PROTECTING THE DURABILITY OF CONCRETE ROAD PAVEMENTS AND BARRIERS BY DUAL CRYSTALLINE WATERPROOFING TOPICAL TREATMENT

R. Al-Rashed
International Chem-Crete Corporation, 800 Security Row Richardson, Texas 75081, U.S.A.
radi@chem-crete.com

M. Al-Jabari
Chem-Crete Europe, Stanicna 13, 90851, Holic, Slovakia
maher@chem-crete.com

ABSTRACT

Concrete roads encounter several durability issues that reduce their sustainability and increase their maintainable costs. Typical concrete durability solutions are formulated to lead a single functionality of waterproofing utilizing crystalline pore blocking or hydrophobic dampproofing by creating a pore lining molecular layer. Each functionality can perform well in some durability parameters but cannot provide an integrated solution. The advancement of dual crystalline engineered (DCE) waterproofing material that integrate hygroscopic, hydrophilic and hydrophobic waterproofing functions in one liquid solution is shown to give a total durability solution to concrete roads. Several publications handled various aspects of DCE functionalities. This paper highlights the durability performance of DCE. It summarizes the reported results of durability parameters including permeability, water absorption, static water contact angle, ice adhesion, alkali silica reactions (ASR), chloride ion penetration, cycles of freezing and thawing, biological deterioration and mechanical properties.

KEY WORDS

CONCRETE, ROAD, PAVEMENT, SUSTAINABILITY, DURABILITY, CRYSTALLINE WATERPROOFING.

1. INTRODUCTION

Due to their porosity and hydrophilic structures, concrete roads encounter several moisture related problems. Moisture gathered within concrete pores function as a transporter and an environment for fatal reactions. Water (in vapor, liquid and solid phases) undergoes various physicochemical actions that cause a decay in the durability of concrete structure (Al-Jabari, 2022b). The durability issues are caused by thermal effects such as ice adhesion and freezing-thawing cycles (Porras, Jones, & Schmiedeke, 2020), or physicochemical effects such as chloride ion penetration leading to scaling, paste deterioration from the formation of expansive oxychloride and the corrosion of embedded steel (Glass & Buenfeld, 2000; Santhanam & Otieno, 2016), carbonation (Tran, Kobayashi, Asano, & Kojima, 2018), alkali silica reactions (ASR) (Fernandes & Broekmans, 2013; Hobbs, 2015; Saha, Khan, Sarker, Shaikh, & Pramanik, 2018; Thomas, Fournier, & Folliard, 2008), and biological deterioration from mould growth (Javaherdashti, Nikraz, Borowitzka, Moheimani, & Olivia, 2009; Lence, Hassan, Zayor, & Rupnow, 2014; Viitanen et al., 2010). In general, concrete durability is determined by its ability for resisting chemical attacks, weathering actions, abrasion, and other service conditions (ACI, 2018), or in more general terms resisting all processes of deterioration (Jianxia, 2012). Furthermore, durability determines road service life and governs their sustainability. The service life of roads decreases with the decline of structural quality of concrete. High durability and long sustainability demand a water tight or well-waterproofed concrete structures that resist the penetration of water (Al-Jabari, Al-Rashed, Ayers, & Clement, 2022; Mehta & Monteiro, 2017).

Water penetration mechanisms depend on the microstructure structure of concrete and its constituents as well as on the hydrostatic pressure. Water can penetrate concrete mainly by capillary suction (sorption or wicking) under low hydrostatic pressure (Al-Jabari & Husein, 2022) and permeation flow under high hydrostatic pressure (Al-Jabari, 2022a). In concrete roads, wicking is the typical penetration mechanism since the hydrostatic pressure from surface wetting is low as illustrated in Figure 1. However, a high hydrostatic pressure can be created from tire loading leading to permeation flow (see Figure 1). Water absorption in concrete is driven by its hydrophilic characteristics that are dependent on the pore size distribution and enhanced with the increase of fine pores (pore refinement) (Al-Jabari & Husein, 2022). Permeation flow is increased with the increase in total porosity and the increase in pore size (Al-Jabari, 2022a). Minimizing water penetration in concrete by waterproofing and dampproofing depends on the controlling mechanism of water penetration. Minimizing water permeation requires creating flow restrictions in the permeable pores (by crystalline materials). On the other hand, minimizing wicking flow demands water repelling treatments which increase the water contact angle to a value over 90° and or over 120° for obtaining over-hydrophobic characteristics (Al-Jabari & Husein, 2022).

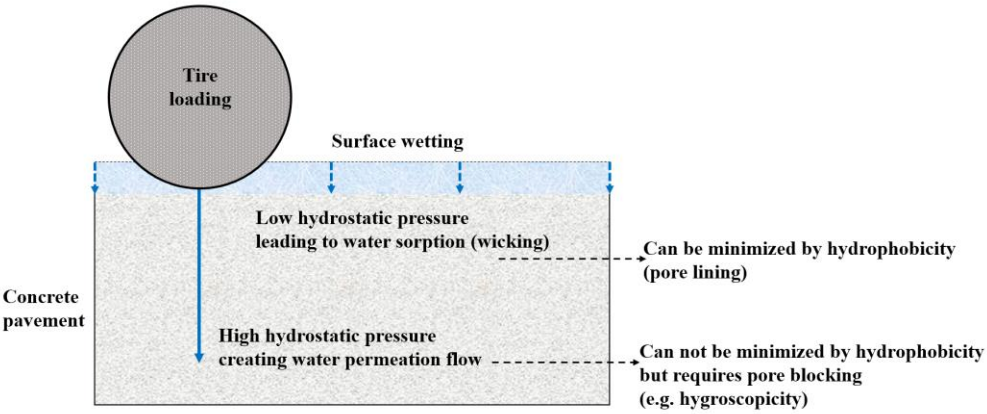

Figure 1: water penetration and waterproofing mechanisms.

