Service Life Prediction: Theorecrete, Labcrete and Realcrete Approaches

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ABSTRACT

Current Concrete Codes and Standards provide specifications for an expected service life of about 50 years. This is insufficient for today's large projects in which service lives of 100 or more years are requested. To fill this void, service life prediction approaches have been developed (predominantly dealing with chlorides- or carbonation-induced corrosion), the strengths and weaknesses of which are discussed. They are based either on the theoretical composition of the mix ("Theorecrete"), or on the measurement of transport properties on laboratory cast specimens ("Labcrete"). Both approaches do not account properly with the importance of concreting practices (batching, placement, compaction, finishing, curing) for the quality of the "Realcrete", as well as on the actual cover depth, which may differ considerably from the nominal ("Theorecrete"). The fundamentals and potential of service life prediction based on site measurements of the "Realcrete" are presented as an alternative.

Keywords. Service Life, Prediction, Cover Depth, Permeability, Chlorides

INTRODUCTION

Traditionally, Concrete Codes and Standards have applied the "Deemed-to-satisfy" approach [Andrade, 2006] to specify durability requirements. Based on the accumulated experience in many countries, a set of primarily prescriptive rules have been established which, when rigorously observed, would result in a service life typically of 50 years (e.g. Eurocode 2 [EN 1992-1-1, 2004]). Today, many important structures are designed for service lives of 100, 150 or even more years, which clearly exceed the reach of existing experience with reinforced concrete and, therefore, requires some extrapolation via modelling.

Also, in the past, the burden of maintenance and repair costs of structures fell predominantly on the shoulders of the owner, with other players (designers, contractors, materials suppliers) assuming the responsibility for durability for a relatively short period (typically 5-10 years). The advent of Design, Build and Operate (DBO) contracts, whereby a private organization designs, builds an operates the facility for a period of several decades has changed the picture. Now, the contractor has a direct interest in the durability of the construction, since maintenance and repair costs plus eventual penalties for reduced operability of the facility will be borne by him/her. Moreover, often, the transfer price of the facility to the final owner is associated to its residual service life, that needs to be fairly established.

These examples show the increasing economical relevance of having tools capable of reliably predicting the service life of concrete structures that are:

- accurate: the prediction is close to the service life actually reached
- meaningful: based on sound principles
- realistic: take into consideration relevant parameters of the end-product
- objective: contain few (if any) parameters that can be freely and subjectively chosen

Various Service Life Prediction (SLP) methods have been developed recently. From them, there are two that have gained wide acceptance: Duracrete [Duracrete, 2000] in Europe and Life-365 [Life-365, 2012] in North America. In addition, there is one included in the Spanish Code [EHE-08, 2008]. They will be discussed in detail in the following sections.

Modelling through Fick's Law. Although the strict validity of Fick's purely diffusive assumption commonly used for SLP is debatable, most models rely on it and we will use it in the rest of this paper. The most used form of Fick's 2nd law solution to calculate the service life is given in Eqs. (1) and (2).

$$T_i = \frac{c^2}{4 \,.\, [D_0\,(t_0 / t)^m]} \; A^2 \tag{1}$$

$$A = \frac{1}{erf^{-1}[1 - (C_{cr} / C_s)]} \tag{2}$$

where

T_i	= time for initiation of corrosion (years)
c	= cover depth (mm)
D_0	= coefficient of chloride diffusion considered/measured at age t_0 (typically 28 days)
t	= hydration time ($t \leq t_{max}$, t_{max} corresponding to the end of hydration)
m	= "ageing exponent" or "diffusion decay exponent"
erf^{-1}	= inverse error function
C_{cr}	= critical concentration of chlorides, capable of initiating the corrosion process
C_s	= concentration of chlorides at the surface of the element

The term in brackets in (1) is the coefficient of chloride diffusion at time t. Please notice that the use of the power decay function goes against the assumption of constant D required for an explicit solution of Fick's 2nd law differential equation. The validity of this power decay function - and of the suggested exponent m values - is a subject of much uncertainty and controversy [Gulikers, 2011] [Oslakovic et al, 2010]. It is said that the effect of m on T_i is "dramatic" [Gulikers, 2006].

The factor A^2 has also an important influence on T_i as shown in Fig. 1, where its relation to the ratio C_s/C_{cr} is presented. Different models propose widely different values of C_s and C_{cr} and of their ratio; an analysis of their impact on A^2 goes beyond the scope of this paper.

Objective. The objective of this paper is to review the most used SLP methods and to present the fundamentals for an Experimental SLP approach, as a new alternative. For the review, the SLP methods are classified as belonging to one of the three following approaches: "Theorecrete", "Labcrete" and "Realcrete".

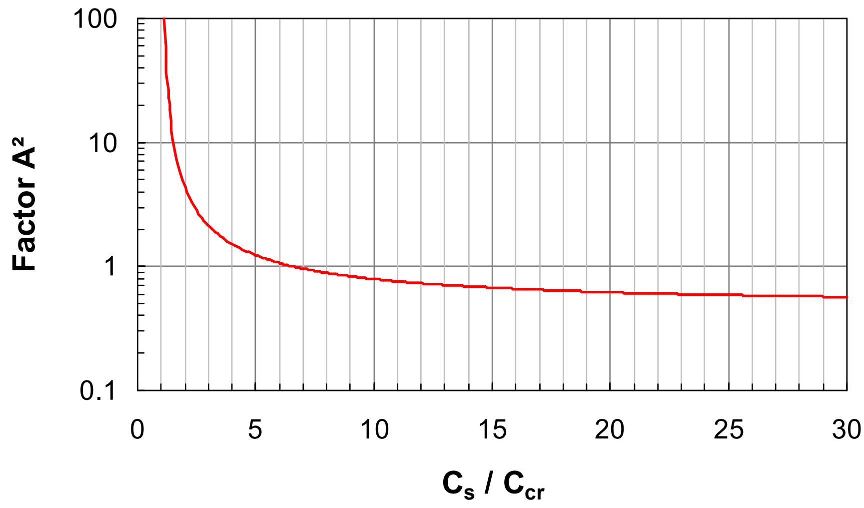

Figure 1. Effect of C_s / C_{cr} ratio on Factor A^2 of Eq. (1)

THE "THEORECRETE" SLP APPROACH

In this approach, the main durability indicators are the w/c ratio of the concrete (sometimes complemented with the binder type/composition) and the cover depth. Two relevant examples are the EN Codes and Standards and the SLP models proposed by the Spanish Standard EHE-08 [EHE-08, 2008] and the already mentioned [Life-365, 2012].

