- Technical Paper -

AN EXPERIMENTAL STUDY OF THE COMBINED EFFECT OF BINDER TYPES AND CURING METHODS ON CHLORIDE INGRESS UNDER ACTUAL ENVIRONMENTAL CONDITIONS

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ABSTRACT

An onsite exposure test in airborne chloride environment has been conducted. After 3-month, 1.5-year, and 3.5-year exposure, the series of chloride penetration profile and carbonation depth of the specimens with different mixtures and several curing methods are shown. Stagnation of chloride ingress is observed in the SCM-containing concrete, whereas perpetual ingress is observed in OPC concrete. Longer curing by the highly water-repellent sheet provides higher chloride and carbonation resistance to concrete, and is effective when using with the SCM, but provides fewer benefits in OPC in terms of chloride resistance.

Keywords: chloride penetration, supplementary cementitious materials, curing methods

1. INTRODUCTION

In Japan, large amounts of budget have been spent to repair and reconstruct existing infrastructures due to corrosion of the steel bars from the aggressive chemical agents (i.e. water, chloride, carbon dioxide). In the actual environment, reinforced concrete structures are damaged by the coupling effect of chloride-and-carbonation-induced corrosion. Therefore, rehabilitation and new construction projects are still necessary due to the lack of durability concern in the past. Plus, highly durable concrete design scheme should be used for sustainable development.

Concrete durability is governed by the resistivity of the concrete cover. Conventionally, thick cover or low W/C for OPC concrete tends to be casted to prolong the service life of concrete structures, which increase the construction cost and cement consumption. Engineers have been trying to utilize supplementary cementitious materials (SCMs: i.e. fly ash (FA) and blast furnace slag (BFS)) to substitute the use of cement. Past research [1 – 3], on chloride penetration in the submerged and tidal zone, have proved that high chloride resistance can be achieved in SCM-containing concrete with W/B ratio of 50 to 55%. However, an effective-adequate curing method is an inevitable requirement for SCM, to mitigate the early strength development. Simple curing methods, i.e. seal after construction, can be difficult to implement for infrastructures, as well as the moisture dissipation through the formwork after the casting is inevitable.

Recently, highly water-repellent sheet curing, a new curing technique, has been constantly developing [4] which can make long-term curing more practical. Since the sheet is initially attached to the formwork preventing moisture dissipation. After demolding, the sheet automatically sticks to the surface of concrete [5]. Initially given water can be retained inside the concrete for the hydration reaction [6]. However, this method still needs more validation regarding durability improvement.

To validate the above statement, the saltwater immersion test is the most common way to investigate long-term chloride ion penetration in concrete. However, according to Fig. 2 [7] showing the 3-month (left) and 15-month (right) immersion test, the difference in each curing method cannot be distinguished. It may be because concrete undergoes the continuous hydration process from the unlimited supply of saltwater. Hence, the gap among each curing method becomes less distinctive.

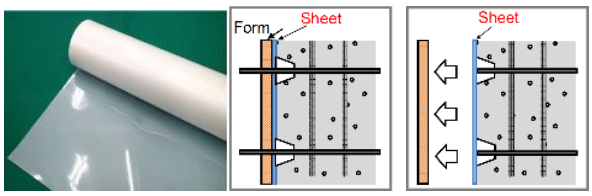

Fig. 1 Highly water-repellent sheet [5]

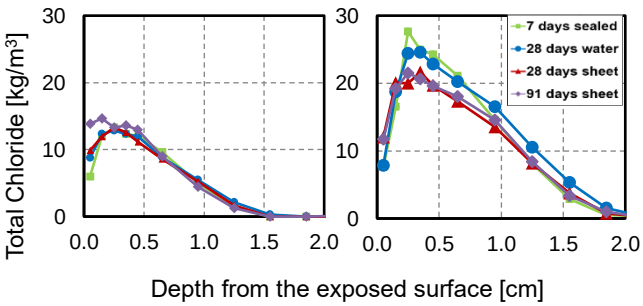

Fig. 2 Immersion test: FA Concrete with W/B55%

In reality, almost all reinforced concrete structures are unsaturated and exposed to limited water supply environments. Only some parts of the structure receive water and some parts remain dry [8]. Rehydration at the

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surface layers may occur only when the concrete sufficiently receives water from the rainfall. In this case, the initial curing condition may become an important factor that needs to be taken into account. However, the research studies about chloride ingress under airborne chloride condition, regarding various binder types and curing methods, are still limited.

