

Investigating the Impermeability of Various Products and Protocols of Crystalline Waterproofing Technology

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Abstract. Concrete buildings and infrastructures encounter several durability issues that are caused or associated with water penetration. Hence, the durability of concrete is correlated to its hydraulic impermeability. In this paper, the waterproofing performance of four types of crystalline waterproofing materials are investigated, the materials being in solution and powder forms. They all involve pore blocking functionality, while some of them involve additional pore lining properties. These included MCE as an admixture, PaviX and SofiX, as crystalline penetrating concrete sealers and ChemCreteX as a cementitious powder slurry coating. The application protocols investigated included two dosages of 1% and 2% of MCE admixtures with or without an additional topical Pavix treatment. The standard permeability testing method was used (U.S. Corp. of Engineering CRD-C48-92) to measure the permeability coefficient of control and crystalline waterproofed concrete samples. The results cover various mix designs utilizing two types of cements (Portland cement and 1L limestone cement) and with various water to cementitious materials (w/cm) ratios. The findings show the efficacy of each of the investigated crystalline technology, in liquid and powder form, for surface treatment (sealer or cementitious coating) as a pore blocking material and for MCE as a Permeability Reducing Admixture at Hydrostatic pressure (PRAH).

Keywords: Concrete, Moisture, Permeability, Waterproofing, Crystallization, Durability, CRD-C48-92, PRAH.

1 Introduction

The pore size in the cement paste has a wide range of 1 nm - 1 μ m [1]. The pores are classified into (1) gel fine pores that have no influence or just a little impact on the mechanical properties or permeability of concrete and capillary pores that create flow channels [2]. Details of size ranges and characteristics of these types of pores and voids are presented in a previous publication [3]. The porosity is a structural characteristics indicating the level of an open space and is determined by both the pore size and size distribution as well as on the connectivity of the pores [4, 5]. On the other hand, permeability is an intrinsic property that determine the rate of water flow within concrete [6]. In general, the permeability is exponentially correlated to the porosity [1, 7, 8].

Pore refining reduces most of the transport properties (including permeability) and durability issues in concrete [3, 9, 10]. Pore blocking and crystalline waterproofing technologies are based on incorporating reactive materials within the pores. Hence, they create flow obstacles and reduce permeability (under hydrostatic pressure) [10-14]. Their functionalities are significantly different from the pore-lining (hydrophobic) materials: The pore lining materials react with silicone sites at the cementitious internal walls creating water-repelling molecular layer. Such a hydrophobic layer is very thin compared to permeable pore sizes and hence it has little or no impact on reducing porosity or permeability. They reduce water (capillary) absorption or wicking flow under no or little hydrostatic pressure (e.g. few centimeters of water head) [15, 16]. According to ACI 212.3R-16 [16], pore lining (hydrophobic) materials are effective in reducing capillary absorption but they are not suitable if there is a possibility of a hydrostatic pressure devolvement during the service life of concrete.

Industrial products are available in the market combining pore lining with pore blocking crystalline waterproofing materials [10]. They contain triple functionalities of hygroscopic and hydrophilic crystals with hydrophobicity. These include an admixture (MCE [14]) that is categorized as a Permeability Reducing Admixture (PRAH, according to ACI 212.3R-10 [16]) and sealer (DCE [13]). The penetration depths of the topical treatment has been reported in previous work [13]. Their durability performance parameters have investigated in previous publications [17-25].

Evaluating the efficacy of waterproofing involve measuring water absorption by capillary action (under no or little hydrostatic pressure) and hydro-permeability under a high hydrostatic pressure. Although water absorption tests are widely used [26], their results can be misleading due to differences in behaviors under different pressure levels and water penetration mechanisms [10]. Forming flow obstacle by pore blocking may not reduce capillary suction [27], instead, reducing the porosity of concrete by partial pore blocking can increase water absorption due to pore refinement effect [11]. However, the absorbed moisture is usually consumed in further crystal growth [14]. The permeability tests are usually performed by subjecting the surface of the specimen to a high-water pressure [16]. It is known that waterproofing efficiency for crystalline technology requires permeability testing under a hydrostatic pressure (as CRD-C48-92) [14]. The high-pressure testing is essential for practical field performance to account for the build-up of hydrostatic pressure from traffic loading on pavements or wind effects on vertical walls and for the submerged concrete [12]. Some previous publications investigated the performance of crystalline waterproofing technology according to U.S. Corp of Engineering method [19, 28, 29]. A previous publication covered the water absorption and porosity of Pavix sealer [24]. There were no in-depth previous investigations of combined treatment (MCE-PaviX) or single sealer treatment or cementitious coating of these multiple crystalline functionalities. This paper aims at investigating and comparing the efficacy of various crystalline waterproofing applications under a hydrostatic pressure. The research objectives include (1) evaluating the waterproofing efficacy of various Chem-Crete waterproofing materials (2) studying the effects of application protocols of these some products (as a single or combined treatment).

