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Performance-based assessment of concrete resistance to leaching

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ABSTRACT

Leaching of calcium and hydrates from concrete is likely to occur when concrete structures are immersed in pure or poorly mineralised water and acid environments. A performance-based test may be used to design concrete for such exposures, provided that it is representative, sensitive, and repeatable. In the experimental study a leaching test was performed on six vibrated concrete mixtures and five self-compacting concrete mixtures, varying aggregate type, water/binder ratio and mineral admixtures, such as fly ash, ground granulated blast-furnace slag and limestone filler. Two indicators have been used to assess damaged depth, taking limestone aggregates into account. Fly ash (20–30% of binder) and slag (60%) significantly improved behaviour of concrete, whereas leaching rate increased with an increase in limestone filler content.

1. Introduction

Leaching takes place whenever concrete is immersed in water. Degradation consists in dissolution of calcium and hydroxide ions out of the matrix. It may be coupled with ingress of aggressive ions such as chlorides, sulphates, magnesium [1]. Leaching is accelerated in poorly mineralised and acidic waters [2]. It results in increased porosity and transport properties of surface concrete [3]. So it has to be taken into account to design concrete structures in contact with ground water such as nuclear waste containers [4], and precast concrete products such as water tanks and sewage pipes.

Standards on concrete specify cement types and threshold values for the composition of concrete in such exposures. But technical issues, sustainable development, and cost effectiveness often require use of innovative concrete mixtures, such as self-compacting concrete (SCC) and concrete mixtures with high percentages of replacement of clinker combined with high range water-reducing admixtures (WRA). A durability criterion may be reached by concrete mixtures that do not comply with prescriptive requirements, as durability also depends on consolidation, curing, and type of cementitious material, and not only on water-cementitious material ratio [5,6]. Conversely, concrete mixtures that comply with the same set of prescriptive requirements are likely to show significantly variable performances when exposed to given environmental conditions [7]. As a consequence, only performance-based specifications can ensure reliable design of concrete mixtures for a given exposure. The Equivalent Performance concept has been defined in the new European standard EN 206-1 [8]. It makes it possible to compare an innovative concrete mixture with a reference concrete mixture which complies with prescriptive requirements on cement content, water/cement ratio and cement type. Comparison may be made using appropriate performance-based tests corresponding to the exposure, for instance leaching and acid attack. The lack of adequate performance-related durability tests is one of the main factors that have delayed the move from prescriptive to performance-based specifications. The performance-based tests must be representative, sensitive, and repeatable. The test is assumed to be representative if it involves the same mechanism of degradation as in natural environment. This can be also investigated comparing natural and controlled degradation [9].

The leaching test proposed in this paper consists in controlling pH at constant value of 5.0 using nitric acid. So the only degradation is dissolution due to acid solution, with no ingress of other aggressive ions. It is also necessary to investigate sensitivity and repeatability because the chosen test and indicators must be reliable enough to show significant differences between behaviours of different concrete mixtures.

Sensitivity has been studied by varying compactness, in terms of water/binder ratio, between 0.3 and 0.6. Repeatability tests have been performed on two specimens made of the same concrete mixture. Fly ash, GGBS, and limestone filler have been used in replacement of cement to show the influence of chemical composition of binder on performance of concrete. The damaged depths are assessed through a pH colorimetric indicator. They can be deduced from amounts of leached ions only for siliceous aggregates, because limestone aggregates are leached in poorly mineralised or acid water. Five out of eleven concrete mixtures are self-compacting concrete with limestone gravels. Assuming amounts of leached

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calcium from limestone aggregates, results of the experimental study are consistent and show the effects of compactness of concrete and chemical composition of binder.

