surface, indicating the penetration front. The Rapid Chloride Migration coefficient D_{RCM} is calculated from the mean chloride penetration depth [Duracrete 2000]. Specimens were tested at ages of 28, 56, 90 and 365 days. In some cases, the chloride had penetrated the complete sample; taking 50 mm as penetration depth was used to produce a lower limit value. The RCM-coefficient can be applied in service life calculations of concrete structures with respect to initiation of chloride induced corrosion [Duracrete 2000].

*3.2 **Electrical resistivity***

Two electrode method (TEM) resistivity: The electrical resistivity of concrete is approximately inversely proportional to the chloride diffusion coefficient [Polder & Peelen 2002]; it may also be taken as a measure for the density of the microstructure. In the TEM test, a concrete specimen is placed between two steel plates. A piece of wet cloth is placed between the concrete and each steel plate to ensure good electrolytic connection and a weight is placed on top of the upper metal plate. The resistance of the concrete was determined using 120 Hz alternating current (AC) by imposing a small voltage over the steel plates and measuring the current. From the measured resistance and the dimensions of the specimen the resistivity can be calculated [Polder 2000], which is called ρ_{TEM}. TEM tests were carried out on 150 mm cubes or on 100 mm diameter by 50 mm discs.

RCM resistivity: The electrical resistance between anode and cathode in the RCM test cell was measured on 100 mm diameter discs of 50 mm thickness before and after RCM testing, using 120 Hz AC. The resistivity before the test was calculated [Polder 2000], which is called ρ_{RCM}.

3.3 *Microstructure*

Microstructure was assessed by polarization-and-fluorescence microscopy (PFM) at different ages. Polarising and fluorescent microscopy is a two-fold integrated method, which allows the mineralogy and the internal structure of hardened cement-based materials to be characterised. In the present study, thin sections were prepared by first sawing small prisms from each of the samples. Each prism measured about 50 mm × 30 mm, with a thickness of about 15 mm. The sawn specimens were then dried in a stove at 40°C and subsequently impregnated under vacuum at about 40°C with an epoxy resin containing a fluorescent dye. After hardening of the resin, a thin section with a surface area of about 50 mm × 30 mm and a thickness of about 25 μm was prepared from each prism by grinding and polishing. Impregnation of the specimens with a fluorescent resin makes it possible to study thin sections by means of both transmitted-light and fluorescent-light microscopy. The fluorescent light intensity gives an indication of the relative amount of capillary porosity.

4 Results and discussion

4.1 *Chloride penetration resistance*

The results obtained in ponding tests for up to ages of 56, 90 and 365 days are shown in Table 3. For all mixes, apparent diffusion coefficients have decreased in time, which means that all mixes have become denser. Both 30% fly ash mixes P30 and B30 reached low values during testing up to one year age. B70 and to a lesser extent P70 have rather high values at one year age. Apparently this combination of cementitious materials does not contain sufficient lime to cause hydration of major parts of the fly ash. Presence of un-reacted particles relate to a poorly developed microstructure and would support the observation of increased chloride diffusivity for such concretes.

*4.2 **RCM tests***

Typical results for Portland cement-fly ash mixes are shown in Figure 1. Open symbols indicate samples where the chloride had penetrated the complete sample, in which case values are lower limits. Results for all mixes are reported in Table 4.

Table 3: Summarized chloride surface contents and apparent diffusion coefficients from ponding test (mean and standard deviations) started at 28 day age

	C_{surf} (% by cement)		D_{app} (m^2/s)	
Concrete mix-age (day)	**mean**	**stdev**	**mean**	**stdev**
P30-56 *	2.0	0.2	4.57E-11	3.09E-11
B30-56	3.2	0.6	7.84E-12	2.31E-12
P70-56	-	-	-	-
B70-56	2.0	0.1	6.55E-11	9.18E-12
P30-90	2.7	0.6	1.21E-11	1.27E-12
B30-90	2.6	0.2	4.23E-12	5.42E-13
P70-90	2.9	0.3	5.24E-11	2.40E-12
B70-90	2.5	0.2	5.37E-11	1.03E-11
P30-365	2.9	0.5	3.53E-12	2.36E-13
B30-365	2.2	0.2	1.40E-12	1.12E-13
P70-365	2.1	0.7	1.10E-11	4.58E-12
B70-365	1.8	0.2	3.40E-11	8.13E-12