The w/c ratio as Durability Indicator. The w/c ratio is a measure of the degree of dispersion of cement grains in the mixing water of fresh concrete. It is rightly assumed that the higher the w/c ratio the more distant apart the cement grains and the larger the void space to be filled with hydration products. As illustrated in Fig. 2, a concrete made with a higher w/c ratio will end up, after hydration, with more and larger voids than one made with a lower w/c. Hence, a concrete with lower w/c will present a tighter porosity and lower penetrability.

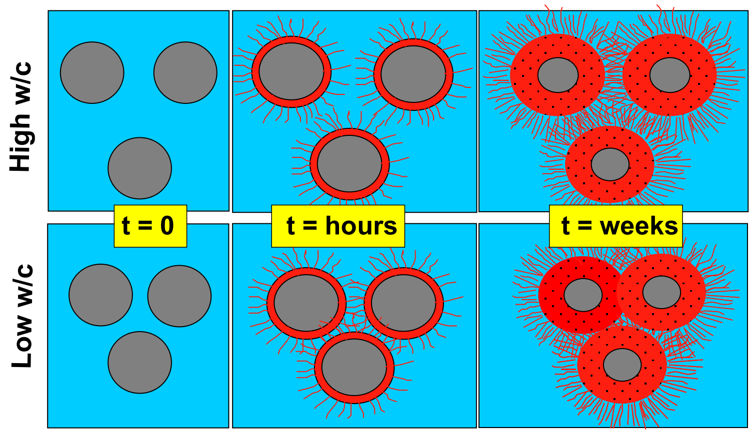

Figure 2. Sketch illustrating the effect of w/c ratio on porosity of concrete

For same ingredients, the w/c is a good "local" indicator of the resistance of concrete to the penetration of aggressive substances. The problem arises when one wants to generalize the approach to any kind of concrete ingredients. OPCs made out of different clinkers and under different grinding techniques and intensity, do not produce exactly the same hydration products in quantity and quality. If the binder, as it happens most usually nowadays, contains other cementing components beside clinker (fly ash, slag, pozzolan, silica fume, etc.) the problem is further complicated by the uncertainty of what is denominator "c" in w/c, since they have - even within the same type - very large differences in "cementitious value".

This can be seen in Fig. 3, where the Cembureau-Permeability to O_2 (kO) of concrete mixes, made with different binders but same aggregates, is plotted against the w/c ratio of the mix. Details of the experimental procedure can be found in [Torrent and Jornet, 1991]. It can be seen that a permeability of about 1.0 10^{-16} m² can be achieved with w/c ratios ranging between 0.37 and 0.77, depending on the cement characteristics.

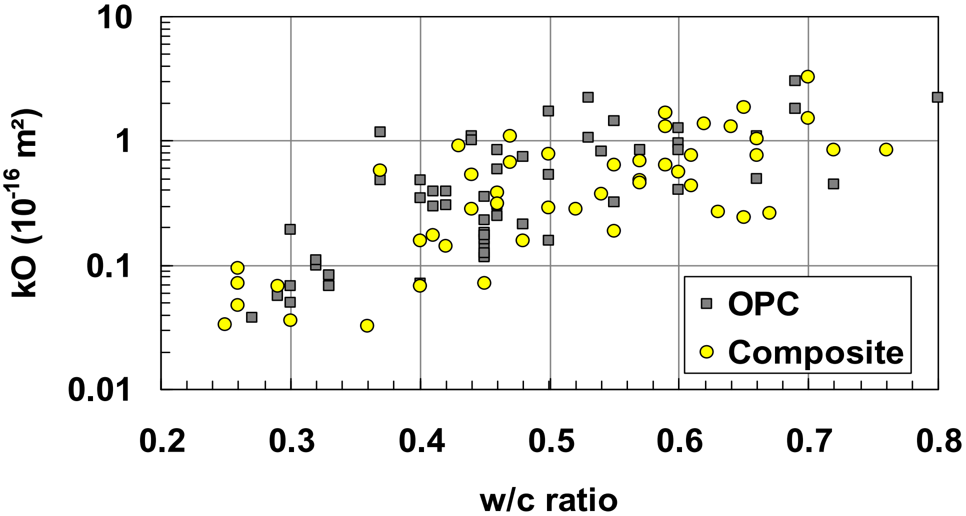

Figure 3 - Effect of cement characteristics on O_2-Permeability vs. w/c relation

The chart in Fig. 3 reflects the "weakness" of w/c ratio as durability indicator, by not considering the wide variety of performance of different cements.

EN "Theorecrete" Standards. The current specifications for durability in the EN Standards are based on prescriptive constraints to the proportions of the mix (typically maximum w/c ratios), with special provisions to account for the "cementitious" contribution of mineral additions (the "k-values") [EN 206-1, 2000] and on descriptive recommendations on how the concrete should be processed at the jobsite (placing, compaction, finishing, curing, etc.) [EN 13670, 2009].

Complementary, absolute minimum values for the depth of the cover to reinforcement are specified. The nominal cover, which is the one to be stated in the drawings is equal to the minimum cover plus a certain tolerance, typically 10 mm. Usually, an upper limit for the cover depth is not specified; the possible consequences of this, both in terms of reduced bearing capacity and/or cracking control, has been explained in [Neville, 2000].