2 Experimental

2.1 Materials

The experimental program included casting control and MCE-dosed concrete specimens for measuring permeability. Various reference samples were needed to cover the various investigated parameters and to make the valid comparisons. For example, these include reference concrete with Portland (I/II type) cement as well as reference concrete with 1L cement. All experiments were performed in the independent laboratories of Construction Material Testing (CMT, Des Moines, Iowa, USA). The investigated independent experimental parameters included type of waterproofing material, dosage of MCE, and protocol of treatment (single or combined addition).

Concrete specimens were prepared using standard Iowa DOT concrete mix designs, labelled as Iowa DOT C-4 and C-4 WRC20 [41]. The C-4 mix involves a cement content of 593 lb while "C20" indicates 20% replacement of the cement content by Class C fly ash, hence the C-4 WRC20 involves 119 lb of fly. The C-4 mixes are commonly used in infrastructure applications, including paving, box culverts, bridge decks, piers and abutments...etc. The amounts of the constituents (per cubic yard of concrete) and their types and sources are listed in Table 1 (For C-4 WRC20). Type 1L cement containing about 12% limestone was used. Several w/cm ratios were used including 0.41, 0.43 and 0.45. The air entrainment and the water reducing agents were obtained from Euclid Admixture (Cleveland, Ohio, USA), GRT SA-50 and GRT 400-NC, respectively. The target air content was 6%, in selected samples, no-air entrainment agent was used for comparing the permeability. Concrete cylinders 15.2x30.4 cm (6x12 inches) were casted. All concrete samples were demolded after 24 hours and then allowed to cure for 28 days under normal laboratory conditions.

Table 1. Iowa DOT C4-WRC20 mix proportions for one cubic yard of concrete.

Component	Type/ Source	Amounts
Cement	Continental (Type 1L)	474 lb
Fly ash	Boral Resources (Class C)	119 lb
Coarse aggregates	Concrete Stone D-57 – A85006 (Martin Marietta – Ames)	1470 lb
Fine aggregates	Concrete Sand – A77534 (Martin Marietta – Saylorville)	1486 lb
Water	Local/ Municipal	266 lb
Air entrainment	GRT SA-50	6%
Water reducer (MRWR)	GRT 400 NC	4.0 lq oz

Four crystalline waterproofing materials from International Chem-Crete Corporation (Dallas, TX, USA) were used. These included water-based waterproofing products (MCE, PaviX and SofiX) and a powder product of ChemCreteX slurry coating. They

all are crystalline pore blocking materials while they involve various manufacturing processes and chemistry. The testing program also included various protocols of MCE and PaviX treatments (as single or combined treatments): The investigated protocols included two dosages of 1% and 2% of MCE admixtures with or without an additional topical Pavix treatment. MCE is a patented Multi-Crystalline, chlorine free and ammonia free, water-based concrete admixture with a total solid content of about 15% [18]. It is a PRAH (ACI 212.3R-10 [16]). DCE (PaviX) is a dual-crystalline penetrating sealer containing a total solid content of about 15% [17]. DCE has triple functionality involving hygroscopic and hydrophilic crystals with hydrophobic water repelling characteristics. SofiX is a dual crystalline water sealer involving hygroscopic and hydrophilic crystals without hydrophobicity. ChemCreteX is a single hygroscopic crystalline slurry coating material.

