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Chloride penetration at different drill depths in concrete slabs

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Abstract

Concrete bridge decks deteriorate upon exposure to severe climatic conditions, followed by the corrosion of steel reinforcement induced by the presence of moisture and de-icing salts. Once deterioration reaches a critical point, the deck must be repaired. Cost-effective management of bridge inventories requires knowledge of the subsurface condition of each bridge deck so that preventative maintenance programs can be employed. The key to an effective preventative maintenance program is accurate, quantitative, and current information on the subsurface condition of the bridge deck. Once a bridge deck is scheduled for rehabilitation, accurate determination of the type and extent of concrete deterioration is required to tender the work. Thus, the de-icing salts are necessary to provide safe winter driving conditions and save lives by preventing the freezing of a layer of ice on concrete infrastructure. However, the safety and sense of comfort provided by these salts is not without a price, as these salts can greatly contribute to the degradation and decay of reinforced concrete transportation systems. The importance of chloride concentration as a durability-based material property has received greater attention only after the revelation that chloride-induced corrosion is the major problem for concrete durability. Therefore, there is a need to quantify the chloride concentration in concrete which is of paramount importance.

Keywords: Concrete, mixture proportion, grade of concrete, pre-conditioning, slump, w/c ratio, chloride penetration, de-icer, snow and ice control, reinforcing steel, corrosion, drill depth, solvent based (SB) material, water based (WB) material.

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1. Introduction

Concrete service life models have proliferated in recent years due to increased interest in designing infrastructure elements with at least a 75-year service life, along with greater emphasis on life-cycle costing in general. While existing models consider a variety of concrete material and environmental factors, at varying levels of complexity, in predicting the time until the onset of chloride-induced corrosion of the steel reinforcement, the influence of cracking is generally beyond their current scope. This paper presents a preliminary strategy for examining the influence of transverse cracking on chloride ion penetration into concrete that includes a graphical approach for adjusting the predicted service life provided by current models to reflect this influence. Comparison to experimental data for saturated concretes indicates that the contributions of binding of the chloride ions by the cement paste play a significant role in slowing the ingress of chlorides and should be accounted for in any modeling efforts [Dale P. Bentz Edward *et al*. 2013]. This paper reports an experimental study of the influence of marble powder used as partial substitute for Portland cement (PC) on the mechanical properties and durability of high-performance concretes. The analysis of the experimental results on concrete at 15% content of marble powder with a fineness modulus (11,500 cm^2/g) in a chloride environment showed that it contributes positively to the perfection of its mechanical characteristics, its durability with respect to migration of chloride ions and oxygen permeability. On the basis of the experiments performed, it can be concluded that the marble powder is suitable for formulation of high-performance concretes (HPC) and their properties are significantly better compared to the reference concrete [Talah *et al*. 2015]. The overall aim of this paper is to establish the process and amount of chlorides penetrating reinforced concrete elements when exposed to a salt-laden environment. For this purpose, a number of slabs were subjected to 70 cycles of wetting-drying regime with a 4% sodium chloride solution over a period of 2-3 years. To examine the direction of transportation of the chlorides, some of the slabs were partially coated with a surface coating system known to be highly resistant to chloride penetration. The amount and depth of penetration of chlorides in the coated and uncoated parts of the slab were then determined. The results show conclusively that, in large exposed areas of concrete, chlorides diffuse both in the direction of depth and in a direction lateral to the depth of the element. The amount of chlorides and the distance of their lateral diffusion depend on the water-to-cement (w/c) ratio of the concrete and the duration of exposure. Concrete mixes with a high w/c ratio (0.75) are highly conducive to this lateral diffusion of chlorides. Although concrete mixes of lower w/c ratios (0.45 and 0.60) are less conducive to lateral diffusion of chlorides, in practice, all concretes should be considered to be prone to chloride diffusion in both the direction of gravity and the lateral direction because of the effects of cracking. In unprotected concrete, reducing the w/c ratio from 0.60 to 0.45 is far more effective in decreasing chloride penetration than that achieved by reducing the w/c ratio from 0.75 to 0.60. The acrylic-based surface coating system is totally resistant to chloride penetration [Suryavanshi *et al*. 1998]. The use of waste materials and industrial by-products in high-strength concrete could increase the sustainability of the construction industry. In this study, the potential of using copper slag as coarse aggregate in high-strength concrete was experimentally investigated. The effects of replacing gravel coarse aggregate by copper slag particles on the compressive strength, chloride ion- migration, water permeability and impact resistance of high strength concretes were evaluated. Incorporating copper slag coarse particles resulted in a compressive strength increase of about 14 % on average partly due to the low Ca/Si ratio through the interface area of this concrete (more homogenous internal structure) as confirmed by the energy dispersive X-ray micro chemical analysis. It was also found that the copper slag high-strength concrete provided better ductility and had much greater load carrying capacity compared to gravel high-strength concrete under dynamic conditions. Finally, it was observed that in comparison to the high strength concrete with slag, the chloride migration coefficient from non-steady state migration was approximately 30 % greater in the gravel high-strength concrete [Savaş Erdem and Marva Angela Blankson, 2014]. There is a need to develop a better understanding of the relationship among short, medium, and long-term tests to assess the resistance of concrete to chloride penetration. In this contribution, a resistivity-based test is compared to a 90-day salt ponding test. The short term (6-h) rapid chloride permeability test has been criticized for its lack of a scientific basis and poor correlation to the so-called control ponding test. Comparative testing is presented for several concrete and mortar mixtures, which suggests that if modifications are made to test procedures and methods of analysis then the relationship between the results of the resistivity-based test and the diffusion-based test is improved. The 90-day salt ponding test can be improved by using a depth of penetration approach rather than integral chloride content and by limiting the transport process to diffusion only. Modification to the rapid chloride test by shortening the test time to 30 min did not improve the correlation to other test methods for the range of concretes studied [Patrick F. McGrath, and Doug Hooton, 1999]. The experimental methods for determination of concrete resistance to chlorides – both the chloride permeability test methods (NT Build 492 Nord Test-Non-Steady state migration Test, AASHTO T277-ASTM C 1202 Test) and the methods for testing concrete resistance to surface scaling due to cyclic freezing and thawing in the presence of NaCl solution (de-icing salts, saline sea water) (e.g. Slab Test according to CEN/TS 12390-9, based on the Borås method according to Swedish Standard SS 13 72 44) are presented in the paper. The Rapid Chloride Test-the method used “in situ” to determine the chloride ion content in concrete is also described [Teresa Zych, 2014]. Corrosion of steel reinforcement causes its expansion in volume due to corrosion products and subsequent cracking and spalling of concrete from the reinforcement. Moreover, chloride ions (from de-icing salts) together with frost attack can cause another form of concrete deterioration-concrete scaling [Richardson, 2002]. The threat of corrosion from chlorides is addressed in the European standard [EN 206-1:2000] under two sets of exposure classes: chlorides from sea water (XS) and chlorides other than from sea water (XD). Exposure class XS1 covers concrete that is exposed to airborne salts from sea water but not in direct contact with sea water. The examples of such structures are those situated along the coast beyond the spray zone. Exposure class XS2 includes concrete that is permanently submerged in sea water (marine and coastal structures). This concrete may be subjected to considerable chloride penetration but significant corrosion may not occur due to the low level of oxygen supply. Exposure class XS3 means that concrete is in the tidal, splash and spray zones. The examples of structures exposed to these conditions include marine and coastal structures. Exposure class XD1 includes the case of concrete of moderate humidity and in contact with airborne chlorides from sources other than sea water, e.g., structures in proximity to highways. Exposure class XD2 covers concrete that is wet, rarely dry, in contact with water containing chlorides other than from sea water. The examples of such structures are swimming pools or structures exposed to industrial waters containing chlorides. Exposure class XD3 means that concrete is exposed to cyclically wet and dry environment and chlorides are not from sea water. The examples of structures are pavements, car park slabs, parts of bridges, highways subjected to de-icing salts or spray from water containing de-icing salts. The action of chlorides (de-icing agents) together with the freeze-thaw attack is classified in [EN 206-1:2000] as: XF2 exposure class when concrete is moderate water saturated, XF4 exposure class in the case of high-water saturated concrete. The examples of such structures are pavements, road and marine structures [Tang *et al.* 2011]. The problem of concrete resistance to chloride ingress occurs in many various structures. The chloride resistance is one of the most important properties of concrete in the design, construction and maintenance of structures. It is well known that the presence of cracks in reinforced concrete structures in aggressive environments accelerates rebar corrosion. The influence of real cracks in concrete structures on the penetration of chlorides and the resulting service life is being investigated in this study. Investigations are carried out at the Magnel Laboratory for concrete research of Ghent University in Belgium within a bilateral agreement with Politehnica University of Timisoara, Romania. Non-steady state migration tests are realized according to NT BUILD 492 using an electrical field and real cracks in order to determine the chloride profile. Samples with different crack patterns obtained by drilling from a reinforced concrete slab exposed to a simulated accidental failure of the central support and subsequent vertical loading until collapse have been used in the study in order to provide a more realistic image of the geometry of the cracks. The crack widths are measured using the optical microscope.