2. Experimental program

2.1. Materials and mixture proportions

Three sets of concrete mixture have been studied. The first set of four concrete mixtures S1, S2, S3, and S4 were designed with siliceous aggregates. In S3 and S4 concrete mixtures, Effective Water/Equivalent Binder content (W_e/Eq.Binder) ratio and Eq.Binder content are kept constant (0.49 and 352 kg/m^3). 'Equivalent Binder' is defined in the European standard EN 206-1 and according to this concept only a part of mineral admixtures are taken into account (see Table 1), from data on compressive strength. In S4, the percentage of replacement of cement by fly ash is 30%. S1 and S2 concrete mixtures have the same W_e/Eq.Binder ratio (0.40) and Eq.-Binder content (385 kg/m^3). In S2, the percentage of replacement of cement by GGBS is 62%, i.e. the same proportion of GGBS as the blended cement CEM III used in S1 concrete mixture.

L4 and L5 concrete mixtures have higher W_e/Eq.Binder ratio (0.58) and lower Eq.Binder content (280 kg/m^3) and limestone aggregates were used. So they are not suitable in environments where leaching is likely to occur, but they were used to investigate the sensitivity of the test. L5 mixture is derived from L4 by incorporating 30% of fly ash in binder.

The third set of concrete mixtures is self-compacting concrete mixtures. Two sets of mix were prepared along with a reference mix called $V_A/V_C = 0$, with V_A the volume of admixtures and V_C the volume of cement. The concrete mixtures are described in Table 2. In the first set of mix, the admixture/cement volume ratio V_A/V_C was equal to 0.8 and in the second set V_A/V_C was reduced to 0.4, keeping the paste volume constant. Limestone filler (LF) and fly ash (FA) were used for each value of V_A/V_C to investigate the influence of the type of mineral admixture. For each mixture the water-reducing admixture (WRA) content was adjusted in order to achieve a slump flow between 60 and 80 cm and to avoid segregation, which was controlled using the sieve test [10].

The fineness and lime content of used cementitious materials are given in Table 3. 'PM ES' refers to low C_3A content for resistance to sea water and sulphates, which were investigated in other studies on the same concrete mixtures [11].

Table 1
Mixture compositions of vibrated concrete.

(kg/m^3)	S1	S2	S3	S4	L4	L5
Palvadeau gravel (Agg1)						
12.5/20	372	366	374	358	–	–
8/12	274	269	275	264	–	–
4/8	419	412	421	403	–	–
Boulonnais gravel (Agg2)						
12/20	–	–	–	–	541	561
4/12	–	–	–	–	416	432
Palvadeau sand						
2/4	57	56	57	55	–	–
1/4	243	239	244	234	–	–
0.5/1	132	130	133	127	–	–
0.315/1	196	193	197	189	–	–
0/0.315	105	104	106	102	–	–
0/0.160	23	23	23	22	–	–
Boulonnais sand 0/4	–	–	–	–	980	900
Cement (C)						
CEM III 42.5 PM ES	385	–	–	–	–	–
CEM I 52.5 PM ES	–	–	352	280	–	–
CEM I 52.5 N 1	–	–	–	–	280	223
CEM I 52.5 R	–	156	–	–	–	–
Mineral admixtures (A)						
Fly ash (k = 0.6)	–	–	–	120	–	95
GGBS (k = 0.9)	–	254	–	–	–	–
Effective water (W_e)	154	154	174	174	162	162
WRA	4.14	3.38	0.73	1.29	3.67	2.98
Binder content ($C + A$)	385	410	352	400	280	318
W_e/binder	0.40	0.38	0.49	0.44	0.58	0.51
Equivalent binder content (C + k.A)	385	385	352	352	280	280
W_e/(C + k.A)	0.40	0.40	0.49	0.49	0.58	0.58
$A/(A + C)$	0	0.62	0	0.30	0	0.30
Volume of paste V_p (L/m^3)	282	293	286	308	322	340

Table 2
Mixture compositions of self-compacting concrete.

