Performance Enhancement of Self-Compacting Concrete in Saline Environment by Hydrophobic Surface Protection

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ABSTRACT

The purpose of this research is to enhance the performance of Self-compacting Concrete (SCC) to make it a more sustainable alternative to traditional concrete. SCC serves the purpose in harsh environments, therefore, requires protection against de-icing agents and harmful saline environments. This paper reports the results from a laboratory study evaluating the efficacy of two impregnants; pure-silane and water-based silane. Both materials were applied on dry and wet SCC specimens manufactured with high and medium doses of superplasticiser. When treatment is applied on dry samples, a significant reduction in chloride penetration was noticed. However, the impregnants were less effective when applied on specimens subjected to intermediate and long-term exposure to water. In dry conditions, pure-silane performed better than the water-based silane, although they had a similar performance when applied on wet specimens. In addition, increasing the internal moisture content has shown an adverse effect on the efficacy of both materials.

Keywords: *Self-compacting concrete, Protection, Impregnation, Moisture content, Sorption*

1. INTRODUCTION

Self-compacting concrete (SCC) has been implemented in the construction industry for a long time since it was first introduced in Japan at the 1980s (Loukili 2011). Many countries, like Japan and Sweden, started to put SCC into service to build and develop tunnels, large buildings, and highway bridges (Persson 2001). The high-performance properties of SCC like its high workability, resistance to segregation, ability to achieve any desired compressive strength and its easiness to handle at the production and placement stages made its use in hard-to-reach areas and congested places more desirable than conventional concrete (De Schutter et al. 2008). The relatively fast deterioration process of conventional concrete that starts within a period of 10 or 15 years from casting, and results from poor compaction, works on decreasing the quality of concrete and at the same time increases the construction costs (De Schutter et al. 2008).

Despite all the advantages, SCC still suffers from deterioration under different environmental impacts and harsh weather conditions. This will increase the demand on repairing the existing SCC, on the long run, to restore concrete to a better state, which will increase the cost of using this kind of concrete (Mesbah et al. 2000; Khayat and De Schutter 2014). Accordingly, protecting SCC at an early age will extend its service life and reduces its need for maintenance procedures, which will reduce its actual construction costs. Adding to that, it is most probably that SCC will start to gain more attention, in the near future, to construct roads, bridges, ports and airports, which will make protecting this kind of concrete a necessity to increase its durability and resistance against harmful chemical agents.

The durability characteristics of SCC was under debate for many years due to the considerable variation in the mix ratios between SCC and traditional concrete, especially when both mixes provide the same strength grade (Zhu and Bartos 2003). Accordingly, research focused on assessing all the durability aspects of SCC like water absorption, strength and chloride diffusion and compare them with traditional concrete (Zhu and Bartos 2003). Many materials have been introduced and planted into the SCC mix to increase its the durability and enhance its compressive strength and impermeability like nano and microparticles of SiO_2, nanoparticles of TiO_2, nanoparticles of Fe_2O_3, coal bottom ash, steel fibers, ultrapulverized fly ash, and many other materials (El-Dieb 2009; Jalal et al. 2012; Beigi et al. 2013; Nazari and Riahi 2010; Khoshakhlagh et al. 2012; Siddique 2013; Xie et al. 2002; Mahalingasharma et al. 2017; Güneyisi et al. 2014; Omrane et al. 2017; Yung et al. 2013; Alsubari et al. 2016). Some of these treatments have shown promising results in terms of increasing the compressive strength and reducing water and chloride pentration of SCC. However, few research have considered using surface protection martials to enhance SCC resistance to water absorption and chloride diffusion. As a result, this research springs from the necessity to protect SCC from water penetration and the attacks of harmful chemical agents by applying cost-effective surface applied treatments.