The MCE was added to the mixing water according to the required dosage. Two dosages were investigated: 1% and 2% (by mass) of the cementitious content. Pavix and SofiX were applied by brushing on fresh concrete surface. The surface coverage for PaviX and Sofix experiments was $3.7 \text{ m}^2/\text{L}$ ($150 \text{ ft}^2/\text{gal}$). The surface coverage of the ChemCreteX (as a slurry coat) was about 1.1 kg/m^2 . The coatings were then allowed to cure for 7 days before permeability testing.

2.2 Measurement of Water Permeability

The permeability testing was performed using fully cured concrete cylinder specimens. The permeability was measured by subjecting the concrete specimens to a hydrostatic pressure of 1.4 MPa (200 psi) according to the standard test defined by the United States Corps of Engineering method (CRD-C 48-92) [30] (see Fig. 1). Then, the water flow through the specimen is measured. The coefficient of permeability is determined using Darcy's equation after establishing a steady state flow through concrete. The average values of duplicated specimens were reported. This test is categorized as a direct method for evaluating the effectiveness of PRAH (admixtures) as per ACI 212. 3R-16 Report on Chemical Admixtures for Concrete [16]. The same method was used in previous research for measuring the permeability of MCE-dosed concrete as a single addition at 2% [19]. This test was performed for all protocols of MCE additions and topical treatments. The percentage reduction in permeability upon using the crystalline waterproofing over that of control concrete reflects a measure of the waterproofing efficacy.



Fig. 1. Permeability tests according to Corps of Engineering method (CRD-C 48-92).

3 Results and Discussion

All permeability results for control, MCE, PaviX, SofiX and ChemCreteX specimens are listed in Table 2. The two data rows for the Texas DOT mix designs are obtained from a previous publication for comparison [19]. It is worth to mention that porous materials with a permeability coefficient less than 10^{-11} m/s are categorized as virtually impermeable media. Overall, each of the investigated waterproofing material achieved a coefficient of permeability less than 10^{-11} m/s, by at least one order of magnitude. Hence, each of the or the investigated protocols produces virtually impervious concrete. These reduction in permeability leads significant enhancement in concrete durability; since durability is controlled by permeability and the consumption of internal moisture and vapor in crystal growth.

Table 2. C4-WRC20 mix proportions for one cubic yard of concrete.

Specimen Type	Cement Type	Mix Design	Age (day)	w/cm	MCE (%)	Topical treatment	Coefficient of Permeability (m/s)
Reference concrete	1L	Iowa DOT C-4 WRC20	28	0.45	0	None	5.24×10^{-7}
Reference concrete	I/II	Texas DOT [19]	435	0.43	0	None	2.2×10^{-8}
Reference concrete	I/II	Iowa DOT C-4	28	0.43	0	None	6.34×10^{-9}
Reference concrete	1L	Iowa DOT C-4 WRC20	28	0.41	0	None	6.65×10^{-9}
Reference - non-Air entrained concrete	1L	Iowa DOT C-4 WRC20	28	0.43	0	None	5.85×10^{-11}
Reference - non-Air entrained concrete	1L	Iowa DOT C-4 WRC20	28	0.43	0	None	6.90×10^{-11}
Concrete with topical PaviX treatment	I/II	Iowa DOT C-4	28	0.43	0	PaviX	3.89×10^{-12}
Concrete with topical SofiX treatment	I/II	Iowa DOT C-4	28	0.43	0	SofiX	4.16×10^{-12}
Concrete with topical PaviX treatment	1L	Iowa DOT C-4 WRC20	28	0.45	0	PaviX	7.15×10^{-12}
MCE dosed-concrete	1L	Iowa DOT C-4 WRC20	28	0.45	1%	None	5.28×10^{-12}
MCE dosed-concrete	I/II	Texas DOT [19]	435	0.43	2%	None	5.2×10^{-12}
MCE Dosed Concrete with topical PaviX treatment	1L	Iowa DOT C-4 WRC20	28	0.45	1%	PaviX	3.67×10^{-13}
MCE dosed concrete	1L	Iowa DOT C-4 WRC20	28	0.45	2%	None	3.39×10^{-13}