In this study, many series of mortar and concrete specimens with various types of binder and curing condition were prepared. The specimens were exposed to the actual airborne chloride condition at site for 3 months, 1.5 and 3.5 years. After that, the specimens were tested for the chloride content and carbonation. The combined effect of various types of binder and curing against chloride ingress and carbonation is discussed.

2. EXPERIMENTAL PROGRAMS

2.1 Specimen series preparation

4 groups of specimens were prepared; 2 series of 10×10×10 cm^3 casted mortar, and 2 series of ϕ10-cm cylindrical cored concrete from the mock-up concrete walls. 4 types of binder were used for mortar (N = only OPC, NB = 60% of OPC and 40% of BFS, NF = 85% of OPC and 15% of FA, NBF = Triple Blended containing 51% of OPC, 34% of BFS, and 15% of FA). 3 types of curing methods were implemented (s = sealed, W = water, sh = highly water-repellent sheet). The mix proportions are shown in Table 1. All mortar specimens were casted and cured in an environmental control room where the temperature is 20°C and RH60%, except the specimens with water curing which were sunk in water. After curing, the specimens were coated with epoxy and installed at the exposure site.

For the sake of description, one specimen is labeled as "[Series]_[Binder][W/B]_[Curing period][method]". For example, Mortar1 OPC with W/B of 55% and 28-day water curing is abbreviated as "M1_N55_28W". The test items are shown in Table 2.

2.2 Exposure site

The exposure site is located at 150-m from the seashore of Japan Sea in Niigata prefecture, Japan. For the figures please refer to [9]. Airborne chloride intensity data differ due to the climate, those in the winter season (December to March) are higher due to the dominants wind from the northwest carrying more inbound salt aerosol [9], compared to those in the summer season (May to August). The mortar and concrete specimens were placed on the rack. The amount of airborne chloride at site has been collected by 2 methods: capture tanks and mortar chips. Fig. 3 shows the average data from the mortar chips installed on the rack which has a slim shape, and the capture tanks which shape like a wall. Therefore, mortar chips show considerable higher values probably because the wind flows through the rack more easily [9].

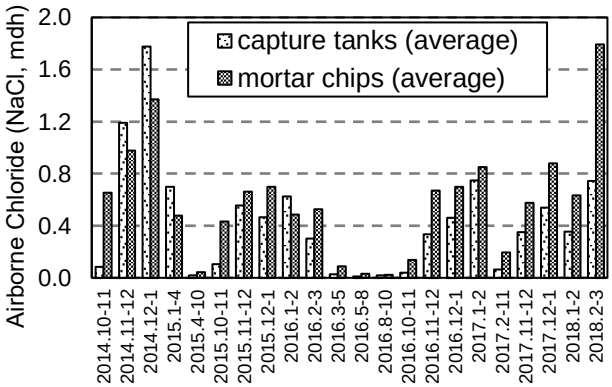

Fig. 3 Airborne chloride data during the exposure test

Table 1 Mix proportions of the specimens

Series	Binder Type	W/B [%]	s/a [%]	Unit weight [kg/m³]							Air [%]
				W	Binder amount			S	G	AD	
					OPC	BFS	FA				
Mortar1 (M1)	N	55	100	380	691	-	-	1000	-	-	2
	NB	55	100	375	409	273	-	1000	-	-	2
	NF	55	100	372	575	-	101	1000	-	-	2
	NBF	55	100	368	341	227	100	1000	-	-	2
Mortar2 (M2)	N	55	100	380	691	-	-	1000	-	-	2
Concrete1 (C1)	NB	52	48.4	173	333		-	855	923	3.50	4.5
Concrete2 (C2)	N	55	48.6	165	300	-	-	889	950	2.75	4.8
	NB	54	48.0	165	306		-	871	952	3.30	5.1
	NF	50	47.4	165	281	-	50	838	958	2.65	5.3

