

# Improvement of the service life of sustainable self-compacting concrete SCC by integrating high dosage of cement replacement

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**Abstract**— Based on simple diffusion theory and a time-dependent factor ( $\alpha$ ) for the chloride diffusion coefficient, chloride penetration through concrete was numerically modelled and the service life was predicted. This was done for two reference mixes (normal vibrated concrete, NVC and self-compacting concrete, SCC) and three other types of sustainable SCC incorporating high levels of cement replacement. All the mixes have a design compressive strength of 50-60 MPa at 28 days with different types of binders. In this study, the non-steady state chloride diffusion coefficients ( $D_{nss}$ ) and the surface chloride concentrations ( $C_s$ ), which are mainly used for the numerical modelling of the chloride penetration phenomena, were calculated according to the recommendations of Nordtest methods NT BUILD 443 with the aid of using a developed excel solver tool. The numerical results indicated that the NVC at the same design strength level of the reference SCC showed lower service life and higher depth of cover design. For the sustainable SCC, the results showed that the incorporation of relatively high partial replacement of fly ash (FA) Class F and the combined high partial replacement of FA with the silica fume (SF) has little effect on the penetration parameter ( $K_{cr}$ ) relative to that of reference-SCC. However, the incorporating of limestone powder (LP) at the same cement replacement ratio as other admixtures increased the  $K_{cr}$ , reduced the service life and increased the depth of cover design even when compared to the NVC at the same strength level.

**Keywords**—Modelling of chloride penetration, Nordtest method NT BUILD 443, sustainable self-compacting concrete; diffusion coefficient; service life; cover design;

## I. Introduction

Everywhere in the world, corrosion of steel in concrete has been recognized as the main reason for concrete structure deterioration. Each type of concrete, even of poor quality, can offer a certain protection to the embedded steel. However, “the question of interest in the use of steel is not whether this process will occur (it will!) but how fast it will occur in practice” [1].

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Due to the expensive cost of repair and maintenance, this problem has a significant impact on the economy. For example, the US Federal highways administration estimated in 2001 that \$6.43 to \$10.15 billion was required for maintenance and replacement of bridges due to corrosion of which maintenance of concrete bridges was valued at \$2.14 to \$5.86 billion [2]. In the UK particularly in England and Wales, the cost of bridge repairing due to this problem only, was about £616.5 million in 1989 [3]. According to these cost statistics, therefore, the influence of concrete steel corrosion problem on the economy of the countries is very significant. Recently, due to the corrosion of steel reinforcement, the US Federal Highway Administration has stated that, among 134,000 reinforced concrete bridges, 23% of them need repairing immediately, and 39 % are in a bad condition and about \$90 billion would be the total cost of repair [4].

Expansion, cracking and finally spalling of the concrete cover is a result of the corrosion of steel reinforcement. This is due to the increase of the volume of rust on the steel surface as compared with the original steel. Furthermore, the steel in reinforced concrete members may endure a reduction in cross-sectional area and bond strength with the concrete due to corrosion and hence, structural failure might become possible [4]. One of the most important cause of steel corrosion is the presence of chloride ions either in the constituents as an internal source (contaminated concrete), or migrating inwards from an external source (sea, underground and de-icing water) which then leads to reduction in the serviceability life of the affected concrete structure. Chloride attack has become an increasingly important area in the study of concrete durability since the middle of the last century [5]. With regard to service life, Tutti 1982 proposed a model which describes the corrosion process with time. He divided the process into two stages: initiation and propagation. The initiation stage can be defined as the time which is needed for the ingress of aggressive substances such as  $Cl^-$  from the external environment to the embedded steel's surface indicating a time before which there is an absolute need for choosing a proper maintenance technique. The second stage is the time between de-passivation of steel until the end of the service life of the concrete structure [6]. In other words, the first phase is the time taken by the chloride penetration to destroy the steel protection provided by the high alkalinity nature of the concrete, while the second one is the time taken for the degradation of the embedded steel. In reality, the initiation stage usually takes a long time to happen especially for high quality concrete, and the steel remains in a passive state.