Waterproofing materials can be added to concrete either as (1) surface (topical) treatments that improve the characteristics of a surface layer or (2) additions to concrete mixtures at the time of batching that manipulate the characteristics of the whole structure (Al-Jabari, 2022d). Penetrating liquids used for topical treatment of concrete include surface hardeners, densifiers and sealers (ACI, 2018). Topically applied penetrating sealers are first absorbed by the concrete surface then they migrate through the concrete structure (by liquid penetration and diffusion) where they react to form the waterproofing materials (Biparva & Gupta, 2010; Jalali & Afgan, 2018). Traditionally, the reduction of moisture in concrete roads can be achieved using (1) pore lining hydrophobic surface treatment which create a molecular layer on the pores surfaces (Al-Jabari, 2022e) (2) pore filling or blocking materials (e.g. hydrophilic or hygroscopic crystals) which creates flow obstacles within the permeable pores of concrete (Al-Jabari, 2022f). The first approach (e.g. Silanes and Siloxanes) can only reduce water absorption as they cannot resist hydrostatic pressure. Typically, hydrophobic materials cannot function well when the hydrostatic pressure exceeds a limit of 120 kg_f/m^2 (12 cm water) (ACI, 2016; Pan, Shi, Shi, Ling, & Li, 2017b). On the other hand, reducing water permeation requires pore blocking materials (see Figure 1). Both approaches can allow moisture release from concrete upon de-wetting since they maintain the pores partially open. Furthermore, hygroscopic crystals formed within concrete pores can consume the water vapor through its adsorption-growth mechanism (Al-Jabari & Husein, 2022). In winter, ice adhesion on concrete roads caused by physicochemical interactions between ice and concrete surface creates safety and durability issues. These interactions include cohesive physicochemical (hydrogen bonding and van der Waals forces (Beeram 2017)) and mechanical interlocking (Makkonen 2012a) (see (Al-Jabari & Husein, 2022) for further details). These entanglement or interlocking mechanical forces arise from the roughness of the surface and the porosity (Ashworth T. 1979). Icephobicity (ice-repelling) is correlated to hydrophobicity (Al-Jabari & Husein, 2022).

This paper summarizes the overall waterproofing and durability parameters for Dual Crystalline Engineered (DCE) treatment (described in Section 2). The parameters include permeability, water absorption, desaturation, static water contact angle, ice adhesion, and concrete resistances to chloride ion penetration, freezing-and-thawing cycles, scaling, ASR and fungal growth. Furthermore, other road serviceability and safety parameters are summarized including effect of DCE on surface smoothness, adhesion strength, compressive strength and water retention in fresh concrete.

2. DCE TREATMENT

DCE waterproofing liquid solution is a patented material that integrates hydrophobic, hygroscopic and hydrophilic functionalities in one surface treatment (Al-Rashed, 2008). It is usually applied by spraying onto green, fully cured or old concrete using typical spraying machines (see Figure 2). The initial absorption (uptake) of the DCE is affected by the temperatures, the humidity and the concrete characteristics (e.g. porosity and level of water saturation). (Rahman, Alkordi, Ragrag, Kamal, & Chamberlain, 2016) found that the DCE material showed higher uptake than tested silane sealer. Then, the active constituents of the DCE penetrate deeper into concrete where they react and produce a hydrophobic layer and crystalline materials that penetrate deeper through concrete with crystal growth (Al-Rashed & Jabari, 2020). According to the experimental study (Xiao, Kevern, Owusu-Ababio, & Schmitt, 2020) (on the penetration depth of sealers within cored (old) concrete pavements samples by treated with various sealers including the DCE and silanes), DCE lead to the highest penetration depth (about 1,2 cm): The crystal growth with time enhance the net penetration depth. The DCE functionality is based on the flow restriction role of hygroscopic and hydrophilic crystals within the permeable pores in addition to the water-repelling role of the hydrophobic molecular layer at the pores walls as illustrated schematically in Figure 2. This happens within a surface section of the concrete. Furthermore, (Rahman & Chamberlain, 2016) reported a self-healing characteristic of cracks with DCE treatment obtained from the dynamic interaction of hygroscopic crystals with vapor: large surface cracks (>1 mm) were occupied with the DCE crystals. A similar technology, namely muti-crystallization enhancer (MCE), is available for addition to concrete mixture that creates similar layer and crystals but within the full depth of concrete which was investigated in previous publications (Al-Jabari, Al-Rashed, Ferrier, & Clement, 2021; Al-Rashed & Al-Jabari, 2021b).

(a) (b)

Figure 2: Filed application of DCE by spraying onto roads (a) and airport runway (b)

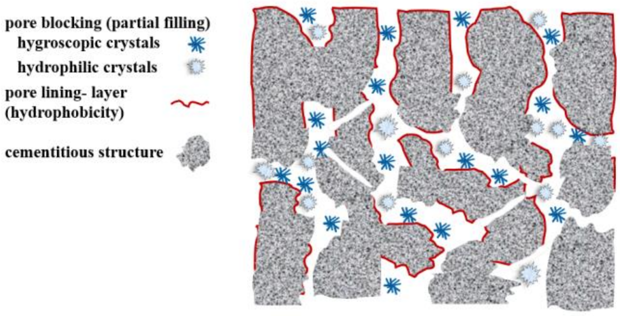

Figure 3: A schematic illustration of the waterproofing mechanisms of DCE within a surface section of a paste showing the hydrophobicity (as a layer) and the crystallinity pore blocking (hygroscopicity and hydrophilicity)

3. MATERIALS AND METHODS

The experimental program included measurements of various mechanical and durability parameters of concrete and mortar using control and treated specimens with DCE solution. The DCE was applied onto green, fully cured (28-days) or aged (cored) concrete. The mix design of tested concrete specimens included Iowa DOT C4 for plain cement and Iowa DOT C4-WRC20 (modified with Class C fly ash at 20% dosage) as prescribed by the Iowa Department of Transportation and TXDOT-Class C as prescribed by the Texas Department of Transportation. The tested water-to-cement (w/c) ratio included a wide range from 0.39 to 0.5 (see (Al-Rashed & Jabari, 2020) and (Al-Rashed & Al-Jabari, 2021a) for details). In some experiments for comparison purposes, cored specimens from old/existing concrete pavement were used. Portland cement (type I/II) conforming to ASTM C150 was used in all experiments. In concrete specimens modified with supplementary cementitious materials, Class C fly ash conforming to ASTM C618 and ASTM C989/C989M was added as a partial replacement of cement. The used materials included crushed limestone as coarse aggregates, gravels, and natural graded. The used DCE material was Chem-Crete Pavix CCC100 patented aqueous solution based on a balanced combination of alkali tartrate and organosilicon compounds. The reactive ingredients include hygroscopic, hydrophilic and hydrophobic compounds with a total solid content of about 15%, a specific gravity of 1.1 (Al-Rashed, 2008). The product was applied by spraying onto concrete and mortar specimens at a coverage within the recommended range of 3.7-4.9 m^2/L (150-200 ft^2/gallon) according to the product specifications. The DCE application was performed on fresh concrete or after 28-days of curing for cured concrete. The experiments were conducted in independent material testing labs: Construction Technology Laboratories, Inc. (CTL Group, 5400 Old Orchard Road, Skokie, IL, USA), and Construction Material Testing (CMT, Des Moines, Iowa, USA) and in the labs of Department of Civil Engineering, the University of Texas at Arlington, TX, USA. The experiments were performed on treated and control specimens according to the applicable standards as detailed in (Al-Rashed & Jabari, 2020) and (Al-Rashed & Al-Jabari, 2021a). The details of the experimental conditions (e.g. specimen type, water-to-cement (w/c) ratio are listed in Tables 1-4.