The chloride penetration depth is measured with a colorimetric method on each specimen and the non-steady state diffusion coefficients are determined. For evaluating the parameters which have the most influence on chloride migration on the samples used in this experiment, a two-level factorial experiment is designed and carried out. The results obtained provide a better understanding of the diffusion process when dealing with concrete structures with real cracks [Corina Sosdean *et al*. 2014]. This paper reports an approach by which laboratory based testing and numerical modelling can be combined to predict the long-term performance of a range of concretes exposed to marine environments. Firstly, a critical review of the test methods for assessing the chloride penetration resistance of concrete is given. The repeatability of the different test results is also included. In addition to the test methods, a numerical simulation model is used to explore the test data further to obtain long-term chloride ingress trends. The combined use of testing and modelling is validated with the help of long-term chloride ingress data from a North Sea exposure site. In summary, the paper outlines a methodology for determining the long-term performance of concrete in marine environments [Nanukuttan et al.].

The prolonged periods of snowfall in countries with advanced infrastructure and transport systems have rendered the use of de-icing agents to a common occurrence on roads and highway structures. They are necessary in order to maintain a good level of service with respect to the transport systems, thus avoiding traffic jams and disruptions, but also to provide a high level of road safety. Today, chloride-based products, such as rock salt, are the most commonly encountered de-icers as they are easy to apply and store but mostly because they efficiently melt ice at an affordable price [TRB, 1991]. However, their widespread use over a long period has left the construction industry and the engineering community with a grave problem regarding the durability of highway reinforced concrete bridges and multi-storey parking structures [Pullar-Strecker, 2002], due mainly to the fact that they cause corrosion of the reinforcement and steel components [Pullar-Strecker, 2002].In cold-climate regions, snow and ice control operations are crucial to maintaining highways that endure cold and snowy weather. The growing use of de-icers has raised concerns about their effects on motor vehicles, transportation infrastructure, and the environment. The deleterious effect of chloride-based de-icers on reinforcing steel bar in concrete structures is well known [Shi *et al*. 2009]. De-icers may also pose detrimental effects on concrete infrastructure through their reactions with cement paste and/or aggregates and thus reduce concrete integrity and strength, which in turn may foster the ingress of moisture, oxygen and other aggressive agents onto the rebar surface and promote rebar corrosion. Large amounts of solid and liquid chemicals (known as de-icers) as well as abrasives are applied onto winter highways to keep them clear of ice and snow. De-icers applied on to highways often contain chlorides because of their cost-effectiveness, including mainly sodium chloride, magnesium chloride, and calcium chloride, sometimes blended with proprietary corrosion inhibitors. The rock salt/sodium chloride, is the most commonly used de-icing agent. It was first used to control snow and ice on roadways to improve transportation safety in the 1930s, and became widespread by the 1960s. The salt works by dissolving into precipitation on roadways and lowering the freezing point, thereby melting ice and snow. Eliminating the ice has enormous safety benefits, but depending on the amount of chemicals used, the dissolved salt can have negative effects on the surrounding environment. The melting snow and ice carries de-icing chemicals onto vegetation and into soils along the roadside where they eventually enter local waterways. Elevated salt levels in soils can inhibit the ability of vegetation to absorb both water and nutrients, which can slow plant growth and ultimately affect animal habitats. This degradation also affects the ability of these areas to act as buffers to slow the runoff of other contaminants into the watershed. Once the salt enters freshwater it can build up to concentration levels that further affect aquatic plants and other organisms. Salt deposits along roadways also attract birds, deer, and other animals which increases the chance of animal-vehicle accidents. While the major effect on public drinking water supplies for humans is merely an alteration of taste, high concentrations of sodium in drinking water can lead to increased dietary intake and possibly hypertension. Since salt is corrosive to automobiles, bridge decks, and other roadway infrastructure, de-icing chemicals are often combined with other substances to block corrosion. While eliminating ice is of great benefit to commerce and human safety, these drawbacks must be taken into consideration by communities as they plan for regular maintenance of the concrete infrastructure, as well as the health of the local ecosystem. The costs of maintaining reinforced concrete infrastructure (bridges, tunnels, harbours, parking structures) are increasing due to aging of structures, which are being exposed to aggressive environment. Corrosion of reinforcement due to chloride ingress is the main problem for existing structures in marine and de-icing salt environments [Bertolini *et al.* 2013]. In the Netherlands 5% of motorway bridges, built predominantly between 1960 and1980, shows cracking and spalling of the concrete cover due to chloride induced corrosion [Gaal, 2004]. This corresponds to 10% of the bridges showing corrosion initiation at an age of 40 years [Polder *et al.* 2012]. Older structures have been built according to older codes, which may not have provided sufficient protection. Moreover, for new infrastructure corrosion cannot be ruled out completely, even with today’s emphasis on design for long service life (typically 100 years), either by composition requirements (Eurocodes) or based on service life modelling and performance testing [fib, 2006].This may be due to various factors, such as unforeseen aggressive loads, e.g. leakage of joints; or to deviations from the intended concrete quality or cover thickness; or to modelling inadequacies [Bertolini *et al.* 2011].Repair of corrosion damage is possible, but costly, potentially disruptive and not necessarily long lived. A European study has shown that 50% of repairs fail within 10 years [Tilly, 2011]. These results were confirmed by a study in the Netherlands [Visser *et al.* 2012]. In the worst case, this means that after about ten years the structure must again be repaired, involving more costs; and possibly this will go on until the structure is taken out of service. Thus, in the present research work, an attempt was made to interpret the concrete chloride absorption in ordered to characterize the different concrete mixtures type for in case of 18 pre-conditioned concrete slabs (450x450x100 mm) such as dry/fully/partially saturated condition and salt ponded with chloride solution for about 160 days. This research will examine the influence of conditioning such as dry/fully/partially saturated condition on the results of chloride concentration in concrete cubes with different mixtures proportion in which slump (0-10, 10-30, 60-180) mm, and w/c ratio value was varied with constant compressive strength (40 N/mm^2) as in the first case and compressive strength (25-40 N/mm^2), and w/c ratio value varied with constant slump (10-30) mm as in the second case at different drill depths (30-40-50 mm).