MCE dosed concrete	1L	Iowa DOT C-4 WRC20	28	0.43	2%	None	2.28×10^{-13}
MCE dosed concrete	1L	Iowa DOT C-4 WRC20	28	0.43	2%	None	3.01×10^{-13}
MCE-Dosed in non-Air entrained concrete	1L	Iowa DOT C-4 WRC20	28	0.43	2%	None	2.20×10^{-13}
MCE-Dosed in non-Air entrained concrete	1L	Iowa DOT C-4 WRC20	28	0.43	2%	None	4.39×10^{-13}
MCE-Dosed concrete	1L	Iowa DOT C-4 WRC20	28	0.41	2%	None	3.58×10^{-14}
MCE Dosed Concrete with topical PaviX treatment	1L	Iowa DOT C-4 WRC20	28	0.45	2%	PaviX	2.93×10^{-14}
ChemCreteX coating	I/II	2:1 Powder/Water	7	1/2	0	Chem-CreteX	6.68×10^{-14}

Generally, the reduction in permeability is dependent on the level of crystallization that is established within the pores of concrete by each case. This is in turn (as shown in Table 2) is governed by the type of cement, the mix design, the w/cm ratio, the age of concrete (and the product addition time) and the type, application method and dosage of the waterproofing products. Furthermore, the waterproofing performance is also slightly dependent on the protocol of the use (application) of crystalline products (i.e. using a single or combined products). It is important in all permeability testing to compare the watertightness of a crystalline treated concrete with the equivalent non-treated (control) concrete, otherwise data can be misleading. Table 2 include 5 types of reference concrete samples that includes different mix design and w/cm ratios. In all of these cases, the non-treated concrete is found to have a relatively high permeability coefficient. Table 2 shows that the addition of fly ash to concrete mixtures (as in the Iowa DOT C-4 WRC20 mix design) permeability. This is achieved because fly ash reduces porosity through refining the pore structure (reducing the volume of large pores) [7]. However, the Iowa DOT C-4 WRC20 mix design still has a higher permeability coefficient than the threshold for impermeable materials. Table 2 also shows that the permeability of non-treated concrete is strongly dependent on (1) the type of cement (Normal Portland Type I/II versus 1L limestone cement), (2) the mix design (Iowa DOT C-4, Iowa DOT C-4 WRC20 or Texas DOT), and (3) the w/cm ratio (0.41, 0.43 and 0.45). As expected, reference concrete at w/cm=0.43 has a lower permeability than that at w/cm=0.45; even when no fly ash is used (Iowa DOT C-4). In general, the waterproofing efficacy can be demonstrated experimentally more noticeably when concrete with high w/cm ratio is used.

Although nearly all concrete mix designs for infrastructure are designed to include air-entrainment (for controlling freezing and thawing effects [1, 5, 31]), Table 2 shows that the non-air-entrained concrete (without crystalline materials) has a lower permeability than that of equivalent air-entrained concrete. The current data emphasizes the previous observations that air bubbles in concrete increase the permeability [4]. The presence of air entrained voids increases the impermeability because they are believed to

become saturated and interconnected through the network of the capillary pores [4, 32] and the porosity near their interface with the paste is roughly 2-3 times larger than that of the bulk paste [1].

Table 2 shows that the crystalline topical treatment (PaviX or SofiX sealer) is efficient in pore-blocking (porosity reduction) even when it is applied as a single treatment. The topical treatment decreases the permeability by three orders of magnitude for PaviX as well as for SofiX. Although they have differences in product chemistry and overall functionalities, SofiX leads to nearly similar level of impermeability as PaviX. This is because SofiX produces hydrophilic and hygroscopic pore blocking crystals in a similar fashion as PaviX, however SofiX does not involve hydrophobic (water-repelling) property. The additional water-repellency of PaviX (over SofiX) does not show a significant difference under high hydrostatic pressure. The hydrophobicity role becomes significant only at low or no hydrostatic pressure. In fact, the performance difference between PaviX and SofiX can appear upon testing and comparing the hydrophobicity of each of them. Table 2 shows that the waterproofing performance of the topical crystalline treatment becomes more obvious when a reference concrete at higher w/cm ratio; PaviX can achieve 4 orders of magnitude when the reference concrete is with w/cm=0.45.

