USE OF SERVICE LIFE MODELLING, ROUTINE TESTING AND MONITORING FOR CONCRETE DURABILITY

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ABSTRACT. The objective of this paper is to outline an approach for achieving the 100 year design service life of concrete by designing the mixes using service life modeling software and then ensuring it is achieved in practice with routine testing and monitoring during concrete production process. The durability design parameters like Chloride migration coefficient, w/cm ratio, concrete cover and percentages of various supplementary cementitious materials are selected based on type of exposure conditions for the structural elements and used as an input in the service life modeling software to estimate the service life. The modelling software use Fick's second law of diffusion for saturated materials or finite element method for both saturated and unsaturated materials to model the transport properties of concrete. Depending on the saturation level of concrete the modelling software is chosen and the input parameters are changed iteratively until the software predicts the service life in excess of 100 years. Concrete trial mixes are then designed by using the resulting software input parameter values and percentages as limiting values. It is further ensured that the trial mix achieve the minimum required compressive strength per governing code based on the specified design compressive strength. Upon commencing of production of the concrete the proportions of mix are constantly monitored using strict quality control process in order to minimize any deviations and routine testing of durability indicators of mix should be carried out at the same frequency as the compressive strength of concrete. This paper aims to define a structured approach that practicing engineers and experienced contractors can follow to design concrete mixes for 100 year service life.

Keywords: Concrete**,** Durability, Design Service Life, 100 year

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INTRODUCTION

Public and private sector clients nowadays are demanding that their structures be designed for more than 100 years of service life. There are two requirements to be met in order for structure to provide the desired service life. Strength design is the first requirement and durability is the second. If either of the requirement is not met, the structure will not be able to attain the 100 year service life.

All the international design codes provide methods and guidance to calculate the loads to be applied on the structure based on its usage and desired service life. In regards to durability most commonly used international standards like ACI and Eurocode provide prescriptive requirements based on the exposure conditions in terms of minimum concrete cover, type of cement to be used, minimum design compressive strength, maximum w/cm ratio and limits on supplementary cementitious materials.

The clients in their contract concrete specifications specify additional requirements for concrete durability indicators like RCPT, Water Absorption, Water Permeability, Chloride Content and Sulfate Content depending on exposure conditions. However neither the Contract specification nor the standards provide any methodology to calculate the service life of concrete even after it meets all the code or contract requirements based on its exposure conditions.

There are several other factors which have to be considered in achieving a durable concrete structure. Service life modeling is done for concrete exposed to chloride, therefore the discussion in this paper is limited to chloride exposure only. The focus of this paper is to outline an approach to quantify and to prove to the clients that the 100 year service life of concrete desired by them for their assets can be achieved by firstly deciding the concrete mix parameters and running them through a service life modelling software. Secondly by controlling these parameters during concrete mix design and production phase by regular QA/QC process and thirdly by making in-situ measurements of the cast concrete.

CURRENT DURABILITY REQUIREMENTS FOR CONCRETE

Chloride is one of the major aggressive agents for concrete structures. Exposure of concrete structures to chlorides can occur from deicing chemicals, salt, brackish water, seawater, spray from any of these sources and chlorides present in concrete itself. The primary mode of failure of concrete structures exposed to chlorides is by corrosion of rebar. The chloride ions travel through concrete cover and start to depassivate the alkaline coating from cement paste on the rebar and corrosion of rebar starts once the chloride concentration exceeds the critical level of 500ppm.

ACI 318-08, Table 4.2.1 defines three classes of exposure to chloride as stated in table 1 below:

Table 1 Extract from Table 4.2.1 ACI 318-08

CATEGORY	SEVERITY	CLASS	CONDITION
C Corrosion protection of reinforcement	Not Applicable	C0	Concrete dry or protected from moisture
	Moderate	C1	Concrete exposed to moisture and not to external sources of chlorides
	Severe	C2	Concrete exposed to moisture and an external sources of chlorides from deicing chemicals, salt, brackish water, seawater, or, spray from these sources

Based on the exposure class determined from the table above, ACI 318-08, Table 4.3.1 specifies the limits of maximum w/cm ratio, minimum compressive strength, and maximum chloride content in the concrete and provides reference to minimum concrete cover. The values of the same are shown in table 2 below

Table 2 Extract from Table 4.3.2 of ACI 318-08

EXPOSURE CLASS	MAX W/CM	MIN F'C MPA	ADDITIONAL MINIMUM REQUIREMENTS		
			Maximum water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement		Recommended Minimum Cover
			Reinforced Concrete	Prestressed Concrete	
C0	N/A	17	1.0	0.06	
C1	N/A	17	0.30	0.06	
C2	0.40	35	0.15	0.06	50mm for walls and slabs 65mm for other members

The concrete structure complying with above stated minimum requirements is deemed to satisfy the durability requirements for typical 50 year design service life. However the clients are requiring 100 year service life and there is no guidance in codes on how to achieve it. In order to overcome that shortcoming infrastructure asset owners typically specify additional testing requirements for concrete exposed to external sources of chlorides i.e. below ground and above ground structures in coastal areas and below ground structures in non-coastal areas. Their commonly used critical values are stated below in table 3.