2. Research objectives

The interpretation of the performance of a concrete mix is not limited to the determination of its mechanical properties since it is of paramount importance to characterize the material in terms of the parameters that rate its durability. The importance of chloride concentration as a durability-based material property has received greater attention only after the revelation that chloride-induced corrosion is the major problem for concrete durability. The present research work was made an attempt to interpret the concrete chloride absorption in ordered to characterize the different concrete mixtures design for in case of pre-conditioned concrete cubes such as dry/fully/partially saturated condition and salt ponded with chloride solution for about 160 days with 10% NaCl solution. Thus, the objectives of this present research is to examine the influence of conditioning such as dry/fully/partially saturated condition on the results of chloride concentration at different drill depths (30-40-50 mm) in concrete slabs with different mixtures proportion in which slump, and w/c ratio value was varied with constant compressive strength as in the first case and compressive strength, and w/c ratio value varied with constant slump as in the second case. Seventy-two concrete cubes (450x450x100 mm) with grades of concrete ranges from 25-40 N/mm^2 were prepared and evaluate the chloride absorption under different exposure condition.

3. Experimental program

In the present research work, six different mixtures type were prepared in total as per [BRE, 1988] code standards with concrete slabs of size (450x450x100) mm. Thus totally 18 concrete slabs of size (450x450x100) mm were fabricated with different six mixtures type (M1-M6). Out of which three mixtures type with constant compressive strength (40 N/mm^2) and varied slump (0-10, 10-30, and 60-180 mm) were designed as one group (M1-M3). In second group (M4-M6), rest of three mixtures type were designed as with different compressive strength (25 N/mm^2, 30 N/mm^2, and 40 N/mm^2), and constant slump (10-30 mm). Actually, the mixture ingredients quantities were found to be more or less same/equivalent that is why, the mixture proportions were adopted in dry conditioned concrete slabs (DCC) as mixture type (M1=M2), (M3=M5), and (M4=M6) for in case of partially saturated (PSC) as well as fully saturated conditioned concrete (FSC) slabs. As concern to DCC concrete slabs, the control/impregnation concrete slabs were represented as (M1CS, M2CS) with solvent based/water based concrete slabs as (M1S1, M2S3) and (M1S2, M2S4). For in case of PSC concrete slabs, the control/impregnation concrete slabs were represented as (M3CS, M5CS) with solvent based/water based concrete slabs as (M3S5, M5S7) and (M3S6, M5S8). With reference to FSC concrete slabs, the control/impregnation concrete slabs were represented as (M4CS, M6CS) with solvent based/water based concrete slabs as (M4S9, M6S11) and (M4S10, M6S12).

Table 1
Concrete slabs mixture proportion (M1-M3)

Mix ID.	Comp/mean target strength (N/mm^2)	Slump (mm)	w/c	C (Kg)	W (Kg)	FA (Kg)	CA (Kg)	Mix Proportions
M1	40/47.84	0-10	0.45	18.23	8.20	29.70	94.16	1:1.63:5.17
M2	40/47.84	10-30	0.44	22.05	9.72	28.49	85.47	1:1.29:3.88
M3	40/47.84	60-180	0.43	27.51	11.85	32.50	72.41	1:1.18:2.63

Table 2
Concrete slabs mixture proportion (M4-M6)

Mix ID.	Comp/mean target strength (N/mm^2)	Slump (mm)	w/c	C (Kg)	W (Kg)	FA (Kg)	CA (Kg)	Mixture Proportions
M4	25/32.84	10-30	0.50	19.44	9.72	30.31	86.27	1:1.55:4.44
M5	30/37.84	10-30	0.45	21.63	9.72	30.86	83.55	1:1.42:3.86
M6	40/47.84	10-30	0.44	22.05	9.72	28.49	85.47	1:1.29:3.87

After 28 days of initial curing in water, the concrete slabs were subjected to different exposure conditions such as drying/fully/partially saturated conditions for specified time duration. Hence, it’s possible to develop a better understanding of the long-term tests to assess the resistance of concrete to chloride concentration under different pre-conditions such as drying/partially/fully saturated conditions with/without impregnation. In which totally 12 concrete slabs were treated with two different impregnation materials such as Solvent based (M1S1, M2S3, M3S5, M5S7, M4S9, M6S11) and Water based (M1S2, M2S4, M3S6, M5S8, M4S10, M6S12). The other 6 concrete slabs were left untreated as control concrete slabs (M1CS, M2CS, M3CS, M4CS, M5CS, and M6CS). The overall details of the mixture proportions were to be represented in Table.1-2. Three concrete slabs of size (450x450x100) mm were cast for each mixture and overall, eighteen concrete slabs were casted for six types of concrete mixture. The coarse aggregate used was crushed stone with maximum nominal size of 10 mm with grade of cement 42.5 N/mm^2 and fine aggregate used was 4.75 mm sieve size down 600 microns for this research work. As concern to impregnation materials, Water based (WB) and Solvent based (SB) impregnate materials were used in this present research work. To avoid criticizing or promoting one particular brand of impregnation materials and for confidentiality reasons, the names of the products used will not be disclosed and they will be referred to as WB and SB respectively. WB is water borne acrylic co-polymer-based impregnation material which is less hazardous and environmentally friendly. It is silicone and solvent free and achieves a penetration of less than 10mm. SB consists of a colourless silane with an active content greater than 80% and can achieve penetration greater than 10mm.

