INVESTIGATION OF POSSIBILITY OF USING STEEL FIBRE REINFORCED SELF-STRESSING CONCRETE (SFRSSC) IN WATERTIGHT CONCRETE STRUCTURES

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Abstract. Steel fibre reinforced self-stressing concrete (SFRSSC) has been developing steadily over the last decades with applications of the material now including ground and pile supported slabs as well as raft foundations. Such building elements commonly come into contact with groundwater and are therefore typically covered on their exterior surface by a waterproofing membrane system in an attempt to prevent water seepage into the structure. The final performance of a waterproofing membrane system is heavily influenced by the quality, skill, and attention to detail both in the installation of the membrane and during subsequent works carried out (e.g., reinforcement placement, concrete pouring, etc.) over top of the membrane. Concrete slabs and foundations constructed using SFRSSC, which is typically less prone to cracking than ordinary concrete, may potentially have improved resistance to water ingress than ordinary concrete. In this paper, water penetration testing per EN 12390-8 and mercury intrusion porosimetry testing are completed on various SFRSSC mixtures and compared to reference concrete mixtures to assess changes in the material pore size distribution and its ability to resist water penetration. The presented test results indicate that SFRSSC can have a more refined pore network with improved resistance to water penetration compared to reference concrete mixes with the same water-to-cement ratio. As discussed in the paper, the SFRSSC additional characteristic of reduced shrinkage (and subsequent reduced potential for cracking) indicates that the material may be able to provide improved watertightness, with a potential to reduce demands for external waterproofing membranes under certain circumstances.

Keywords: SFRC, water penetration, MIP.

Introduction

Concrete floors and base slabs are prone to leaking when exposed to external water pressure, for example in basements, tunnels, and other underground structures. Leaks can be both an aesthetical issue, as well as a long-term durability issue, as shown in Fig. 1. Leaks can lead to significant durability issues for the concrete itself, including signs of efflorescence seen in Fig. 1 a), reinforcement corrosion problems, etc. In addition, leaks will also harm the floor surface finishes or coatings, with an example shown in Fig. 1 b), where an epoxy coating is blistering apart from the underlying concrete due to build-up of water at the interface. Often external waterproofing membrane is applied on the external/underside of the structural concrete element (i.e. slab and walls) in an attempt to avoid groundwater seeping into the structure. However, these membranes are sensitive to the skill and quality of labour used during installation and leaks are not always completely prevented.

a) b)

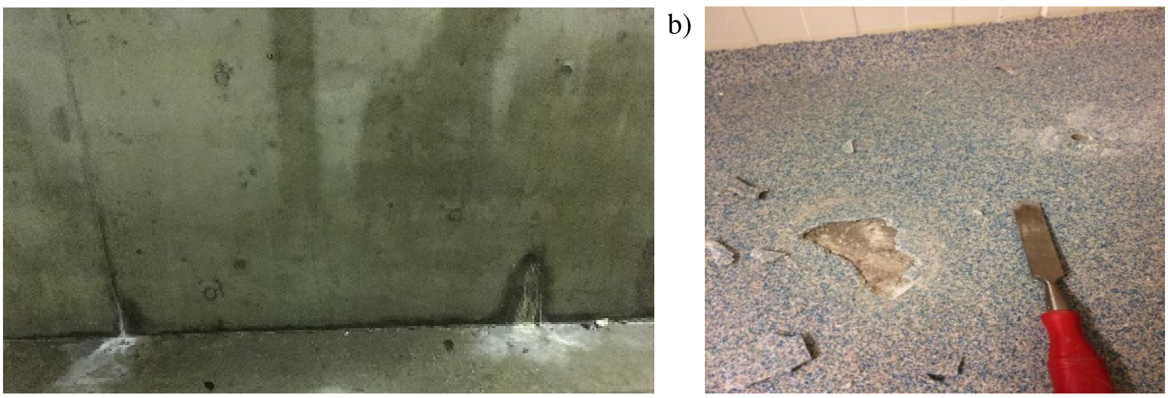

Fig. 1. **Examples of issues caused by leaking groundwater through concrete floors in underground structures including:** a – unsightly leaks, collection of water and long-term durability concerns; b – poor performance of floor coatings or covering

Ideally, the structural concrete itself would be sufficiently resistant to prevent water ingress into the structure. And, while bulk (i.e. uncracked) concrete has a high degree of watertightness (as discussed more in Section 4 herein), openings in the concrete, be it from cracks or required joints in the structural concrete element, offer a drastically reduced resistance to water ingress.

