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Efficacy of crystalline waterproofing additives for basement concrete

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One of the methods for achieving waterproof basement concrete is the addition of crystallising waterproof additives to the concrete mix. This paper examines whether the effectiveness of these additives is supported by independent testing as reported in the research literature. A number of articles and reports reviewed here cite laboratory studies on the use of crystallising waterproofing additives. On the whole, they are found to be effective. However, the studies are typically diverse and it is challenging to compare one set of experimental results directly with another. For example, several studies fail to take account of changing the water/cement ratio. No studies were found that took account of the impact of hydraulic gradient on the effectiveness of waterproofing additives. These deficiencies in the literature leave industry specifiers facing genuine uncertainty. The use of concrete to exclude water from basements is one of the most significant forms of waterproofing. In achieving waterproof concrete for basements, the use of a waterproofing additive to the concrete mix is a common consideration. However, within the industry there are significant doubts as to how well these additives work in practice. This paper reviews the research literature that studies the effectiveness of crystallising waterproofing additives. It finds there is a lack of research on the effect of hydraulic gradient on the performance of crystallising waterproofing additives. Consequently, civil engineers face uncertainty when preparing appropriate specifications.

1. Introduction

Concrete is used extensively in the construction of basements throughout the world. As well as supporting structural loads, concrete is often expected to exclude water from basements. In order to achieve a ‘waterproof’ concrete structure, one common consideration is the use of a waterproofing additive in the concrete mix.

One of the most prominent groups of waterproofing additives may be identified as crystallising additives. These are intended to grow crystals into cracks and capillaries on contact with water, thereby preventing the passage of water. This paper focuses on these crystallising admixtures.

2. Waterproof concrete

Concrete is the most used material in construction in the world and there are many different forms with varying water–cement ratios, various binders, different aggregate sizes, diverse reinforcements and many other variables besides. The hydration reactions that form hardened cement paste are complicated and well beyond the expertise of industry specifiers (Bullard *et al*., 2011).

In addition to the complexities of concrete, crystallising admixtures are claimed to be dynamic, in that should a crack occur (or water come to bear on a crack) years after the concrete has cured, the additive will begin to block cracks through crystal growth. This makes understanding and testing more challenging.

Within the UK basement waterproofing industry, crystallising admixtures have been available for at least 20 years and form a significant feature within the commercial landscape. Crystallising admixtures are, to a greater or lesser extent, understood to be different from other ‘waterproofing admixtures’ in that crystallising admixtures are intended to be ‘pore blockers’ as opposed to ‘pore liners’. The latter group are typically systems intended to line pores such that they become hydrophobic. The American Concrete Institute’s report on chemical admixtures for concrete (ACI, 2016) would class these groups as permeability reducing admixtures: non-hydrostatic conditions (PRAN) rather than permeability reducing admixtures: hydrostatic conditions (PRAH). Crystallising admixtures would fit into the PRAH group. There is some debate as to whether pore liner (PRAN) additives are suitable for hydrostatic conditions such as basements, however that discussion is outside the scope of this paper. (Interestingly, one of the articles later examined in this paper would suggest that pore liner admixtures are in fact effective under hydrostatic conditions (Mohammadreza Hassani *et al*., 2017).)

There is debate on whether waterproofing additives for basement concrete are effective. One waterproofing supplier’s website shows a guest article by a former President of the Concrete Society (Cather, 2018). This briefly examines the water permeability test results recorded on several additives' British Board of Agrément (BBA) certificates. It should be noted that the selected waterproofing additives are not identified and therefore may or may not include crystallising admixtures (in addition, presumably, to pore-lining additives). The table within Cather's article shows the variation between the control and test samples.

In Table 1, the left column allocates various waterproofing additives a Greek letter. The subsequent columns show the data from the BBA certificate of each product. This table shows variation in the makeup of concrete samples for different products and, more remarkably, inconsistency in the makeup of the control and test samples.

Cather suggests towards the end of the article that there is 'little benefit in adopting a special formulation waterproofing admixture to achieve better resistance against liquid water ingress'.