In order to predict the time of this period and proposed a cover design to protect the embedded steel, accelerated

laboratory tests are often used in order to shorten this period and predict the service life. Among the different proposed laboratory accelerated tests are ASTM C1202, NT Build 355, NT Build 492 and NT Build 443. The last is considered as the test method most similar to the real condition for submerged concrete structures from which the apparent non-steady state chloride diffusion ( $D_{nss}$ ) and the surface chloride concentration ( $C_s$ ) can be obtained [7]. These two parameters are mainly used for chloride penetration modelling and for predicting the service life of the concrete structures with the aid of the theoretical chloride diffusion process.

Recently, SCC has been used widely in highway bridge construction. Moreover, it is used in widespread applications such as buildings, bridges, culverts, tunnels, tanks, dams, and precast concrete products. Nowadays, SCC forms a remarkably large and vital part of infrastructure and substructures in the world which can be exposed to external environmental attack. In addition, it is expected that NVC will be replaced by SCC in many future applications [8-11]. In particular, medium strength SCC has been used widely for various precast concrete elements and it is planned for many other applications [12]. This widespread use of medium strength SCC could increase probability of the exposure to severe chloride environment.

One of the most recent potential developments that could contribute effectively to achieving low cost sustainable SCC construction, and improve both the mechanical and durability characteristics of concrete in general and SCC in particular, is the use of relatively high dosages of reactive and non-reactive natural fillers or manufacturing by-products as a partial replacement of cement [13-15]. With appropriate selection and mix design, these replacements need not interfere with the development of concrete strength so that the modified mix still obtains a medium to high design compressive strength at 28 days. But much less is known about the ability of these modified SCCs to resist chloride penetration. Therefore, the main aim of the investigation reported here is to examine the use of relatively high dosages of different types of filler such LP, FA and the combined partial replacement of cement of FA plus SF to improve the service life against chloride penetration of a medium to high strength SCC as compared to other two reference mixes (NVC and SCC) at the same design strength level (50-60) Mpa.

## II. Experimental program

### A. Materials

Ordinary Portland cement CEM I, 52.5 R conforming to EN 197-1 was used for the purpose of production of all concrete and mortars. Natural limestone filler (LP) which is mainly  $CaCO_3$  was used as non-reactive filler. Fly ash (FA) class F conforming to BS EN 450-1 and densified silica fume (SF) were used as reactive filler and mineral admixture respectively. Table1 shows some physical and chemical properties of these materials while Fig.1 shows their partial size distribution.

TABLE I. SOME CHEMICAL AND PHYSICAL FEATURES OF THE CEMENT, USED FILLERS AND MINERAL ADMIXTURE

Chemical composition% /property	Material			
	Cement	Fly ash	Limestone	Silica fume
SiO <sub>2</sub>	20.09	50	0.3	> 90
Fe <sub>2</sub> O <sub>3</sub>	3.87	6.9	--	--
Al <sub>2</sub> O <sub>3</sub>	8.84	26	--	--
CaCO <sub>3</sub>	--	--	99	--
L.O.I	2.36	< 3	42.3	< 3
Sp. Gr.	3.15	2.21	2.7	2.2

L.O.I: Loss on ignition, Sp. Gr.: Specific gravity

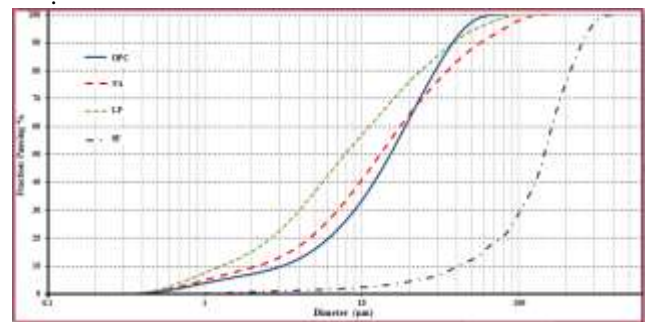


Figure 1 Particle size distribution of the cement, fillers and mineral

Uncrushed quartz gravel and sand was used as coarse and fine aggregates with maximum sizes of 10 mm and 5 mm respectively. The specific gravity and the water absorption of the gravel were 2.65 and 0.8 % respectively while for the fine aggregate they were 2.65 and 1.5 %. The grading of the coarse and the fine aggregate confirms to the limits of BS 882:1992 [16] as shown in Fig.2.