Table 2 shows that the internal crystalline treatment is efficient in pore-blocking (porosity reduction) regardless of the selected MCE dosage among the acceptable range (1% and 2%). The MCE admixture decreases the permeability by at least 4 orders of magnitude even with 1% addition of MCE and without additional topical treatment. MCE waterproofing achieves a larger permeability reduction than topical treatment (4-5 orders of magnitude for MCE in comparison with 3-4 orders of magnitude reductions for PaviX or SofiX). The MCE waterproofing performance becomes more obvious when a reference concrete at higher w/cm ratio is used; MCE can achieve 6 orders of magnitude when the reference concrete is with w/cm=0.45.

Table 2 shows that the enhancement of internal crystalline treatment (MCE admixture) with PaviX topical treatment achieves more pore-blocking i.e. larger reduction in porosity and hence in permeability than single treatment. The enhancement of MCE addition with additional PaviX topical treatment can achieve an additional one order of magnitude reduction in permeability over single MCE addition. The reduction in permeability of 1% MCE with PaviX topical treatment is close (in the same order of magnitude) to that for permeability reduction of the 2% MCE single addition. This indicates that the enhancement of MCE with PaviX treatment can promote increasing w/cm ratio while achieving the same waterproofing performance, since the additional PaviX treatment compensate for the porosity increase due to increasing w/cm ratio, and hence achieve a permeability reduction as the case with lower w/cm ratio that involves only MCE addition.

Table 2 shows that the ChemCreteX has a high efficiency which is in the same order of magnitude as MCE addition to low w/cm ratio (e.g. 0.41) or to the MCE with Pavix additional treatment at higher w/cm ratio (e.g. 0.45). ChemCreteX produces impermeable concrete surface.

Reducing water penetration decreases the penetration of harmful chemicals that causes water-related durability issues and reduces the availability of moisture within the pores which reduces thermal issues.

4 Conclusions

There is a consistency in the results confirming the efficacy of the investigated crystalline materials, with all protocols, as pore blocking and porosity reduction waterproofing solutions. Each of the investigated crystalline materials or protocols produces virtually impervious concrete; achieving a coefficient of permeability less than 10^{-11} m/s, by at least one order of magnitude. At least, there are three orders of magnitude reduction in permeability is achieved by each of the waterproofing products. This indicates that more than 99% reduction in permeability is obtained for each tested product and protocol. The investigated products, as single or combined treatments, provide significant waterproofing performance that enhances durability of concrete and then extends its service life.

References

1. Ye, G., *Experimental study and numerical simulation of the development of the microstructure and permeability of cementitious materials*. 2003, Delft University of Technology.: TU Delft, The Netherlands.
2. Bapat, J.D., *Mineral admixtures in cement and concrete*. 2012: CRC Press.
3. Al-Jabari, M., 2 - *Concrete porosity and transport processes*, in *Integral Waterproofing of Concrete Structures*, M. Al-Jabari, Editor. 2022, Woodhead Publishing. p. 37-68.
4. Van Breugel, K., *Modelling of cement-based systems—the alchemy of cement chemistry*. cement and concrete research, 2004. **34**(9): p. 1661-1668.
5. Chindapasirt, P., et al., *Cement paste characteristics and porous concrete properties*. Construction and Building materials, 2008. **22**(5): p. 894-901.
6. Mehta, P.K. and P.J. Monteiro, *Concrete microstructure, properties and materials*. 2017, New York, NY 10019, USA: McGraw-Hill Publishing.
7. Meddah, M.S. and A. Tagnit-Hamou, *Pore structure of concrete with mineral admixtures and its effect on self-desiccation shrinkage*. ACI Materials Journal, 2009. **106**(3): p. 241.
8. Ye, G., *Percolation of capillary pores in hardening cement pastes*. Cement and Concrete Research, 2005. **35**(1): p. 167-176.
9. Al-Jabari, M., 3 - *Concrete durability problems: physicochemical and transport mechanisms*, in *Integral Waterproofing of Concrete Structures*, M. Al-Jabari, Editor. 2022, Woodhead Publishing. p. 69-107.
10. Al-Jabari, M., 7 - *Concepts and types of integral waterproofing materials*, in *Integral Waterproofing of Concrete Structures*, M. Al-Jabari, Editor. 2022, Woodhead Publishing. p. 199-246.