4. Chloride ingress in concrete slabs

The unidirectional salt ponding was adopted as per [AASHTO T 259] method. In which the slabs are typically moist cured for a length of time followed by a period of drying at 50% relative humidity before ponding with a 10% sodium chloride solution. AASHTO T 259 calls for 14 days moist curing followed by 28 days of drying. The ponded slabs are stored to allow air circulation around the slabs in a room at 50% relative humidity. A cover is placed over the solution pond to prevent evaporation of water from the solution. AASHTO T 259 stipulates for a ponding period of 90 days. For low-permeability concretes, this is typically found to be too short for significant penetration of chloride ions into the concrete, and ponding is often extended for longer periods. But in this present research work, certain concrete slabs were pre-conditioned such as fully saturated (60 days)/partially saturated (40 days) conditioned in water for certain time duration and dry pre-conditioning for specified time duration (28 days) before salt ponding test which was carried out for about 160 days at 10% NaCl solution. The chloride profiles were analysed by drilling the slabs. The drilling was done with a diameter of 20 mm (max aggregate size) and drill depths of (30, 40, and 50) mm. The dust sample were collected, weighted between 1-5 grams as specified by [BS EN 15629:2007] for the determination of the chloride penetration. The chloride concentration for each of the dust samples, including from the control specimens was determined in accordance with [BS EN 15629:2007] in hardened concrete. The chloride content was calculated as a percentage of chloride ion by mass of the sample of concrete. Volhard's method was used for the determination of the total chloride content in the concrete. Samples of dust powder drilled from the concrete specimens at different drill depths (30 mm, 40 mm, and 50 mm) were used for the determination of the chloride penetration in the concrete samples for in case of six mixtures type (M1-M6). The chloride salt ponding, and analysis in pre-conditioned concrete slabs as shown in Figure 1.

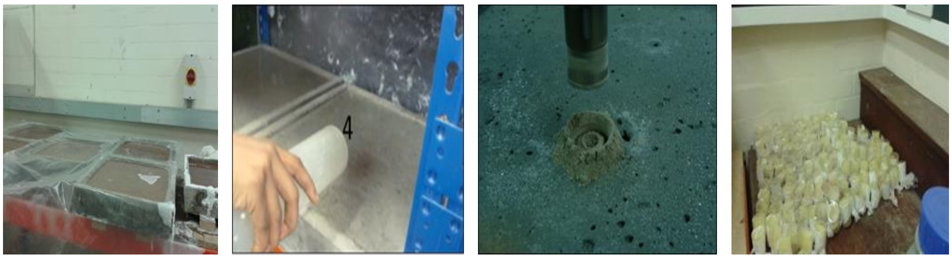

Fig. 1. Cl$^-$ profile analysis in pre-conditioned concrete slabs.

The variation of chloride concentration in pre-conditioned control/impregnation concrete slabs was represented in Table.3. As observed from the results that (Table.3), the chloride concentration was found to be increased at drill depth (30 mm) in DCC/PSC/FSC control/impregnation concrete slabs as when compared to DCC/PSC/FSC control/ impregnation concrete slabs at drill depths (40 mm, and 50 mm) respectively.

Table 3
Chloride concentration in different pre-conditioned concrete slabs

Final CC (%) results for DCC Slabs				Final CC (%) results for PSC Slabs				Final CC (%) results for FSC Slabs			
Mixture type [M1=M2]				Mixture type [M3=M5]				Mixture type [M4=M6]			
Slab ID.	30 mm	40 mm	50 mm	Slab ID.	30 mm	40 mm	50 mm	Slab ID.	30 mm	40 mm	50 mm
M1CS	0.092	0.086	0.082	M3CS	0.079	0.0731	0.069	M4CS	0.072	0.071	0.0650
M1S1	0.0894	0.084	0.075	M3S5	0.074	0.0711	0.066	M4S9	0.069	0.067	0.0624
M1S2	0.0915	0.085	0.080	M3S6	0.075	0.0722	0.067	M4S10	0.070	0.069	0.0634
M2CS	0.0821	0.078	0.065	M5CS	0.085	0.0736	0.062	M6CS	0.065	0.060	0.0558
M2S3	0.0773	0.067	0.061	M5S7	0.080	0.0613	0.058	M6S11	0.063	0.052	0.0501
M2S4	0.0783	0.068	0.063	M5S8	0.081	0.0705	0.059	M6S12	0.064	0.055	0.0536

5. Discussion about results

The process of wetting/drying is a major problem for concrete infrastructures which was exposed to chlorides and its effects are most severe in many concrete infrastructure locations such as marine structures, particularly in the splash and tidal zones, parking garages exposed to de-icer salts, and highway structures, such as bridges and other elevated roadways for instance the Gardner expressway. When the concrete is dry/partially dry, which was then exposed to salt water, it will imbibe the salt water by capillary suction. The concrete will continue to suck in the salt water until saturation or until there is no more reservoir of salt water. A concentration gradient of chlorides will develop in the concrete, stopping at some point in the interior of the concrete. If the external environment becomes dry, then pure water will evaporate from the pores, and salts that were originally in solution may precipitate out in the pores close to the surface. The point of highest chloride concentration may exist within the concrete. On subsequent wetting, more salt solution will enter the pores, while re-dissolving and carrying existing chlorides deeper into the concrete. The rate to which the chlorides will penetrate the concrete depends on the duration of the wetting/drying periods. If the concrete remains wet, some salts may migrate in from the concrete surface by diffusion. However, if the wetting period is short, the entry of salt water by absorption will carry the salts into the interior the concrete and be further concentrated during drying. The process of wetting/drying increases the concentrations of ions such as chlorides, by evaporation of water. The drying of the concrete also helps to increase the availability of the oxygen required for steel corrosion, as oxygen has a substantially lower diffusion coefficient in saturated concrete. As the concrete dries and the pores become less saturated, oxygen will have a better chance to diffuse into the concrete and attain the level necessary to induce and sustain corrosion. There is an increased availability of oxygen that also contributes to the deterioration compared to the submerged part of the structure. The concrete is fully submerged less chloride would enter the concrete as the dominant penetration factor is diffusion through the pore solution. There are several factors that can affect the degree that chlorides will enter concrete through wetting/drying. In fact, the ingress of chlorides into concrete is strongly influenced by the sequence of wetting/drying, and on the time duration. Thus, in the present research work, the effectiveness of 18 pre-conditioned concrete slabs of size (450x450x100) mm on chloride concentration in dry/fully/partially saturated condition was evaluated for in case of six designed mixtures type (M1-M6). The variation of chloride penetration in pre-conditioned concrete slabs such as dry/partially/fully saturated conditioned concrete slabs was represented in Figs.1a-1f. The variation of chloride concentration is interpreted by chemical analysis at different drill depths (30-40-50) mm for in case of control/impregnation (SB/WB) pre-conditioned concrete slabs in order to characterize various designed mixtures type. Its varied average chloride concentration at different drill depths is increased for in case of DCC slabs as when compared to PSC concrete slabs.