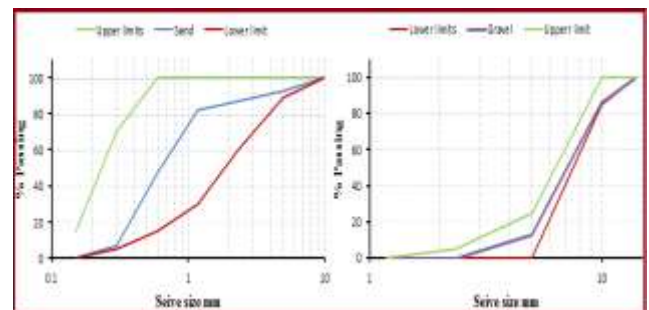


Figure 2 Grading curves of fine and coarse aggregate

To maintain the required fresh properties of both SCC and mortars, Superplasticizer (SP) based on polycarboxylic ether (PCE) polymer was implemented

### B. Mix design and production of normal vibrated concrete NVC and SCC

The mix design of NVC and SCC mixes and their fresh requirements are shown in Tables 2 and 3 respectively. The binder types were cement for NVC and the reference-SCC and cement with relatively high partial cement replacement (33%) of fillers or mineral admixtures FA, LP and SF for the other three sustainable SCC mixes. The preliminary mix design was based on a Japanese method (based on volumetric contents). The optimized SCC mixes in Table 2 were based on several trial batches with different SP dosages.

Slump flow test was used to assess both the flowability of SCC (diameter of greater than 600mm) and  $T_{50}$  (time to obtain 500 mm flow less than 5 seconds) while the J-ring and segregation tests were used for both calculating  $B_j$  (blocking step) and SI (segregation index). The mini slump flow was used to assess the flowability of the SCC mortars which were between 240-300mm using the same original dosage of SP as for the full concrete.

The mix design of the NVC is completely different from that of SCC. In preliminary work, five NVC mixes were designed using the absolute volume method with a fixed mix proportion of 1:2:3 (cement: fine aggregate: coarse aggregate) by weight and nominal cement content of 365 kg/m<sup>3</sup> with different water to cement ratios (w/c) (0.4, 0.45, 0.5, 0.6 and 0.7). Then, the NVC-mix in Table 2 was typically selected when a 50 MPa compressive strength at 28-days was achieved (see Section 4.1). This is in addition to achieve an acceptable slump of 15 mm for casting purposes.

The NVC and SCC mortars contained the same constituents in the same proportion but without coarse aggregate. However, the water quantity for the mortar was reduced by about 0.8% (coarse aggregate absorption) in order to ensure the same available water content as for the full concrete.

TABLE II. MIX DESIGN DETAILS

Materials (kg/m <sup>3</sup> )	Mix title				
	NVC	R-SCC	LP-SCC	FA-SCC	FA-SF-SCC
OPC	365	450	300	300	300
C-agg.	1095	875	860	825	825
F-agg.	730	900	900	900	900
Water	183	180	180	180	180
FA	--	--	--	150	120
LP	--	--	--	150	--
SF	--	--	--	--	30
SP% by wt.	--	3.9	2.6	1.83	3.1

TABLE III. FRESH REQUIREMENTS OF THE FRESH CONCRETE MIXES

Property	Mix title				
	NVC	R-SCC	LP-SCC	FA-SCC	FA-SF-SCC
Slump flow mm	15-slump	610	700	720	680
$T_{50}$ sec	--	3.7	4.5	3.2	3.6
$B_j$ -±2mm	--	10	7	6.25	5
SI (%)	--	3	11.2	9.25	8.2

### III. Methodology and tests performed

#### A. Compressive strength test

100 mm cubes were used for the compressive strength test. The test was conducted on three cubes at 7, 14, and 28 days according to BS EN 12390-3: 2002 [17].

#### B. Chloride penetration test

The chloride penetration test was performed in accordance to the recommendation of the Nordtest method NT BUILD 443[18] standard using 70mm mortar cubes. This was done in order to reduce any variation in the chloride penetration path resulted from differences due to coarse aggregate proportion in the mix design of full NVC and SCC. The NVC and SCC mortars have the same proportions of the fine aggregate (See Table 2). To a large extent this should minimize the effect of the aggregate phase in determining the chloride penetration path taking into account that the aggregate (fine/coarse) is considered as an impermeable phase for the chloride ions as compared to the cement matrix. Further, the diffusion of the free chloride ions occurs in the pore water solution through the continuous capillary pores of the cement matrix and the percolated pores of Interfacial Transition Zones (ITZs) formed around the aggregate (both fine and coarse).