A wide range of protective materials has been used in treating and reserving conventional concrete with different application methods; coating materials, pore blockers, sealers, impregnants, and many other generic types (Medeiros and Helene 2009). Many researchers have discussed these treatments and their impact on conventional concrete, where cementitious coatings, moisture blocking materials, and different hydrophobic impregnants were applied to concrete with different dosages to increase its resistance to weather and environmental attacks (Al-Kheetan et al. 2017a; Al-Kheetan et al. 2017b; Al-Kheetan et al.

2017c; Al-Kheetan et al. 2018a; Al-Kheetan et al. 2018b; Al-Kheetan et al. 2018c). Some promising results were obtained, after applying such treatments to conventional concrete, as water absorption and chloride ingress have dropped significantly compared to untreated concrete (Al-Kheetan et al. 2018b; Al-Kheetan et al. 2018c; Rahman et al. 2013). In a study conducted by Reiterman and Pazderka (2016), where a crystalline coating was applied to the surface of conventional concrete, water absorption has dropped by more than 60% when compared to the reference mix. However, this reduction in water absorption could be higher in the case of using Silane and Siloxane derivatives (Medeiros and Helene 2008).

Recently, there has been an increasing acceptance of surface impregnation materials as it provides an effective resistance, compared to coatings and pore blocking materials, by suppressing chloride diffusion by forming a water-resistant barrier in the concrete itself and improving the service life of the structure.

2. RESEARCH SCOPE AND OBJECTIVES

Conventionally, hydrophobic impregnants using the high active content of Silane and Siloxane materials were the most commonly used protective materials for reinforced concrete in the UK (Calder and McKenzie 2009). Accordingly, some concerns have emerged recently regarding this common and wide usage of solvent-based Silanes in the construction industry, especially after some studies have proven its dangerous effects and the risks they impose to the environment, particularly to marine life (SIDS 2004; Bubalo et al. 2014). As the construction industry is moving towards an improved environmentally friendly construction, the methods and materials used within its regulations need to be updated. As a result, over the past decade, there has been increasing use of water-based Silanes and other less-harmful materials.

Compliance of such alternatives with EN1504-2 has acted as a driving force for this change (British Standards Institution 2004). On the other hand, there has been growing concern regarding the on-site performance of all hydrophobic impregnation materials; traditional and alternative, where a marked discrepancy between outcomes of laboratory testing and apparent defence of actually treated structures have appeared (Rahman and Chamberlain 2016). It is recommended that the application of the impregnants should take place on a "dry surface" to allow a correct penetration of the product and hence reach the maximum performance. A dry surface does not necessarily mean that concrete should be fully dried with a very low internal moisture content, but to have a moisture content of 5.0% ± 0.5 at the time of application, as the code of practice EN 1504-2 and BD 43/03 suggest (British Standards Institution 2004; Highways Agency 2003; Al-Kheetan et al. 2018d). Therefore, it is important that the efficacy of all impregnants is determined in relation to moisture content within the concrete. This bears directly on the achievable dosage of protective materials, and thus the level of protection they could provide. These influences are evaluated in this study.

This paper reports results from a comprehensive laboratory testing to evaluate the water absorption and the chloride penetration resistance of protected and unprotected SCC specimens. Additionally, concrete was subjected to different conditions before applying the protective materials. A dry surface condition following the guidelines of EN 1504-2 and the manufacturer instructions was prepared before application, in addition to another two wet conditions that simulate different periods of wet weather. The first exposure is referred to as "dry condition", and the second exposure which includes 24 hours immersing of concrete in water, before the application of impregnation, is referred to as "intermediate exposure" and it represents a medium rainfall. Finally, 168 hours immersing in water, before the application of

impregnation, is referred to as “long exposure” or “Fully saturated”, and it represents a severe exposure to rain.

The selection of the protective materials was based on earlier research conducted by authors, where the performance of four non-solvent based impregnants, to protect conventional concrete from chloride attack, was evaluated (Rahman et al. 2013; Rahman and Chamberlain 2017; Rahman et al. 2014; Rahman et al. 2016). The adopted material for this trial showed good performance as an alternative to harmful solvent based Silanes and Siloxanes. The results were compared with untreated specimens subjected to similar wet exposure regimes.