(kg/m^3)	No mineral admixture $V_A/V_C = 0$	A = LF		A = FA2	
		$V_A/V_C = 0.80$	$V_A/V_C = 0.40$	$V_A/V_C = 0.80$	$V_A/V_C = 0.40$
Gravel 3/8 mm (Agg3)	790	790	790	790	790
Sand 0/4 mm	670	670	670	670	670
Cement (C) CEM I 52.5 N 2	663	365	470	365	470
Mineral admixture (A)	0	255	165	203	131
W_e	204	199	198	199	200
WRA	12.22	5.20	4.84	6.66	8.59
VA	0.66	0.66	0.66	0.66	0.66
Binder content ($C + A$)	663	620	635	568	601
W_e/binder	0.31	0.32	0.31	0.35	0.33
$A/(A + C)$	0	0.41	0.26	0.36	0.22
Volume of paste V_p (L/m^3)	420	415	415	415	417
Slump flow (cm)	61	80	76	78	68
fc (MPa)	64.1	44.8	52.3	54.5	60.1

Table 3
Physical and chemical characteristics of cementitious materials.

	Blaine surface (cm^2/g)	CaO proportion (%)	SiO_2 proportion (%)
CEM I 52.5 N 1	3440	63.77	20.21
CEM I 52.5 N 2	4150	65.12	20.69
CEM I 52.5 R	4130	64.10	19.45
CEM I 52.5 N PM ES	3650	64.95	21.25
CEM III 42.5 PM ES	4300	50.40	28.60
Fly ash 1 (FA1)	3840	2.2	52.5
Fly ash 2 (FA2)	–	3.76	52.78
GGBS	4620	41.03	34.49
Limestone filler (LF)	3970	$CaCO_3$: 97.3	0.5

2.2. Experimental procedures

After mixing concrete was cast in cylindrical Ø 11 × 22 cm moulds and vibrated, except for self-consolidating concrete mixtures. After 24 h of sealed curing the specimens were cured under water until testing. Strength was assessed at 28 days on three cylindrical Ø 11 × 22 cm specimens. Porosity was measured at 28 days on three samples, according to AFPC-AFREM procedure [12]. At 50 days a steady state migration test was carried on three cylindrical Ø 11 × 5 cm specimens to assess chloride diffusivity.

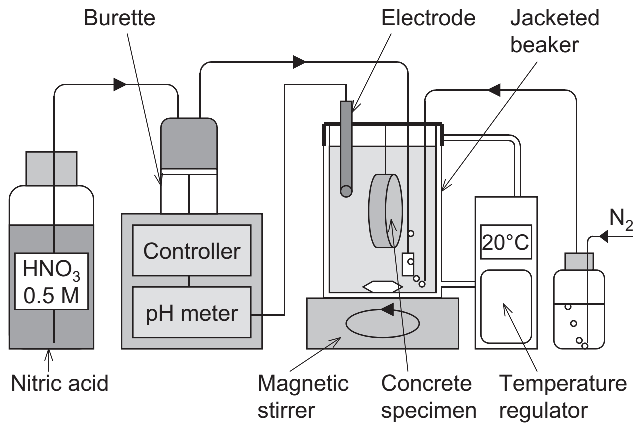

Fig. 1. Experimental setup of leaching test.

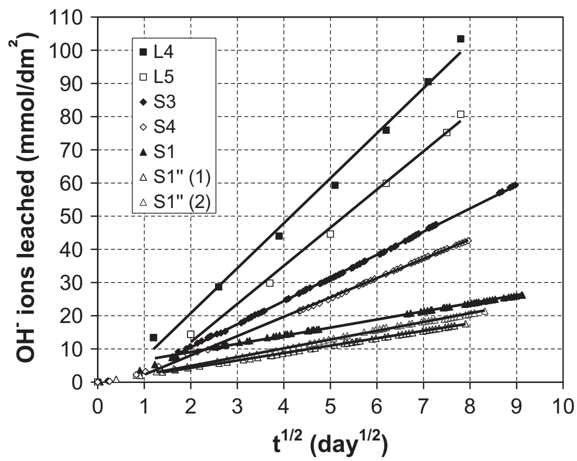

Fig. 2. Leached hydroxide ions for vibrated concrete mixtures.

