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 the theoretical background of Fick's second law of diffusion and the time-dependent factor (α) for the chloride diffusion coefficient, the chloride penetration was numerically modelled and the service life was predicted using a simplified separate excel sheet. 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 level 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 concentration (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 433 with the aid of using a developed excel solver tool.

The numerical results indicated that the NVC at the same design strength level of reference SCC showed lower service life and higher depth for 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) only can keep the penetration parameter (K_{Cr}) as similar as that for the R-SCC. Further, the incorporating of LP at the same cement

replacement percentage of other admixture 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 methods NT BUILD 433, sustainable self-compacting concrete; diffusion coefficient; service life; cover design; cement replacement,

1. 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]**. For the last 20 years, corrosion of embedded steel in concrete has been considered as one of the most serious problems for civil engineers. Due to the expensive cost of repair and maintenance, this problem has a significant impact on the economy. For example, the US spends more than $150 million per year in repairing bridges and buildings that suffering from steel corrosion. 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. These two countries together have only 10% of the bridges in the UK. Therefore, steel corrosion problem has a major influence on the economy of this country **[2]**. 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 **[3]**. 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 **[3]**. 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 from an external source (sea, underground and de-icing water) which then leads to reduction in the serviceability life of the affected concrete structure. This chloride attack has become an increasingly important area in the study of concrete durability since the middle of the last century **[4]**. With regard to the 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^- or CO_2 from the external environment to the embedded steel's surface indicating a time for a real 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 concrete structure **[5]**. In other words, the first phase is the time taken by the chloride penetration and the carbonation reaction to destroy the steel protection provided by the high alkalinity nature of the concrete, while the second one is the time of 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 mostly used in order to shorten this period and predict the service span in. Among the different proposed laboratory accelerated test such as ASTM C1202, NT Build 355, NT Build 492 and NT Build 433, the latter is considered as the most similar test method to the real condition for the submerged concrete structure where the apparent non-steady state chloride diffusion (D_{nss}) and the surface chloride concentration (Cs) could be obtained **[6]**. These two parameters are mainly used for the chloride penetration modelling and predicting the service life of the concrete structure with the aid of the theoretical basis of chloride diffusion process.

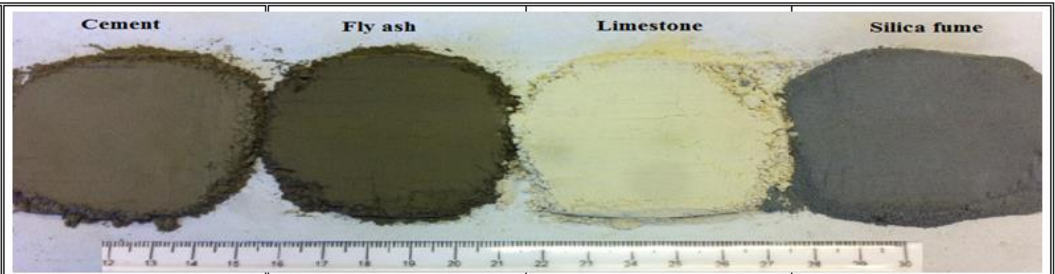
Recently, SCC has been used widely in highway bridge construction. Moreover, it is used in widespread application such as buildings, bridges, culverts, tunnels, tanks, dams, and precast concrete products. Nowadays, SCC forms a remarkably large and vital part of infrastructure and substructures in the world which can be exposed to external environmental attack. In addition, it is expected that the NVC will be replaced by SCC in many future applications **[7-10]**. In particular, medium strength SCC has been used widely for various precast concrete elements and it is desired for many other applications**[11]**. This widespread use of medium strength SCC could increase probability of the exposure to severe chloride environment. One of the most recent potential to contribute effectively on achieving, low cost sustainable SCC construction and to improve both the mechanical and durability characteristics of concrete in general and SCC in particular is the use of relatively high dosage of reactive and non-reactive natural or manufacturing by-products as a partial replacement of cement as reported by several investigations **[12-14].** However, this is without ignoring the development of concrete strength to obtain a medium to high strength design compressive strength at 28 days. Therefore, the main aim of the present investigation is to examine the ability of using relatively high dosages of different types of filler such LP, FA and the combined partial replacement of cement of FA plus SF in improving the service life of a medium to high strength SCC as compared to other two reverence mixes (normal vibrated concrete and SCC) at the same design strength level (50-60) MPa.