3. EXPERIMENTAL WORK

3.1 Mix Design and specimen preparation

Two mix designs for two different SCC mixtures were prepared, following the recommendations of the European Guidelines for Self-compacting Concrete. Polycarboxylic superplasticiser (Glenium C315) was added to both mixtures with two different proportions; high and low (EFNARC European Project Group 2005). The mix design of both blends is shown in **Table 1.** Both mixtures had water to cement ratio of 0.53, mix design ratios of 1:3.2:1.7, and 1.43% Glenium for mixture 1 and 0.96% Glenium for mixture 2. In this research, the w/c ratio value was chosen following the recommendations of the BS EN 206-1 for exposure conditions that are related to the environmental actions (British Standards Institution 2000). According to the BS EN 206-1, concrete resistant to corrosion induced by chloride, either sourced from sea water or other than sea water, should have maximum w/c ratios of 0.50 for XS1 (sea water) and 0.55 for XD1 and XD2 (other than sea water). Also, the minimum

strength class of the used concrete should be C30 grade for the tested exposure conditions. The mix design, of both mixtures in this research, has been set to meet the mentioned requirements.

As specified in the European guidelines, SCC with similar water to binder ratio to that in conventional concrete will usually have a slightly higher strength than traditional vibrated concrete. This refers to the lack of vibration in the SCC which gives an improved interface between the aggregates and hardened paste. Therefore, it was decided to design the mixes in this study so they will have a strength similar to conventional concrete used in bridges and other heavy structural applications.

As specified in the European guidelines, the fresh mixtures went through some inspections for consistency, flowability and passing ability by the slump, V-funnel and L-box tests respectively. In total, 36 cubes of 100 mm x 100 mm x 100 mm size were manufactured; 18 cubes for each mixture. After 24 hours, specimens were carefully removed from the steel moulds ensuring that their corners and surfaces were not damaged during the demoulding process. Samples are then cured in a water tank for 28 days.

At the end of the curing period, all cubes were taken out from the water tank and went through a drying cycle, to determine the time that internal moisture needs to evaporate completely, to ensure that all the cubes are dried to the same level before carrying out the sorption test. In the drying cycle, cubes were surface dried and weighed after 5, 10, 20, 30 minutes, 1 hour, 2 hours, and 24 hours up to 168 hours of drying. From 100 hours and on, cubes were oven dried overnight at 50 $^{\circ}$C to accelerate the drying process. The concrete specimens were then taken out from the oven and allowed to settle in atmospheric conditions for further two days.

3.2 Compressive strength

The two mixes were designed to achieve a compressive strength of 30 MPa. Accordingly, compressive strength test was run, following the BS EN 12390-3, to assure that both mixes have achieved the desired strength grade (British Standards Institution 2009). To attain this objective, three cubes of 100 mm x 100 mm x 100 mm size for each mixture were cast and tested after 28 days of curing in a water bath.

3.3 Sorption test on hardened specimens

The sorption test aims to measure the rate of absorption of water by capillary suction of unsaturated samples by fully submerging them in water. This test also helps to determine the water content in each cube after specific periods of time, so that the moisture content can be used to compare the performance of applied impregnants. The sorption test was performed following the instructions and guidelines of BS EN 13057 (British Standards Institution 2002). The weight gain of specimens from both mixes was recorded by a high precision balance with ±0.01 gm. Cubes were removed in groups of threes from the water bath, surface dried using wet towels and then weighed at 5, 10, 20, 30 minutes, 1, 2, 19, 24, 72, 77, 98, 146 and 168 hours. After the sorption test is finished, the specimens were then left to dry under atmospheric conditions for 15 days. They were further dried in an oven for 72 hours at a temperature of 50 $^{\circ}$C and then left for further three days to adjust to atmospheric conditions.