SFRSSC offers some advantages over traditional concrete. As discussed elsewhere (e.g. [1]; [2]) shrinkage-compensating concretes like SFRSSC can be engineered to compensate for long-term (drying) shrinkage with an initial expansion force that helps reduce potential for shrinkage-induced cracking. Further, the number of joints can be reduced or eliminated due to the improved shrinkage situation with SFRSCC. The aim of the study presented herein was to assess the impact SFRSSC has on concrete's ability to resist water penetration. To realize this, a standardized test method was employed as discussed below. To gain additional insight on the results of this testing, mercury intrusion porosimetry testing was also completed to better understand the cause behind the changes in the performance of SFRSSC compared to traditional concrete.

Experimental Programme

To investigate the impact of varying concrete composition on its resistance to water penetration, 150x150x150 mm³ concrete cubes were subjected to EN 12390-8 [3] testing. It was the aim of this research to assess the impact various concrete mineral additives and steel fibre have on the concrete resistance to water penetration. Basic details on the investigated concrete compositions are provided in Table 1, with the individual concrete mix design identified by a numbering system in the first column. The mixture IDs introduced in the table are utilized throughout. As shown in Table 1, Mixtures 1 and 5 are considered as reference concrete compositions to establish baseline performance values. These concrete compositions contained Portland cement only, with no additional mineral additives.

Mixtures 2 and 6 were SFRSSC that included a proprietary calcium sulphoaluminate-based expansive cementitious component, identified as PrīmX DC, together with 45 $kg \cdot m^{-3}$ of a hooked-end steel fibre with varying water-to-cementitious materials (w/c) ratio of 0.55 and 0.40, respectively. While the precise composition of proprietary calcium sulphoaluminate components (also referred to as "Klein's compound" or ye'elemiteper [4]) vary, these components are known to form large quantities of ettringite through processes described in the literature (see, e.g. [5]-[8]), causing a bulk expansion during early stages of concrete hardening. Two series of the Mixture 2 cube samples were prepared to assess whether external restraint of the material impacts results, with the Mixture 2-Unrest cubes being cured under standard conditions and Mixture 2-Rest cubes cured in steel forms.

For comparison of the performance of the SFRSSC, two commercially available additives marketed as crystalline waterproofing additives were also investigated in Mixtures 3 and 4, indicated as "Type 1" and "Type 2", respectively. Steel fibre was not included in these samples, which were cured under standard conditions (i.e. without external restraint from steel forms).

Table 1

Overview of concrete compositions investigated

Mixture ID	w/c ratio	Steel fibre content, $kg \cdot m^{-3}$	Details on mineral additives		Additional Notes
			Type	Content, $kg \cdot m^{-3}$	
1	**0.55**	**0**	**None**	**-**	**Reference concrete**
2-Unrest	0.55	45	PrīmX DC	40	No external restraint
2-Rest	0.55	45	PrīmX DC	40	External restraint
3	0.55	0	Type 1	4	-
4	0.55	0	Type 2	3	-
5	**0.40**	**0**	**None**	**-**	**Reference concrete**
6-Rest	0.40	45	PrīmX DC	40	External restraint

For all concrete types, a CEM I 52.5N strength class Portland cement complying with EN 197-1 was used with a 0-4 mm fine aggregate and coarse aggregate with a maximum size of 22 mm. Steel fibre used in Mixtures 2 and 6 consisted of 1 mm diameter hooked end with a wire tensile strength of 1 500 MPa.