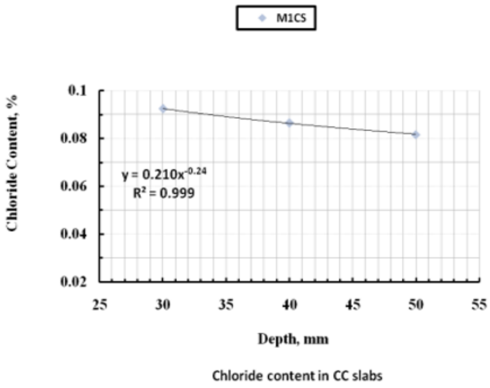

Fig. 1a. Cl⁻ in control concrete slabs

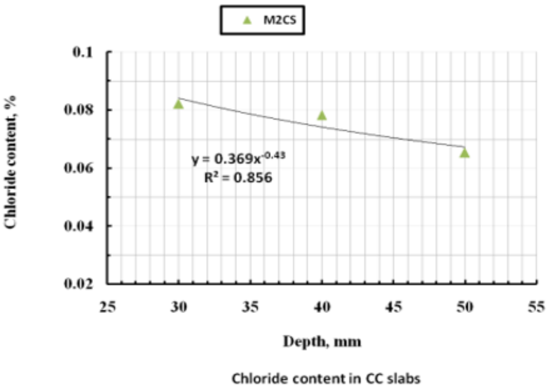

Fig. 1b. Cl⁻ in control concrete slabs

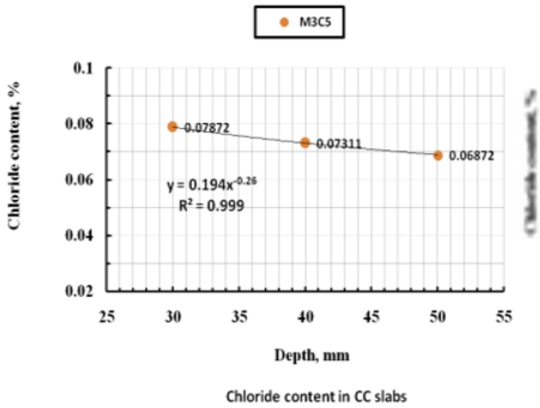

Fig. 1c. Cl⁻ in control concrete slabs

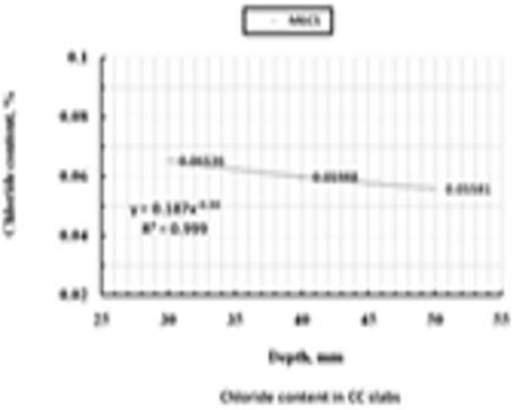

Fig. 1d. Cl⁻ in control concrete slabs

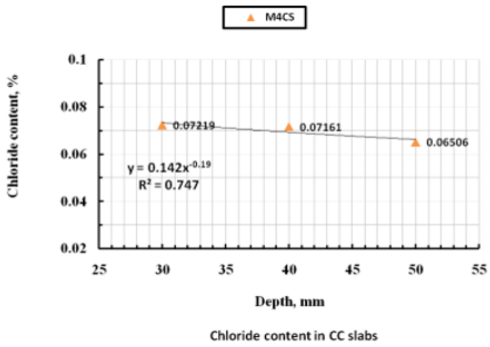

Fig. 1e. Cl⁻ in control concrete slabs

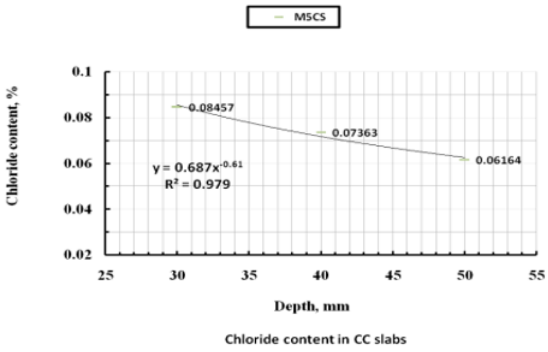

Fig. 1f. Cl⁻ in control concrete slabs

Its varied values are represented as M1CS (15.23%), M1S1 (15.23%), M1S2 (16.61%), M2CS (2.55%), M2S3 (3.08%), M2S4 (0.8%) respectively. In addition to that, the chloride concentration is also increased in case of DCC concrete slabs as when compared to FSC concrete slabs and its varied average chloride concentration at drill depths are interpreted as

M1CS (19.73%), M1S1 (19.78%), M1S2 (21.21%), M2CS (19.74%), M2S3 (19.39%), M2S4 (17.38%) respectively.