A discussion document from the Concrete Society (2013) titled *The Influence of Water-Resisting Admixtures on the Durability of Concrete* concludes that there is a 'lack of suitable quantitative information to allow water-resisting admixtures *per se* to be specified with confidence to enhance durability' (p. 55).

In a design guide published in *The Structural Engineer*, the Concrete Centre (2015) asserts that '[w]atertightness and durability can be achieved using good-quality concrete alone without any special additives or admixtures'.

Into this context of relatively weak evidence to support waterproofing admixtures, industry must grapple with significant best practice literature that does not recognise the use of crystallising admixtures. The current Eurocode 2 (BS EN 1992-3 (BSI, 2006)), released in 2006, focuses on waterproof concrete structures but makes no mention of waterproofing additives whatsoever. Rather, its focus is on limiting crack widths in concrete; presumably in order to allow autogenous crack healing to prevent water passage.

This paper now goes on to examine what evidence is available in the academic literature to support crystallising admixtures for waterproof concrete basement structures, and what evidence manufacturers of these systems should produce to encourage their specification.

3. Autogenous crack healing

The sealing of cracks in concrete occurs through several means including further hydration of unreacted cement on exposure to water, and the formation of calcium carbonate. It is reported that the maximum crack width sealed through autogenous crack healing is around 200–300 μm (Aldea *et al*., 2000; Clear, 1985; Edvardsen, 1999; Reinhardt and Jooss, 2003). Other studies have shown normal concrete recovers mechanical strength when immersed in water through autogenous crack healing (Jacobsen and Sellevold, 1996).

The presence of water is perhaps the most important factor in whether autogenous crack healing will take place. Where basement waterproofing failure is the main area of interest, this condition is met.

4. Crystallising waterproofing additives

Crystallising admixtures work through a mechanism that is hard to distinguish from autogenous crack healing, which occurs in concrete without any such waterproofing additives (Tang *et al*., 2015). Crystallising admixtures are also difficult to assess because they are dynamic, in that they are meant to react with water and form additional crystals in cracks and pores in the event that water ingress occurs, thereby sealing the cracks.

Nearly all tests on this topic require a control concrete sample and a test sample. The comparison between the two is required

Table 1. Summary of data from concrete assessment certificates compiled by Cather (2018)

Product	Water permeability control: m/s	Water permeability test: m/s	Water/cement ratio		Strength: MPa	
			Control	Test	Control	Test
α	$6{\cdot}9 \times 10^{-14}$	$1{\cdot}28 \times 10^{-14}$	0·5	0·4	47·0	64·0
β	$2{\cdot}23 \times 10^{-12}$	$1{\cdot}14 \times 10^{-12}$	n/a	n/a	n/a	n/a
γ	$4{\cdot}29 \times 10^{-14}$	$1{\cdot}28 \times 10^{-14}$	0·49	0·47	54·3	59·0
δ	$3{\cdot}20 \times 10^{-15}$	$0{\cdot}64 \times 10^{-15}$	0·45	0·35	63·0	82·0
ε	$1{\cdot}98 \times 10^{-13}$	$1{\cdot}61 \times 10^{-13}$	0·50	0·37	47·8	62·9
η	$3{\cdot}26 \times 10^{-13}$	$1{\cdot}99 \times 10^{-13}$	0·47	0·45	57·8	64·2

Source: Cather (2018)

to assess the efficacy of the waterproofing additive. However, the use of a waterproofing additive changes the water/cement ratio and makes comparisons invalid. This is something of the complaint made earlier by Cather (2018) in the analysis of BBA certificate results.

Table 2 shows details of eight studies identified in the research literature.

Bhandari *et al*. (2016) expressly set out to determine the efficacy of waterproofing admixtures. The study thoroughly examined the coarse and fine aggregates, which is important as changes in density would affect results. The research examined the admixtures in use as surface coatings, which is outside the scope of this paper, but also compared the performance of three integral waterproofing admixtures (Kryton, Penetron, Bauchmie) at various water pressures (ranging from 5 to 10 kg/cm^2). While the study is useful in determining which crystallising waterproofing additive to use, it did not clearly compare the admixture samples with a control sample and therefore did not enable comparison between the waterproofing admixture and autogenous crack healing.