The permeability was measured at a pressure of 1.4 MPa according to the standard test of the United States Corps of Engineering (CRD-C 48-92) (CRD, 1992) using concrete cylinders made according to Iowa DOT C4 mix design. The DCE was applied on concrete specimens after 24 days curing. Water absorption and volume of permeable pores were measured according to ASTM C642 using DCE on fully cured TXDOT concrete specimens with w/c=0.5 (Al-Rashed and Jabari 2020). Ice adhesion strength was measured using direct shear tests and static water contact angle was measured using a Goniometer/Tensiometer using TXDOT concrete specimens with w/c=0.43 and 0.45, as detailed elsewhere (Xinbao Yu, Unpublished work).

The experiments for investigating the chloride ion penetration were performed according to ASTM C1202, AASHTO T277, AASHTO T259 and AASHTO T260. The performed experiments (ASTM C1202) included cases with the application of DCE to NaOH side, to NaCl side, and to both sides. Investigating the resistance of concrete to rapid freezing and thawing was performed according to ASTM C666. The scaling resistance was examined by subjecting control and DCE-treated concrete surfaces to freezing thawing cycles subjected to a solution of deicing chemicals (4% by weight $CaCl_2$), according to ASTM C672. The percentage mass loss and percentage change in length were reported as functions of the number of cycles. Investigating concrete resistance to biological attack through fungal growth was performed according to MIL-STD 810G, Method 508.6. The effect of DCE on resistance to ASR was investigated according to ASTM C1260 using mortar specimens prepared with aggregates at three w/c ratios of 0.39, 0.43 and 0.47. Two types of aggregates were tested including non-reactive crushed limestone aggregates from Martin Marietta Ames Mine and reactive gravels obtained from Platte River. The impacts of applying the DCE on the mechanical and serviceability characteristics of concrete were investigated according to ASTM D 4541, ASTM C 944, ASTM F609, ASTM E303 and ASTM D7234.

4. RESULTS AND DISCUSSION

4.1. DCE resistance to water in all phases (impermeability, hydrophobicity, hygroscopicity and icephobicity)

DCE treatment creates concrete surface resistances against water in all phases (ice, liquid and vapor). These resistances lead to multifunctional performance including waterproofing, damproofing (structural dryness) and reduced ice formation and adhesion strength. Table 1 lists the mechanisms of these performances correlated to DCE functionalities and water resistance parameters. Table 1 also summarizes waterproofing performance parameters of treated concrete as detailed in the following paragraphs.

Table 1: Water interactions and waterproofing, damproofing and reduced ice formation and adhesion multifunctional performance of the DCE treatment on fully cured and fresh concrete.

DCE functionality	DCE mechanism	Water Resistance/ structural parameter	Type of concrete specimen	Condition	Testing standard	DCE Performance
Crystalline (Hygroscopicity and hydrophilicity)	Pore filling/ blocking (reducing permeation)	Permeability	TXDOT concrete with w/c=0.42	Under a pressure of 1.4 MPa	CRD-C 48-92	94% reduction
		permeable pore fraction	TXDOT concrete w/c= 0.5	According to standard	ASTM C642	45-60% reduction
Hydrophobicity	Pore lining (reducing sorption)	Water absorption	TXDOT concrete with w/c=0.5	Low hydrostatic pressure	ASTM C642	60-75% reduction
	Water repelling	Static water contact angle	TXDOT concrete with w/c=0.43 or 0.45	Normal conditions	N.A.	Over 90^{o} up 120^{o}
Icephobicity	Repelling ice formation and binding	Ice adhesion strength	TXDOT concrete with	Freezing surface conditions	direct shear testing	83-98% reduction

			w/c=0.43 or 0.45			
Hygroscopicity	Vapor adsorption (Moisture sucking)	Vapor adsorption – self-drying	Iowa DOT C4 with w/c=0.42	Data for MCE (Al-Rashed & Al-Jabari, 2021b)	ASTM F2170	13-22% reduction
Breathability – (vapor-gas permeability) (Adil et al., 2022)	Partial blocking	Physical open fine pores	Iowa DOT C4-WRC30with w/c=0.45	Under air pressure	UCT method	No significant difference from control specimen

Table 2 lists the results of permeability testing in terms of permeability coefficient for control and DCE treated concrete specimens subjected to 1.4 MPa (200 psi) hydrostatic pressure. Also shown are results of permeability testing for another dual crystalline product (Chem-Crete Sofix CCC700). When compared to the control specimen, the permeability coefficient of DCE treated concrete is decreased by three orders of magnitude; yielding about 94% reduction in the permeability coefficient for both types of surface treatments. A similar performance was reported by (Al-Kheetan, Rahman, & Chamberlain, 2018) for DCE treatment when the permeability under a pressure of 0.5 MPa (74 psi) was measured according to BS EN 12390-8 (BS 2000): no water penetration was noticed for the treated concrete specimen; yielding a 100% reduction in permeability (based on penetration depth).

Such a high reduction in the permeability is ascribed to the reduction in **porosity** through the pore blocking mechanism obtained from the hygroscopic and hydrophilic crystallization. The permeable pore fraction was reported to be reduced by a percentage in the range of 45-60% when high porosity concrete specimens of TXDOT mix design with w/c=0.5 was tested according to ASTM C642 (Al-Rashed & Jabari, 2020). There is an exponential relationship between porosity and permeability (Al-Jabari, 2022a), thus a moderate reduction in the fraction of pores can lead to a very significant reduction in the permeability. The reduction in porosity is reflected in having an increase in the density over that of the control specimens at a percentage in the range of 6-7%.

Table 2: permeability of control and treated concrete specimens (with DCE and with Chem-Crete Sofix).