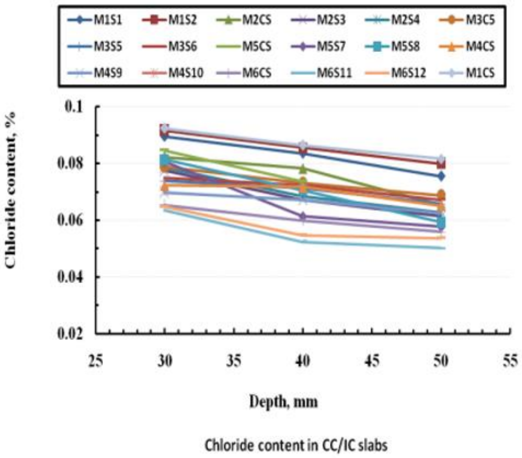

Fig. 2a. Cl$^-$ in CC/IC concrete slabs

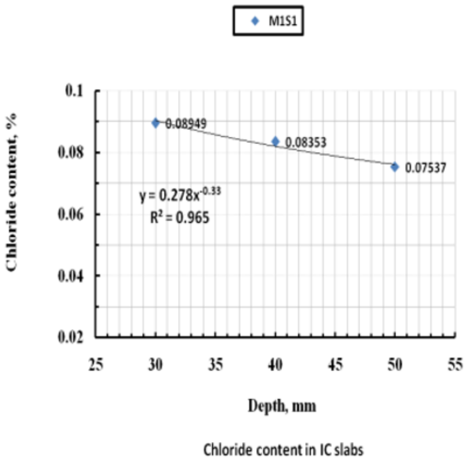

Fig. 2b. Cl$^-$ in impregnation concrete slabs

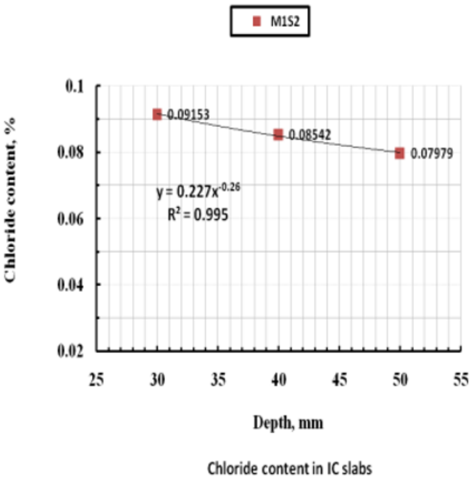

Fig. 2c. Cl$^-$ in impregnation concrete slabs

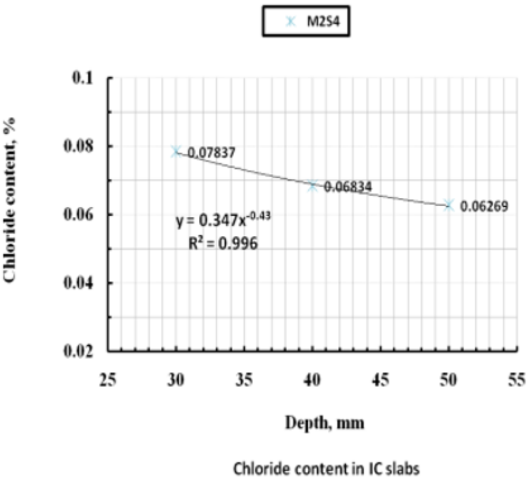

Fig. 2d. Cl$^-$ in impregnation concrete slabs

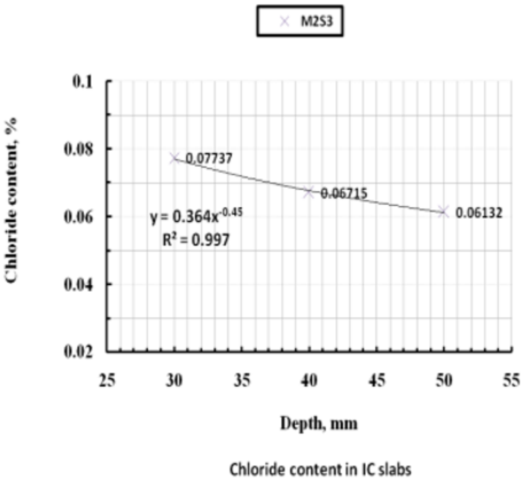

Fig. 2e. Cl$^-$ in impregnation concrete slabs

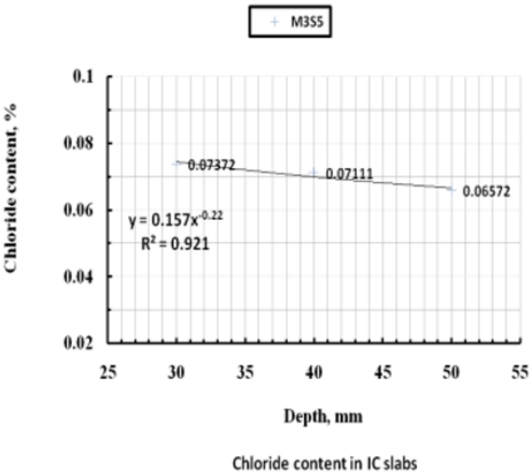

Fig. 2f. Cl$^-$ in impregnation concrete slabs

Similarly, the chloride concentration is also increased in PSC concrete slabs as when compared to FSC concrete slabs in which its average variation of chloride concentration at different drill depths were represented as M3CS (5.30%), M3S5 (5.36%), M3S6 (5.52%), M5CS (17.64%), M5S7 (16.82%), and M5S6 (18.04) respectively.

The average chloride concentration at different drill depths from (30-50) mm is found to be slightly increased in control concrete slabs for in case of mixtures type (M1CS-M2CS). As concerned to the average chloride concentration at different drill depths from (30-50) mm is reduced in solvent based impregnation concrete slabs as when compared to control concrete. Furthermore, the chloride concentration in water-based impregnation concrete slabs is slightly increased as when compared to solvent based impregnation concrete slabs in all mixtures type (M1CS-M2CS). The chloride concentration is also increased at drill depth 30 mm for in case of control, solvent, and water-based impregnation concrete cubes as when compared to drill depths (40-50) mm and its varied values were represented as M1CS (6.42%, 11.66%), M1S1 (6.65%, 15.77%), M1S2 (6.67%, 12.82%), M2CS (4.84%, 20.46%), M2S3 (13.20%, 20.74%), M2S4 (12.79%, 20%) respectively. The chloride concentration in solvent based impregnation concrete slabs was decreased as when compared to control concrete slabs at different drill depths (30-50) mm and in which its varied values were determined as M1S1 (96.95%, 96.71%, 92.44%), and M2S3(94.20%, 85.92%, 93.87%) respectively. Whereas the chloride concentration in water-based impregnation concrete slabs was reduced at different drill depths (30-50) mm as when compared to control concrete slabs for in case of all mixtures type (M1CS-M2CS) in its varied values are at different drill depths (30, 40, and 50) mm as M1S2 (99.16%, 98.90%, 97.86%), and M2S4 (95.42%, 87.44%, 95.97%) respectively.