Takagi *et al*. (2018) focused on the implications of crystallising admixtures with particular reference to their influence on blast furnace slag and showed clear evidence that blast furnace slag together with crystallising admixture led to enhanced crack healing. Blast furnace slag is a recognised binder in concrete mix design and an important area of research for basement waterproof concrete due to its reduction in early age cracking, however this is outside the scope of this literature review. Unfortunately, Takagi *et al*. (2018) did not consider the crystallising admixture to be a binder and as a result the samples with crystallising admixtures included would have incorporated a higher proportion of cement–binder material than the control sample. As a result, it could be questioned whether adding 10 kg of ordinary Portland cement (OPC) instead of 10 kg of crystallising admixture to the concrete mixtures described would have shown the same improved crack healing. Nevertheless, this study demonstrated the ability to use crystallising additives in conjunction with blast furnace slag for waterproof basement concrete.

The study by Ferrara *et al*. (2016) focused on enhanced self-healing of cracks through the use of crystallising additives with regard to mechanical properties (as opposed to waterproofing) and demonstrated up to 60% crack sealing in normal strength concrete and higher in fibre-reinforced concrete. Similarly to Takagi *et al*. (2018), Ferrara *et al*. (2016) show the concrete mix composition for the test samples contains the same cement ratio but then add to the test samples the crystallising admixture. The study explains on page 3 that crystallising admixtures ‘generally consist of a proprietary mix of active chemicals, carried out in a carrier of cement and sand’ and goes on to articulate that the energy-dispersive X-ray spectroscopy (EDS) of the crystallising admixture tested is ‘comparable with that of ordinary Portland cement’. This makes it difficult to distinguish the benefits of the crystallising admixture studied from merely using more cement in the mix composition. Nevertheless, the study showed clear visual and mechanical evidence of enhanced autogenous healing, particularly in the fibre-reinforced samples.

Mohammadreza Hassani *et al*. (2017) examined unnamed crystallising admixtures incorporating a significant proportion of carbonates (or nitrates) as well as silica and alumina oxides. Among other things, the tests attempted to distinguish the permeability improvements arising from changes in water/cement

Table 2. Salient details of relevant studies on this topic

Study	Crystallising admixtures tested (by weight of cement)	Maintains water/cement ratio	Examines rehydration crack healing	Examines healed crack contents	Considers hydraulic gradient
Bhandari *et al*. (2016)	Assume products from Kryton, Penetron and Bauchmie (A chart with no title after Table 6 on page 2132 cites these names.) (1%, 2% and 1%)	No	No	No	Yes
Takagi *et al*. (2018)	Xypex Admix c-500 (2·5%)	No	Yes	No	No
Ferrara *et al*. (2016)	Not disclosed (1%)	No	Yes	Yes	No
Mohammadreza Hassani *et al*. (2017)	Not disclosed (contains carbonates) (1%)	Yes	No	No	No
Roig-Flores *et al*. (2015)	Not disclosed (contains tricalcium silicate) (4%)	Yes	Yes	No	No
Ahn and Kishi (2010)	Not disclosed (contains carbonates) (2%)	Yes	Yes	Yes	No
Sisomphon *et al*. (2012)	Xypex C1000-NF + expansive agent (1·5% up to 4%)	Yes	Yes	Yes	No
Qureshi and Al-Tabbaa (2016)	Magnesium oxide (not a commercial additive) (4–12%)	Yes	Yes	Yes	No

ratio from those generated by admixtures. The study concluded that the admixtures improved the permeability; more important in the reduction of permeability is the water/cement ratio and binder types selected. Again, research studies successfully demonstrated that replacement of OPC with ground granulated blast furnace slag (up to 40%) enhanced the performance of the waterproofing additive.