The 0.55 w/c ratio reference concrete mixture (i.e. Mixture ID 1) was supplied by a ready-mix concrete plant. Samples of Mixture ID 1 were directly collected from the ready-mix truck. Mixture IDs 2-4 were obtained by placing 20 l of the reference concrete into a laboratory mixer for remixing to incorporate the steel fibre and/or mineral additives. The 0.4 w/c ratio samples were mixed in laboratory pan-type mixer. Three150 x 150 x 150 mm^3samples of each concrete mixture were cast in standard forms. The cast cubes were left to harden for 24 hours at 20 ± 3 ºC whereupon the samples were demoulded (in some cases, see Table 1) and allowed to cure under lime saturated water to a total age of 28 days. As noted in Table 1, Mixture 2-Rest samples were cured inside the steel forms to assess the impact of differing restraint situations on the concrete's performance. After 28 days of curing, the samples were removed from the curing tanks and tested.

All samples were tested according to the standard test method EN 12390-8 [3] for water penetration under pressure. In accordance with the standards, the concrete samples are held in a specialized testing apparatus and the concrete surface was exposed to a water pressure of 500 ± 50 kPa, equivalent to approximately 51 m of water pressure, for 72 ± 2 hours. After releasing the water pressure, the samples were removed from the testing apparatus, excess water was wiped from the specimen's surface and the specimen was split in half. The specimen was split perpendicular from the face exposed to water pressure so that the waterfront (clearly identifiable by the colour variation from the wettened to the still dry concrete, as shown in Fig. 2) was visible. The maximum water penetration depth was marked on the split surface, measured and recorded to the nearest millimetre. In the results section below, a sample numbering systemis used, combining the Mixture ID from Table 1 and the sample number (i.e. [Mixture ID]-[Sample number]).

Mercury intrusion porosimetry (MIP) testing was conducted on samples of Mixture 1, 2-Rest, 5 and 6-Rest to study the impact of PrīmX DC hydration on the capillary volume and pore size distribution in the hardened cement paste. Cement mortar pieces with approximate weight of 0.6-0.7 g were used for MIP testing. The contact angle and the surface tension used were 140º and 0.48 $N \cdot m^{-1}$, respectively. The increase in pressure in the system was completed in two stages, from 0-100 kPa and then 0.1-300 MPa at the rate of 6 $kPa \cdot s^{-1}$ and 15 $MPa \cdot s^{-1}$, respectively. The intrusion profile of the test was used to correlate the pore size with the intrusion pressure. The samples were 183days old at the time of MIP testing.

Results and Discussion

Fig. 2a) shows an example of the appearance of the concrete surface after splitting. The colour difference, due to the increased water saturation in the outermost concrete after exposure to water pressure for 72 hours, is readily visible. The water penetration profile, marked onto the split surface, was then used to measure the maximum penetration depth for the individual samples, as plotted in Fig 2 b). In Fig 2 b), the darker coloured lines are the averaged maximum water penetration depth from the three individual results, which are shown in faded colour. Coefficients of variation of the measured results are shown in Fig 2 b).

Mixtures 1-4 should be viewed independently from Mixtures 5 and 6 due to the varying w/c ratio; hence, the dark vertical line separating these results. Based on the averages of the individual results of the 0.50 w/c ratio concretes (i.e. Mixtures 1-4), Mixture 2 shows a clear reduction in the water penetration depth compared to the reference, Mixture 1 with 19 mm average. There is a nominal difference in the average water penetration depths with and without external restraint (i.e. 2-Unrest and 2-Rest). The 15.7 mm average penetration depth without external restraint is slightly higher than the 14.3 mm average with external restraint. It is, however, noted that the average result without external restraint is skewed by a higher result from Sample 2, having a coefficient of variation of 30 %. Mixtures 3 and 4, with two commercial crystalline waterproofing additives (see Table 1), yielded worsened performance compared to the reference mix design (Mixture 1). These crystalline waterproofing additive materials are commonly described as requiring extended exposure to water for the beneficial impact of the material to be realized. Testing after 28 days of curing may be insufficient to capture all potential impact of such materials.