Similarly, the chloride concentration in solvent based impregnation concrete slabs is decreased as when compared to water-based impregnation concrete cubes in which its varied values at different drill depths (30-50) mm as M1S1 (97.77%, 97.78%, 94.46%), M2S3 (98.72%, 98.25%, 97.81%) respectively. The average chloride concentration is increased in control concrete slabs for in case of mixtures type (M3CS, and M5CS) at different drill depths (30-40-50) mm as when compared to impregnation concrete slabs. The average chloride concentration at different drill depths from (30-50) mm is reduced in solvent based impregnation concrete slabs as when compared to control concrete slabs for in case of mixture type (M3CS) and (M5CS). Furthermore, the chloride concentration in water-based impregnation concrete slabs was slightly increased as when compared to solvent based impregnation concrete slabs in all mixtures type (M3CS-M5CS). The chloride concentration is also increased at drill depth 30 mm for in case of control, solvent, and water-based impregnation concrete slabs as when compared to drill depths (40-50) mm and its varied values were represented as M3CS (7.12%, 12.70%), M3S5 (3.54%, 10.85%), M3S6 (3.46%, 10.29%), M5CS (12.93%, 27.11%), M5S7 (23.89%, 28.44%), M5S8 (13.25%, 27.21%) respectively. The chloride concentration in solvent based impregnation concrete slabs is decreased as when compared to control concrete slabs at different drill depths (30-50) mm and in which its varied values were determined as M3S5 (93.64%, 97.26%, 95.63%), and M5S7 (95.24%, 83.25%, 93.51%) respectively. Whereas the chloride concentration in water-based impregnation concrete slabs is reduced at different drill depths (30-50) mm as when compared to control concrete slabs for in case of all mixtures type (M3CS-M5CS) and its varied values are at different drill depths (30, 40, and 50) mm as M3S6 (95%, 98.75%, 97.62%), and M5S8 (96.16%, 95.81%, 96.04%) respectively. Similarly, the chloride concentration in solvent based impregnation concrete slabs was decreased as when compared to water-based impregnation concrete cubes in which its varied values at different drill depths (30-50) mm as M3S5 (98.56%, 98.49%, 97.95%), M5S7 (99.04%, 86.88%, 97.36%) respectively. The variation of chloride concentration in control concrete slabs (M1CS-M6CS), and impregnation concrete slabs (M1SB-M6SB and M1WB-M6WB) for in case of designed mixtures type at different drill depths (30-40-50) mm as representing in the Figure 4. The chloride concentration were higher in control concrete slabs (M1CS:0.092-0.082; M2CS:0.082-0.065; M3CS:0.079-0.069; M4CS:0.072-0.065; M5CS:0.086-0.062; and M6CS:0.065-0.056) and impregnation concrete slabs (M1SB:0.089-0.075; M2SB:0.077-0.061; M3SB:0.074-0.066; M4SB:0.069-0.062; M5SB:0.080-0.058; and M6SB:0.063-0.050 M1WB:0.092-0.080; M2WB:0.078-0.063; M3WB:0.075-0.067; M4WB:0.070-0.063; M5WB:0.081-0.059; and M6WB:0.064-0.054) at lower drill depth (30 mm) as when compared to higher drill depth (40-50 mm). The variation of chloride concentration in control concrete slabs (M1CS-M6CS), and impregnation concrete slabs (M1SB-M6SB and M1WB-M6WB) for in case of designed mixtures type at different drill depths (30-40-50) mm as representing in the Fig.5.The chloride concentration were higher in control concrete slabs (M1CS:6.42; M2CS:4.85; M3CS:7.83; M4CS:0.80; M5CS:12.94; and M6CS:8.38) and impregnation concrete slabs (M1SB:6.66; M2SB:13.21; M3SB:3.54; M4SB:3.48; M5SB:23.90; and M6SB:17.33; M1WB:6.68; M2WB:12.80; M3WB:3.46; M4WB:2.62; M5WB:13.25; and M6WB:15.34) at lower drill depth (30 mm) as when compared to higher drill depth (40 mm). The variation of chloride penetration in pre-conditioned concrete slabs such as dry/partially/fully saturated conditioned concrete slabs was represented in Figures 2a-2f.

The average chloride concentration is increased in control concrete slabs for in case of mixtures type (M4-M6) at different drill depths (30-40-50) mm as when compared to impregnation concrete slabs and their varied values were interpreted as M4CS (0.072%, 0.071%, 0.065%), M6CS (0.065%, 0.059%, 0.055%). Similarly, the average chloride concentration at different drill depths from (30-50) mm is reduced in solvent based impregnation concrete slabs as when compared to control concrete slabs for in case of mixture type (M4CS) and (M6CS). The interpreted average values of chloride concentration at different drill depth from (30-50) mm is represented as M4S9 (0.069%, 0.067%, 0.062%), M6S11 (0.063%, 0.052%, 0.050%) respectively. Furthermore, the chloride concentration in water-based impregnation concrete slabs is slightly increased as when compared to solvent based impregnation concrete slabs in all mixtures type (M4CS-M6CS). Its varied values is found to be as MS10 (0.070%, 0.068%, 0.063%), M6S12 (0.064%, 0.054%, 0.053%) respectively. The chloride concentration is also increased at drill depth 30 mm for in case of control, solvent, and water-based impregnation concrete slabs as when compared to drill depths (40-50) mm and its varied values were represented as M4CS (0.80%, 9.87%), M4S9 (3.47%, 10.28%), M4S10 (2.61%, 9.87%), M6CS (8.38%, 14.61%), M6S11 (17.32%, 20.80%), M6S12 (15.33%, 16.91%) respectively. The chloride concentration in solvent based impregnation concrete slabs is decreased as when compared to control concrete slabs at different drill depths (30-50) mm and in which its varied values were determined as M4S9 (96.42%, 93.82%, 95.98%), and M6S11 (96.94%, 87.47%, 89.91%) respectively. Whereas the chloride concentration in water-based impregnation concrete slabs is reduced at different drill depths (30-50) mm as when compared to control concrete slabs for in case of all mixtures type (M4-M6) in its varied values are at different drill depths (30, 40, and 50) mm as M4S10 (97.45%, 95.67%, 97.44%), and M6S12 (98.85%, 91.34%, 96.18%) respectively. Similarly, the chloride concentration in solvent based impregnation concrete slabs is decreased as when compared to water-based impregnation concrete cubes in which its varied values at different drill depths (30-50) mm as M4S9 (98.94%, 98.07%, 98.50%), M6S11 (98.06%, 95.76%, 93.47%) respectively. The chloride concentration in control concrete slabs (M1CS-M6CS) were increased as when compared to impregnation concrete slabs (M1SB-M6SB and M1WB-M6WB) for in case of designed mixtures type at different drill depths (30-40-50) mm. Chloride concentration in impregnation concrete slabs (M1WB-M6WB) were increased as when compared to impregnation concrete slabs (M1SB-M6SB) for in case of designed mixtures type at different drill depths (30-40-50) mm. The variation of chloride penetration in pre-conditioned concrete slabs such as dry/partially/fully saturated conditioned concrete slabs was represented in Figures 3a-3f.