Unfortunately, this study does not address one of the main claims of crystallising additives for basement concrete. In practice it is not unusual to carry out construction of basements while 'dewatering' in order to prevent flooding of excavated sites and avoid weak concrete being subjected to hydrostatic pressure. In this scenario early shrinkage cracking would occur while the concrete is not subjected to hydrostatic head but, at a later date it will become subject to hydrostatic pressure. It is reported elsewhere that highly reinforced concrete structures crack later than expected (Bilcik *et al.*, 2016). Crystallising admixtures are expected to enhance crack healing under these conditions, however the study by Mohammadreza Hassani *et al.* (2017) did not explore rehydration or crack healing but was focused on compressive strength and volume of permeable voids and depth of penetration of samples all at 28 d after curing in a lime tank.

A study by Roig-Flores *et al.* (2015) adjusted the proportion of limestone between the control and test samples to account for the addition of the crystallising admixture powder due to their similar effect on concrete workability and densification of the paste matrix phase. Using a water/cement ratio of 0·45 the crystallising waterproofing admixture (which contained tricalcium silicate) was subjected to a variety of rehydration scenarios. The study concluded that concrete with the crystallising admixtures showed enhanced crack healing when compared with the control, if provided with appropriate water sources. In order to corroborate that the crystallising admixtures were indeed behaving as expected and causing crystal growth (different from the normal autogenous crack healing) examination of the contents of healed cracks might have been beneficial. Without this element in the study, it can only be assumed that the crystallising admixture caused enhanced crack healing, but it remains unclear how it was achieved. This study demonstrated the importance of the presence of liquid water in order to achieve crack healing, which highlights the suitability of this technology for waterproof basement concrete.

Ahn and Kishi (2010) employed partial cement replacement in examining crack healing during rehydration. This study examined 'expansive concrete' (with 90% OPC and 10% expansive agent) and then upgraded this mix design to 93% OPC, 5% expansive agent and 2% crystallising admixture (with a water/cement ratio of 0·45). The results showed the use of a crystallising admixture producing growth of fibrous phases and point to benefits arising from the use of crystallising admixtures. The most significant crack healing in this study, however, was through the combined use of an expansive agent with a crystallising admixture.

Sisomphon *et al.* (2012) also examined an expansive agent used in conjunction with a crystallising admixture. This study appears unusual in that the commercially available crystallising admixture that was tested was clearly cited (Xypex C1000-NF). Test samples had a similar partial cement replacement system, however the water/cement ratio used was very low (0·25). Cracks were generated in cured concrete and then rehydrated to examine crack healing. This study concludes that the addition of the crystallising admixture and expansive additive enhanced autogenous crack healing from ~150 μm to 250–400 μm.

Qureshi and Al-Tabbaa (2016) examined the use of a magnesium oxide (MgO) additive in concrete. Again, partial cement replacement was used to achieve consistent water/cement ratio at 0·35. This ratio is a low water content and the required slump to achieve good compaction in practice at this water content would probably demand additional additives. Nevertheless, this study examined rehydration and demonstrated a different composition of the sealed crack between autogenous samples and those incorporating the magnesium oxide additives. This study used a gas permeability test, which is inconsistent with other studies in the field, which appear to favour a depth of water penetration test. The study concluded that magnesium oxide additives enhanced autogenous crack healing (typically up to 160 μm) such that cracks of up to 400–500 μm were sealed (see Figure 1).

5. Hydraulic gradient

None of the aforementioned studies covers the significance of hydraulic gradient with regard to the efficacy of crystallising admixtures. Edvardsen (1999) completed some important research into autogenous crack healing with different crack lengths and pressures. The results showed that with longer crack lengths and lower pressures, autogenous healing occurred more rapidly. This notion is reflected in the industry standard BS EN 1992-3 (BSI, 2006), which gives specifiers guidance on the maximum allowable crack widths varying depending on the hydrostatic pressure and section thickness (which corresponds to the length of through-crack).