Table 2 Test items

TEST ITEMS	SPECIMEN SERIES	EXPOSURE PERIOD
Time-dependent effect of binders	M1_(N55, NB55, NF55, NBF55)_28W	3 months, 1.5 and 3.5 years
Effect of different curing conditions	M2_N55_(1s, 7s, 91sh) and C1_NB52_(7s, 28sh, 91sh, 182sh)	1.5 and 3.5 years
Combined effect of binders and sheet curing	C2_(N55, NB54, NF50)_(7s, 91sh, 182sh)	2.5 years
Comparison between sheet and water curing	M1_55_(28sh, 28W)	3.5 years

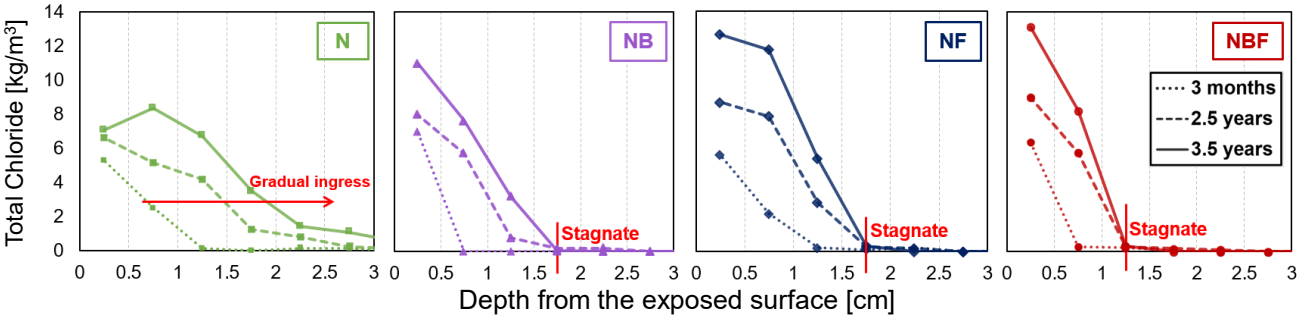

Fig. 4 Onsite exposure test: Time-dependent chloride ingress in M1_55_28W

2.3 Test for total chloride content and carbonation

After the exposure, each series of the specimens was tested for total chloride content and carbonation depth. For total chloride content, the mortar and concrete specimens were cut transversely into 0.5-cm and 1.0-cm thick slices, respectively. The slices were then ground into powder for titration test, following the JCI-SC4 standard. For carbonation test, the specimens were cut vertically and sprayed with phenolphthalein. After that, the carbonation depth of each specimen was measured with a 15-mm pitch along the cross section.

3. RESULTS AND DISCUSSIONS

3.1 Time-dependent effect among binder types

Fig. 4 shows the comparison of M1_55_28W with various binder types for 3 months, 1.5 and 3.5 years. Chloride gradually penetrated inside with time for N series. Unlike NB, NF, and NBF, clear stagnation can be observed between the 1.5 – 2.0-cm portion for NF and NB, and 1.0 – 1.5-cm portion for NBF. Even though the time went by from 1.5-year to 3.5-year, chloride still did not penetrate further inside. Similar chloride profiles of N and NF series were also found in 10-year exposure in the tidal zone [3], where the total chloride content of FA concrete barely increased and stopped at a certain depth, whereas those of OPC continuously penetrated inside. However, the mechanisms of stagnation are not fully understood. Possible reasons may be explained by the electrokinetic phenomena of blended cement matrix [10].

For long-term exposure, Fig. 5 shows that the SCM-containing specimens with W/B 55% give as good performance as a low W/C specimen like N40, or even better if NBF is used. Therefore, engineers can exploit the combined effect of BFS and FA in a mix design to maintain workability and improve chloride resistance.

3.2 Effect of different curing conditions

(1) M2_N55_(1s, 7s, 91sh) series

According to the JSCE Concrete Materials and Construction Standard Specification [11], the suggested period of moist curing is about 5 – 7 days. However, the suggested period may be skeptical whether it is enough for long-term durability or not. Fig. 6 shows that the longer and better quality of curing, the better chloride resistance of mortar becomes. However, the difference between 7s and 91sh may not be so significant during the 1.5-year exposure, so further long-term exposure tests should be carried on.