2. Experimental program

2.1 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 confirming 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 1 Some chemical and physical features of the cement, used fillers and mineral admixture



Chemical compound% - Property	Cement	Fly ash	Limestone	Silica fume
SiO_2	20.09	50	0.3	> 90
Fe_2O_3	3.87	6.90	---	---
Al_2O_3	4.84	26	---	---
$CaCO_3$	---	----	99	---
L.O.I*	2.36	Category B < 3	42.9	< 3
Sp. Gr.**	3.15	2.21	2.7	2.2

* Loss on Ignition ** Spesific gravity

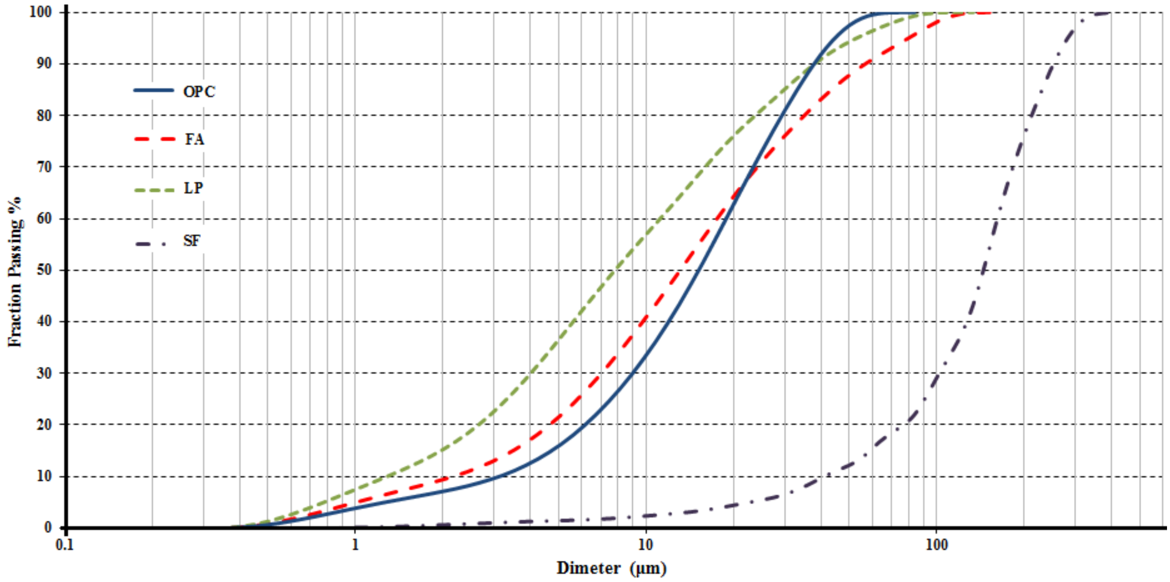


Figure 1 Particle size distribution of the cement, used fillers and mineral admixture

Originally quartz uncrushed 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 % while they were 2.65 and 1.5 % respectively. The grading of the coarse and the fine aggregate confirms to the limitation of **BS 882:1992 [15]** as shown in