** Concrete age at end of test*
- No reliable results

*Table 4: RCM coefficients for mixes with 250 kg/m³ powder (unit * 10^{-12} m²/s)*

age	P30	P50	P70	B30	B50	B70
28	24.0	63.0	200	6.8	13.0	63.0
57	11.0	31.0	160	3.8	5.1	28.0
91	8.3	15.8	49	3.0	3.3	4.8
410	1.7	2.0	2.8	1.0	0.8	4.0

Figure 1 clearly shows that the RCM-coefficient decreases significantly with the age of the concrete, especially for mixtures with higher fly-ash contents. The hydration of fly-ash starts to occur typically after 28 days and will contribute to the densification of the microstructure and the consequent decrease in RCM-coefficient [Polder & Peelen 2002]. This explains the significant drop in RCM coefficient after 28 days. As shown in Table 4, blast furnace slag – fly ash mixes showed a similar overall pattern, but with significantly lower values. This result was expected because blast furnace slag cement normally results in a denser microstructure with lower RCM coefficients. For both cements, the RCM coefficients for 70% replacement are higher than for 50% replacement. This suggests that not all fly ash takes part in the hydration process, such that in the 70% replacement mix, there is relatively more fly ash acting as filler than in the 50% replacement mix. This apparently results in a more open microstructure (see below) with higher RCM values in the 70% replacement mix than in the 50% replacement mix. Three samples from the cycling track showed a mean RCM value of 1.9 * 10^{-12} m^2/s at an age of 470 days, which is comparable to most values of the laboratory mixes at 410 days.

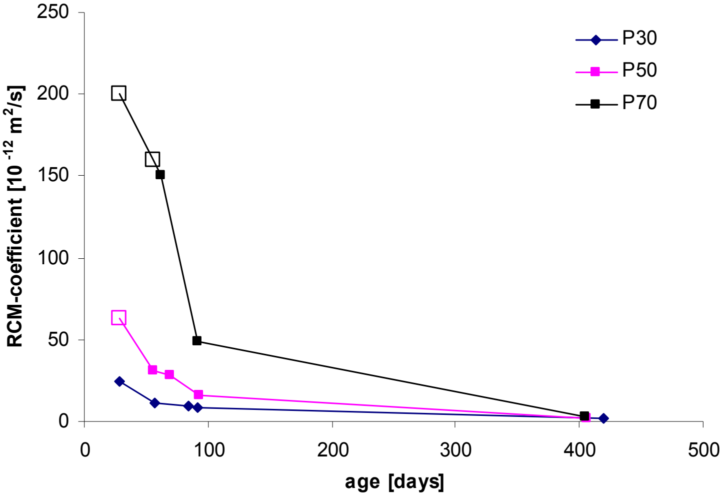


Figure 1: RCM coefficients of Portland mixtures. Open symbols are suspect results and can be considered as lower limit boundaries

4.3 *Resistivity*

The resistivity is represented in Figure 2, showing that the resistivity increases through time. This is normal and is caused by on-going hydration. However, hydration of fly ash only starts to contribute well after 28 days of age [Polder et al. 2002]. So, in particular for Portland cement – fly ash mixtures the early increase is due to Portland clinker hydration. Later increase is mainly due to hydration of fly ash, which is supported by stronger resistivity increase after 90 days for mixes with 50 and 70% fly ash than with 30%. The resistivity of high filler concrete samples made with CEM III is about 5 times higher than these made with CEM I. This result was expected because concrete with blast furnace slag cement normally results in higher resistivity due to the denser pore structure. Resistivity for mixes with 50% replacement is higher than for 30% and 70%. This suggests that increasing the fly ash content to 50% results in more hydration and a denser microstructure with higher resistivity than for a 30% replacement. However, increasing the fly ash content above 50% does not contribute to the hydration process; any excess fly ash may only act as a filler. This is comparable to the observation from RCM test.