3.4 Chloride penetration test

The ability of treated and untreated concrete mixes to resist chloride attacks were tested following the British Standard, BS EN 13580 (British Standards Institution 2002). All cubes were put on a steel mesh to allow air to circulate all over their six faces, and then they were placed under room temperature to dry for 24 hours, before submerging them in NaCl solution

with 10% chloride concentration. This was achieved by adding 10 gm of rock salt in one litre of water. Specimens are then submerged for a month in salt solution following the guidelines of the BS EN 13580, and the gain in weight against time was regularly monitored. After 30days, specimens were taken out from the NaCl solution, and dust samples were extracted by dry drilling. Drilling was performed at the centre of one face in each sample, and at 5 mm - 20 mm depths with 5 mm interval. Chloride concentration levels were checked by Volhard's method of titration as specified in BS EN 14629 (British Standards Institution 2007). Before Volhard's test, a blank titration test was performed on a certain amount of the dust to get an indication of the endpoint of the reaction.

3.5 Surface applied materials

Two impregnants, a Nano-Silane, and an Aqueous Silane are used in this research. The nano-silane material is a pure Silane, a non-water based and a non-solvent based material, with one nano-size molecule and an active content higher than 80%. The aqueous Silane, on the other hand, is water-based polymer Alkylalkoxy Silane product with 40% active content. Both materials are solvent free and claimed to be substantially less hazardous than traditional solvent-based Silane/Siloxane materials. An attempt was made to quantify and compare the hazards of each product; however, this was a difficult procedure for the water-based material. The toxicity of Nano-Silane was easy to be classified by using the 48-hour Acute Toxicity Testing method, explained in the EN 1504-2, however, the same classification was not appropriate for the Aqueous Silane (British Standards Institution 2004).

Nnao-Silane is classified, according to EN1504-2, as Class II because it achieves a penetration depth greater than 10.0 mm. On the other hand, the water-based product is a water-borne acrylic copolymer with 0% VOC content. Thus it is friendly to the environment and low hazardous. In addition to that, It is Silicone and solvent free and achieves a penetration depth greater than 1.0

mm, so it could be classified as a Class I hydrophobic material, complying with EN1504-2 (British Standards Institution 2004).

3.6 Application of Impregnation

From each mixture, six specimens were treated with Nano-Silane, six were treated with Aqueous Silane, and the remaining six cubes were left untreated. According to the manufacturer instructions, each layer applied to one cube requires 9 gm of the impregnant. However, it was decided to use 10 gm per cube, as some of the material may be absorbed by the brush or washed off from the cube surface. The impregnation materials were weighed in a glass beaker and carefully applied using a brush to all the surfaces of the cube. In order to avoid cross-contamination, separate containers and brushes were used for measuring and applying the two impregnants. **Table 2** shows the percentage loss of the applied materials that were applied. It is noteworthy to mention that the uptake of the materials was evaluated based on the mass of the concrete cube before and after treatment, the mass of the applied material, and the weight of the leftover material in the brush and the cup.

It can be seen that the effective uptake of both impregnants is reduced by approximately 40% when applied to saturated or nearly saturated specimens. It is clear that a prolonged period of exposure to wet weather is detrimental to achieve the correct dosage on the concrete substrate, even when a pre-treatment drying period is operated.

Specifications for the impregnation process are presented in **Table 3**. As shown in the table, 18 specimens in each mixture were grouped in three batches, comprising six specimens in each batch. In the first batch, in order to simulate the treatment in a dry condition, two specimens were treated with Nano-Silane, two with Aqueous Silane and the remaining two were used as

a control. The second batch was taken from the water tank after 24 hours, surface dried and four specimens were impregnated; two with Nano-Silane, two with Aqueous Silane and the other two specimens left untreated. The third group was removed from water tank after 168 hours, and the same previous procedures were followed with the same number of treated and untreated cubes.

4. RESULTS

4.1 Properties of fresh mixtures

The filling ability, passing ability and segregation resistance of the mixes are compared as suggested in the BS EN 206-9 **(**British Standards Institution 2010), and results are presented in **Table 4**. The final two mixtures were chosen by adjusting the superplasticiser content and the water/powder ratio in three different trial mixes.