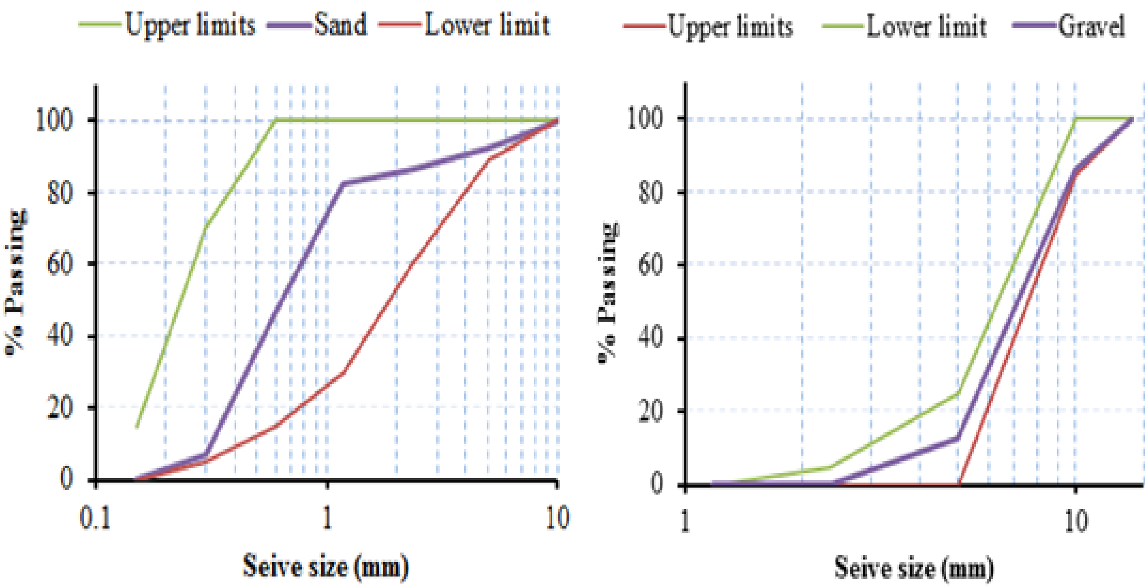


Figure 2 Grading curves of fine and coarse aggregate

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

2.2 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 Japanese method (based on volumetric contents). The optimized SCC mixes in Table 3 where based on several trial batches with different SP dosages. Slump flow test was used to assess both the flowability of SCC (greater than 600mm) and T_{50} (time to obtain 500 mm flow) less than 5 seconds while the J-ring and segregation test were used for both calculating Bj (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 for the full concrete. The mix design of NVC is completely different from SCC. In a preliminary work, five NVC mixes were designed using the absolute volume method with a fixed mix proportion 1:2:3 by weight and nominal cement content of 365 kg/m^3 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 3 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 for the full concrete.

Table 2 Mix design details

Mix title	NVC	R-SCC	LP-SCC	FA -SCC	FA-SF-SCC
OPC (kg/m^3)	365	450	300	300	300
C. agg. (kg/m^3)	1800	875	860	825	825
F. agg.(kg/m^3)	900	900	900	900	900
W (kg/m^3)	183	180	180	180	180
FA (kg/m^3)	---	---	---	150	120
LP (kg/m^3)	---	---	150	---	---
SF (kg/m3)	---	---	---	---	30
SP% by wt.	----	3.9	2.6	1.83	3.1

Table 3 Fresh requirements of the fresh concrete mixes

Mix type	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
Bj (±2mm)	----	10	7.0	6.25	5
SI (%)	----	3	11.2	9.25	8.2

3. Methodology and tests performed

3.1 Compressive strength and density tests

100 mm cubes were used for the compressive strength test .The test was conducting on an average of three cubes at 7, 14, and 28 days according to **BS EN 12390-3: 2002 [16]** using Hydraulic Test Machine.

3.2 Chloride penetration test

The test was performed in accordance to the recommendation of **Nordtest methods NT BUILD 433 [17]** standard using 70mm mortars cubes. This was done in order to reduce any variation in the chloride penetration path resulted from the differences of the mix design of full NVC and SCC i.e. high quantity of coarse aggregate used in the NVC-mix. The NVC and SCC mortars have the same proportions of the fine aggregate (**See Table 2**). To 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 the cement matrix. Further, the diffusion of the free chloride ions occurs through the continuous capillary pores of the cement matrix and the percolated pores of ITZs formed around the aggregate (fine/coarse). After casting and demoulding, the mortar specimens were cured for 28 days in potable water before the exposure to the full immersion in NaCl solution with a concentration of 2M (165 gm/L). Prior the immersion, the mortar cubes were vacuumed using 100 mb for 3 hours and then left in a saturated $Ca(OH)_2$ solution for three days to ensure the 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 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 [17]** standard proposed an immersion period of at least 35 days for low quality concrete and 90 days for high quality one.

3.3 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 specimen then were exposed to a surface crushing using a grinding machine for each 1mm and the resulting powder was collected with the aid of a hand vacuum device. 0.3 to 1 gm from the powders sample were weighed using a high sensitive balance with an accuracy of 0.0001 gm and kept in a sealed glass containers up to the day of the titration test to calculate the their chloride contents.