Specimen	Coefficient of permeability (cm/s)
Control concrete (Iowa DOT C4 mix design)	$6.40x10^{7}$
Pavix treated concrete	$3.89x10^{9}$
Sofix treated concrete	$4.16x10^{9}$

In principle, the reduction in porosity can be associated with an increase in the water absorption due the increase in the number of fine pores (Al-Jabari, 2022a). However, due to the combined characteristics of DCE (hydrophobicity, hygroscopicity and hydrophilicity) a significant **reduction in water absorption** was obtained (in addition to the major reduction water permeation) (Al-Rashed & Jabari, 2020). Table 1 shows that the percentage reduction in water absorption is within the range of 60-75% (when tested according to ASTM C642); depending on mix design (e.g. w/c ratio). A similar range of reduction in water absorption was also reported by (Al-Kheetan, Rahman, & Chamberlain, 2019) when control and DCE treated specimens where tested according to ASTM D6489. On the other hand, a lower reduction in water absorption (in the range of 37-56%) was reported by (Xiao et al., 2020) when the tests were done using mortar specimen with vertical application of DCE according to ASTM C1585 rather than concrete specimens. It is believed that the higher reductions in water absorption with concrete specimens can be attributed to DCE role in densifying the interfacial transition zone (ITZ) between the aggregates and the bulk of the paste that is normally more porous than the bulk of the paste (Al-Jabari, 2022a).

The reduction in water absorption is correlated to pore lining with a hydrophobic molecular later that is reflected in creating a high-water contact angle. The DCE treated concrete surface has a static water contact angle above 90^o and hence the surface is hydrophobic (see (Al-Jabari, Al-Rashed, & Ayers, 2022) for images of water repelling concrete surface). The value of water contact angle depends on concrete mix design. For TXDOT concrete the static contact angle was in the range of 98^o-105^o for w/c of 0.43 and 0.45 as reported by (Xinbao Yu, Unpublished work). Furthermore, for Iowa DOT with w/c=0.45, (Adil et al., 2022) reported an over-hydrophobic surface with DCE treatment (contact angle=120^o) surpassing all other compared treatments (including 40% Silanes for which the contact angle was 105^o). Such an increase in the surface hydrophobicity confirms the performance of DCE in reducing water absorption. It is worth mentioning here that having a moderate percentage reduction in water absorption (compared to high percentage in the case of hydrophobic treatment) cannot be isolated from the additional mechanisms of DCE (i.e. consuming moisture (liquid and vapor) in crystal growth). Thus, a comparison of water absorption performance of hydrophobic and DCE treatments ignoring that role (as reported by (Adil et al., 2022)) is not valid.

It is important to point out that the reduction in water absorption (controlled by pore lining) is not correlated to reduction in permeability (controlled pore blocking). Some authors have inappropriately limited their evaluations of waterproofing effectiveness based only on the level of reduction in water absorption (Adil et al., 2022). The first mechanism is the only functionality of silanes and siloxane based hydrophobic treatments (increasing water repelling on the surface), while such treatments are not valid for reducing the permeability (i.e. reducing permeation flow under a pressure). Although concrete road applications usually involve low levels of hydrostatic pressures, however, a high hydrostatic pressure due to tire loading on the road and wind effects (see Figure 1) (Al-Jabari, 2022c). Such permeation flow cannot be evaluated by measuring only water absorption.

In addition to reducing water permeation and sorption of liquid water, DCE has a unique rule of reducing internal humidity (i.e. creating a self-drying mechanism) in concrete through the hygroscopic crystal growth mechanism by interaction with water vapor. There is no data for quantifying the level of reduction in internal humidity with DCE treatment, however, similar data are available for similar crystals in MCE: In a previous study, the performance of the same type of hygroscopic crystals in reducing internal humidity of concrete was tested by measuring the internal humidity of control and MCE dosed concrete at various depths (Al-Rashed & Al-Jabari, 2021b): major reductions in the relative humidity for MCE dosed concrete compared to control concrete were reported for fully cured concrete. The reported reductions were 22%, 17% and 13% for the depths of 2, 3 and 4 inches, respectively as a result of water vapor suction from air by promoting its adsorption on the hygroscopic crystals (hygroscopic crystal growth).

Figure 3 shows the strength of ice adhesion on concrete surface for control and DCE treated specimens. Figure 3 shows a major reduction in ice adhesion strength (from 600 KPa to less than 80 KPa) with treated surface. The percentage reduction in ice adhesion depends on the concrete mix design (e.g. w/c ratio) and the temperature: a recent experimental study on DCE indicated that the range of reduction in ice adhesion is 83-98% (Xinbao Yu, Unpublished work). The mechanism of DCE treatment in reducing ice adhesion is based on its functionalities: (a) hydrophobicity of DCE that ~~it well correlation~~ to icephobicity as well documented in the literature (see (Al-Jabari & Husein, 2022)): DCE hydrophobicity minimizes surface wetting, decreases the freezing temperature of water at the surface and detaches water from the surface thus minimizes the amount and rate of ice deposition on the surface (b) crystalline pore blocking that minimizes the networking of any formed ice with surface (preventing "leg" formation of ice or interlocking within concrete surface structure) due to reduced porosity (i.e.

“cutting the legs” of ice) and (c) DCE dynamic crystal growth that consumes part of penetrated water and hence minimize water availability for freezing. Thus, DCE add an icephobicity characteristic to treated concrete surface.

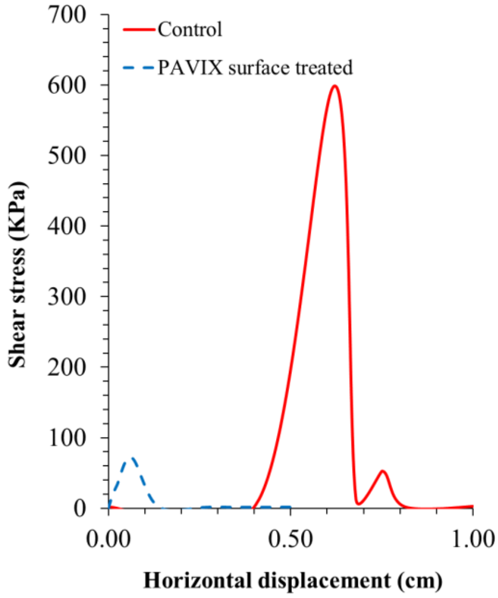

Figure 3: Results of ice adhesion strength for control and DCE treated TXDOT concrete surfaces (with w/c = 0.43) using direct shear testing at -1^{o}C.