Slump values were found within the recommended limits, indicating consistent mixtures. The difference in slump values between the two mixtures shows that the higher quantity of the superplasticiser in SCC1 increased its flow compared to SCC2. The required time for concrete to spread to 500 mm can also be used as an indicator of viscosity and bleeding tendency of the mixture. Values of 500 mm or marginally less are indicative of highly viscous mixtures which in turn increase the high yield point and segregation. Both mixtures achieved the required 500 mm spread without any bleeding with flow time greater than 2 seconds. Following the European Guidelines for Self-Compacting Concrete, T5min test was also carried out using V-funnel test (EFNARC European Project Group 2005). The funnel was filled with concrete and allowed to settle for five minutes, before opening the bottom stopper. A significant increase in flow time indicates segregation. According to latter guidelines, the recommended time for

concrete to qualify for SCC is 6 seconds. Both mixtures passed the 6 seconds test, and they achieved an adequate flowability (EFNARC European Project Group 2005).

The passing ability of concrete was also determined by using the 3 bar L-box test. It was carried out by filling the vertical section of the L-Box with concrete before opening the gate, in the horizontal section, to check for its passing ability. The passing ability is expressed in a ratio that represents the divergence between the height of concrete at the end of the horizontal section and the height of the remaining concrete at the vertical section. If the ratio is greater than 0.8, then the filling rate is considered adequate. It can be seen in **Table 4** that both mixtures have satisfied the filling ability criteria.

4.2 Compressive strength

Results from the compressive strength test have shown a convergent performance for both mixtures with higher strength grade for mixture 1. An average compressive strength of 35.4 MPa was obtained for mixture 1, and 31.2 MPa for mixture 2.

Although the surface treatment of matured SCC does not affect its strength, knowing the strength grade of the tested concrete would help in explaining the performance of SCC when tested for water absorption and chloride penetration.

4.3 Sorption profile

In order to assess the internal moisture content in the tested concrete specimens, the water uptake and moisture release in the wetting cycle and drying cycle respectively were determined by weighing the cubes before submerging them in water and reweighing them after specific periods of times from submersion. Results are shown in **Figure 1a and b**. It can be seen that water uptake is marginally higher in mixture 2. This refers to the effect of the high amount of

superplasticiser added to mixture 1, which reduces the voids and results in a denser mixture than mixture 2. This could be associated with the higher compressive strength of mixture 1 (section 4.2), which gives an indication for the reduced air voids content that will ultimately help in reducing water penetration.

Regardless of mixture types, there was a rapid increase in mass in the first 24 hours of the wetting cycle, and this increase in mass started to slow down as the specimen pores were saturated. In the drying test, all cubes followed a similar trend to that in the wetting cycle although the trend was more gradual. After 102 hours, both wetting and drying patterns were gradual until the end of the test at 168 hours. Moreover, the mass would continue to increase/decrease slowly after the seven days of wetting/drying, but the magnitude of the increase/reduction would be very small. Therefore, it was decided to take 168 hours as the optimum time to reach the fully saturated/dry state in this research.

4.4 Absorption of chloride solution

This test aimed to evaluate the efficacy of both impregnants against water and salt solution absorption when concrete is subjected to different saturation levels before the application of these impregnants. Results presented in **Figure 2a and b** show that for both mixtures, all cubes have followed a similar trend; increasing the chloride intake with time. It can be seen that, regardless of mixture types, cubes that were exposed to a long period of saturation levels had a lower intake of the solution than cubes exposed to dry and intermediate saturation conditions. This refers to the level of saturation reached by the near-surface pores, blocking further water penetration.