Table 3 Typical tests and their critical values specified in contract concrete specifications

TEST	TYPICALLY SPECIFIED CRITICAL VALUE
Rapid Chloride Penetration Test(RCPT)	<1000 Coulombs
Water Absorption	1.5%
Water Permeability	10mm
Chloride Content in Concrete	0.15% by wt. of cement
Sulphate Content in Concrete	3.7% by wt. of cement

However the above stated values even if achieved by the design concrete mix during production still do not provide confidence to the owner, engineer and contractor if the concrete will achieve the required 100 year service life.

CONCRETE MIX DESIGN USING SERVICE LIFE MODELLING

Step 1
Based on the chloride content of soil and water samples from the geotechnical investigation an exposure class of concrete is determined.

Step 2
Using the exposure class determined in step 1 in the above stated Code requirements, Contract concrete specifications and structural design, minimum compressive strength, maximum w/cm ratio and minimum concrete cover are chosen.

Step 3
Chloride concentration determined in step 1 is used to evaluate the maximum surface chloride concentration of concrete using the approach given in research literature or default values of the surface chloride concentration are used from the Life-365 program database.

Step 4
Rate of buildup of the maximum surface chloride concentration can be determined from available studies for the location or by using the similar location rate from the Life-365 program database

Step 5
Monthly average temperatures are taken from the local weather data.

Step 6
Clear concrete cover and maximum w/cm ratio determined in step 1, maximum surface chloride concentration and its rate of buildup in step 3 and 4, monthly average temperatures from step 5 are input into the program and base case is run to evaluate the service life.

Step 7
If the service life evaluated by the program is more than 100 years for the chloride exposure conditions defined in steps 1 to 4. Then the mix is designed accordingly.

Step 8

If the service evaluated by the program is less than 100years SCMs are added based on the maximum limits specified for the type of SCM according to the code requirements.

Step 9

Percentages of SCMs and w/cm ratio are varied for different mixes in order to achieve the desired service life of 100 years.

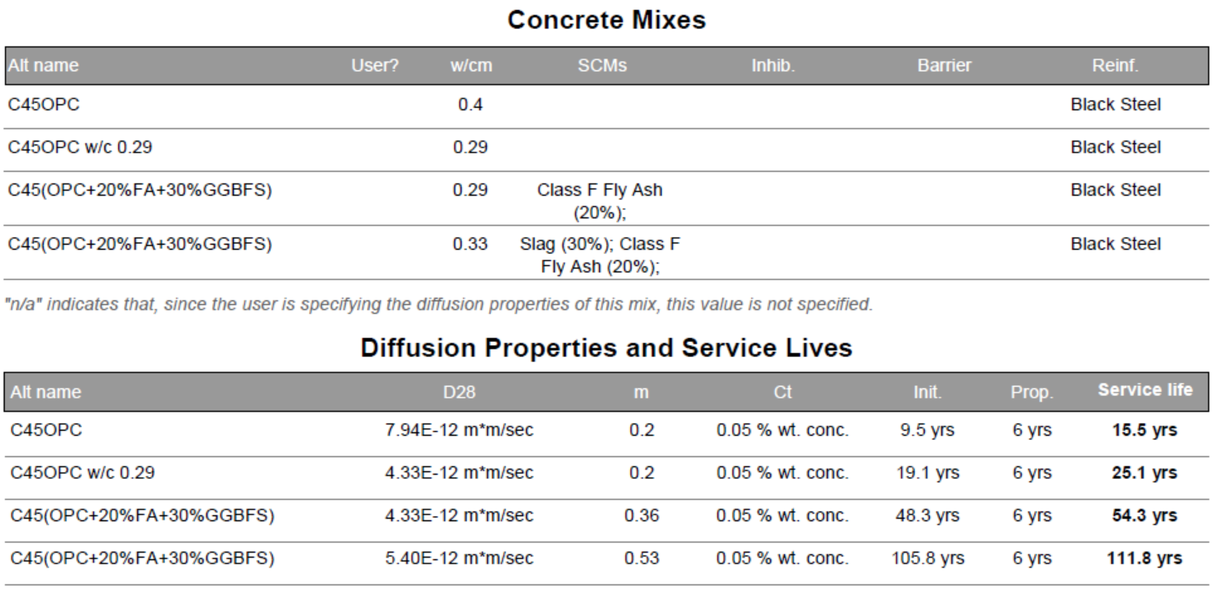
Step 10

The input and output parameters such as concrete cover, w/cm ratio, percentages of SCMs and diffusion coefficient are taken as limiting values for the design of trial mix for concrete.