The gas permeability for DCE treated concrete was investigated by (Adil et al., 2022) using UCT method (according to (Alexander, Ballim, & Mackechnie, 2009)) and compared to five other treatments (including 40% Silanes): The measured “Air Permeability Index” (API) for the investigated sealers (excluding the acrylic) were within the same performance classification of (9.5<API<10.0 Good). The reported value of API for DCE treated concrete was 9.91 with no significant differences from that of the control concrete (API=9.78) or that of 40% Silanes (API=9.71). These results confirm that the DCE treatment maintains concrete breathability performance by allowing the transport of water vapor. Furthermore, a unique rapid water desorption mechanism of DCE treated distressed concrete was reported by (Kevern, Adil, Taylor, Sadati, & Wang, 2022): A substantial water desaturation was reported for DCE-treatment compared to other treatments including 40% Silane. The rapid water desorption confirms the dynamic (reversible hygroscopicity of the crystals) through reversible adsorption/desorption mechanism of DCE hygroscopic crystals.

4.2. Durability Performance

Table 3 summarizes the durability parameters of DCE topical treatment of concrete. It lists the percentage durability improvements (e.g. percentage reduction in the measured parameter) at the given specifications and according to the listed testing conditions and procedures. Overall, significant reductions in chloride ion penetration, damages from cycles of freezing and thawing, scaling and ASR with a percentage ranging from 20%-100% depending on the durability parameter and the details of the testing (e.g., type of the mix design and water to cement (w/c) ratio). The obtained performance of DCE is comparable with that of a similar crystallization technology that is based on adding MCE to the concrete mixture as documented elsewhere (see (Al-Rashed & Al-Jabari, 2021b, 2022)). These parameters can be used for determining economic indicators as a percentage reduction in certain deterioration can be correlated into a percentage reduction in maintenance and cost saving.

The increased resistance against chemical and thermal deterioration is obtained through minimizing water penetration into concrete as presented and discussed in Section 4.1: The dynamic crystallization and crystal growth with moisture consumes any available free water (in liquid and vapor phase). The system also responds to solid-state water problems by minimizing freezing and ice adhesion (as shown in Section 4.1). The reversible hygroscopic behavior of the crystals (vapor adsorption upon saturation and then desaturation) solves the vapor-state water problems, resulting from the re-condensation of vapor into pores, which if not consumed become the main medium for water associated problems.

The enhancement in concrete resistance against chloride ion penetration (54-98% reduction) can have a positive effect in the stability of cement paste and the reinforcing steel bars which enhances the structural sustainability. A major reduction in the penetration of chloride ion using DCE treatment was also reported by (Chamberlain & Boswell, 2005; Rahman et al., 2016): (Rahman et al., 2016) reported that the percentage reduction in the total chloride content after 60-days of salt ponding of concrete samples was about 60%, while the equivalent value for an investigated silane-based sealer was about 40%. Furthermore, according to the experimental study of (Adil et al., 2022), DCE treatment had led to a significant reduction in the formation of expansive oxychloride (CaOXY) (thus reducing paste deterioration). According to the reported data of the potential CaOXY formation (3.07 for control and 0.506 for DCE treated concrete), the percentage reduction is about 83.5%.

The enhancement in concrete resistance against cycles of freezing and thawing appears as 57% reduction in length change and 100% reduction in mass loss. In fact, such a reduction is correlated to the reduction in ice adhesion (see Section 4.1). Reducing concrete deterioration due to cycles of freezing and thawing using DCE treatment was also reported by (Al-Kheetan et al., 2020; Chamberlain & Boswell, 2005): For applying DCE onto cured concrete, a larger protection could be achieved when the DCE was applied to saturated surfaces than when it was applied to a fully dry surface (Al-Kheetan et al., 2020). Their results showed that a 90% reduction in sorptivity (water absorption) of DCE treated concrete (reference to that of control sample) was obtained after about 1000 cycles of freezing and thawing (in water). Furthermore, the enhancement in scaling resistance due to freezing and thawing in the presence of deicing salts appears in reducing mass loss by about 94% after 70 cycles. Similarly, (Chamberlain & Boswell, 2005) reported a significant reduction in the mass loss when the DCE treated concrete was tested under 100 cycles according to ASTM C672: The scaling damage (mass loss) was reduced by about 50%.

Table 3 also lists the rating of DCE treated and control surfaces (according to MIL-STD 810G) after being exposed to biological attack: The DCE treated surface did not show any noticeable fungal growth (zero rating) while the control surface showed a trace of fungal growth with scattered and sparse fungal growth (one rating). These observations confirm the functionality of DCE in limiting mold growth through maintaining a relatively dry surface. This functionality of DCE was also tested through a field experiment as shown in Figure 4. The DCE was applied on a concrete slab with heavy mold growth (as seen in the control sample (right)), without cleaning. Obviously, the DCE has the capability to retard mold growth. Up to the authors knowledge, such a capability reducing biological attack on concrete is distinctively reported for the DCE material; as no comments on the possibility of traditional surface treatments for resisting mold growth were reported in review papers on the durability of concrete (e.g. see (Almusallam, Khan, Dulaijan, & Al-Amoudi, 2003; Berndt, 2011; Muhammad, Keyvanfar, Abd. Majid, Shafaghat, & Mirza, 2015; Pan, Shi, Shi, Ling, & Li, 2017a; Pan et al., 2017b), or even for the crystalline admixtures (Azarsa, Gupta, & Biparva, 2019, 2020; de Souza Oliveira, Dweck, de Moraes Rego Fairbairn, da Fonseca Martins Gomes, & Toledo Filho, 2020; Reiterman, Davidová, Pazderka, & Kubissa, 2020; Žáková, Pazderka, & Reiterman, 2020).

Figure 4: Images of existing concrete slabs: DCE-treated (left) and untreated (right). No cleaning was made to the surface prior to applying the DCE.

Table 3: Durability performance of topical Pavix treatment of concrete.