Among the different proposed techniques to determine the chloride contents of the powdered cementitious material, titration method is recognized to be an accurate method for calculating the chloride concentration/content. As reported by Dhir, 1990 **[18]**, this method is able to detect up to 94% of the total chloride content (free plus combined ions). Thus, standard Volhard titration method was used for this purpose. The profiled powder samples were dissolved in 50 ml distilled water and acetified with 10ml of nitric acid (HNO_3 5 M). The beakers and the solution were boiled to about 150 ºC 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 additional 40ml 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 ($AgNO_3$ 0.041M) after adding 3-5 drops of Potassium dichromate ($K_2Cr_2O_7$). The calculated chloride content represent an average of three titration trials of each solution sample where (V_1-V_2) is ± 0.02 ml. The chloride content was calculated using **Eq. 2.1**:

$$Cl^{-} gm = [0.041 \times (V_1 - V_2/25] \times 35.5$$ ………….. **Eq. 2.1**

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 reach 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)

0.041: molarity of the titrant ($AgNO_3$)

The preparation of the profiled powder samples and the titration steps are summarized in **Fig.3**.

Figure 3 Powder samples collection and titration process

4. Results and discussions

4.1 Compressive strength

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

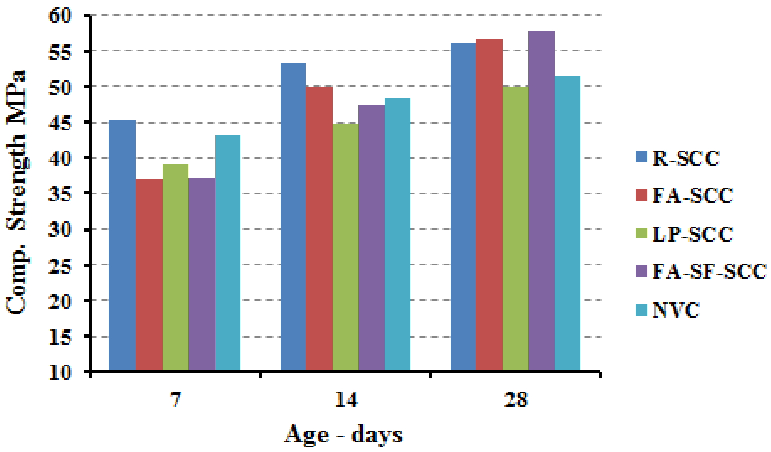


Figure 4 Compressive strength development

In general, the results indicate that all sustainable SCC showed a lower strength in comparison with the control SCC mix at early ages (7 and 14 days). As can be anticipated, this behavior might be attributed to the reduced degree of hydration caused by the relatively high partial replacement of fillers as compared with the reference SCC mix. However, it is seen that the difference in the compressive strength between the SCC mixes becomes less at 28 days where all SCC mixes developed a compressive strength between 50-60 MPa. At this age, the SCC made with 33% partial replacement of cement established a compressive strength of 56.5 MPa which is similar to that of R-SCC. These results are consistent with Dinakar et al. **[14]** 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 obtained with 30-50 % fly ash replacement. At 28 days, FA-SF-SCC demonstrated a slightly higher strength level with relative to the reference and the other SCC types. However, the results 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, NVC and LP-SCC showed approximately the same strength development trend and the same strength level up to 28 days.

4.2 Calculation of apparent chloride diffusion coefficients (D_{nss}), surface chloride concentrations (C_s) and penetration parameter (K_{cr})

The apparent D_{nss} and 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 square method for minimizing the errors between the obtained experimental results and the theoretical model with the aid of using a developed excel solver tool. This tool and the steps of the non-linear regression implementation is included in the same separated excel sheet for the chloride modelling in **section 4.3** for each concrete type. An example of best curve fitting is given in **Fig.5a** and **b** for the NVC. The theoretical model in **Fig.5b** is identical to the solution of Fick's second law of diffusion in accordance to the **Nordtest methods NT BUILD 433** as shown in **Eq. 3.1**.

$$C(x,t) = C_s - (C_s - C_i)\ .\ erf\left(\frac{x}{\sqrt{4D_{nss}\,t}}\right) \quad \text{…………..} \quad \textbf{Eq. 3.1}$$

$C(x,t)$ = chloride content measured at depth x at exposure time t, % by weight of concrete