Step 11

Trial mix is designed for the required compressive strength based on the specified compressive strength from the structural design and the limiting values taken in step 10.

A case study was done for the purpose of this paper to highlight the process defined in above steps. Sample output from the Life-365 program is attached below in Figure 1.



Concrete Mixes

Alt name	User?	w/cm	SCMs	Inhib.	Barrier	Reinf.
C45OPC		0.4				Black Steel
C45OPC w/c 0.29		0.29				Black Steel
C45(OPC+20%FA+30%GGBFS)		0.29	Class F Fly Ash (20%);			Black Steel
C45(OPC+20%FA+30%GGBFS)		0.33	Slag (30%); Class F Fly Ash (20%);			Black Steel

"n/a" indicates that, since the user is specifying the diffusion properties of this mix, this value is not specified.

Diffusion Properties and Service Lives

Alt name	D28	m	Ct	Init.	Prop.	Service life
C45OPC	7.94E-12 m*m/sec	0.2	0.05 % wt. conc.	9.5 yrs	6 yrs	**15.5 yrs**
C45OPC w/c 0.29	4.33E-12 m*m/sec	0.2	0.05 % wt. conc.	19.1 yrs	6 yrs	**25.1 yrs**
C45(OPC+20%FA+30%GGBFS)	4.33E-12 m*m/sec	0.36	0.05 % wt. conc.	48.3 yrs	6 yrs	**54.3 yrs**
C45(OPC+20%FA+30%GGBFS)	5.40E-12 m*m/sec	0.53	0.05 % wt. conc.	105.8 yrs	6 yrs	**111.8 yrs**

Figure 1 Life 365-Output Report

Diffusion coefficient in the Life-365 report is calculated by the program and is taken as an upper bound limiting value for the trial mix design. The diffusion coefficient using NT492 test is determined at 28 days during the trial mix design and compared with program output value. In addition RCPT value is also evaluated and compared with the Contract specification. If both the above test results comply with the limiting reference values then the trial mix is deemed to meet the design requirement of 100 year service life for chloride penetration. The lower of RCPT value from the test or the contract specification shall be used in the concrete production phase.

QUALITY ASSURANCE AND CONTROL DURING CONCRETE PRODUCTION

Monitoring the quality of production concrete is of utmost importance in order to achieve the desired result of 100year service life. Concrete compressive strength results at the batching plant can be used as an indicator showing the trend in change of durability characteristics if the strength results show significant variation from the required compressive strength of the trial mix. Also the batching and mixing of concrete at the plant should be carefully monitored and deviations shall be minimized.

Durability tests stated in table 3 above shall be carried out at the same frequency as the compressive strength results for strict quality control. Frequency of testing shall be as specified in the contract concrete specifications or in accordance with governing design codes of the project. More stringent requirements of the two shall be followed. Critical values of the durability test results shall follow the characteristic compressive strength principle and no more than 5% of the results shall be above the chosen limiting value assuming a normal distribution of the test results. In any case the chloride content in the concrete shall not exceed the code stipulated value for the respective exposure class.

CONCLUDING REMARKS

This paper provides a step by step procedure of how to design concrete mixes for durability. Software like Life-365 provides a simplified approach for concrete durability against chloride penetration. However as a note of caution the principle behind it is suitable for saturated materials only (i.e. Fick’s law of diffusion) and for unsaturated materials it makes an approximation for calculating the chloride penetration. Furthermore it does not account for cement chemistry as C3A content in cement affects its chloride binding capacity significantly. Therefore it will give false positive if concrete mix uses sulfate resistant cement.

Fortunately, advanced programs like STADIUM which are based on finite element analysis are available, which overcome all the limitations of Life-365. Another advantage of the programs like STADIUM is that they do physical and chemical equilibrium checks and thus cement chemistry can be accounted. The approach outlined in this paper can be used with finite element analysis software as well and thus giving a robust solution for concrete service life engineering.

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