After casting and demoulding, the mortar specimens were cured for 28 days in potable water before full immersion in NaCl solution with a 2M concentration (165 gm/L). Prior to the immersion, the mortar cubes were vacuumed using 100 mb for 3 hours and then left in a saturated Ca(OH)<sub>2</sub> solution for three days to ensure full saturation, which is essential for the chloride diffusion test. Finally, five faces of the mortar cubes were sealed very well, to ensure only one direction of chloride penetration which was perpendicular to the casting direction, and then the cubes were submerged in the salt solution. The containers were covered by polyethylene and kept in the laboratory for 90 days. The Nordtest methods NT BUILD 433 standard proposed an immersion period of at least 35 days for low quality concrete and 90 days for high quality ones[19].



### C. Preparing of concrete powder sample and titration test

After 90 days, the specimens were extracted from the salt solution and kept in the laboratory for a suitable time for drying. The specimens then were placed in grinding machine to remove 1mm layers and the resulting powder was collected with the aid of a hand vacuum device. 0.3 to 1 g from the powders sample were weighed using a high sensitive balance with an accuracy of 0.0001 g and kept in a sealed glass containers up to the day of titration tests to calculate the their chloride contents.

Among the different proposed techniques to determine the chloride contents of the powdered cementitious material, the titration method is recognized to be an accurate method for calculating the chloride concentration/content. As reported by Dhir, 1990 [20], this method is able to detect up to 94% of the total chloride content (free plus combined ions). Thus, the standard Volhard titration method was used for this purpose. The profiled powder samples were dissolved in 50 ml distilled water and acidified with 10ml of nitric acid ( $\text{HNO}_3$ , 5M). The beakers and the solution were boiled to about 150 °C for 4-5 minutes with continuous stirring to allow complete dissolution of the chloride ions from the powder samples. Then, the solutions were filtrated using a filtration paper and an additional 40ml of distilled water was added to maintain a total volume of 100ml of the solution. The 100ml solutions were kept in well-sealed standard plastic bottles and provided for the titration test. Four solution samples (each 25 ml) were used for the titration test against a standard titrant ( $\text{AgNO}_3$ , 0.041M) after adding 3-5 drops of Potassium dichromate ( $\text{K}_2\text{Cr}_2\text{O}_7$ ). The calculated chloride content represent an average of three titration trials of each solution sample where  $(V_1 - V_2)$  is  $\pm 0.02$  ml. The chloride content was calculated using (1):

$$[Cl^- \text{ g}] = [0.041 \times (V_1 - V_2) / 25] \times 35.5 \quad (1)$$

$V_1$ : the volume of the titrant in the burette before titration

$V_2$ : the volume of the titrant in the burette after titration up to the equilibrium point when the solution color changed from yellow to brown, as shown in Fig.3.

35.5: atomic mass of the chlorine, 25: the volume of the solution (ml) and 0.041: molarity of the titrant ( $\text{AgNO}_3$ ). The preparation of the profiled powder samples and the titration steps are summarized in Fig.3.



Figure 3 Powder samples collection and titration process

## IV. Results and discussions

### A. Compressive strength test

The developments of the compressive strength of the NVC and SCC up to 28 days are summarized in Fig.4.