C_s = calculated surface chloride content, % by weight of concrete

C_i = initial chloride content, % by weight of concrete

x = depth, mm

D_{nss} = apparent chloride diffusion (non-steady state), m^2/sec

t = exposure time, sec

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

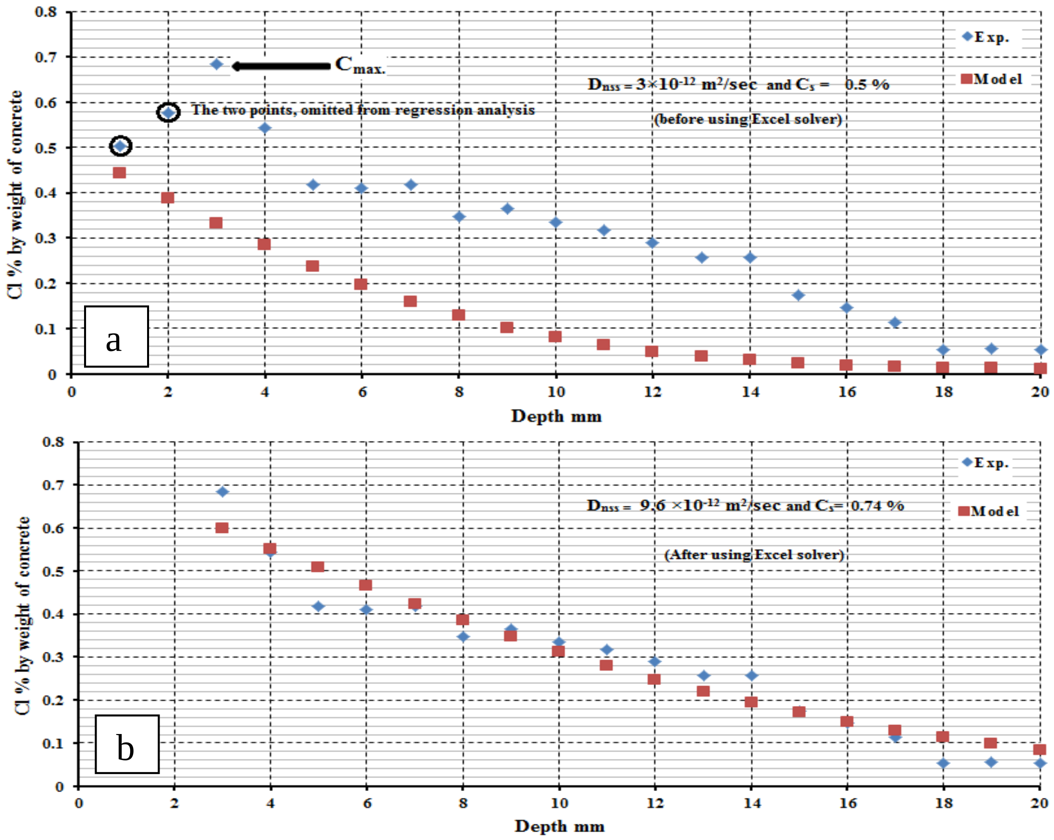


Figure 5 Curve fitting data a) before b) after using Excel solver

The lower chloride contents than the maximum detected one was omitted from the non-linear regression as shown in **Fig.5b**.These values are normally appeared in chloride content-depth relationships **[19]** and they were two points 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 were summarized and listed in **Table 4**. The penetration parameter (K_{cr}) which takes into account both the effect of resulted surface chloride contents and the computed diffusion coefficients has considered more relevant for the chloride resistance comparison purposes **[20]**. Thus it was calculated and listed in the same table according to the **Eq. 3.2 [20]**:

$$K_{cr} = 2\sqrt{D_{nss}}\; erf^{-1}\left(\frac{C_s - C_r}{C_s - C_i}\right) \qquad \textbf{Eq. 3.2}$$

erf^{-1} = the inverse of erf

C_r = critical chloride content =0.05 and K_{cr} is defined only when $C_s > C_s > C_s$

Table 4 D_{nss} , C_s and K_{cr} values of the concrete mixes

Mix title	$D_{nss} \times 10^{-12}$ (m^2/sec)	Cs (% 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	9.26	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. This might attributed to the fact that the matrix of this type of SCC with high replaced percentage of LP does not have the similar chloride binding ability as compared to the cement itself in NVC and R-SCC even with the low water to cementitious material ratio used relative to NVC. Hence, increase the content of the free chloride ions which have the ability to diffuse more easily in the pore water solution and increased the chloride diffusion coefficient value. On the other hand, the results also indicated that the NVC established the highest surface chloride content compared to the SCC types. The calculation of the penetration parameter might explain the misleading of these results. The LP-SCC showed the highest K_{cr} signifying the lowest chloride resistance followed by the NVC-mix and R-SCC. The incorporation of high dosage of FA and FA plus SF only has kept the same K_{cr} as R-SCC. In other words, these two types of SCC have approximately the same chloride resistance relative to the R-SCC if they were cured for 28 days while LP-SCC and NVC demonstrated lower chloride resistance with high values of penetration parameter, 47.2 and 51.8 mm / $\sqrt{year}$ respectively. It should be highlighted here that the K_{cr} is not represent the actual chloride penetration velocity. However, it can be used for the compassion bases between the different concrete types only **[20]**.