In both cases (concrete quality and cover depth), the requirements are related to the severity of the environment to which the structural element is to be exposed. Table 1 presents the values of both indicators for Exposure Classes related to steel corrosion. It is worth mentioning that these requirements show important local variations [CEN/TC104/SC1, 2007].

The minimum cover depths indicated in Table 1 correspond to a service life of 50 years.

Table 1 - Durability Indicators specified in EN Standards for 50-year service life

	Environmental Aggressivity (Exposure Classes X)									
	Carbonation				Marine Chlorides			Other Chlorides		
Indicator	XC1	XC2	XC3	XC4	XS1	XS2	XS3	XD1	XD2	XD3
w/c_{max}	0.65	0.60	0.55	0.50	0.50	0.45	0.45	0.55	0.55	0.45
c_{min} (mm)	15	25		30	35	40	45	35	40	45

It is important to remark that Eurocode 2 [EN 1992-1, 2004] explicitly states "The design procedures are valid only when the requirements for execution and workmanship given in [EN 13670, 2009] are also complied with". In other words, if the concrete mix poured has a w/c ratio below the specified limits, has been correctly processed on site and the final cover does not exceed the specified values, the structure is expected to last 50 years under the applicable exposure class conditions.

Spanish Code "Theorecrete" Method. The Spanish Concrete Code [EHE-08, 2008] includes a method to estimate the Service Life of concrete structures subjected to carbonation or chloride-induced steel corrosion.

Regarding chlorides, the Standard provides values of the Coefficient of Cl^- Diffusion at 28 days (D_{28d}), which are a function of the w/c ratio and the type of cement. These values have been plotted in Fig. 4a as black symbols and full lines for an OPC, a cement containing 20% of PFA and another with 65% of GGBFS, respectively.

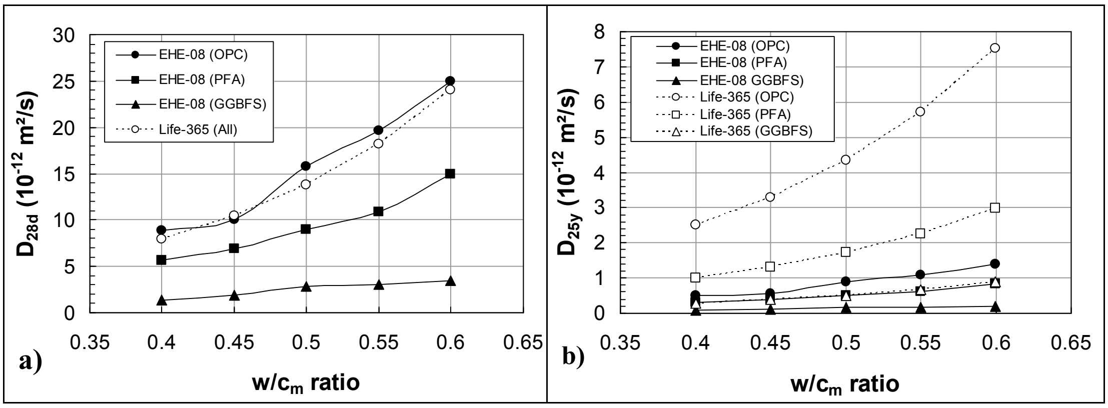

Fig. 4 - Effect of cement type on the Coefficient of Chloride Diffusion: a) at 28 days; b) at 25 years, according to EHE-08 and Life-365 Methods

The standard assumes a value of exponent m= 0.50 in Eq. (1), the same for all cement types, without an explicit maximum time t_{max} to which the decay effect applies. The Coefficient of Diffusion at 25 years has been calculated, using m=0.50, from those at 28 days and the results plotted in Fig. 4b as black symbols and full lines.

The initiation time for corrosion is computed with a simplified approximation to Eq. (1), assuming that the cover depth is known (not indicated whether the minimum or nominal).

Life-365 "Theorecrete" Method. The way Life-365 [Life-365, 2012] computes the Coefficient of Diffusion differs entirely from EHE-08. In Life-365 the value at 28 days is computed with the formula:

$$D_{28d}\ (m^2/s) = 10^{(-12.06 + 2.4\ .\ w/c)} \tag{3}$$

which applies for all cements types, except when Silica Fume is used. The values given by this formula are plotted in Fig. 4a as white circles and dotted line. It can be seen that the predicted D_{28d} values of Life-365 correspond very well to those of EHE-08 for OPC, but are much higher than the EHE-08 ones for binders containing PFA and GGBFS.

In addition, contrary to EHE-08, that has a constant value of the "decay exponent" m now, for Life-365, it is a function of the binder composition:

$$m = 0.20 + 0.4\ .\ (\%\ PFA / 50 + \%\ GGBFS / 70) \quad ; \quad m \leq 0.60 \tag{4}$$

If we assume the three cements analyzed for EHE-08 as OPC, 20% PFA and 60% GGBS, the m values yielded by Eq. (4) are 0.20, 0.36 and m= 0.57, respectively. Therefore, we will have widely different values of D at 25 years, starting from the same D_{28d} . This can be seen in Fig. 4b, where now the Coefficient of Diffusion at 25 years, calculated by Life-365, are plotted for the three cements (white symbols and dotted lines).

The end result is that the values of D_{25y} proposed by Life-365 at 25 years are 3 to 6 times higher than the corresponding ones according to EHE-08, which would mean 3 to 6 times less service life if introduced into Eq. (1).

One positive aspect of Life-365 is that Eq. (1) is solved in time steps, thus allowing the coefficient of diffusion D to be adjusted with time according, whilst other models assume for the calculation of T_i that D is constant at its minimum value for t_{max}. Moreover, the decay effect is limited to a maximum of 25 years, beyond which the value at 25 years is assumed as constant (end of hydration).