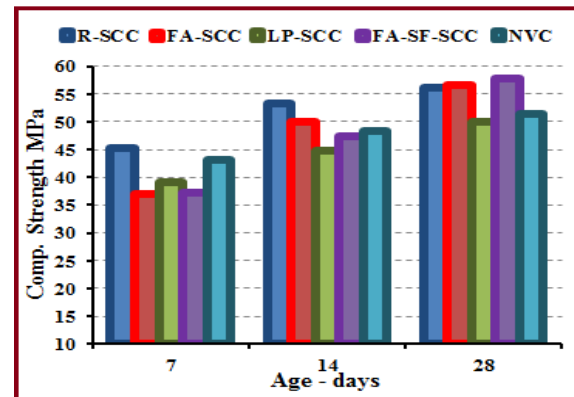


Figure 4 Compressive strength development

In general, the results indicate that all sustainable SCCs showed a lower strength in comparison with the control SCC mix at early ages (7 and 14 days). Clearly, this behavior can be attributed to the reduced opportunity for rapid hydration of cement due to its relatively high partial replacement by other fillers. However, it is seen that the difference in the compressive strength between the SCC mixes becomes less at 28 days by which time all the SCC mixes had developed a compressive strength of 50-60 MPa. At this age, the SCC made with 33% partial replacement of cement by FA achieved a compressive strength of 56.5 MPa, similar to that of the R-SCC. These results are consistent with Dinakar et al. [15] who stated that for high volume fly ash SCC (HVFA-SCC), a designed compressive strengths level from 20 to 30 MPa could be achieved with a high level of fly ash replacement (70-85%) while a higher compressive strengths (60-90) MPa could be obtained with 30-50 % fly ash replacement.

At 28 days, FA-SF-SCC demonstrated a slightly higher strength level (57.5 MPa) relative to the reference and the other SCC types. This relatively slow development of strength in the mixes with active filler replacements (FA and FA-SF) is reflects the slower hydration of the pozzolans in these materials than of the cement in the reference-SCC. The results also showed that the FA-SCC developed a higher strength at 14 days as compared with FA-SF-SCC and only a small difference in the compressive strength was recorded at 28 days. On the other hand, the NVC and LP-SCC showed approximately the same strength development trend and the same strength level at 28 days.

### B. Diffusion calculation

The apparent chloride diffusion coefficients ( $D_{nsc}$ ) and surface chloride concentrations ( $C_s$ ) values for the NVC and SCC were calculated from the non-linear curve best fitting of the chloride content (% by weight of concrete) versus the

depth in mm. The curve fitting was based on a numerical solution using the least squares method for minimizing errors between the obtained experimental results and the theoretical model with the aid of the Excel solver tool. This tool and the steps of the non-linear regression implementation are included in the same Excel sheet as for the chloride ingress modelling (Section 4.3) for each concrete type. An example of the best curve fitting is given in Fig.5 for the NVC. The theoretical model in Fig.5 is a plot of the solution of Fick's second law of diffusion (as used by Nordtest method NT BUILD 443) as shown in (2).

$$C(x,t) = C_s - (C_s - C_i) \times \operatorname{erf}^{-1} [x/\sqrt{(4D \times t)}] \quad (2)$$

$C(x,t)$ : chloride content measured at depth  $x$  at exposure time  $t$ , % by wt. of concrete

$C_s$ : calculated surface chloride content, % by wt. of concrete

$C_i$ : initial chloride content, % by wt. of concrete

$x$ : depth, mm

$D$ : apparent chloride diffusion coefficient (non-steady state  $D_{nss} \times 10^{-12}$ ),  $m^2/sec$ ,

$t$ : exposure time, sec

$\operatorname{erf}^{-1}$ : error function =  $\operatorname{erf}(z) = 2/\sqrt{\pi} \int_0^z \exp(-u^2) du$

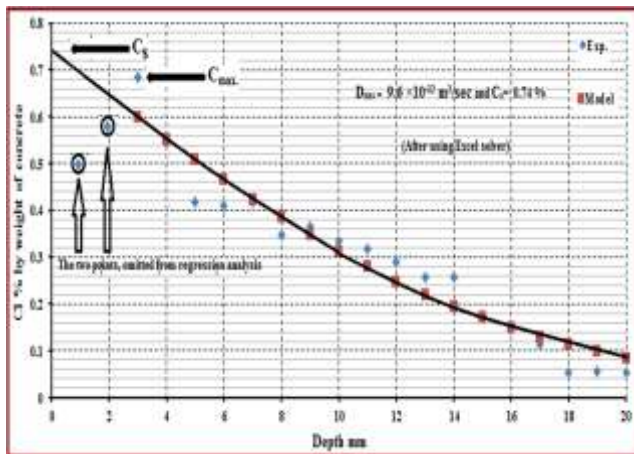


Figure 5 Curve fitting data after using Excel solver

The lower chloride contents than the maximum detected one was omitted from the non-linear regression as shown in Fig.5. These values are normally appear in chloride content-depth relationships [21]. Two such points were observed for the NVC-mix and one point for all the other types of SCC.  $D_{nss}$  and  $C_s$  values for the all concrete types are summarized and listed in Table 4. The penetration parameter ( $K_{cr}$ ) in mm /  $\sqrt{\text{year}}$  which takes into account both the effect of the resulting surface chloride contents and the computed diffusion coefficients is considered more relevant for the chloride resistance comparison purposes although it does not represent the actual chloride penetration velocity [22]. Thus, it was calculated and listed in the same table according to the (3) [22]:

$$K_{cr} = 2 \sqrt{D_{nss}} \times \operatorname{erf}^{-1} [(C_s - C_r) / (C_s - C_i)] \quad (3)$$