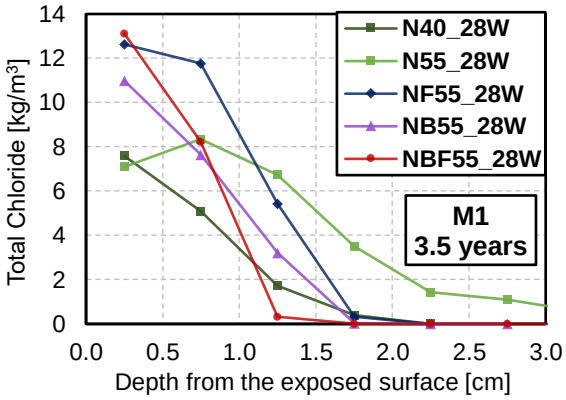

Fig. 5 Effect of SCMs on chloride ingress in M1

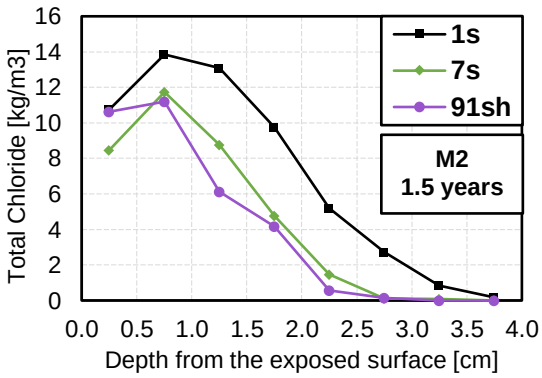

Fig. 6 Chloride ingress in M2_N55 series

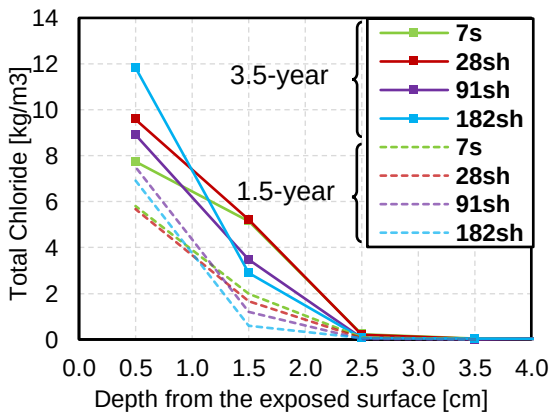

Fig. 7 Chloride ingress in C1_NB52 series

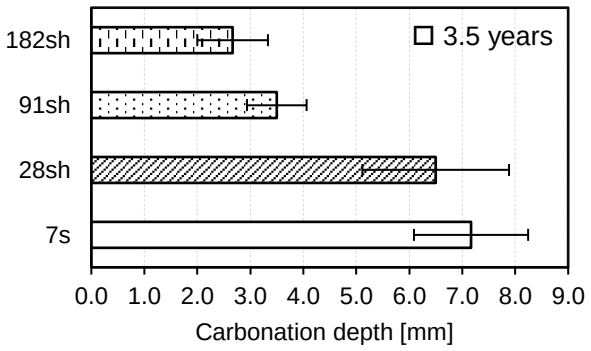

Fig. 8 Carbonation depths of C1_NB52 (3.5 years)

(2) C1_NB52_(7s, 28sh, 91sh, 182sh) series

Fig. 7 shows the comparison results among the curing conditions of 1.5-year and 3.5-year exposure. From the overall trends, better curing conditions yield better chloride resistance. Even though the difference is not clear in 1.5-year exposure, a significant difference can be observed between (7s, 28sh) and (91sh, 182sh) in 3.5-year exposure. Fig. 8 shows the average carbonation depths with the standard error bars of the measurements. The reason of the difference mentioned above may be that the bound chloride ions are released and penetrated inside as the concrete get carbonated [12]. Carbonation constantly proceeded farther in 7s and 28sh, compared to 91sh and 182sh. However, in both cases, chloride ingress still stagnated at 2.0 – 3.0-cm portion due to the utilization of BFS in concrete. Similar trends were also found in C2_NB54 series shown in the following section.