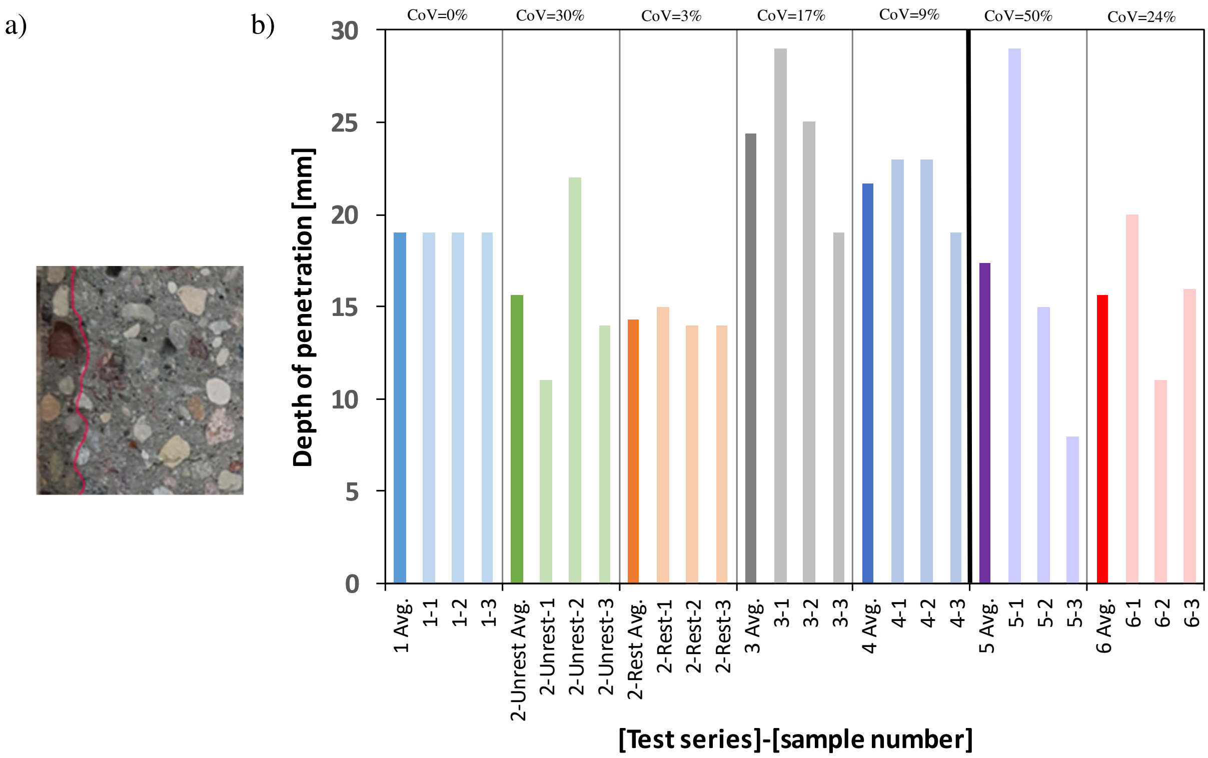

Fig. 2. **Image of clear colour difference, used to measure the maximum water penetration depthand (a) measured average (dark colour) and individual (pale colours) water penetration depths for the various Mixture Ids (b)**

Mixtures 5 and 6, with a 0.40 w/c ratio show a marginal improvement (i.e. reduction) in the water penetration depth compared to the 0.50 w/c ratio reference concrete. Mixture 6 SFRSSC provides an improved average penetration depth of 15.7 mm compared to the 17.3 mm average for Mixture 5. Although, it is noted that results from the individual samples have a higher variability than the 0.55 w/c ratio samples (CoV = 50 % and 24 %).