Durability parameter	Type of concrete specimen	DCE application	Standard Measurement	Reduction using DCE
Chloride ion penetration	TXDOT concrete with w/c=0.5	On fully cured concrete	ASTM C1202	54%
	Cored specimens	On old/ existing concrete	ASTM C1202	57%
	Iowa DOT C4-WRC20 with w/c=0.4	On freshly poured concrete with DCE on NaCl side	ASTM C1202	98%
	Iowa DOT C4-WRC20 with w/c=0.4	On freshly poured concrete with DCE on NaOH side	ASTM C1202	97%
	Iowa DOT C4-WRC20 with w/c=0.4	On freshly poured concrete with DCE on both side	ASTM C1202	90%
Cycles of freezing and thawing	TXDOT with w/c=0.5	On fully cured concrete	ASTM C666 (length change after 300 cycles)	57%
	TXDOT with w/c=0.5	On fully cured concrete	ASTM C666 (mass loss after 300 cycles)	100%
Scaling (in deicing salts)	TXDOT with w/c=0.5	On freshly poured concrete	ASTM C672 (mass loss after 70 cycles)	94%
Mold Growth	Cored specimens	On old/ existing concrete	MIL-STD 810G Method 508.6	Reduced Rating from 1 to 0
ASR	Iowa DOT C4 at /c=0.39,0.43 and 0.47	On fresh concrete with non-reactive aggregates (Ames Mine)	Modified ASTM C1260 (28 days–length change)	26-43%
	w/c=0.39,0.43 and 0.47	On freshly poured concrete with reactive aggregates (Platte River)	Modified ASTM C1260 measuring 28 days–length change	20-28%

The reduction in ASR deterioration is dependent on the mix design, types of aggregates and w/c ratio. Figure 5 shows sample curves of ASR expansions for reactive aggregates (from Platte River) for control and DCE treated specimens at two different w/c ratios (0.39 and 0.47). Obviously, the treatment enhances the concrete resistance against ASR attack with a percentage that seems to increase with measurement time. At 28-days testing, the percentage reduction in ASR was in the range of 20-43%. It is dependent on the type of aggregates and the w/c ratio. For reactive aggregates (Platte River), a percentage ASR reduction within the range of 20-28% was obtained with DCE, while a percentage within the range of 26-43% was obtained for non-reactive aggregates (Ames Mine). Figure 5 shows that the ASR expansion curve for DCE treated specimens with w/c=0.47 is very close to that of control specimens with w/c=0.39. Since decreasing w/c ratio decreases the porosity of the cementitious structure, the treated DCE structure seems to function as if a more watertight concrete is used (when DCE treatment is applied).

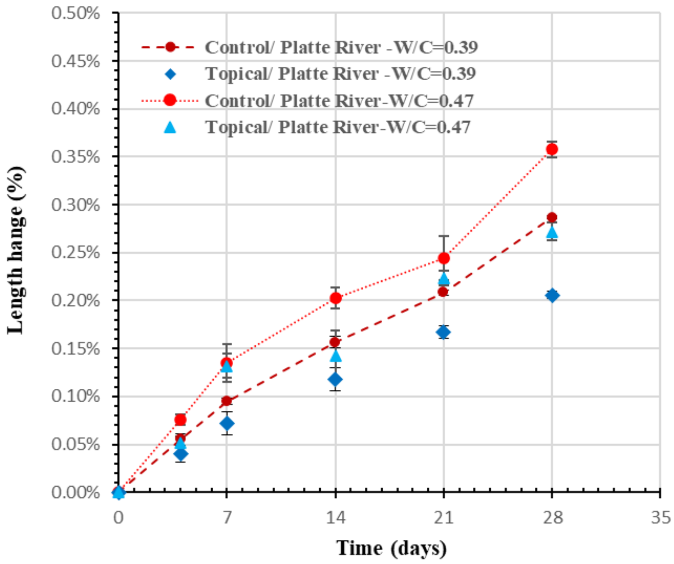

Figure 5: Percentage length change from ASR for reactive aggregates (from Platte River) comparing the results at w/c =0.39 and 0.47, showing the averages of three replicates with error bars (data from (Al-Rashed & Al-Jabari, 2021a)).

4.3. Mechanical, serviceability and safety parameters

Table 4 summarizes the mechanical and serviceability parameters characterizing the performance of DCE topical treatment of concrete. Overall, DCE increases the concrete density (by pore filling) and hence enhances the abrasion resistance. Furthermore, an enhancement in the compressive strength of DCE treated concrete was reported in a previous study [57]. Due to its ability to fill surface pores and its hydrophobicity, DCE treatment can cause a minor increase in the surface smoothness. On the other hand, surface adhesion characteristics are improved as the adhesion strength of a top polymeric coating (when needed) is increased by 13%. This is attributed to the surface dryness of the DCE treated cementitious structures through water-repelling characteristics and consuming the moisture content in crystal growth. Furthermore, (Al-Kheetan et al., 2018; Rahman & Chamberlain, 2016) pointed out that DCE enhanced concrete hydration during the curing stage when applied within about three hours after concrete casting. Hence, applying DCE on green concrete leads to 5% strength increase over control concrete (Rahman & Chamberlain, 2016).

Table 4: Mechanical and serviceability parameters which characterizes the performance of Pavix topical treatment of concrete.

Mechanical or serviceability Criteria	Type of concrete specimen	DCE application	Standard Measurement	DCE impact
Density	TXDOT with w/c=0.5	On fully cured concrete	ASTM C642-97	6-7% improvement
abrasion resistance	Ready mix concrete: medium porosity - moderate-strength concrete with w/c=0.43	On fully cured and old concrete	ASTM C 944-99	improvement (7% reduction in mass loss)
the pull off strength	cored specimens.	On old concrete	ASTM D 4541-95	no major difference (-3.7%)
adhesion strength	Ready mix concrete (moderate strength) with w/c=0.48	On freshly poured mortar	ASTM D7234	13% improvement
Surface smoothness - coefficient of friction	TXDOT with w/c=0.5	On fully cured concrete	ASTM F609	5.3% reduction in coefficient of friction
	TXDOT with w/c=0.5	On fully cured concrete	ASTM E303	7.3% reduction in the British pendulum number
	Ready mix concrete (moderate strength) with w/c=0.48	On freshly poured mortar	ASTM F609	No significant difference

5. CONCLUSIONS

The DCE treatment reduces water penetration through concrete by both permeation and capillary absorption and hence improves concrete resistance against thermal, physicochemical and biological degradations. This is achieved by pore blocking coming from crystal formation and growth, and pore lining coming from forming a water repellent molecular layer. Moreover, the dynamic hygroscopic crystallization process provides an ongoing mechanism to retard moisture-associated problems. DCE treatment creates concrete surface resistances against the impacts of water in all its phases including ice, liquid and vapor: Due to its hygroscopicity and hydrophilicity (pore blocking), it reduces concrete permeability under hydrostatic pressure by 94% and concrete porosity (permeable pore fraction) by 45-60% without a significant change in gas permeability. Furthermore, due to its hydrophobicity, it reduces water (capillary) absorption by 60-75% and enhances icephobicity (reducing ice adhesion by 83-98%).