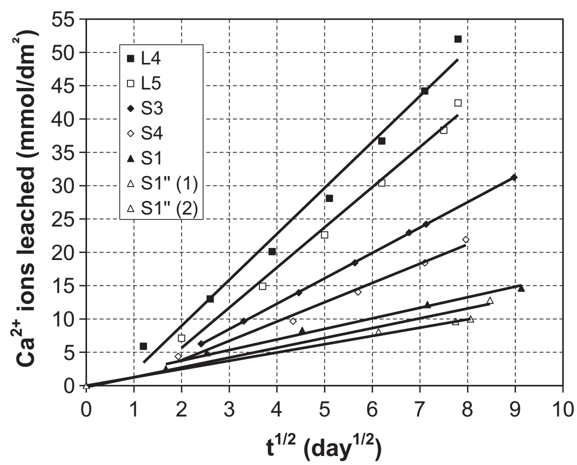

Fig. 3. Leached calcium ions for vibrated concrete mixtures.

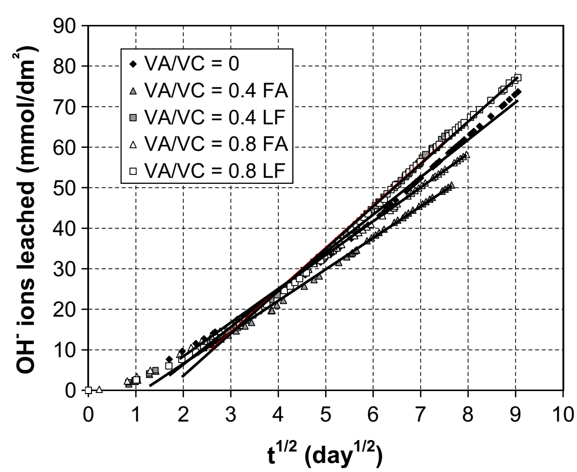

Fig. 4. Leached hydroxide ions for self-compacting concrete mixtures.

2.3. Leaching test

The test is adapted from the test developed by Planel on cement pastes [4] and Bourdette on mortars [13]. The test consists of immersion of concrete sample during at least 60 days in a solution maintained at pH = 5 using nitric acid solution (HNO_3) of concentration 0.5 mol/L. The solution was renewed after every 30 mL of acid used. The quantity of leached hydroxide ions was assessed through the added volumes of nitric acid solution, and leached calcium by the titration of the solutions by atomic absorption spectrometry. The quantity of added acid gives the amount of leached OH- ions. Acid used and cumulated calcium ions dissolved allow assessing the kinetics of leaching.

Two identical experimental setups were built, as repeatability was to be studied and as the test is to be used in a comparative performance-based approach (Fig. 1). A nitrogen flow was used to avoid carbonation [14]. For each test a 25-mm thick specimen was sawed from an Ø 11 × 22 cm specimen for S1, S2, S3, S4, L4, L5 concrete mixtures and from a 7 × 7 × 28 cm^3 prismatic specimen for SCC mixtures. The specimen was laterally coated with a waterproof vinylester resin, and hence was exposed to leaching on its two plane surfaces.

After immersion a 1% phenolphthalein solution was sprayed onto a fresh fracture to measure the damaged depth using the colouration front.

S1, S2 (1), S2 (2), S3, S4, L4 and L5 samples were respectively tested 42, 45, 38, 43, 56, 41, and 40 days after batching. SCC specimens were tested at 2 years, after free shrinkage tests, so they were partially carbonated.

3. Results and discussion

The quantity of leached hydroxide ions and leached calcium are plotted against square root of time in Figs. 2 and 3 for vibrated concrete mixtures, and Figs. 4 and 5 for SCC mixtures. The variable *t* is the time of exposition of concrete specimens to acid solutions.

Assuming that calcium ions only came from binder and that no portlandite remained in corroded layers, equivalent damaged depths may be calculated, dividing the total amount of leached calcium by the theoretical initial total calcium content of binder.