4.2 Modelling of chloride penetration and prediction of service life

The estimation of the service life of the normal and SCC mixes was numerically performed in a separate excel sheet at different ages to find $C(x,t)$ and based on the solution of the second Fick's law (**Eq. 3.1**) considering the following assumptions and parameters (**Figs. 6 to10** show the final result of this solution):

- The diffusion is the most familiar controlling mechanism for the chloride ingress process (submerged concrete structure) **[21]** and the calculated diffusion coefficients at 90 days is time-dependent **[22]** (**Eq. 4.1**) :

$$D_a(t) = D_{ao}(t)\left(\frac{t_0}{t}\right)^{\alpha} \quad \text{………….. } \textbf{Eq. 4.1}$$

$D_a(t)$: 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)

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

- In spite of the use of various types of supplementary cementitious material (SCM), the current experience indicated that the aging factor of CEM I based concretes; FA based concrete is 0.4 and 0.6 respectively and may still be used for the estimation of a proper aging factor **[19]**. The aging factor of LP based concrete is not available in the literature. Therefore, it is assumed to be similar to the NVC mix due to the same trend in compressive strength development up to 28 days (**see section 4.1**)
- 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 [19, 23].
- The fact that a relation between the field exposure and the laboratory exposure according to the Nordtest methods NT BUILD 433Accelerated Chloride Penetration test has been found for the concrete, as reported by Frederiksen et al. 1997 quoted by Nilsson, 2001 **[24]** . 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 sever chloride environments in the natural field for different exposure ages **[19]**.