DCE reduces chloride ion penetration (ASTM C1202) through concrete by a percentage in the range of 54-98% and the potential CaOXY formation by 83.5%. It also reduces concrete deterioration by cycles of freezing and thawing in water (ASTM C666) by reducing length change by 57% and mass loss by 100% and in deciding salt (scaling-ASTM C672) by about 94% after 70 cycles. It also reduces mold growth and ASR expansion (ASTM C1260). The reduction in ASR expansion is in the range of 20-43% depending on the types of aggregates and the w/c ratio. This is achieved without a significant effect on surface characteristics. The increase in concrete density (by pore filling) is associated with an enhancement in the abrasion resistance.

References

ACI. (2016). Committee 212, ACI 212. 3R-16 Report on Chemical Admixtures for Concrete. In. Farmington Hills, MI, USA: American Concrete Institute.

ACI. (2018). CT-18 Concrete Terminology In. Farmington Hills, MI, USA: American Concrete Institute.

Adil, G., Sadati, S., Ling, Y., Taylor, P., Wang, K., & Kevern, J. T. (2022). Penetrating Sealer Effects on the Durability Performance of Concrete Joints. *Materials Journal, 119*(6).

Al-Jabari, M. (2022a). 2 - Concrete porosity and transport processes. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 37-68): Woodhead Publishing.

Al-Jabari, M. (2022b). 3 - Concrete durability problems: physicochemical and transport mechanisms. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 69-107): Woodhead Publishing.

Al-Jabari, M. (2022c). 6 - Fundamentals and categorizations of waterproofing technologies. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 165-198): Woodhead Publishing.

Al-Jabari, M. (2022d). 7 - Concepts and types of integral waterproofing materials. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 199-246): Woodhead Publishing.

Al-Jabari, M. (2022e). 8 - Hydrophobic integral dampproofing materials. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 247-282): Woodhead Publishing.

Al-Jabari, M. (2022f). 9 - Hydrophilic crystallization waterproofing. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 283-322): Woodhead Publishing.

Al-Jabari, M., Al-Rashed, R., & Ayers, M. E. (2022). 10 - Dual crystallization waterproofing topical treatment. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 323-356): Woodhead Publishing.

Al-Jabari, M., Al-Rashed, R., Ayers, M. E., & Clement, D. (2022). 4 - Materials selection and proportioning for watertight and durable concrete. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 109-134): Woodhead Publishing.

Al-Jabari, M., Al-Rashed, R., Ferrier, S., & Clement, D. (2021). *Managing Thermal Effects in Waterproofed Concrete with Multi-Crystallization Enhancer*. International Chem-Crete Co. Richardson, Texas, USA.

Al-Jabari, M., & Husein, M. (2022). 5 - Physical and chemical interactions of water with surfaces and particles. In M. Al-Jabari (Ed.), *Integral Waterproofing of Concrete Structures* (pp. 135-163): Woodhead Publishing.

Al-Kheetan, M. J., Rahman, M. M., & Chamberlain, D. A. (2018). A novel approach of introducing crystalline protection material and curing agent in fresh concrete for enhancing hydrophobicity. *Construction and Building Materials, 160*, 644-652. doi:10.1016/j.conbuildmat.2017.11.108

Al-Kheetan, M. J., Rahman, M. M., & Chamberlain, D. A. (2019). Moisture evaluation of concrete pavement treated with hydrophobic surface impregnants. *International Journal of Pavement Engineering*, 1-9. doi:https://doi.org/10.1080/10298436.2019.1567917

Al-Rashed, R. (2008). Aqueous chemical mixture to mitigate water associated problems in concrete pavements. In: USA Patents.

Al-Rashed, R., & Al-Jabari, M. (2021a). Concrete Protection by Combined Hygroscopic and Hydrophilic Crystallization Waterproofing Applied to Fresh Concrete. *Case Studies in Construction Materials, 15* e00635. doi:https://doi.org/10.1016/j.cscm.2021.e00635

Al-Rashed, R., & Al-Jabari, M. (2021b). Multi-crystallization enhancer for concrete waterproofing by pore blocking. *Construction and Building Materials, 272*, 121668. doi:https://doi.org/10.1016/j.conbuildmat.2020.121668

Al-Rashed, R., & Al-Jabari, M. (2022). Managing Thermal Effects in Waterproofed Concrete with Multi-Crystallization Enhancer. *CEMENT, 10*, 100050.

Al-Rashed, R., & Jabari, M. (2020). Dual-crystallization waterproofing technology for topical treatment of concrete. *Case Studies in Construction Materials, 13*, e00408. doi:https://doi.org/10.1016/j.cscm.2020.e00408

Al-Kheetan, M. J., Al-Tarawneh, M. a., Ghaffar, S. H., Chougan, M., Jweihan, Y. S., & Rahman, M. M. (2020). Resistance of hydrophobic concrete with different moisture contents to advanced freeze–thaw cycles. *Structural Concrete, 22*, E1050-E1061.

Alexander, M., Ballim, Y., & Mackechnie, J. (2009). Durability index testing procedure manual. *University of Cape Town, Cape Town*.

Almusallam, A. A., Khan, F. M., Dulaijan, S. U., & Al-Amoudi, O. S. B. (2003). Effectiveness of surface coatings in improving concrete durability. *Cement and concrete composites, 25*(4), 473-481. doi:https://doi.org/10.1016/S0958-9465(02)00087-2

Azarsa, P., Gupta, R., & Biparva, A. (2019). Assessment of self-healing and durability parameters of concretes incorporating crystalline admixtures and Portland Limestone Cement. *Cement and concrete composites, 99*, 17-31. doi:https://doi.org/10.1016/j.cemconcomp.2019.02.017

Azarsa, P., Gupta, R., & Biparva, A. (2020). Inventive Microstructural and Durability Investigation of Cementitious Composites Involving Crystalline Waterproofing Admixtures and Portland Limestone Cement. *Materials, 13*(6), 1425. doi:https://doi.org/10.3390/ma13061425

Berndt, M. L. (2011). Evaluation of coatings, mortars and mix design for protection of concrete against sulphur oxidising bacteria. *Construction and Building Materials, 25*(10), 3893-3902. doi:https://doi.org/10.1016/j.conbuildmat.2011.04.014

Biparva, A., & Gupta, R. (2010). *Smart Waterproofing System: A Review.* Paper presented at the Proceedings of the International Conference on Future Concrete.

Chamberlain, D. A., & Boswell, L. F. (2005). *The Use of Pavix CCC100 as a Reinforced Concrete Impregnate and as an Alternative to Silane*. Paper presented at the Performance Based Rehabilitation Of Reinforced Concrete Structures Conference, Prague, Czech Republic.