Table 5 reports resistivity values for the second group of mixes (300 kg powder per m^3, 50% fly ash) at the two ages and as a function of curing conditions. These results are from TEM on specimens (cubes and discs) as received from their curing conditions; and on discs after vacuum saturation measured in the RCM cell. The *as cured* cubes show lower resistivity values for immersed cured samples than for those stored in 96% or 65% RH. For vacuum saturated samples, those cured under water have higher resistivity values. However, the resistivity after vacuum saturation of concrete cured in lower humidity, is lower than that of concrete cured under water. This means that the drier climates have hindered hydration and have left a more open pore structure. This effect is more pronounced at an age of 90 days. Three samples from the cycling track showed a mean resistivity after vacuum saturation of 460 Ωm at an age of 467 days.

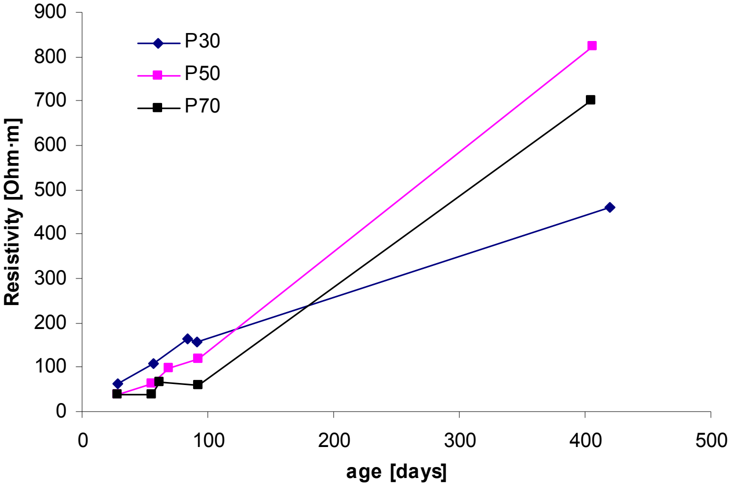


Figure 2: Resistivity of Portland mixtures measured before RCM test, ρ_{RCM}

Table 5: Resistivity (Ωm) for laboratory series with 300 kg powder per m³

Mix	300P50						300B50					
Curing	imm.*		20/96		20/65		imm.*		20/96		20/65	
Age (day)	28	90	28	90	28	90	28	90	28	90	28	90
Average TEM, cube	58	183	93	380	203	285	232	679	336	695	572	3470
Average TEM, disk	59	196	76	234	125	328	256	787	236	519	298	745
RCM	52	151	71	73	49	80	242	373	143	181	113	172

* Immersed in saturated lime solution

4.4 *Microstructure*

4.4.1 Microstructure of mixtures with 250 kg m⁻³ powder

At 28 days, the microstructure of all laboratory mixtures with 250 kg m^{-3} cement + fly ash show common characteristics, regardless the fly ash content (30/50/70 %). Hydration of the clinker and/or slag is low in mixtures with 30 and 50 % fly ash to very low in mixtures with 70 % fly ash, and most fly ash has not reacted (Figure 3). This results in a high capillary porosity as seen in mixtures with 30 and 50 % fly ash to very high in mixtures with 70 % fly ash. Mixtures with higher fly ash content (some of the 50 % fly ash, most of the 70 % fly ash) suffered from poor compaction, with a continuous cement paste being (almost) absent (Figure 3).

At 182 days, laboratory mixtures with 30 and 50 % fly ash show a homogeneous, well developed binder matrix. Capillary porosity is slightly lower than at 28 days and hydration is moderate (but difficult to assess in samples with low clinker content). In the mixtures with 50 % fly ash, the amount of free portlandite is relatively low in mixtures with blast furnace slag cement, but high, and remarkably coarse in the mix with ordinary Portland cement. Compared to the 28 day samples, part of the portlandite seems to have been consumed, indicating reaction of the fly ash, also in mixtures with 70 % fly ash.