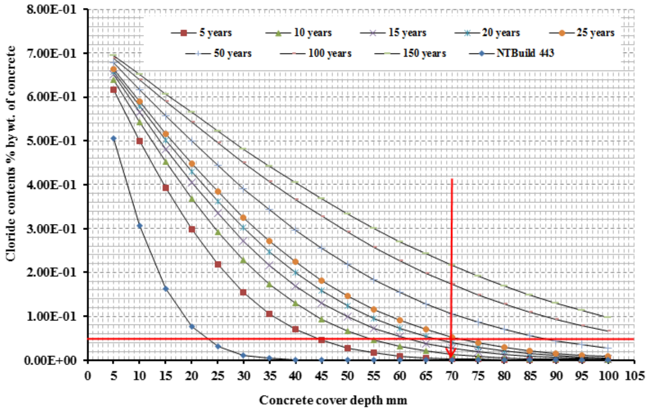


Figure 6 chloride model - NVC

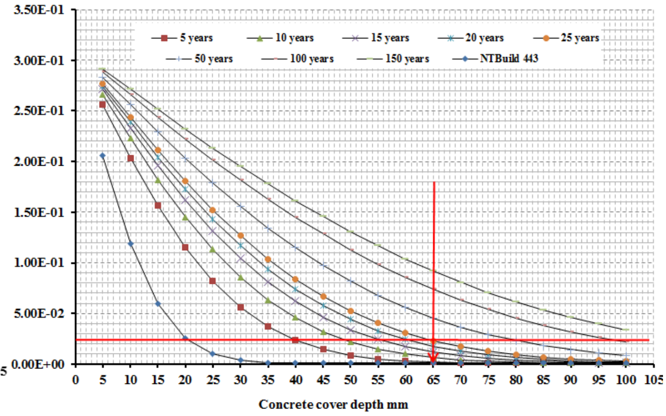


Figure 7 chloride model - R-SCC

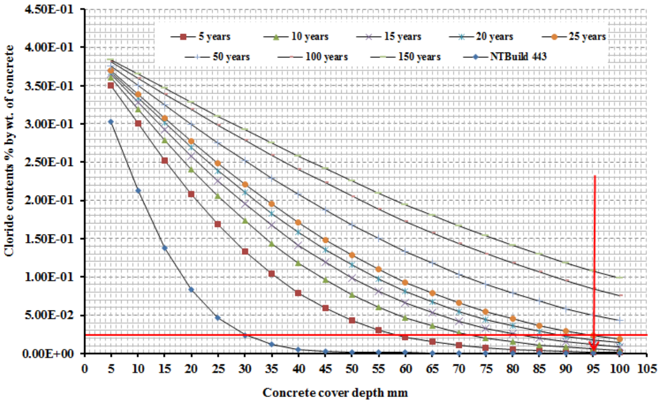


Figure 8 chloride model – LP-SCC

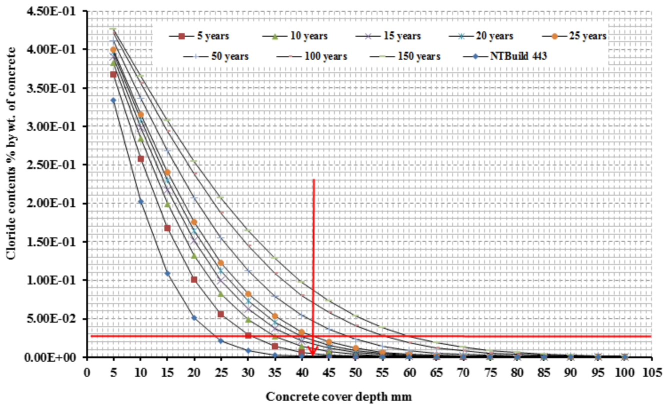


Figure 9 chloride model – FA-SCC

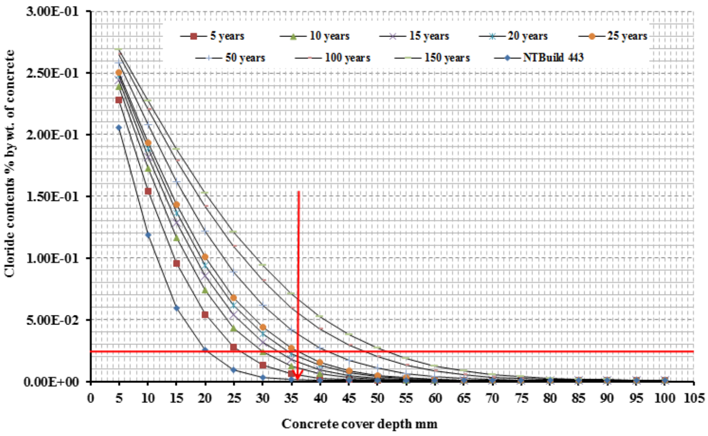


Figure 10 chloride model – FA-SF-SCC

The analysis showed that, in order to achieve a service life design of 25 and 50 years, the theoretical designed concrete cover for the NVC mix should be 70mm and 90 mm respectively while it should be 65mm and 80 mm for the R-SCC. Further, for the LP-SCC, it was not able to achieve 50 years' service life even with a concrete cover greater than 100mm. It should be beard in mind that the increase of the cover thickness beyond 70 mm could have an adverse effect which can increase the probability of the concrete cover cracks due to the external load in accordance to the load design purposes and increase the whole cost of concrete element construction effectively. The FA-SCC and FA-SF-SCC decrease the required cover thicknesses to about 42mm and 36mm for 25 years' service life and 47mm and 41mm for 50 years' service life respectively.

5. Conclusion

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

- The incorporating of relatively high replacement of cement by LP increased the apparent D_{nss} and K_{cr} of the SCC as compared to NVC, R-SCC and other sustainable SCC types at the same design strength. However, the K_{cr} of this type of SCC was slightly higher relative to NVC even with the use of lower water to cementitious material ratio.
- The NVC exhibited the highest surface chloride content assessed by **Nordtest methods NT BUILD 433** test among all the other types of SCC. However, it achieved slightly lower penetration parameter.
- A simplified service life model for the chloride ingress in concrete in a separate excel sheet has been proposed using a developed numerical tools in excel solver to calculate the D_{nss} and C_s according to NT build 433 accelerated test.
- According to this model, the theoretical thicknesses for the concrete cover design were 70mm, 65 mm, 95mm, 42mm and 36mm 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 90mm, 80mm, 47mm and 41mm for 50 years' service life for NVC, R-SCC, FA-SCC and FA-SF-SCC respectively. The LP-SCC did not achieve 50 years' service life with a cover thickness less than 100mm.

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