To investigate the cause for changes in the water penetration results presented in Fig. 2(b), MIP testing was completed for Mixture IDs 1, 2-Rest, 5, and 6-Rest to measure the pore size distribution of the hydrated cement paste at an age of 183 days. Fig. 3 provides the cumulate pore volume curves for the various samples. As would be expected, the 0.40 w/c sample with Portland cement alone (i.e. Mixture ID 5, dark red curve) has a more reduced pore volume, than the equivalent 0.55 w/c ratio sample (i.e. Mixture ID 1, black curve). Mixture ID 2-Rest (red curve), with PrīmX DC added, shows a notable reduction in the cumulative pore volume compared to Mixture ID 1 (black curve). Mixture ID 6-Rest, however, has an increased cumulative pore volume compared to the 0.40 w/c reference sample. Similar increases in the cumulative pore volume for 0.40 w/c paste samples with and without a similar expansive component are reported in the literature [9]. Results in Fig. 3, however, indicate that for certain w/c ratios, the additional hydration products formed by the expansive cementitious component have a beneficial effect, refining the measured pore size distribution.

Fig. 4 presents the same test data as in Fig. 3, with the incremental change in the pore volume plotted against the pore size. Fig. 4(a) presents the 0.55 w/c ratio samples with the blue curve representing Mixture ID 1 and the green curve representing Mixture ID 2-Rest. The peak in the Mixture ID 1 curve from 0.07 to 0.2 µm is clearly removed in the Mixture ID 2-Rest curve. Therefore, the volume of the largest pores is reduced in the 0.55 w/c ratio sample with PrīmX DC added. Figure 4(b) shows the incremental change in the pore volume by pore size for the 0.40 w/c ratio sample with the dark red curve representing Mixture ID 5 and the blue curve representing Mixture ID 6-Rest.The prominent peak in the Mixture 5 data between 0.02 and 0.07 µm is reduced in Mixture 6-Rest and to some extent replaced by a peak in smaller pores between 0.01 and 0.02 µm. There is a clear reduction in the critical pore size of the system, when there is an addition of PrīmX DC. A notable increase in the volume of relatively large pores (i.e. 0.1 to 1.0 µm) is observed in Mixture 6-Rest, which explains the sizeable increase in the cumulative pore volume for Mixture 6-Rest seen from 0.01 to 10 µm in Fig. 3.

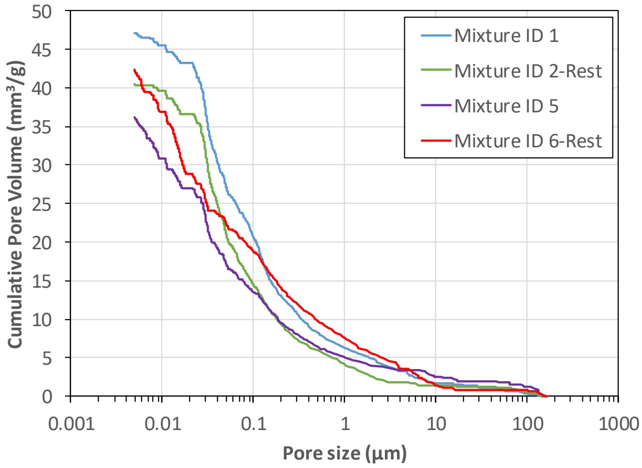

Fig. 3. **Cumulative pore volume distribution for Mixture IDs 1, 2-Rest, 5 and 6-Rest**

The MIP results clearly indicate that the additional reactions from PrīmX DC influence the pore size distribution. In the 0.55 w/c ratio mixtures in Fig. 4(a), the additional reactions (with associated anticipated formation of ettringite [5-8]) have caused a notable reduction in pores with the size greater than approximately 0.7 µm. MIP results from the 0.40 w/c ratio mixtures in Fig. 4(b) and Fig. 3, however, indicate an increased overall pore volume with only particular pore size ranges indicating a refinement in the pore network with the addition of PrīmX DC. The reduction in the critical pore size may be attributed to the formation and deposition of ettringite in the pores. While these limited results cannot be entirely conclusive, it appears that an optimal w/c ratio between 0.40 and 0.55 may lead to the maximal beneficial refinement of the pore network.