Similarly, Yi *et al.* (2011) also examined autogenous crack healing in concrete without crystallising admixtures. The study examined the water penetration of crack-induced concrete at various crack widths and hydraulic pressures. The findings supported autogenous healing in that the flow rate reduced over time regardless of crack width and hydraulic pressure. The

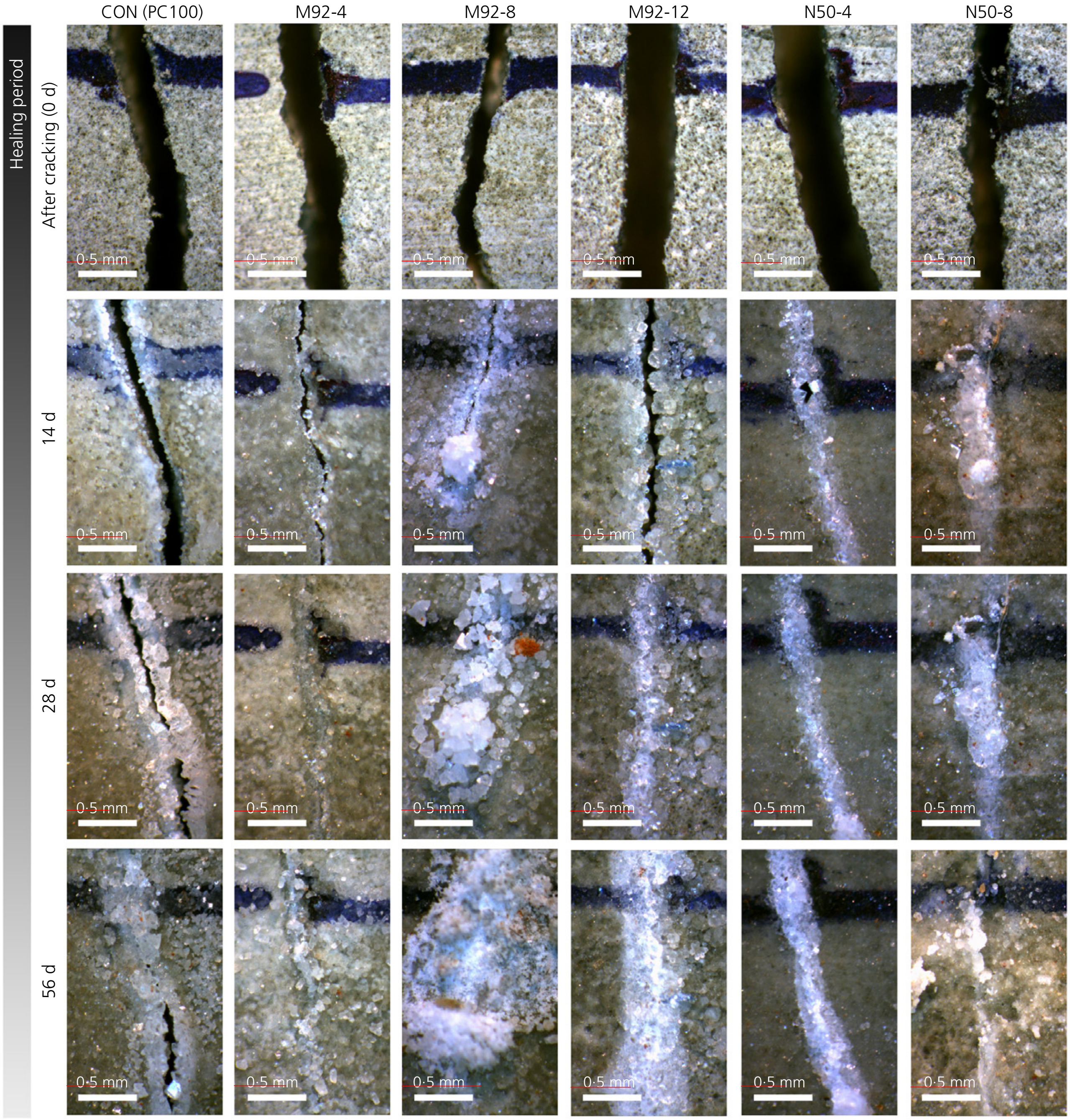

Figure 1. Crack healing with varying magnesium oxide compounds. The left column shows a control sample with autogenous crack healing (reproduced with permission from Qureshi and Al-Tabbaa (2016))

findings also showed that penetrating flow increased significantly with wider crack widths and higher hydraulic pressure.