$\operatorname{erf}^{-1}$ : the inverse of  $\operatorname{erf}$

$C_r$ : critical chloride content = 0.05% by wt. of concrete and  $K_{cr}$  is defined only when  $C_s > C_r > C_i$

TABLE IV.  $D_{nss}$ ,  $C_s$  AND  $K_{cr}$  VALUES OF THE CONCRETE MIXES

Mix ID	Diffusion parameters		
	$D_{nss} \times 10^{-12}$ ( $m^2/sec$ )	$C_s$ (% by wt. concrete)	$K_{cr}$ (mm / $\sqrt{year}$ )
NVC	9.60	0.74	47.2
R-SCC	8.35	0.31	34.5
LP-SCC	16.03	0.40	51.8
FA-SCC	9.62	0.49	34.9
FA-SF-SCC	8.46	0.31	34.5

The results in Table 4 demonstrated that all the concrete types show approximately similar apparent diffusion coefficients ( $8.35$ - $9.60$ )  $\times 10^{-12}$   $m^2/sec$  including the NVC except LP-SCC. In all mortar samples assessed, except the LP-SCC, the ratio of the active binder (cement, cement plus FA, cement plus FA-SF) to fine aggregate was 1:2, and these for mixes all exhibited similar diffusion coefficient. In contrast the LP-SCC mortar, with an active binder to fine aggregate ratio of 1:3, had a significantly higher diffusion coefficient although the mortar's mix design maintained approximately the same volume of the fine aggregate to the total volume of the cement matrix (50.7% for LP-SCC mortar and 49.7-51.2% for the other mortars). Therefore, it seems likely that chloride diffusion is reduced by interaction with an active binder. Chemically, the matrix of LP-SCC might not have similar chloride binding ability as compared to the cement itself in NVC and R-SCC and cement plus active fillers even with the low water to cementitious material ratio used. Physically, the quantitative analysis of the pore structure of this type of concrete and the micro-features of its ITZ indicated a more open microstructure, with less homogeneity ITZ [23, 24].

The results also indicated that the NVC established the highest surface chloride content (the highest impact of the chloride load ( $C_s$ )) as compared to the other SCC types. At the same time, it showed slightly higher chloride resistance as compared to LP-SCC. The calculation of the penetration parameter  $K_{cr}$  might help to explain these results. The LP-SCC showed the highest  $K_{cr}$  signifying the lowest chloride resistance followed by NVC with only a little greater resistance. All the SCCs containing fully active cementitious material (i.e. cement or active-cement replacement) show much greater, and broadly similar, resistance to chloride penetration. Thus, it is apparent that the SCCs mixes provide a denser matrix more resistance to chloride penetration, but that this improvement is undermined when some of the active filler (cement) is replaced by passive filler (LP). This, in part, resistance to chloride penetration is provided by interaction of the chloride with hydration products. Given the hydration in progressive, this implies a non-constant diffusion coefficient.



### C. Modelling of chloride penetration and prediction of service life

The estimation of the service life of the normal and SCC mixes was performed numerically for different ages to find  $C(x,t)$ , based on the solution of Fick's second law (2) as shown in Figs. 6-10. As indicated above hydration and diffusion are interacting mechanisms for the chloride movement through concrete. Therefore, to predict long-term diffusion, which is the most familiar controlling mechanism for the chloride ingress process (submerged concrete structure) [19], the values obtained in the short term ( $D_{nss}$  at 90 days as given in Table 4) must be adjusted to a time-dependent value. This is achieved using the formula presented as (4)[25]:

$$D_{a(t)} = D_{ao(t)} (t_0/t)^\alpha \quad (4)$$

$D_{a(t)}$ : Time dependent chloride diffusion coefficient

$t$  : Maturity age and  $t_0$  : Reference maturity age (when concrete exposed to chloride)

$D_{ao(t)}$ : Achieved apparent chloride diffusion coefficient ( $D_{nss}$ ) at maturity age  $t_0$

$\alpha$  : Aging factor (reduction in  $D_{nss}$  with time due to continuous hydration plus binding effect.