As most of natural environments are likely to combine various exposures such as carbonation, chloride ingress, and leaching, some performance-based approaches have introduced so-called 'general durability indicators' to estimate potential durability [15]. Some of these indicators have been assessed in this study, namely: strength, porosity, and chloride diffusivity. The values are given in Table 4. Strength values show that *k* coefficients of activity of mineral admixtures (Table 1) are verified but they do not correlate with resistance to leaching, as they are based on strength. Porosity and diffusivity are useful data to analyse the results of the test, since leaching is due to diffusion and diffusion takes place through the porous network of concrete. Moreover,

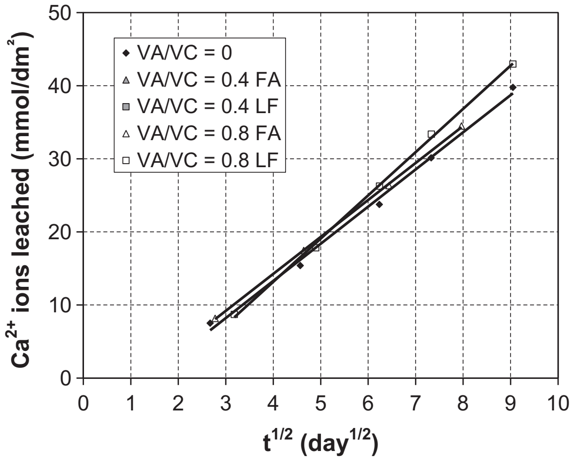

Fig. 5. Leached calcium ions for self-compacting concrete mixtures.

Table 4
Durability indicators.

	28-day strength (Mpa)	Water porosity (%)	Porosity/volume of paste (%)	Chloride diffusivity (10^{-12} m^2/s)
S1	53.2	11.6	41.1	0.8
S2	55.2	10.6	36.2	–
S3	47.6	11.2	39.0	1.1
S4	42.8	–	–	–
L4	52.1	14.2	44.0	1.6
L5	52.7	14.2	41.8	1.3

even if the study mainly deals with leaching, it is interesting to get an estimate of the potential durability of the studied concrete mixtures in other exposure conditions, for instance conditions involving diffusion of aggressive solutions into saturated concrete.

Porosity generally decreases with an increase in strength, which is observed here, even if porosity of S3 may seem rather low. As degradation of concrete generally involves paste (defined as binder + water), porosity/volume of paste ratio could give more

Table 5
Parameters of leaching kinetics.

	Hydroxide ions (OH^-)		Calcium ions (Ca^{2+})	
	a (mmol/dm^2/day$^{1/2}$)	*b* (mmol/dm^2)	*a* (mmol/dm^2/day$^{1/2}$)	*b* (mmol/dm^2)
S1	2.45	4.19	1.59	0.58
S2	2.44	−0.25	1.36	−0.10
S2 (1)	2.23	−0.15	1.24	0
S2 (2)	2.64	−0.35	1.47	−0.21
S3	6.97	−3.44	3.81	−2.95
S4	5.82	−3.59	2.90	−1.97
L4	13.56	−6.34	6.90	−4.83
L5	11.50	−10.94	6.03	−6.40
V_A/V_C = 0	9.24	−12.1	5.08	−7.04
V_A/V_C = 0.4 FA	7.75	−8.90	–	–
V_A/V_C = 0.4 LF	10.41	−16.98	–	–
V_A/V_C = 0.8 FA	8.33	−8.28	5.06	−5.97
V_A/V_C = 0.8 LF	10.46	−17.34	5.91	−10.49

reliable data to compare concrete mixtures of different volumes of paste. Diffusion has a predominant part in leaching; it is shown by linear increase of leached ions with reference to square root of time. Chloride diffusivities have been compared with leaching rates. These indicators give properties of porous net of concrete, but they do not take into account chemical reactivity of binder and paste, so they can lack sensitivity to explain behaviour of concrete exposed to leaching.

Parameters of leaching kinetics may be deduced from the amounts of leached ions vs. square root of time curves. Steady state was assumed to be reached after one day. Corresponding parameters are given in Table 5, for the following Eq. (1):

$$N(t) = a \cdot \sqrt{t} + b \tag{1}$$

The amount of leached calcium or hydroxide ions can be considered as a first indicator provided by the test for a comparative approach of potential durability. Repeatability was studied on S2 concrete mixture. The leaching rates of S2 (1) and S2 (2) concrete specimens were 8.4% higher or lower than the mean value for the two tests, which was 2.44 mmol/dm^2/day$^{1/2}$. Previous experiments according to the same procedure at CERIB [9] gave the same value of uncertainty of about 10% for 4 tests. So significant differences may be deduced from experimental results.