Limitations of "Theorecrete" Approach. The author defines the concrete specified on the basis of the w/c ratio and the nominal concrete cover as “Theorecrete”, because it assumes expected (theoretical) conditions often not met in practice:

1. it relies on a weak durability indicator, the w/c ratio, the assumed *theoretical* relation of which with the actual concrete performance is rather arbitrary and weak, depending strongly on the method chosen and the quality of the raw materials
2. *theoretical* and arbitrary assumption of contribution of mineral additions
3. often the real w/c ratio of the concrete poured in the structure exceeds the *theoretical* value specified (accidental or deliberate deviations impossible to detect on site [Neville, 2000])
4. *theoretical* good concrete production and construction practices (not always observed by the suppliers and contractor, including the endemic lack of curing)
5. *theoretical* cover thickness (often out of tolerances and seldom controlled on the finished structure [Neville, 1998]).
6. *theoretical* assumption of reduction of the coefficient of diffusion D through a power law, Eq. (1), the validity of which is controversial

THE "LABCRETE" SLP APPROACH

In this approach, the main durability indicators are transport properties of concrete measured applying short-term tests in the laboratory, on cast specimens or cores drilled from them, and the cover depth. Since the measurement of the coefficient of diffusion takes months to be completed, faster standard tests are usually adopted, the most popular being:

a) Rapid Chloride Migration [NT Build 492, 1995; SIA 262/1-B, 2003]
b) Water Sorptivity [ASTM C1585, 2004; SIA 262/1-A, 2003]
c) "Rapid Chloride Permeability Test" or "Coulombs Test" [ASTM C1202, 2010]
d) Water Penetration under Pressure [EN 12390-8, 2009]

A few application examples of these durability indicators are:

- The Canadian Standard [CSA A23.1, 2006] specifies for concretes exposed to chlorides, maximum values of 1000 or 1500 Coulombs (depending on "durability expectations"), applying test method c), after 56 days of curing
- In the extension of the Panama Canal, a maximum of 1000 Coulombs (together with a w/c_{max} = 0.40), test method c), has been specified for the concrete exposed to the most severe marine conditions which, together with a minimum cover of 75 mm, is expected to achieve 100 years of service life [ACP, 2008]. No indication of the age at which the concrete should be tested is given. Failure of the contractor to design a mix satisfying the performance requirement led to costly delays [Leach, 2012]
- The Spanish Code [EHE-08] specifies (Section 37.3.3 'Impermeability of concrete') maximum values of water penetration, test method d), for different severe aggressive environments

Duracrete "Labcrete" Method. The Duracrete method for SLP [Duracrete, 2000] is one of the most used in Europe and has been adopted by *fib* [fib, 2010]. It covers both the cases of carbonation- and chloride-induced steel corrosion; here we will concentrate on the latter.

The time to initiation of corrosion is calculated by equation 11.1 of [Duracrete, 2000], which derives from Eq. (1). Following a semi-probabilistic approach, the action (surface concentration C_s) is increased and the resistance (C_{cr} and Resistance to Cl^- ingress) decreased by partial factors ɣ; similarly, the cover thickness is decreased by a margin Δ[1]. These factors and margin are a function of the cost of mitigating the risk relative to the cost of repair.

The resistance to chloride penetration R_{cl} is inversely proportional to D, with D_0 in Eq. (1) taken as the result of the RCM test [NT Build 492, 1995], conducted at age t_0, on cast specimens. The "ageing exponent" m varies between 0.30 and 0.93, depending on the binder and exposure characteristics (for which limitation 6. of the "Theorecrete" approach also applies).

Trying to take real conditions into consideration, R_{cl} is reduced by a "curing factor" (dependant on the length of curing, being equal to 1.0 for 7 days curing) and an "environmental factor" (dependant on the type of binder and the exposure condition).

The Swiss "Labcrete" Standard. The Swiss Standards are possibly the most advanced regarding performance specification for durability. Table 2 shows the transit from purely

[1] All these factors are actually applied to "characteristic values" of the variables

prescriptive specifications in 2003, to the inclusion of performance requirements for "Labcrete" in 2008 [SN EN 206-1, 2008]. Maximum values of Water Sorptivity (q_w) and of Rapid Cl^- Migration (M_{Cl}), are now specified.

Table 2 – Evolution of Swiss Standards from "Theorecrete" to "Labcrete" to "Realcrete"

Year		Exposure Class →	Carbonation				Chlorides			
			XC1	XC2	XC3	XC4	XD1	XD2a	XD2b	XD3
2003	Theorecerete	Strength (MPa) Class$_{Cube\ min}$	30	30	30	37	30	30	37	37
		C_{min} (kg/m³)	280	280	280	300	300	300	320	320
		w/c_{max}	0.65	0.65	0.60	0.50	0.50	0.50	0.45	0.45
2008	Labcrete	q_{wmax} (g/m²h)	---	---	---	10	10	10	---	---
		M_{Clmax} (10^{-12} m²/s)	---	---	---	---	---	---	10	10
2013	Realcrete	Site kT_s (10^{-16} m²)	---	---	---	2.0	2.0	2.0	0.5	0.5

C_{min} = minimum cement content
q_{wmax} = coefficient of water absorption max. (SIA 262/1-A)
M_{Clmax} = coefficient of chloride migration max. (SIA 262/1-B)
kT_s = "characteristic" maximum coefficient of air-permeability (SIA 262/1-E)

Although the concrete producer has still to comply with the prescriptive requirements ("Theorecrete"), he must also prove, by regular testing of his mixes (on cores drilled from cast specimens), that the concrete complies with the performance requirements (maximum values of q_w and M_{Cl}) introduced in the revision of 2008 [SN EN 206-1, 2008].

The last row in Table 2 corresponds to the next move to a "Realcrete" approach, based on site NDT of air-permeability, to be discussed later.

Limitations of the "Labcrete" Approach. The concrete specified on the basis of laboratory tests conducted on cast specimens (or cores drilled from them) is known as "Labcrete". It is a clear step forward, since the first 3 out of the 6 limitations listed for the "Theorecrete" have been resolved. However, limitations 4. to 6. are also applicable to the "Labcrete" Approach.