Current experience indicated that the aging factor of CEM I based concretes and of FA based concrete is 0.4 and 0.6 respectively and may still be used for the estimation of a proper aging factor [21]. The aging factor of LP based concrete is not available in the literature. Therefore, it is assumed to be similar to the NVC mix (i.e. 0.4) due to the same trend in compressive strength development up to 28 days (see Section 4.1). For the FA-SF SCC the FA aging factor has been adopted (0.6). The critical chloride content for the steel corrosion initiation is between 0.05-0.07 by weight of concrete for different exposure humidity and conditions and normally is taken as 0.05% by weight of concrete [21, 26] (See horizontal lines on Figs. 6-10).

In interpreting the results, we can note that relation between the field exposure and the laboratory exposure assumed by the Nordtest method NT BUILD 443 has been found for the concrete, as reported by Frederiksen et al. 1997 quoted by Nilsson, 2001 [27]. The result of the present investigation shows that the values of the surface chloride concentrations were between (0.31-0.74) which occurs in the range of various types of concrete structure exposed to severe chloride environments in the natural field for different exposure ages [21].

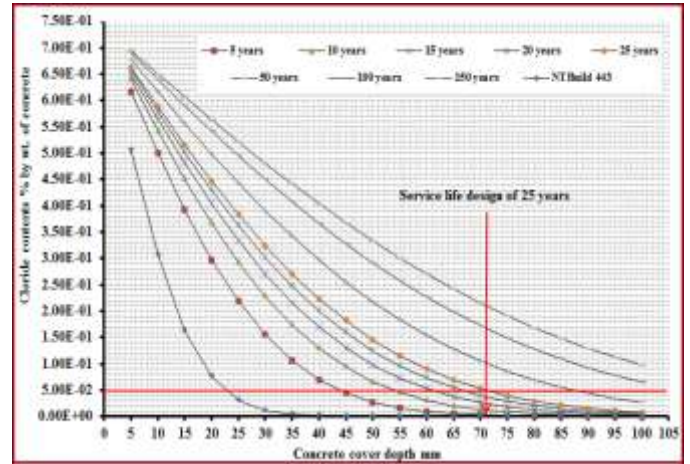


Figure 6 Chloride ingress model – NVC

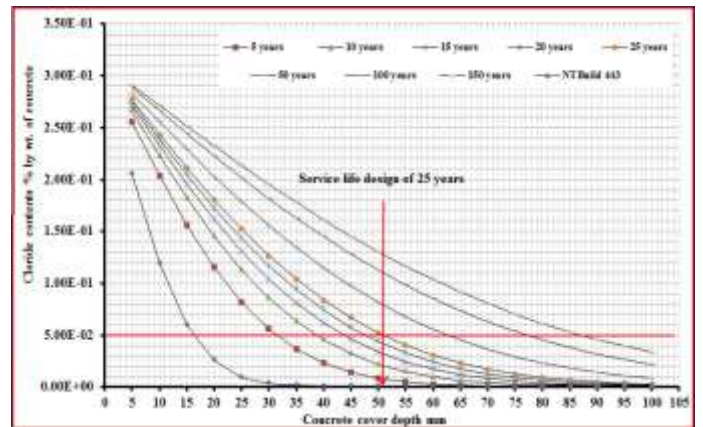


Figure 7 Chloride ingress model – R-SCC

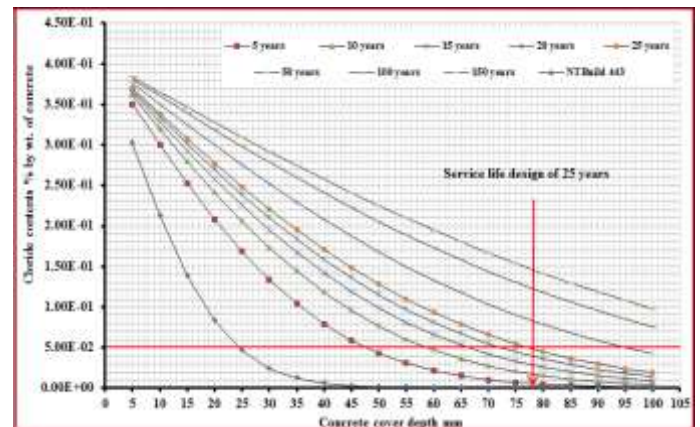


Figure 8 Chloride ingress model – LP-SCC

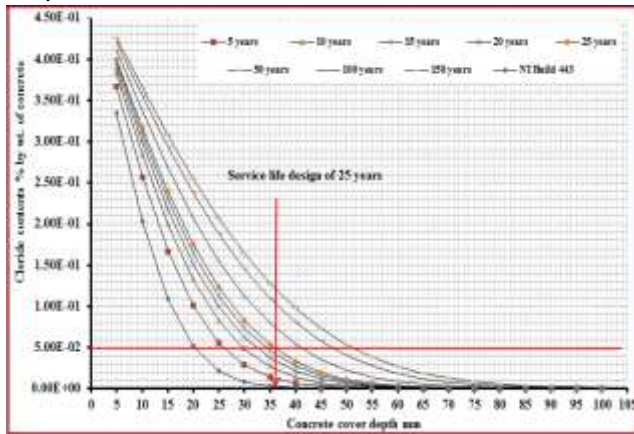


Figure 10 Chloride ingress model – FA-SCC

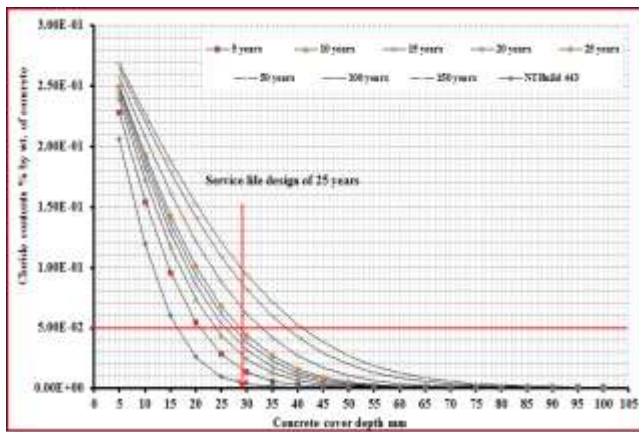


Figure 9 Chloride ingress model – FA-SF-SCC

Using these approaches Figs. 6-10 show that, in order to achieve a service life design of 25 or 50 years, the theoretical designed concrete cover for the NVC mix should be 71mm or 87 mm respectively while it should be 51mm or 63 mm for the R-SCC. Further, for the LP-SCC, to achieve 50 years' service life would require excessive concrete as much as 78mm being