Ratios of leaching rates a_{OH}/a_{Ca} are close to 2. So leaching would mainly come from dissolution of portlandite $Ca(OH)_2$ (see Eq. (2)). Ratios are actually above 2, and a part of leached calcium ions could come from CSH. For L4, L5 and SCC mixtures, leaching of calcite from limestone cannot be excluded by this approach, because leaching of each calcium ion from calcite $CaCO_3$ (from aggregates, filler, or carbonation) also requires two H_3O^+ ions from acid solution (see Eq. (3)).

$$Ca(OH)_2 + 2H_3O^+ \rightarrow Ca^{2+} + 4H_2O \tag{2}$$

$$CaCO_3 + 2H_3O^+ \rightarrow Ca^{2+} + H_2O, CO_2 + 2H_2O \tag{3}$$

After immersion the corroded depth was measured using phenolphthalein solution. Results in Table 6 show that corroded layer was very thin, for all concrete mixtures. So a more sensitive criterion was looked for. From experimental data of the leaching test and data on the cimentitious materials, the following ratio can be calculated and provide an equivalent damaged depth (d_{eq}):

$$d_{eq} = \frac{\text{Total leached calcium}}{\text{Initial calcium content in binder}} \tag{4}$$

From microstructural analyses on concrete specimens that underwent the same testing procedure, the equivalent damaged depth would actually underevaluate the damaged depth, because the observed damaged layer was not totally decalcified, which was an assumption of the previous calculation [9]. Equivalent damaged depths were compared with damaged depths measured using the colouration front (d_{exp}). As far as siliceous aggregates are concerned, in S1, S2, S3, and S4 concrete mixtures, d_{eq} may be regarded as a relevant indicator, taking into account uncertainty on d_{exp}. But significant differences can be found for L4, L5, and SCC specimens. Overestimation of damaged depth may come from dissolution of calcite $CaCO_3$ from limestone aggregates or filler. Pictures of colouration front on SCC specimens are shown in Fig. 6. Pictures appeared as a good way to use the test in a comparative approach. They showed that damaged depth had been overestimated by d_{eq}. In pictures 6.a and 6.c it can be seen that the interface of aggregates has drawn back faster than the interface of the matrix. Degradation of the matrix of V_A/V_C = 0 concrete mixture is so thin that it cannot be measured, and corroded layer of V_A/V_C = 0.8 FA is thinner than corroded layer of V_A/V_C = 0.8 LF. Better behaviour of concrete incorporating fly ash could come from the physicochemical

Table 6
Experimental and equivalent damaged depths.

	Total leached calcium at 60 days (mmol/dm^2)	Initial binder calcium content (mol/dm^3)	Leached calcium from aggregates (mmol/dm^2)	Equivalent damaged depth d_{eq} (mm)	Equivalent damaged depth d'_{eq} (mm)	Experimental damaged depth d_{exp} (mm)
S1	12.9	3.47	–	0.37	–	<0.5
S2	10.5	3.60	–	0.29	–	<0.5
S2 (1)	9.6	3.60	–	0.27	–	<0.5
S2 (2)	11.3	3.60	–	0.32	–	<0.5
S3	26.6	4.08	–	0.65	–	0.5
S4	21.0	3.29	–	0.64	–	0.5
L4	52.0	3.19	27.0	1.63	0.79	1
L5	42.4	2.61	26.2	1.65	0.62	0.5
$V_A/V_C = 0$	32.5	7.70	23.7	0.42	0.11	0
$V_A/V_C = 0.4$ FA	30.0	5.50	23.7	0.55	0.11	0
$V_A/V_C = 0.4$ LF	35.0	5.46	23.7	0.64	0.16	0
$V_A/V_C = 0.8$ FA	33.3	4.31	23.7	0.77	0.22	<0.5
$V_A/V_C = 0.8$ LF	35.7	4.24	23.7	0.84	0.18	0.5