CONCEPT OF "REALCRETE"

The difference between the "as-built" quality ("Realcrete") and that reflected by the results of laboratory tests conducted on cast specimens, prepared, compacted and cured under almost perfect conditions, i.e. "Labcrete", is well known [Gulikers, 2007]. The effect on durability of much too frequent bad practices such as: insufficient mixing time, bad compaction (especially in the space between the steel bars and the form), and lack or absence of moist curing (affecting more strongly the most exposed outer concrete layers) is discussed in [Neville, 2000]. In the same reference, the problem of cover to reinforcement is also addressed, highlighting the negative consequences for durability of too thin or too thick cover depths. Something that is not so commonly acknowledged is the negative effects of excessively large covers, on the one hand for bearing capacity and, on the second, for crack control. Sometimes one finds specified concrete covers reaching values of 125 mm (based on blind application of durability models), that entails a high risk of excessive surface cracking which, in turn will have a negative effect on the "penetrability", an effect often not considered in models. Australian Standard [AS 3600, 2001] states that "the distance from the side or soffit of a beam to the centre of the nearest longitudinal bar shall not exceed 100 mm", for crack control reasons.

Fig. 5a illustrates that the quality of the concrete in a real structure (the “Realcrete”) is not homogeneous. Indeed, the surface layers (the “Covercrete”) are usually of lower quality than the core, due to the following causes:

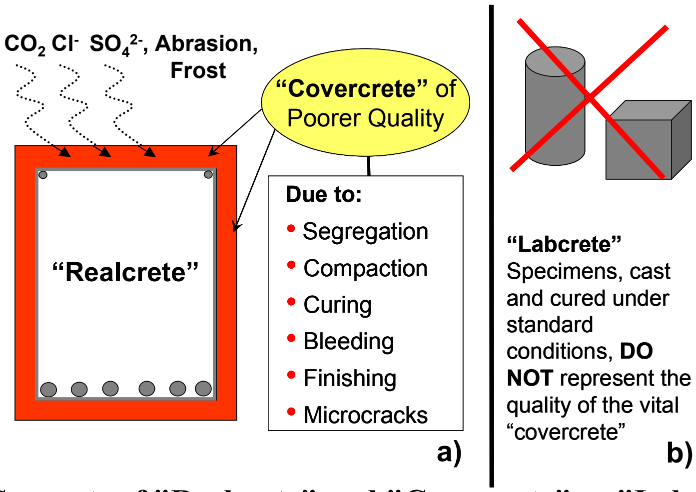

Fig. 5 - Concepts of "Realcrete" and "Covercrete" vs "Labcrete"

- Segregation tends to take place in that space (e.g. “honeycombing”)
- Compaction is more difficult in the narrow space between bars and form
- A special form of segregation, bleeding, manifests itself as an enrichment in water of the upper surface of elements (especially slabs)
- The endemic absence or lack of moist curing affects more strongly the surface layers, more exposed to evaporation and drying, with incomplete hydration and higher risk of shrinkage cracking
- Bad finishing techniques of slabs (typically the spread of cement and/or water) affect negatively the quality of the upper surface layers
- Microcracks (e.g. due to thermal or moisture gradients) usually develop in the near-surface layers

As also sketched in Fig. 5a, the “Covercrete” is the defence barrier of the structural element against the penetration of external aggressive agents. We find, therefore, the unfavourable situation that this defence barrier is the weakest in terms of quality. On the contrary, in a few cases we find processes that may end in “Covercretes” that are tighter than the bulk of the “Realcrete”, e.g. the dewatering of moulded surfaces by means of controlled permeable formwork liners [Long et al, 1995; Torrent et al, 2012a] and of finished surfaces by means of “vacuum treatment”, the use of shrinkage-compensating concretes, the power finishing of hardened floors’ surfaces, etc.

Both in the usual cases of weaker “Covercretes” and of the few cases of stronger “Covercretes”, the cast specimens used to measure the “penetrability” of the material are not representative of that of the “Covercrete” (Fig. 5b). In fact, the only way of knowing the “penetrability” of the vital “Covercrete” is by mean of site tests.

The same applies to the thickness of the cover concrete that protects the steel. The actual cover seldom coincides with the nominal value [Neville, 1998] and is rarely checked on the finished structure, despite the fact that there are electromagnetic covermeters capable of making a sufficiently accurate assessment of its value [Torrent and Fernández, 2007].

THE "REALCRETE" SLP APPROACH

In this approach, the main durability indicators are transport properties of concrete, measured on site via short-term non-destructive tests (NDT), or laboratory tests applied on cores drilled from the structure. In addition, the actual value of the cover depth is also measured on site by NDT or, destructively, by removing the cover to expose the steel.

Air-Permeability as Site Durability Indicator. Several test methods, intended to measure transport properties of the "Covercrete" on site, have been developed in the last decades, some ending in commercial instruments [Figg, 1973; Basheer et al, 1992; Torrent, 1992]. A review of such methods can be found in [Torrent and Fernandez Luco, 2007]. More methods continue being developed, some in Japan [Imamoto et al, 2006; Usman et al, 2011].

So far, the only standard method used to specify and control the "penetrability" of the "Covercrete" on site is the "Air-Permeability on the Structure" method standardized in Switzerland [SIA 262/1-E, 2003]. This entirely NDT method is capable of measuring the coefficient of air-permeability (kT) on site in up to 6 minutes [M-A-S, 2012; Torrent, 2012], producing meaningful results if the Recommendations issued by the Swiss Federal Highway Administration [Jacobs et al, 2009] are followed. These recommendations will become part of a new version of the Swiss Standard [SIA 262/1-E, 2013]. The method is being intensively used worldwide [M-A-S, 2012], particularly in Japan, where its potential as specification and control tool is being thoroughly investigated [Kishi and Kurashige, 2009].