By contrast, there is a lack of research showing the crack healing enhancement supplied by crystallising admixtures with different hydraulic gradients. This makes it difficult for specifiers to quantify a benefit to the use of a crystallising admixture, leaving specifiers to use their 'professional judgement' to anticipate some level of enhancement over autogenous crack healing.

The most common permeability test used in relation to the crystallising admixture experiments reviewed here is specified in BS 12390-1-2009 (BSI, 2009). It stipulates subjecting samples to a pressure of 5 bar for 72 h. Such testing does not examine variation in hydraulic pressure (such that one could compare with a given water table height) or the length of crack (such that one could compare with a given thickness of a concrete section). Yet the leading best practice guidance in designing waterproof concrete structures (BS EN 1992-3 (BSI, 2006)) demands the consideration of these factors.

Typically, tests on crystallising admixtures (used by the BBA) fail to examine rehydration and there appear to be no standard test methodologies to explore the efficacy of crystallising admixtures under these conditions.

6. Conclusion

The research results reviewed here are generally supportive of the benefits of crystallising admixtures in enhancing autogenous crack healing. A number of studies clearly show crystallising admixtures test samples achieving crystal growth into cracks over and above the crack healing achieved by normal concrete. On the basis of these studies, the use of crystallising admixtures (most frequently containing carbonates) for achieving 'waterproof' concrete basement structures is supported as a result of enhanced autogenous crack healing.

However, when testing crystallising admixtures, failure to use control samples of the same water/cement ratio significantly diminishes the value of results. In addition, failure to effectively test the implications of rehydration limits the relevance of results. For this reason, the BBA certificates carried by commercially available crystallising admixtures are considered weak evidence to support their use.

Academic research seems to avoid mentioning which crystallising admixtures have been tested, presumably to protect commercial interests. However, this limits the repeatability of tests and reduces the standing of such test results, as well as limiting their value to civil engineering specifiers in industry.

Waterproofing technology for basement concrete must continue to improve in order to meet sustainability requirements, which are becoming more stringent within construction. Current academic literature gives a lot of attention to self-healing concrete. Within this literature there is an array of subjects which may be of use in 'waterproof' concrete for basements including: use of bacteria to aid crack healing (although most research in this area relates to applications above ground where access to oxygen would be less of an issue), expansive agents and super-absorbent polymers, encapsulation, fibre reinforcement and more. However, if these developments are to be translated into something meaningful to industry, it is vital that research is designed so that results are relevant to commercial applications and may be compared with other research findings.

This paper implies that manufacturers of crystallising admixtures should undertake and publish research that

(*a*) ensures control and test concrete has the same water/cement ratio
(*b*) examines rehydration crack healing
(*c*) examines the contents of healed cracks (in comparison with autogenous healed cracks)
(*d*) examines the performance of crystallising admixtures with reference to hydraulic gradients listed in BS EN 1992-3 (BSI, 2006).

The test results would enable specifiers to understand the effectiveness of crystalline waterproofing additives in achieving 'waterproof' concrete for basements under varying conditions. If, however, the results of such studies fail to demonstrate conclusively the efficacy of crystallising admixtures (or indeed, if no such studies are completed) specifiers will have no reason to challenge the current best practice as per BS EN 1992-3 (BSI, 2006), which disregards any benefit arising from their use.

REFERENCES

ACI (American Concrete Institute) (2016) *Report on Chemical Admixtures for Concrete*. American Concrete Institute, Farmington Hills, MI, USA.

Ahn T and Kishi T (2010) Crack self-healing behavior of cementitious composites incorporating various mineral admixtures. *Journal of Advanced Concrete Technology* **8(2)**: 171–186.

Aldea CM, Song WJ, Popovics JS and Shah SP (2000) Extent of healing of cracked normal strength concrete. *Journal of Materials in Civil Engineering* **12(1)**: 92–96, https://doi.org/10.1061/(ASCE)0899-1561(2000)12:1(92).

Bhandari N, Harry Sidhu C and Sharma SK (2016) To determine the efficacy of crystalline waterproofing system in concrete. *International Research Journal of Engineering and Technology (IRJET)* **3(8)**: 2129–2134.