Referring to mixture 1, as shown in **Figure 2a**, Nano-Silane performed better than Aqueous Silane only under dry conditions, as the aqueous silane surpassed the Nano-Silane performance under fully saturated and intermediate saturation conditions. However, chloride intake in untreated concrete was less than all treated concrete under intermediate and fully saturated conditions. Similar performance for the Nano-Silane was observed in mixture 2, as shown in **Figure 2b** when applied under dry conditions, where its performance exceeded the aqueous Silane and untreated concrete. However, both Nano-Silane and Aqueous Silane performed similarly under intermediate saturation conditions, at most times, and they were less effective than control. In the same mixture, Aqueous Silane provided better protection than Nano-Silane under fully saturated conditions, with a significant difference in performance. Nevertheless, control concrete performed the best with marginal absorption rate for chloride solution. The reduced performance of treated samples compared to untreated ones, preconditioned with intermediate and high levels of water, refers to the incompetence of materials to work with moisturised concrete, which was pointed out previously in **Table 2**, where larger amounts of the applied materials were lost during application on wet surfaces.

4.5 Chloride concentration profile in concrete

The average percentage of chloride content at different depths, for mixture 1 and 2, either for control specimens or protected ones are presented in **Figures 3a-c and 4a-c.**

In general, it can be seen that chloride concentration decreases with depth, and the control specimens had higher chloride concentration at all depths in both mixtures. Results demonstrated that impregnation had enhanced the protection of self-compacting concrete against chloride penetration.

For mixture 1, as shown in **Figure 3a**, Nano-Silane has delivered the best protection under dry conditions between 5-15 mm depths, with the maximum efficacy of 42%, compared to control, at 5 mm depth, and minimum efficacy of 20% at 15 mm depth. However, both Nano-Silane and aqueous Silane materials delivered the same level of protection at 20 mm with an efficacy of 21%. On the other hand, Nano-Silane applied to concrete, pre-conditioned with intermediate water exposure, as shown in **Figure 3b**, delivered similar performance to aqueous Silane at 10-20 mm depths. Whereas, aqueous Silane provided better protection than Nano-Silane at 5 mm depth. When it comes to fully saturated concrete, **Figure 3c**, aqueous Silane delivered the best protection, along the 10-20 mm depth, with the maximum efficacy of 37% at 10 mm depth, and similar performance to Nano-Silane at 5 mm depth.

For mixture 2, and as shown in **Figure 4a**, Chloride penetration through dry concrete treated with Nano-Silane was the least through all the depths, with a maximum efficacy of 34% at 5 mm. In the same pre-conditions, aqueous Silane performed similarly to untreated concrete until 20 mm depth, where a marginal enhancement in performance could be noticed in treated specimens. On the other hand, pre-conditioning concrete with intermediate moisture content decreased the efficacy of Nano-Silane at the first 5 mm depth and increased the performance of the water-based Silane, and they both performed similarly with increasing the depth. However, when comparing the dry and intermediate pre-conditions together, applying both treatments to dry concrete offered better protection against chloride ingress than applying them to semi-saturated concrete (**Figure 4a and b**). Finally, saturated concrete negatively affected the performance of the aqueous Silane at 5 mm depth, and increased the efficacy of Nano-Silane. Moreover, the aqueous Silane performed similarly to untreated specimens at 15 mm and 20 mm depths, whereas Nano-Silane performance exceeded them at former depths. Independent from mixture types, specimens treated with Nano-Silane impregnant appeared to have a relatively high chloride concentration at all depths, at intermediate and long

exposure condition. However, better protection was noticed when applied to dry specimens. On the other hand, water-based Silane has shown a less effective performance when applied to dry specimens, and similar performance to Nano-Silane impregnant when applied to specimens exposed to intermediate and long exposure conditions. This indicates that as the moisture content within concrete increases the effectiveness of the impregnant decreases.

In order to evaluate the efficacy of treatment against chloride ingress through concrete, the reduction percentage of chloride content from 5 mm to 20 mm depths at different saturation levels was calculated, and it is presented in **Figure 5a and b**. When comparing the reduction in chloride content in both mixtures, it is obvious that mixture 1 has managed to absorb less chlorides than mixture 2. This could be linked with the compressive strength results, obtained in section 4.2, where mixture 1 has shown higher strength than mixture 2, which indicates that the internal structure of mixture 1 is more dense than mixture 2 and has less voids content.