Several researches have shown a good correlation between kT and carbonation rate of concrete [Kubens et al, 2003] [Imamoto et al, 2008] [Kurashige and Hironaga, 2010] [Torrent et al, 2012b]. Furthermore, this correlation has been exploited to predict service life of important concrete structures, e.g. Tokyo Museum of Western Art [Imamoto, 2012] and Port of Miami Tunnel [Torrent et al, 2013].

Any attempt to use values of air-permeability measured on site to predict service life of concrete exposed to chlorides requires a relation between kT and the coefficient of chloride diffusion D_{Cl}.

Results of kT and D_{Cl} (measured under Cl^- ponding/immersion long-term tests) are plotted with black symbols in Fig. 6. The empty circles in Fig. 6 correspond to kT and Coulomb [ASTM C1202, 2010] values available in the literature [Torrent et al, 2012b]. The Coulomb values were converted into D_{Cl} applying the following formula, established at Purdue University [Olek et al, 2002]:

$$D_{Cl}\ (10^{-12}\ m^2/s) = 0.4 + 0.002\ .\ \text{Coulomb} \tag{5}$$

A relation between kT and D_{Cl} has been fitted to the values in Fig. 6, of the form:

$$D_{Cl} = 10\ .\ kT^{1/3} \qquad \text{with } D_{Cl} \text{ in } (10^{-12}\ m^2/s) \text{ and kT in } (10^{-16}\ m^2) \tag{6}$$

More results of kT and direct tests of D_{Cl} are needed to validate Eq. (6), some expected during 2013; for the moment, this relation has to be taken as tentative.

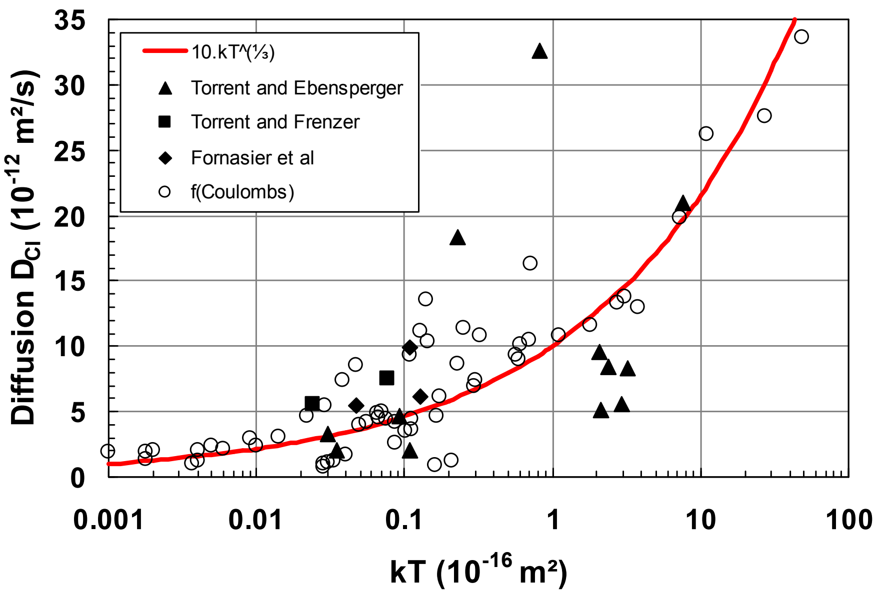

Figure 6. Tentative relation between D_{Cl} and kT

The Swiss "Realcrete" Standard. The Swiss Concrete Code [SIA 262, 2003] specifies that "The impermeability of the cover concrete shall be checked by means of permeability tests (e.g. air permeability measurements) on the structure or on core samples taken from the structure". The coming [SIA 262/1-E, 2013] will give precise instructions about site Air-permeability testing, limiting values of kT (see last row of Table 2) and compliance rules.

The last row of Table 2 indicates the specified values of kT for different exposure classes. They are statistical maximum ("characteristic") values, following a non-parametric compliance criterion defined in [Jacobs et al, 2009] and [SIA 262/1-E, 2013].

Now, the compliance of the end-product is checked with site kT tests, overcoming limitation 4. of the "Theorecrete" Approach (present also in the "Labcrete" Approach).

The South African "Realcrete" Method. The approach followed in South Africa is well summarized in [Alexander and Beushausen, 2008]. The South African method is based on drilling Ø 68 mm cores from the finished structure, saw-cutting them to a thickness of 25 mm (in the process removing the outermost layer of 10 mm, actually part of the "Covercrete") and subjecting them to one or more of the following tests in the laboratory:

- Oxygen Permeability Index (OPI), OPI = - logarithm of the coefficient of O_2 permeability
- Water Sorptivity Index
- Chloride Conductivity Index (CCI)

Prior to testing, the specimens are conditioned by drying at 50°C for the first two tests which, for the third test is followed by vacuum saturation [Alexander et al, 1999].

The interpretation of the results is given in [Alexander and Beushausen, 2008] and a more elaborated one in [Alexander et al, 2008]. Part of the former is presented in Table 3.

Table 3 - South African Performance requirements for 50 years Service Life

	Carbonation XC4	Marine Chlorides XS3		
Indicator		70% CEM I + 30% PFA	50% CEM I + 50% GGBS	90% CEMI + 10% CSF
OPI_{min}	9.7	---	---	---
CCI_{max} (mS/cm)	---	1.10	1.25	0.35
c_{min} (mm)	30	50		

Currently, an attempt of incorporating the NDT site measurement of Air-Permeability kT to complement the tests on drilled cores is being pursued [Beushausen et al, 2012].

The Ref-Exp "Realcrete" Method. A method of service life prediction for carbonation or chloride-induced corrosion of steel, developed by the author has been applied for the first time within the framework of RILEM TC 230-PSC "Performance-based Specification and Control of Concrete Durability". Several TC members investigated panels prepared with different cement types, w/c ratios and cover depths, applying a variety of site tests. The final goal of the exercise was to assess the potential service life of the panels, assumed to be exposed to de-icing salts (EN Exposure Class XD3). This required the participants not only to perform tests on the panel, but also to apply their results in some service life prediction method.