4.4.2 Microstructure of mixtures with 300 kg m⁻³ powder

At 28 days, laboratory mixtures with 300 kg m^{-3} CEM I + fly ash (50 %) show moderate to good compaction, while for CEM III mixes, poor compaction occurred. For mixtures made with CEM I and fly ash, the degree of hydration of the clinker is moderate in the samples cured under water, while for the samples cured differently, it is low. In all mixtures, a large amount of fly ash had not yet reacted; as a result, the capillary porosity was relatively high in all samples. A moderate degree of fly ash reaction was observed only in the CEM I plus fly ash sample cured at 20 °C, 65 %RH. For the mixtures made with CEM III and fly ash, the degree of hydration of clinker and slag particles is moderate (cured immersed in water) to low (cured at 65 and 96 %RH); the degree of reaction of fly ash is low. As a result, the capillary porosity is quite high in all samples. No significant differences were observed between the surface zones of the differently cured mixtures. Carbonation was observed in all samples, for the CEM I mixes it was 3-14 mm and for the blast furnace slag mixes 3-5 mm depending on the curing regime. Few micro cracks were observed on the cement paste samples irrespective of the curing condition.

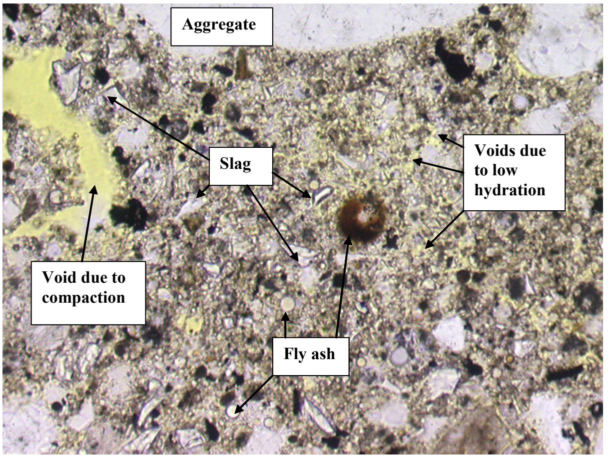
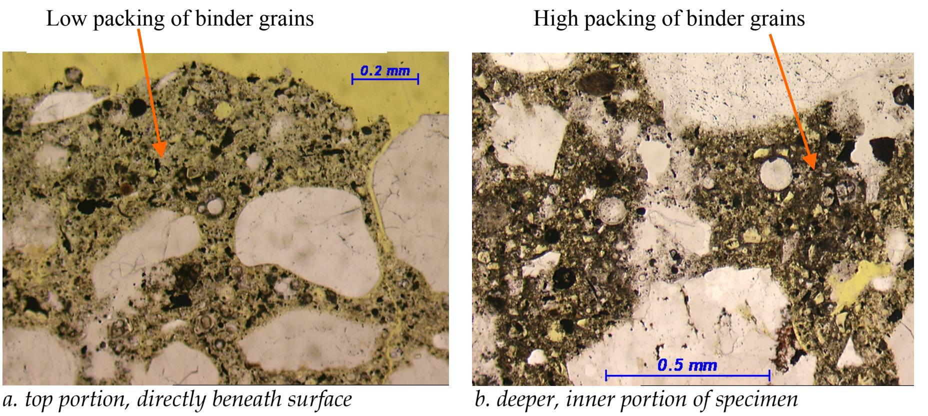


Figure 3: Microphotograph of detail of the matrix in mix B50 20/65 at 28 days. Note the low hydration of binder particles and the resulting open matrix, reflected by minute voids (yellow). View 0.7 x 0.45 mm, plane polarized light.
Note: this paper is printed in greyscale; colour plots are available in the online version.