CRD. (1992). C48-92 Standard Test Method for Water Permeability of Concrete. In: U.S. Army Corps of Engineers.

de Souza Oliveira, A., Dweck, J., de Moraes Rego Fairbairn, E., da Fonseca Martins Gomes, O., & Toledo Filho, R. D. (2020). Crystalline admixture effects on crystal formation phenomena during cement pastes' hydration. *Journal of Thermal Analysis and Calorimetry, 139*(6), 3361-3375. doi:10.1007/s10973-019-08745-0

Fernandes, I., & Broekmans, M. A. (2013). Alkali–silica reactions: an overview. Part I. *Metallography, Microstructure, and Analysis, 2*(4), 257-267. doi:https://doi.org/10.1007/s13632-013-0085-5

Glass, G., & Buenfeld, N. (2000). Chloride-induced corrosion of steel in concrete. *Progress in Structural Engineering and Materials, 2*(4), 448-458. doi:https://doi.org/10.1002/pse.54

Hobbs, D. W. (2015). *Alkali-silica reaction in concrete*. London, UK: Thomas Telford Publishing.

Jalali, U. H., & Afgan, S. (2018). Analysis of Integral Crystalline Waterproofing Technology for Concrete. *International Research Journal of Engineering and Technology (IRJET), 5*(10).

Javaherdashti, R., Nikraz, H., Borowitzka, M., Moheimani, N., & Olivia, M. (2009). On the impact of algae on accelerating the biodeterioration/biocorrosion of reinforced concrete: A mechanistic review. *European Journal of Scientific Research, 36*(3), 394-406. Retrieved from https://www.scopus.com/inward/record.uri?eid=2-s2.0-70350231468&partnerID=40&md5=8eaf269da601b56050929d8805c648ae

Jianxia, S. (2012). 6.14 - Durability Design of Concrete Hydropower Structures. In A. Sayigh (Ed.), *Comprehensive Renewable Energy* (pp. 377-403). Oxford: Elsevier.

Kevern, J. T., Adil, G., Taylor, P., Sadati, S., & Wang, K. (2022). *Evaluation of Penetrating Sealers for Concrete*. Retrieved from Iowa, USA:

Lence, A., Hassan, M., Zayor, A., & Rupnow, T. (2014). *Best practices for maintenance of concrete bridge elements against mold and mildew growth.* Paper presented at the Construction

Research Congress 2014: Construction in a Global Network - Proceedings of the 2014 Construction Research Congress.

Mehta, P. K., & Monteiro, P. J. (2017). *Concrete microstructure, properties and materials*. New York, NY 10019, USA: McGraw-Hill Publishing.

Muhammad, N. Z., Keyvanfar, A., Abd. Majid, M. Z., Shafaghat, A., & Mirza, J. (2015). Waterproof performance of concrete: A critical review on implemented approaches. *Construction and Building Materials, 101*, 80-90. doi:https://doi.org/10.1016/j.conbuildmat.2015.10.048

Pan, X., Shi, Z., Shi, C., Ling, T.-C., & Li, N. (2017a). A review on concrete surface treatment Part I: Types and mechanisms. *Construction and Building Materials, 132*, 578-590. doi:https://doi.org/10.1016/j.conbuildmat.2016.12.025

Pan, X., Shi, Z., Shi, C., Ling, T.-C., & Li, N. (2017b). A review on surface treatment for concrete – Part 2: Performance. *Construction and Building Materials, 133*, 81-90. doi:https://doi.org/10.1016/j.conbuildmat.2016.11.128

Porras, Y., Jones, C., & Schmiedeke, N. (2020). Freezing and Thawing Durability of High Early Strength Portland Cement Concrete. *Journal of Materials in Civil Engineering, 32*(5). doi:10.1061/(ASCE)MT.1943-5533.0003168

Rahman, M., Alkordi, N., Ragrag, A., Kamal, S., & Chamberlain, D. (2016). *Moisture efficacy of impregnant in concrete protection*. Paper presented at the Transportation Research Board 95th Annual Meeting, Washington DC, United States.

Rahman, M., & Chamberlain, D. (2016). Application of crystallising hydrophobic mineral and curing agent to fresh concrete. *Construction and Building Materials, 127*, 945-949. doi:https://doi.org/10.1016/j.conbuildmat.2016.08.150

Reiterman, P., Davidová, V., Pazderka, J., & Kubissa, W. (2020). Reduction of concrete surface permeability by using crystalline treatment. *Revista Romana de Materiale, 50*(1), 69-74.

Saha, A. K., Khan, M., Sarker, P. K., Shaikh, F. A., & Pramanik, A. (2018). The ASR mechanism of reactive aggregates in concrete and its mitigation by fly ash: A critical review. *Construction and Building Materials, 171*, 743-758.

Santhanam, M., & Otieno, M. (2016). 5 - Deterioration of concrete in the marine environment. In M. G. Alexander (Ed.), *Marine Concrete Structures* (pp. 137-149): Woodhead Publishing.

Thomas, M. D., Fournier, B., & Folliard, K. J. (2008). *Report on determining the reactivity of concrete aggregates and selecting appropriate measures for preventing deleterious expansion in new concrete construction*. Retrieved from

Tran, P. C., Kobayashi, K., Asano, T., & Kojima, S. (2018). Carbonation Proofing Mechanism of Silicate-Based Surface Impregnations. *Journal of Advanced Concrete Technology, 16*(10), 512-521. doi: https://doi.org/10.3151/jact.16.512

Viitanen, H., Vinha, J., Salminen, K., Ojanen, T., Peuhkuri, R., Paajanen, L., & Lähdesmäki, K. (2010). Moisture and bio-deterioration risk of building materials and structures. *Journal of Building Physics, 33*(3), 201-224. doi:https://doi.org/10.1177/1744259109343511

Xiao, D. X., Kevern, J. T., Owusu-Ababio, S., & Schmitt, R. (2020). *Evaluation of Penetrating Sealers Applied to Saw Cut Faces in Concrete Pavement Joints*. Retrieved from

Xinbao Yu, H. H. S., Gang Lei, Radi Al-Rashed, Maher Al-Jabari. (Unpublished work). An Experimental Study on Icephobicity and Hydrophobicity of Concrete Surface with Dual Crystallization Engineered Topical Treatment.

Žáková, H., Pazderka, J., & Reiterman, P. (2020). Textile Reinforced Concrete in Combination with Improved Self-Healing Ability Caused by Crystalline Admixture. *Materials, 13*(24), 5787.