Within this context, the author developed a method[2], which will be just summarized here, containing two distinctive components: Experimental and Reference

<u>Experimental Component</u>: it combines on site measurement of the coefficient of air-permeability kT (SIA 262/1-E) and of the thickness of the concrete cover ("covermeter")

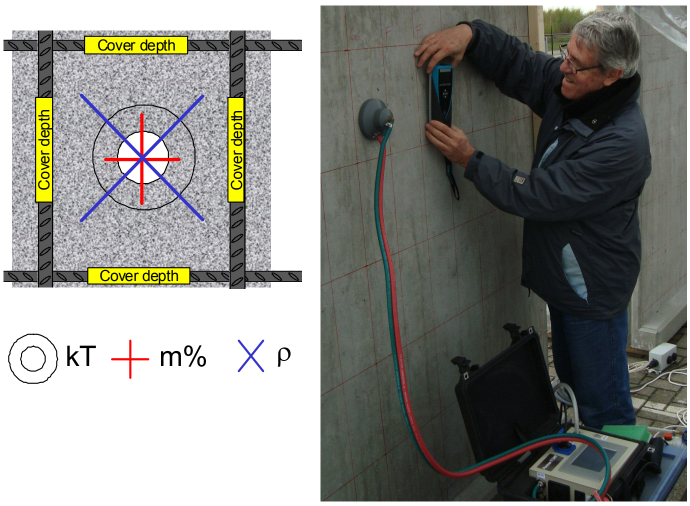

Fig. 7 - Measurement scheme for SLP according to Ref-Exp approach

Fig. 7 shows the scheme of measurements necessary to establish the predicted service life for a certain measuring point. Values of kT at the point and minimum cover depth c around it

[2] To be published elsewhere

are complemented with surface moisture content (m%) and eventually by Wenner resistivity ρ to check that the concrete is sufficiently dry for measuring kT [Jacobs et al, 2009].

Reference Component: the Reference Component consists in establishing the prescriptive specifications of the EN Standards, shown in Table 1, as reference. These conditions mean that, if the w/c_{max} as well as the minimum cover c_{min} have been respected, the reference service life T_{ref} (50 years for EN) will be achieved, provided that the concrete has been processed according to EN 13670.

The following assumptions are made:

1. The service life corresponds to the time for initiation of corrosion T_i
2. It is assumed that between the reference service life (e.g. 50 years) and the target service life (usually longer), no changes in the following elements of Eqs. (1) and (2) will take place: C_s , C_{cr} and $(t / t_0)^m$.
3. The reference w/c ratio is assumed as the target recommended by [EN206-1, 2000]:

$$w/c_{ref} = w/c_{max} - 0.02 \tag{7}$$

4. The reference cover depth is assumed equal to the nominal cover, or

$$c_{ref} = c_{min} + 10 \text{ mm} \tag{8}$$

5. The reference air permeability kT_{ref} can be calculated from:

$$\log kT_{ref} (m^2) = - 19 + 5 \cdot w/c_{ref} \qquad \text{(Eq. 2.1-107 of [CEB-FIP, 1991])} \tag{9}$$

Fig. 8 shows that formula (9) fits reasonably well to published data of kT and w/c (all the individual points in Fig. 8).

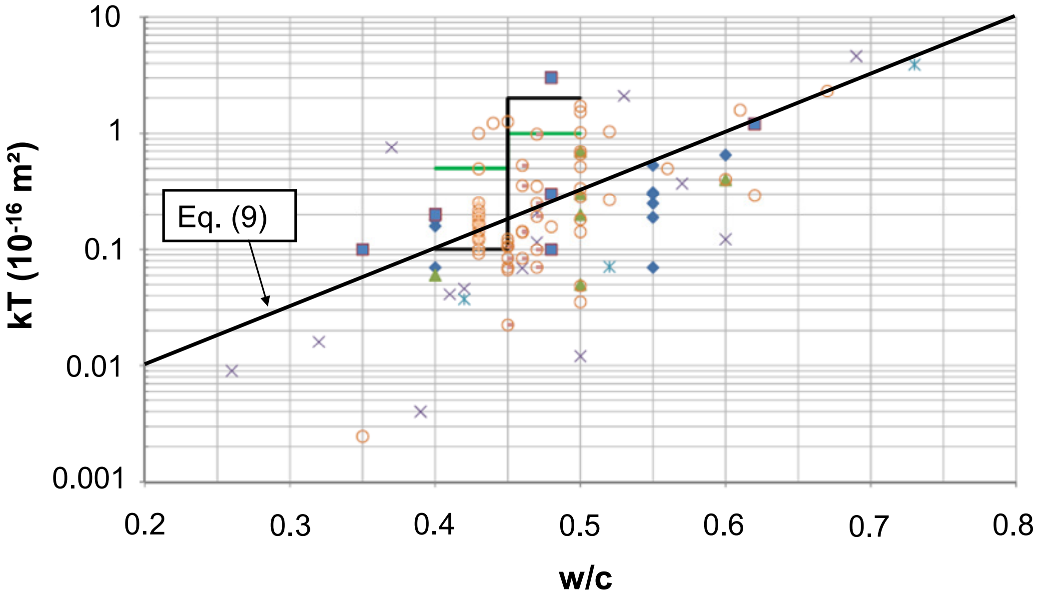

Fig. 8 - Formula (9) vs. kT and w/c data compiled in Fig. D-8 of [Jacobs et al, 2009]

Introducing Eq. (6) into (1) we have the service life T_i for measured values of kT and c:

$$T_i = \frac{c^2}{4\ .\ [10.\ kT^{1/3}\ (t/t_0)^m]}\ A^2 \tag{10}$$

For the Reference condition, it is $T_i = T_{ref}$, $kT = kT_{ref}$ and $c = c_{ref}$, which are all known

$$T_{ref} = \frac{c_{ref}^{\ 2}}{4\ .\ [10.\ kT_{ref}^{\ 1/3}\ (t/t_0)^m]}\ A^2 \tag{11}$$

Dividing (10) by (11) and remembering the assumptions that $(t/t_0)^m$ and C_{cr}/C_s, and therefore A, have not changed between T_{ref} and T_i:

$$T_i = T_{ref}\ (c\ /\ c_{ref})^2\ .\ (kT_{ref}\ /\ kT)^{1/3} \tag{12}$$

Eq. (12) allows us to calculate the expected Service Life of a point of a structure on which we have measured, non-destructively, the air-permeability kT and the cover depth c.