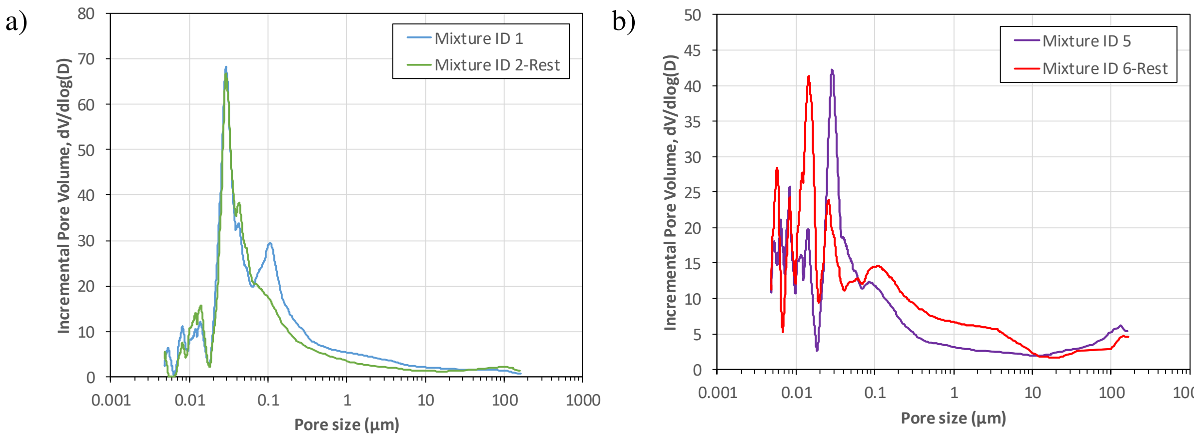

Fig. 4. **Pore size distribution for the 0.55 w/c ratio mixture IDs 1 and 2-Rest (a) and the 0.40 w/c ratio mixture IDs 5 and 6-Rest (b)**

Using equation (1) from [10], the measured penetration depthin Fig 2 b) can be converted to the coefficient of permeability, K_w:

$$K_W = \frac{e^2 v}{2ht}, \tag{1}$$

where e – depth of water penetration, m;
v – volume fraction of concrete occupied by pores;
h – hydraulic pressure head, m;
t – time under pressure, seconds.

For calculations here, the volume fraction of concrete occupied by pores was assumed to be 4 %, which is the median of typical value ranges reported in [10]. The computed coefficients of permeability are presented in Fig. 5a). Rearranging equation 1 allows for estimation of the time- and pressure-dependent water penetration depth. Fig. 5b) presents the estimated penetration depths for up to 50 years and under a 3 meter pressure head for the various Mixture IDs (note that Mixture 6 is not shown, but was calculated to be equivalent to Mixture 2-Unrest with the same computed coefficient of permeability). As is shown in Fig 5b), both Mixtures 2-Rest and 2-Unrest show a reduced estimated water penetration depth compared to the 0.40 w/c reference concrete (Mixture 5, shown in purple), meaning that in this situation the addition of 40 kg·m^{-3} of PrīmX DC had a similar impact on the concrete water resistance as reducing the w/c ratio by a value of 0.15.

a) b)