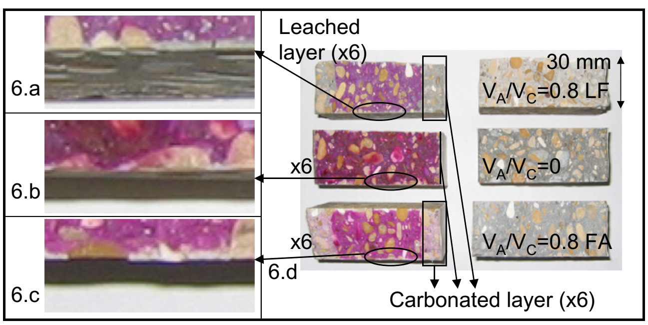

Fig. 6. Measured damage depths: colouration fronts on SCC specimens.

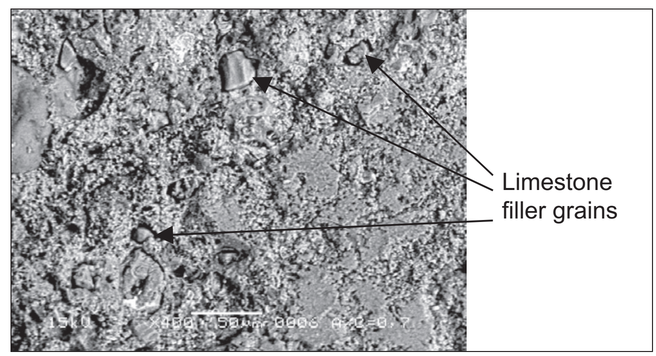

Fig. 7. SEM picture of leached zone of $V_A/V_C = 0.8$ LF specimen.

properties of the mineral admixtures. Fly ash is mainly composed of silica (Table 3), whereas limestone filler is essentially composed of calcite $CaCO_3$ which is likely to be leached. This was actually observed by SEM on leached zone $V_A/V_C = 0.8$ LF specimen. A depleted zone can be seen around limestone filler grains on picture of Fig. 7.

In order to explain discrepancies between d_{exp} and d_{eq} of concrete mixtures with limestone aggregates, the ratio providing d_{eq} has been calculated taking into account leached layers of aggregates (see picture 6.a):

$$d'_{eq} = \frac{\text{Total leached calcium} - \text{Leached calcium from aggregates}}{\text{Initial calcium content in binder}} \quad (5)$$

The amount of leached calcium from aggregates (mmol/dm^2) is assessed by assuming the thickness of the dissolved layer, and taking into account the volume proportion of aggregates and the molar mass of calcite $CaCO_3$. The thickness of the dissolved layer was assumed to be 0.15 mm for Boulonnais aggregates (L4 and L5 mixtures) and 0.3 mm for the aggregates of SCC mixtures, which is consistent with what was observed on degraded specimens. The results are given in Table 6 and Fig. 8. d'_{eq} values are in good agreement with d_{exp} values, excepted for $V_A/V_C = 0.8$ LF.

Leaching tended to increase with an increase in water/binder ratio, which can be explained by corresponding variations of porosity and diffusivity (Fig. 8). Porosity does not account for all the differences. For instance L4 and L5 had the same porosity, but L5 had a better behaviour as far as leaching is concerned: leaching rate is reduced by 15%. Similarly, S4 would have a better behaviour than S3 concrete, and leaching rate is reduced by 18%. So incorporating 30% of fly ash in binder would improve resistance to leaching. Blended cements or binder incorporating such pozzolanic materials actually produce less portlandite $Ca(OH)_2$, with equal or enhanced compactness of the matrix. Conversely, substitution of cement by limestone filler would be detrimental. Actually dissolution of filler could significantly increase diffusivity in damaged zone and accelerate leaching. So behaviour would not only depend on porosity but on chemical composition of binder.