Long term development is illustrated by the mixture with 50 % CEM I and 50 % fly ash cured immersed in water for 90 days. This sample showed a generally well developed microstructure. The main feature observed and discussed here is the variation in microstructure with depth. The sample shows local carbonation up to a depth of about 30 mm. In this top zone, few clinker and fly ash particles are observed and the cement matrix is poorly developed and not cohesive. This caused the capillary porosity to be relatively high compared to the inner portion of the sample (Figure 4). In the inner part of the sample, the amount of clinker and fly ash grains per unit area in the bulk matrix is higher than in the top portion (Figure 4). The increased concentration of grains in the interior appears to have created a more reactive environment for fly ash: higher concentration of alkalis and $Ca(OH)_2$, less or no carbonation and relatively high moisture content, resulting in a higher degree of hydration of the clinker and consumption of the fly ash. The matrix at this location is denser and the capillary porosity is lower than in the top portion (Figure 4). In general, bonding of the cement matrix to the aggregate particles is good, but locally, due to a non-optimum compaction of the mix, areas exist where the bonding is not optimum. Matrix contains few or no microcracks.



a. top portion, directly beneath surface　　*b. deeper, inner portion of specimen*

Figure 4: PFM micrograph of sample P50, 90 days cured in water, showing the characteristics of the cement matrix in the top portion, directly beneath the surface and that in the deeper, inner portion. Plane polarised light.

Note: This figure printed in greyscale; colour plots are available in the online version.

4.4.3 Microstructure of field concretes

Two field concretes have been studied, both with 350 kg m^{-3} cement + fly ash (50%), one using ordinary Portland cement (mixture CT in Table 2) and one using portland-fly ash cement, CEM II/B-V with additional fly ash (mixture IF in Table 2). The CT and IF mixtures have been sampled at ages of 525 and 467 days, respectively. Both mixtures show similar microstructures; an example is shown for CT concrete in Figure 5. The concrete is well compacted, has a generally homogeneous distribution of aggregate, and shows good adhesion between the binder matrix and the aggregate. The amount of air voids is less than 1 vol.%. The microstructure of concrete between the exposed surface and the deeper regions is comparable, except for the amount of micro bleeding and carbonation. Some small domains without (fine) aggregate are present, indicating minor separation. The amount of air voids is < 1 vol.%. The clinker shows good hydration, but a major part of the fly ash did not react and acts as a filler. The effective water/binder ratio is quite variable, with microbleeding channels of high w/b intersecting domains of a low w/b. There are only few microcracks. Carbonation along the exposed surface is less than 1 mm in the CT mix and 2-2.5 mm in the IF mixture.

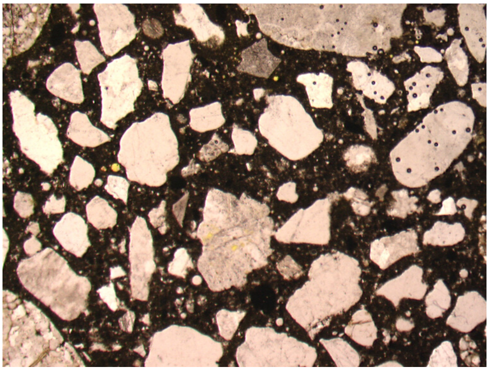


Figure 5: Micrographs of the microstructure in 'high filler' concrete from the CT field sample. View 5.4 X 3.5 mm, Plane polarized light

Note: This figure is printed in greyscale; colour plots are available in the online version.