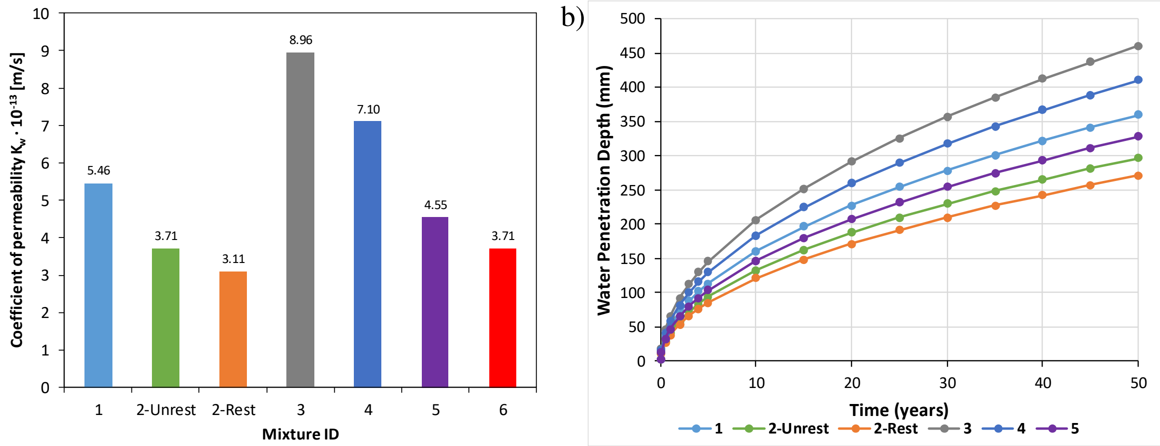

Fig. 5. **Computed coefficient of permeability, per equation (1), for the indicated Mixture Ids (a) and estimated water penetration depths for the indicated Mixture Ids (b)**

Conclusions

Conclusions of the investigation into the impact of differing concrete compositions on water penetration include the following.

1. SFRSSC has improved resistance to water ingress at both investigated w/c ratios, whereas the addition of two types of crystalline waterproofing additives leads to worsened water penetration results.
2. Applying external restraint to the SFRSSC samples may have had a slight impact on water penetration; however, results are not conclusive regarding the impact of the external restraint. It was, however, clear that the combination of materials (i.e. steel fibre reinforcement plus expansive cementitious component) does appear to generally improve concrete's natural resistance to water ingress, decreasing the water penetration depth in the specimens.
3. In these experiments, the addition of 40 kg·m^{-3} of PrīmX DC in a 0.55 w/c ratio concrete had an increased influence (i.e. improvement) on water penetration results compared to reducing the concrete w/c ratio to 0.40.

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References

[1] Destrée X., Pease B. Reducing CO_2 Emissions of Concrete Slab Constructions with the PrimeComposite Slab System, American Concrete Institute (ACI) Special Publication 299, pp. 1-12, 2015.

[2] ACI Committee 223, ACI 223R-10 – Guide for the Use of Shrinkage-Compensating Concrete, American Concrete Institute, 2010, 16 p.

[3] European Standard EN 12390-8:2019, Testing hardened concrete. Depth of penetration of water under pressure, 2019.

[4] ASTM C845 / C845M-18, Standard Specification for Expansive Hydraulic Cement, ASTM International, West Conshohocken, PA, 2018, www.astm.org

[5] Klein A., Karby T., Polivka M. Properties of an Expansive Cement for Chemical Prestressing, Journal of the American Concrete Institute, Vol. 58, Issue 7, 1961, pp. 59-82.

[6] Cohen M. Modeling of Expansive Cements, Cement and Concrete Research, Vol. 13, 1983, pp. 519-528.

[7] Lobo C., Cohen M. Hydration of Type K Expansive Cement Paste and the Effect of Silica Fume: II. Pore Solution Analysis and Proposed Hydration Mechanism, Cement and Concrete Research, Vol. 23, 1993, pp. 104-114.

[8] Collepardi M., Borsoi A., Collepardi S., Ogoumah Olagot J.J., Troli R. Effects of Shrinkage Reducing Admixture in Shrinkage Compensating Concrete Under Non-Wet Curing Conditions, Cement & Concrete Composites, Vol. 27, 2005, pp. 704-708.

[9] Lobo, C. and Cohen, M., Pore Structure Development in Type K Expansive Cement Pastes, Cement and Concrete Research, Vol. 21, 1991, pp. 229-241.

[10] Neville. A.M. Properties of Concrete (Fourth Edition),Pearson Education, 1995, 844 p.