The results shown in Fig. 8 suggest that the behaviour of self-compacting concrete mixtures followed the same trend as vibrated

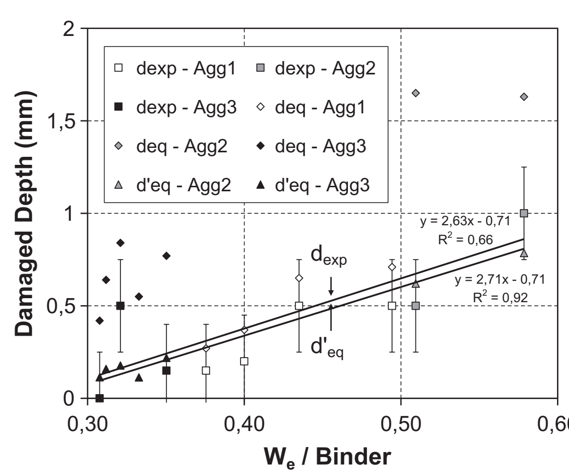

Fig. 8. Damaged depths of concrete specimens after leaching test.

concrete. SCC showed equivalent or better resistance to leaching, as their W_e/Binder ratios were lower. However the global results could be due to opposite effects of composition parameters. On the one hand an increase in the volume of paste is likely to increase diffusivity and leaching rate [16]. On the other hand, better consolidation of SCC mixtures due to higher amounts of water-reducing admixtures would reduce diffusivity [17]. Finally, for given water to cementitious materials ratio, SCC generally show equivalent or enhanced behaviour, but high contents of limestone filler are likely to affect long-term behaviour.

In the set of tested concrete mixtures, high amounts of GGBS (62%) lead to good resistance to leaching. S1 and S2 concrete mixtures showed the lowest leaching rates and total amounts of leached calcium and hydroxide ions. They had the same leaching rates (respectively 2.45 and 2.44 mmol/dm^2/day). So including GGBS in concrete mixture instead of using blended cement had not a significant effect, with the used materials.

4. Conclusions

The results presented in this paper are part of a study on durability of concrete exposed to chemically aggressive environments. The aim is to design performance tests to be used in comparative performance-based specifications according to the Equivalent performance concept.

- Such performance tests must be representative, sensitive, and repeatable. As far as leaching is concerned, this test could provide relevant data. It may be considered as representative, as the mechanism of degradation is not changed. The concentration of the aggressive solution is not increased in order to accelerate the degradation of concrete. For instance, pH values are to be chosen according to the definition of the exposure classes in the European standard EN 206-1 [18]. The repeatability of the test has been investigated. Taking into account the dispersion of the experimental results, significant differences may be deduced.
- Performance-based indicators can be assessed from the experimental data. Two results of the test should be taken into account, namely: equivalent damaged depth (d_{eq}) and experimental damaged depth (d_{exp}) from colouration front given by phenolphthalein. Equivalent performance could only be deduced from consistent results from both indicators. Provided that siliceous gravels are used, an equivalent damaged depth, defined as the ratio of Total leached calcium at 60 days to Initial binder calcium content, can give an estimation of the thickness of corroded layer. But gravels or sand often include limestone and thus equivalent damaged depth may not be a reliable indicator. So the damaged depth has to be assessed from the colouration front of a pH indicator (phenolphthalein in this study). The two assessments of damaged depth are consistent, provided that dissolution of calcite from limestone aggregates is taken into account.
- 30% replacement of cement with fly ash improved the performance of the concrete mixtures exposed to leaching. The experimental results also confirmed the good resistance of binders including high proportions (more than 60% of the equivalent binder content) of ground granulated blast-furnace slag (GGBS), using either blended cement or replacement of Portland with GGBS.
- The leaching resistance of SCC mixtures was consistent with their composition (in terms of W_e/binder ratio), provided that limestone filler is not used in high proportions (40%) in binder. Self-consolidating concrete mixtures are actually often designed with relatively low water to cementitious materials ratios and high amounts of cement and mineral admixtures. Their relatively good behaviour in this study can be explained by their lower W_e/binder ratio. However, one of the mixtures showed relatively low resistance to leaching, which confirms the need for performance-based specifications. When compared with vibrated concrete mixtures, the consolidation and the volume of paste did not affect significantly the behaviour of the concrete exposed to the leaching test.

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