needed even for 25 years protection. It should be borne in mind that the increase of the cover thickness beyond 70 mm could have an adverse effect, as it can increase the probability of the concrete cover cracks due to the external load, depending on the design purpose and it will increase the whole cost of concrete element construction. The FA-SCC and FA-SF-SCC decrease the required cover thicknesses to about 36mm and 29mm for 25 years' service life and 42mm and 33mm for 50 years' service life respectively.

## v. Conclusion

Based on the results of the present study, the following concluding remarks are derived:

- ✚ The incorporation of relatively high replacements of cement by LP increased the apparent diffusion of chloride through SCC and penetration parameter ( $K_{cr}$ ) as compared to NVC for the same design strength. The  $K_{cr}$  of this type of SCC was slightly higher than that of the NVC even with the use of lower water to cementitious material ratio.
- ✚ The NVC exhibited the highest surface chloride content assessed by Nordtest method NT BUILD 443 test among all the tested types of SCC. However, it achieved a slightly lower penetration parameter as compared to the LP-SCC.
- ✚ A simplified service life model for the chloride ingress in concrete has been proposed using a numerical tool developed in Excel solver to calculate the diffusion coefficient and surface chloride content according to the NT build 443 accelerated tests.
- ✚ According to this model, the theoretical thicknesses for the concrete cover design were 71mm, 51 mm, 78mm, 36mm and 29mm for 25 years' service life for NVC, R-SCC, LP-SCC, FA-SCC and FA-SF-SCC (having the same design compressive strength, 50-60 MPa) respectively. The corresponding values were 87mm, 63mm, more than 95mm, 42mm and 33mm for 50 years' service life. Thicknesses greater than 70mm are often viewed as undesirable, thus only the mixes with cement or cement plus active fillers achieve practical resistance to chloride penetration in the long term.

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