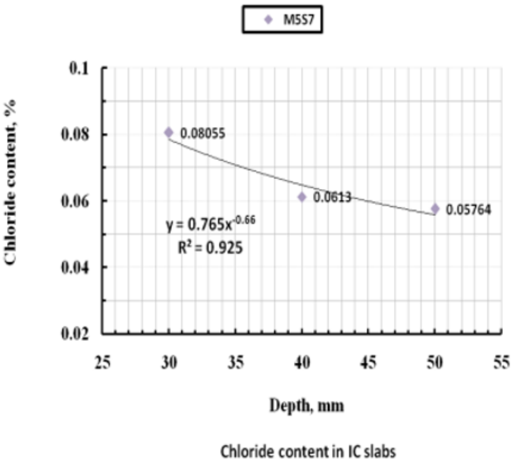

Fig. 3a. Cl- in impregnation concrete slabs

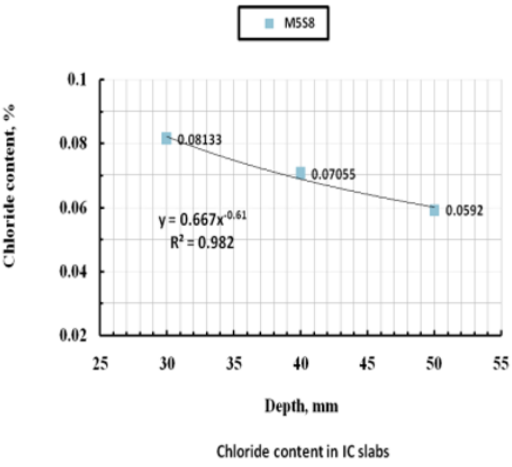

Fig. 3b. Cl- in impregnation concrete slabs

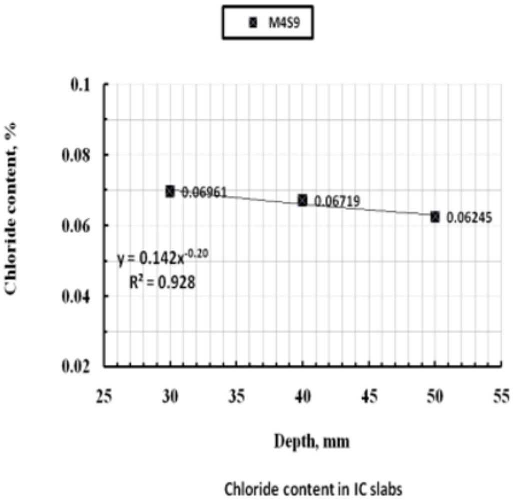

Fig. 3c. Cl- in impregnation concrete slabs

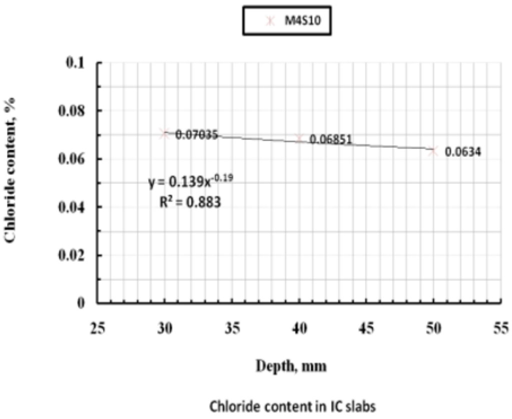

Fig. 3d. Cl- in impregnation concrete slabs

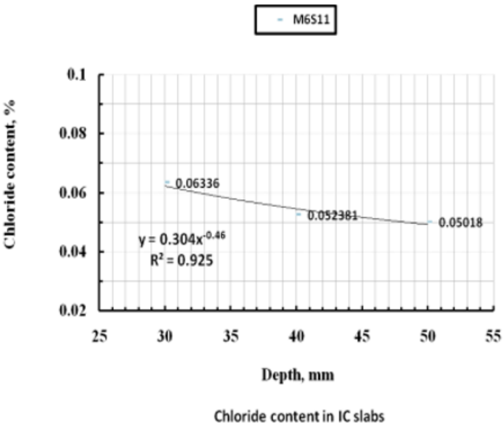

Fig. 3e. Cl^- in impregnation concrete slabs

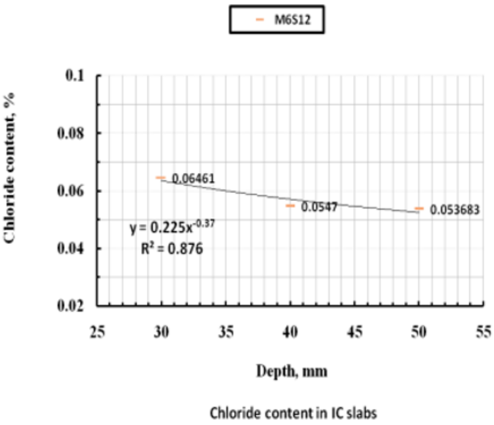

Fig. 3f. Cl^- in impregnation concrete slabs

Chloride concentration in impregnation concrete slabs (M1SB:96.96%, M2SB:94.20%, M3SB:93.65%, M4SB:96.43%, M5SB:95.25%, M6SB:96.94%) were decreased as when compared to control concrete slabs (M1CS-M6CS) for in case of designed mixtures type at different drill depths as representing in the Fig.8. Chloride concentration in impregnation concrete slabs (M1SB:97.77%, M2SB:98.72%, M3SB:98.57%, M4SB:98.95%, M5SB:99.04%, M6SB:98.07%) were decreased as when compared to control concrete slabs (M1WB-M6WB) for in case of designed mixtures type at different drill depths.

6. Conclusions

- It’s possible to correlate chloride concentration with different drill depths by power type of equation in pre-conditioned (DCC/FSC/PSC) control/impregnation concrete slabs.
- The chloride concentration is increased in DCC pre-conditioned concrete slabs at different drill depths (30-40-50) mm as when compared to PSC/FSC pre-conditioned concrete slabs at different drill depths.
- The chloride concentration is decreased in solvent/water-based impregnation DCC/PSC/FSC concrete slabs as when compared to control DCC/PSC/FSC concrete slabs.
- In addition to that, the chloride concentration is decreased in solvent based impregnation DCC/PSC/FSC as when compared to water-based impregnation DCC/PSC/FSC concrete slabs.
- It’s also observed from the results that, the chloride concentration is slightly increased in control/ impregnation PSC (SB/WB) as when compared to control/impregnation FSC (SB/WB) concrete slabs.

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