In mixture 1, as shown in **Figure 5a**, it can be seen that the rate of absorption and concentration of chloride was reduced the most through control concrete under all pre-conditions, with a maximum 70% reduction in chloride content, through the tested depth, under intermediate saturation conditions. On the other hand, control concrete has achieved the most effective chloride reduction rate in mixture 2, under fully saturated conditions, as shown in **Figure 5b**. The untreated fully saturated (long exposure) cubes were able to reduce chloride ingress, from 5 mm to 20 mm depths, with an efficacy of 72%. This refers to the high saturation level inside the pores in mixtures exposed to prolonged water contact.

Regarding the protective materials, some differences in the performance of Nano-Silane and water-based impregnants are also shown in **Figure 5**. From the results, it can be noted that the

optimum performance of Nano-Silane is reached when concrete is preconditioned with intermediate water exposure, regardless of the amount of superplasticiser added to the mix. However, Nano-Silane had managed to exceed the performance of Aqueous Silane when concrete, with a high dosage of plasticiser, was pre-conditioned with intermediate and prolonged contact with water. Also, concrete with a low dosage of plasticiser (**Figure 5b**) and treated with Nano-Silane performed better when it was pre-conditioned with an intermediate exposure level of water. Aqueous Silane followed a similar pattern to Nano-Silane when applied to specimens with high superplasticiser content; its optimum performance was noticed when concrete was pre-conditioned under intermediate exposure to water. However, Aqueous Silane, when applied to mixture 2, performed the best when the surface of the material was dry, and its performance exceeded that of Nano-Silane.

5. CONCLUSION

Key conclusions from this research are as follows:

[1] For immersed SCC the major part of water absorption occurs within the first 24 hours. Take-up of either Nano-Silane or water-based Silane is substantially reduced with approximately 40% reduction for 168 hours immersion pre-conditioning. Long-term dry conditions are necessary to achieve the manufacturer's recommended dosage.

[2] Impregnation enhances the protection of self-compacting concrete against chloride penetration. The performance of the impregnant in dry condition is similar to earlier research by the authors on normal vibrated concrete. It can be concluded that the addition of

superplasticiser to improve the flowability of the material, does not have any immediate adverse effect on the protection performance.

[3] Increasing superplasticiser in the mixtures reduces surface voids, which ultimately reduces the penetration of impregnants, results in marginally higher penetration of chloride. It is therefore essential to use an optimum amount of superplasticiser to reach the ideal SCC mix, with adequate protection against chloride ingress.

[4] The internal moisture affects the protection of SCC adversely. As the moisture content increases due to prolonged exposure to water, the effectiveness of the impregnant decreases significantly. The results indicate that internal moisture content increases the rate of absorption and concentration of chloride levels by as much as 50%. A practical interpretation is that the specified 24 hours drying period may not be sufficient to secure the benefit from hydrophobic impregnation.

[5] Results demonstrated that, compared to water-based Silane, the Nano-Silane impregnant is more effective when applied in dry conditions. However, as the internal moisture increases, the effectiveness of the applied impregnants, regardless of their type, is greatly hindered making them less effective

CONFLICT OF INTEREST

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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Figures Legends:

Figure 1: Drying and wetting cycles in (a) mixture 1 and (b) mixture 2

Figure 2: Chloride intake in: (a) mixture 1 and (b) mixture 2

Figure 3: Chloride content in mixture 1 at different depths for: (a) Dry application conditions, (b) Intermediate moisture content application conditions and (c) Saturated moisture application conditions

Figure 4: Chloride content in mixture 2 at different depths for: (a) Dry application conditions, (b) Intermediate moisture content application conditions and (c) Saturated moisture application conditions

Figure 5: Reduction in chloride content levels from 5 mm to 20 mm depths for: (a) mixture 1 and (b) mixture 2