4.5 Overview of results and discussion

Hydration of binder components at 28 days, whether clinker, fly ash or blast furnace slag, is generally low in all laboratory specimens, even in the mixtures with higher cement fractions (P30 20/96, B30 20/96, P30 20/65 and B30 20/65), that are comparable to regular CEM II/B-V. This is especially remarkable as far as the Portland clinker is concerned. The reaction of pozzolanic materials such as fly ash is slow and free calcium hydroxide (portlandite) is still available for reaction of the fly ash. At 28 days, the low hydration results in a rather porous binder matrix, which affects the durability negatively. At 182 days, hydration is moderate in all mixtures and capillary porosity is has decreased. Here, the well compacted mixtures show a well-developed microstructure with homogeneous capillary porosity. However, the matrix is still more open than in common concretes, due the low total powder content, whereby the open character (capillary porosity) of the matrix increases with the fly ash percentage. Field samples have higher total binder contents than the laboratory samples, which resulted in a (potentially) better developed, less porous microstructure (at the scale of capillary pores). As might be expected, a major part of the fly ash in the field samples acts as filler only and in all mixtures, free portlandite is still present for reaction at 182 days. However, even in the 70 % fly ash mixtures, some portlandite has evidently been consumed at 182 days. Any effect of different curing of the laboratory samples (20/96 vs. 20/65) could not be discerned because other effects, notably low hydration, are probably dominant.

The improved microstructural development of the cement matrix in the inner parts of the specimens seems to arise from a combination of improved packing of clinker and fly ash particles during mixing, placing and compaction and the availability of sufficient moisture in these parts of the specimen. An increased packing is quite favourable for promoting the pozzolanic reaction of the fly ash particles because the increased cement hydration tends to generate high pH (high alkali content of the pore solution) and a high concentration of portlandite, $Ca(OH)_2$, as buffer in the matrix. All these activities, in the absence of carbonation (as is the case in the inner parts of the specimens), may be the cause of the development of a more cohesive, denser and more continuous cement matrix system than the top, outermost parts of the specimens.

In contrast to part of the PFM observations, the durability tests showed a more promising perspective for using low powder contents. This might be related to the fact that these tests measure a 3D bulk property, while thin sections for PFM merely sample a local 2D area. With regard to chloride penetration induced corrosion, the chloride surface contents found in the ponding test were similar to those for normal concrete. At early ages, the RCM chloride diffusion coefficients were either normal for the 30% fly ash mixes or higher than normal for the 50-70% fly ash mixes. The latter become normal at an age of about one year. Higher diffusion coefficients at early age have probably been caused by low levels of fly ash reaction despite the presence of supposedly sufficient calcium hydroxide in the CEM I plus fly ash mixes. Portland mixes with 30, 50 and 70% fly ash (250 kg total binder per m^3) at 410 days have normal RCM diffusion values, which are similar to those of samples from the cycle track at about 470 days (at 50% fly ash and 350 kg binder per m^3). Modern service life calculation models (e.g. DuraCrete) could in principle be applied to these mixes on the basis of input parameters determined with the usual compliance tests (RCM). A side remark outside the present study concerns the critical chloride content for corrosion initiation. For fly ash binders in general, there is more uncertainty about the critical chloride content than for pure Portland cement. The effect of lower binder contents increases this uncertainty. For application in reinforced concrete, this issue requires further study. Both chloride diffusion and resistivity testing and also PFM observations suggest that 50% of fly ash may be an optimum value for a dense pore structure, provided that the concrete receives good, that is wet and long, curing. For higher fly ash contents than 50%, too much fly ash remains as filler and there is not enough binder to create a dense microstructure, resulting in low resistivity values, up to 3 months. At about one year the low binder content is no longer an obstacle to obtain a high electrical density.

5 Conclusions

In this study, the durability has been tested for concretes made with low total powder (cement + fly ash) contents (<350 kg m^{-3}). The powder consists of CEM I or CEM III with high amounts of fly ash (30-70%). At young ages, the experiments with low powder content (250-300 kg m^{-3}) locally showed poor compaction and contained areas of low hydration. However, after longer curing (preferably under water), the samples with 50% fly ash started to show reasonably well developed microstructures as reflected by both microscopy (PFM) and electrical resistivity (TEM), as well as chloride diffusion coefficients (RCM). In the case of the field concretes with slightly higher total powder contents (350 kg m^{-3}) the quality of the concrete is very good. The results indicate that high fly ash concrete mixes with low powder content have the potential to be applied where high strengths are not needed but further research is required in order to study the best packing density, optimum clinker replacement and hydration rate of the fly ash [Fennis 2011].

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