Bilcik J, Sonnenschein R and Gajdosova K (2016) Design and execution of watertight concrete constructions. *Key Engineering Materials* **691**: 209–219, https://doi.org/10.4028/www.scientific.net/KEM.691.209.

BSI (2006) BS EN 1992-3:2006: Eurocode 2: Design of concrete structures – part 3: liquid retaining and containment structures. BSI, London, UK.

BSI (2009) BS 12390-1:2009: Testing hardened concrete. Shape, dimensions and other requirements for specimens and moulds. BSI, London, UK.

Bullard JW, Jennings HM, Livingston RA *et al.* (2011) Mechanisms of cement hydration. *Cement and Concrete Research* **41(12)**: 1208–1223, https://doi.org/10.1016/J.CEMCONRES.2010.09.011.

Cather B (2018) *'Waterproofing' of Concrete – Admixtures*. Newton Waterproofing, Tonbridge, UK. See http://www.newtonwaterproofing.co.uk/235/news-articles/waterproofing-of-concrete-admixtures (accessed 18/09/2018).

Clear CA (1985) *The Effect of Autogenous Healing upon Leakage of Water through Cracks in Concrete*. Cement and Concrete Association, Slough, UK, Technical Report 559.

Concrete Centre (2015) Technical No. 1, guidance on the design of liquid retaining structures. *The Structural Engineer* **93(1)**: 44–48.

Concrete Society (2013) *The Influence of Integral Water-Resisting Admixtures on the Durability of Concrete*. Concrete Society, Camberley, UK.

Edvardsen C (1999) Water permeability and autogeneous healing of cracks in concrete. *ACI Materials Journal* **96(4)**: 448–454.

Ferrara L, Krelani V and Moretti F (2016) On the use of crystalline admixtures in cement based construction materials: from porosity reducers to promoters of self healing. *Smart Materials and Structures* **25(8)**, https://doi.org/10.1088/0964-1726/25/8/084002.

Jacobsen S and Sellevold EJ (1996) Self healing of high strength concrete after deterioration by freeze/thaw. *Cement and Concrete Research* **26(1)**: 55–62, https://doi.org/10.1016/0008-8846(95)00179-4.

Mohammadreza Hassani E, Vessalas K, Sirivivatnanon V and Baweja D (2017) Influence of permeability-reducing admixtures on water penetration in concrete. *ACI Materials Journal* **114(6)**: 911–922, https://doi.org/10.14359/51701002.

Qureshi TS and Al-Tabbaa A (2016) Self-healing of drying shrinkage cracks in cement-based materials incorporating reactive MgO. *Smart Materials and Structures* **25(8)**, http://dx.doi.org/10.1088/0964-1726/25/8/084004.

Reinhardt HW and Jooss M (2003) Permeability and self-healing of cracked concrete as a function of temperature and crack width. *Cement and Concrete Research* **33(7)**: 981–985, https://doi.org/10.1016/S0008-8846(02)01099-2.

Roig-Flores M, Moscato S, Serna P and Ferrara L (2015) Self-healing capability of concrete with crystalline admixtures in different environments. *Construction and Building Materials* **86**: 1–11, https://doi.org/10.1016/j.conbuildmat.2015.03.091.

Sisomphon K, Copuroglu O and Koenders EAB (2012) Cement & concrete composites self-healing of surface cracks in mortars with expansive additive and crystalline additive. *Cement and Concrete Composites* **34(4)**: 566–574, https://doi.org/10.1016/j.cemconcomp.2012.01.005.

Takagi EM, Lima MG, Helene P and Medeiros-Junior R (2018) Self-healing of self-compacting concretes made with blast furnace slag cements activated by crystalline admixture. *International Journal of Materials and Product Technology* **56(1–2)**: 169–186.

Tang W, Kardani O and Cui H (2015) Robust evaluation of self-healing efficiency in cementitious materials – a review. *Construction and Building Materials* **81**: 233–247.

Yi ST, Hyun TY and Kim JK (2011) The effects of hydraulic pressure and crack width on water permeability of penetration crack-induced concrete. *Construction and Building Materials* **25(5)**: 2576–2583, https://doi.org/10.1016/j.conbuildmat.2010.11.107.

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