11. Al-Jabari, M., 9 - *Hydrophilic crystallization waterproofing*, in *Integral Waterproofing of Concrete Structures*, M. Al-Jabari, Editor. 2022, Woodhead Publishing. p. 283-322.
12. Al-Jabari, M., 6 - *Fundamentals and categorizations of waterproofing technologies*, in *Integral Waterproofing of Concrete Structures*, M. Al-Jabari, Editor. 2022, Woodhead Publishing. p. 165-198.
13. Al-Jabari, M., R. Al-Rashed, and M.E. Ayers, 10 - *Dual crystallization waterproofing topical treatment*, in *Integral Waterproofing of Concrete Structures*, M. Al-Jabari, Editor. 2022, Woodhead Publishing. p. 323-356.
14. Al-Jabari, M., R. Al-Rashed, and Y. Xinbao, 11 - *Multicrystallization waterproofing enhancer for concrete mixtures*, in *Integral Waterproofing of Concrete Structures*, M. Al-Jabari, Editor. 2022, Woodhead Publishing. p. 357-391.
15. Al-Jabari, M., 8 - *Hydrophobic integral dampproofing materials*, in *Integral Waterproofing of Concrete Structures*, M. Al-Jabari, Editor. 2022, Woodhead Publishing. p. 247-282.
16. ACI, *Committee 212, ACI 212. 3R-16 Report on Chemical Admixtures for Concrete*. 2016, American Concrete Institute: Farmington Hills, MI, USA.
17. Al-Rashed, R., *Aqueous chemical mixture to mitigate water associated problems in concrete pavements*. 2008, USA Patents.
18. Al-Rashed, R., *Multiple Crystallization Enhance (MCE) Intermix for Portland Cement Concrete*. 2021, Google Patents.
19. Al-Jabari, M., R. Al-Rashed, and M.E. Ayers, *Mitigation of alkali silica reactions in concrete using multi-crystalline intermixed waterproofing materials*. CEMENT, 2023. **12**: p. 100065.
20. Al-Rashed, R. and M. Al-Jabari, *Concrete Protection by Combined Hygroscopic and Hydrophilic Crystallization Waterproofing Applied to Fresh Concrete*. Case Studies in Construction Materials, 2021. **15** p. e00635.
21. Al-Rashed, R. and M. Al-Jabari, *Multi-crystallization enhancer for concrete waterproofing by pore blocking*. Construction and Building Materials, 2021. **272**: p. 121668.
22. Al-Rashed, R. and M. Al-Jabari, *Managing Thermal Effects in Waterproofed Concrete with Multi-Crystallization Enhancer*. CEMENT, 2022: p. 100050.
23. Al-Rashed, R. and M. Al-Jabari, *Managing Thermal Effects in Waterproofed Concrete with Multi-Crystallization Enhancer*. CEMENT, 2022. **10**: p. 100050.
24. Al-Rashed, R. and M. Jabari, *Dual-crystallization waterproofing technology for topical treatment of concrete*. Case Studies in Construction Materials, 2020. **13**: p. e00408.
25. Jabari, M. and R. Al-Rashed, *Managing Thermal Effects in Waterproofed Concrete with Multi-Crystallization Enhancer (under preparation for submission)*. Materials.
26. Muhammad, N.Z., et al., *Waterproof performance of concrete: A critical review on implemented approaches*. Construction and Building Materials, 2015. **101**: p. 80-90.
27. Mundo, R.D., et al., *Recent Advances in Hydrophobic and Icephobic Surface Treatments of Concrete*. Coatings, 2020. **10**(5): p. 449.
28. Chen, S.-C., et al., *Evaluation of penetration depth and protective effectiveness of concrete-penetrating sealer materials*. Journal of Marine Science and Technology, 2016. **24**(2): p. 18.

29. Ma, S.-H., et al., *Reduction in Water Permeability of a Penetrating-Sealer-Incorporated Liquid Deicer*. KSCE Journal of Civil Engineering, 2024. **28**(2): p. 557-565.
30. CRD, *C48-92 Standard Test Method for Water Permeability of Concrete*. 1992, U.S. Army Corps of Engineers.
31. Shetty, M., *Concrete technology theory and practice*. S. chand & company LTD, 2005: p. 420-453.
32. Wong, H., et al., *Effect of entrained air voids on the microstructure and mass transport properties of concrete*. Cement and Concrete Research, 2011. **41**(10): p. 1067-1077.