For clarification, let us run an example for the particular case of XS3 exposure (Table 1):

In the case of the Reference condition for the example, it is T_{ref} = 50 years, w/c_{max} = 0.45 and c_{min} = 45 mm. Applying Eqs. (7), (8) and (9) we compute $w/c_{ref} = 0.43 \rightarrow kT_{ref} = 0.14\ 10^{-16}\ m^2$ and c_{ref} = 55 mm. Introducing these reference values into Eq. (12) we get:

$$T_i = 50\ (c\ /\ 55)^2\ .\ (0.14\ /\ kT)^{1/3} = 0.0086 * c^2\ /\ kT^{1/3} \tag{13}$$

Equation (13) relates the service life T_i (years) with the measured values of c (mm) and kT ($10^{-16}\ m^2$), for Exposure Class XS3.

If a design for service life T_i = 100 years is desired, for instance a nominal cover c = 70 mm (c_{min}= 60 mm) can be specified, requiring from Eq. (13), a maximum kT = 0.075 $10^{-16}\ m^2$.

Experimental tests, both at laboratory and field scale, will define the best set of components and their proportions which, linked to the proposed concreting practices will ensure that the specified c_{min} and kT_{max} are achievable.

For compliance, the measured values of kT and c on the real structure can be introduced into the interaction diagram shown in Fig. 9 (the dashed line is for 50 years and the full line for 100 years Service Life). The compliance region has a curved boundary which corresponds to Eq. (13) and two horizontal boundaries corresponding to ± 20 mm (i.e. twice the typical tolerance) from the nominal cover.

The approach is simple, compare Eq.(12) with Eqs. (1) and (2). It is also robust, since there is little or no subjective influence of the user in the selection of parameters to compute the service life.

Furthermore, since to each measured point a different service life T_i can be attributed, through Eq. (12) or (13), a probabilistic treatment is feasible.

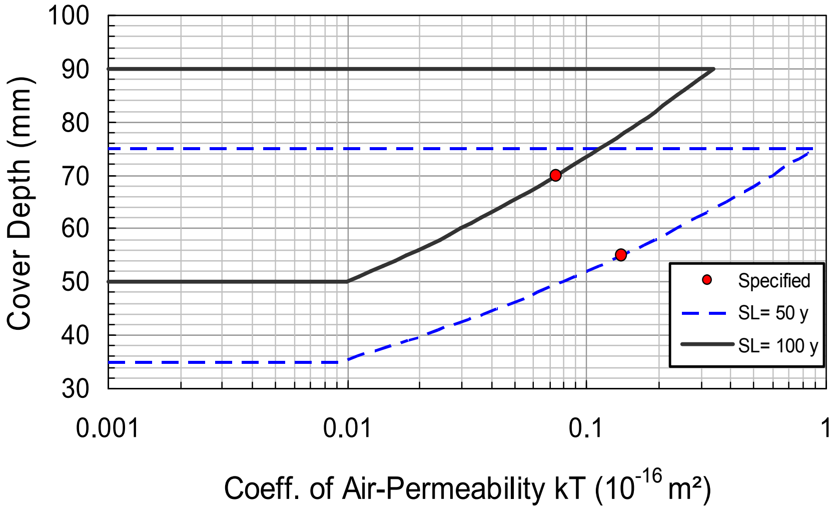

Fig. 9 - Compliance interaction c - kT diagrams according to Ref-Exp approach

CONCLUSIONS

A review of the more widely used SLP approaches has been made, classifying them into "Theorecrete", "Labcrete" and "Realcrete" types.

"Labcrete" approaches show a progress with respect to "Theorecrete" ones, because they base their predictions on measured relevant transport properties of concrete, rather on theoretical relations between the latter and the composition of the mix (w/c ratio) that are arbitrary and neglect the influence of materials characteristics on concrete performance.

A weak point of both "Labcrete" and "Theorecrete" approaches is that none is concerned with the quality actually achieved in the as-built structure. Important factors for the durability performance of the structure, such as concrete production, placement, compaction, finishing and curing, as well as proper placement and fixing of the steel reinforcement, are not duly taken into account by these approaches, making their predictions often not realistic.

Moreover, the final result is strongly affected by the values selected by the user of elusive variables, such as "ageing exponent" m, surface chloride concentration C_s and critical chloride threshold C_{cr}.

The "Realcrete" approach, based on measurements conducted directly on the structure, in particular of the 'penetrability' and thickness of the "Covercrete" is, in the author's opinion, the way to go. Two approaches were presented, the South-African approach, based on laboratory tests on cores drilled from the structure and the still embryonic Ref-Exp approach, based on NDT of air-permeability and cover depth on site. Hopefully, more will come in the future.

Laboratory research is easier, cheaper and sometimes shorter-termed than site investigations. It has provided important knowledge on transport mechanisms through concrete, their governing laws and also useful tests to measure their parameters. It has also created the foundations for the development of theoretical models for SLP. However, this is not sufficient and, despite higher costs and complexity, more site investigations are needed.

Therefore, as final recommendation, it is suggested that more efforts are placed on long-term research projects, investigating structures under different exposure conditions, combining laboratory tests and site testing at early ages, followed by condition monitoring as the structures age, so as to have stronger relations between early properties and long-term behaviour. Industries with an interest on durability of concrete structures should support financially such projects.

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