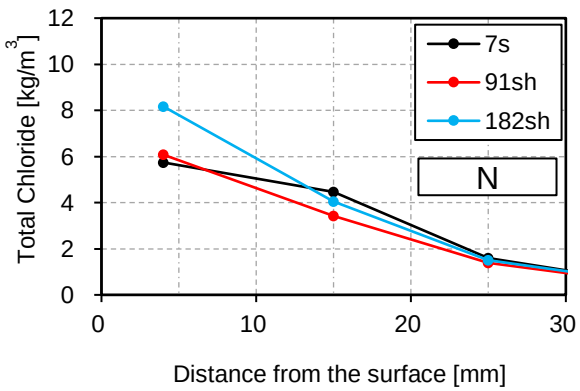

Fig. 9 Chloride ingress in C2_N55 series

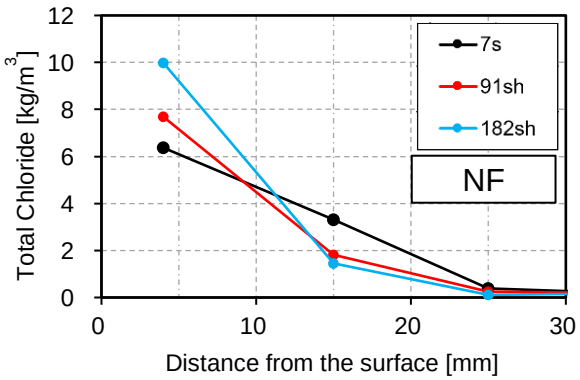

Fig. 10 Chloride ingress in C2_NB54 series

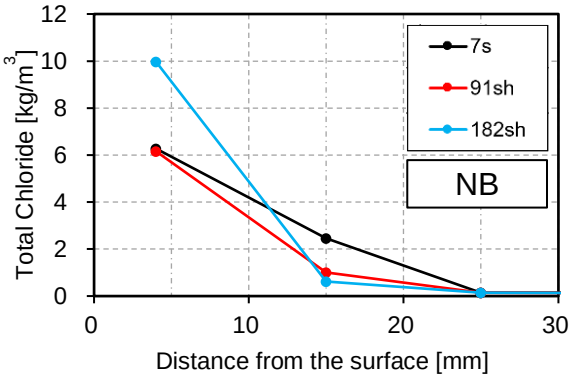

Fig. 11 Chloride ingress in C2_NF50 series

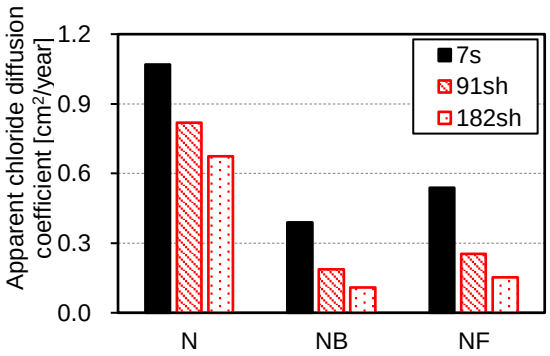

Fig. 12 Apparent diffusion coefficients of C2

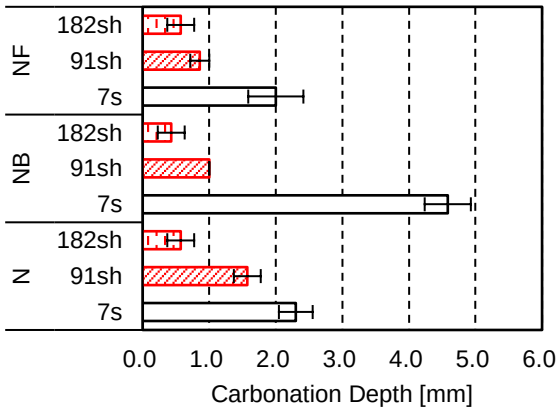

Fig. 13 Carbonation depths of C2 series

3.3 Combined effect of binder types and curing

This section will examine C2 series with 2 variables: binder types and curing conditions. The specimens had been exposed for 2.5 years. The chloride ingress results of N, NB, and NF are shown in Fig. 9, Fig. 10 and Fig. 11, respectively. The apparent diffusion coefficients are presented in Fig. 12, which infers that curing conditions have notable effects on the apparent chloride diffusion coefficients. Plus, the carbonation depths are shown in Fig. 13. It should be noted that NB is more vulnerable to carbonation than N, because of more CSH carbonation [13 - 14]. However, Fig. 13 shows that this problem can be reduced if the specimens are subjected to better curing conditions. Sheet curing seems to be an effective method to improve the chloride-carbonation resistance for SCM concrete, as the quality of the surface layers increases [4].

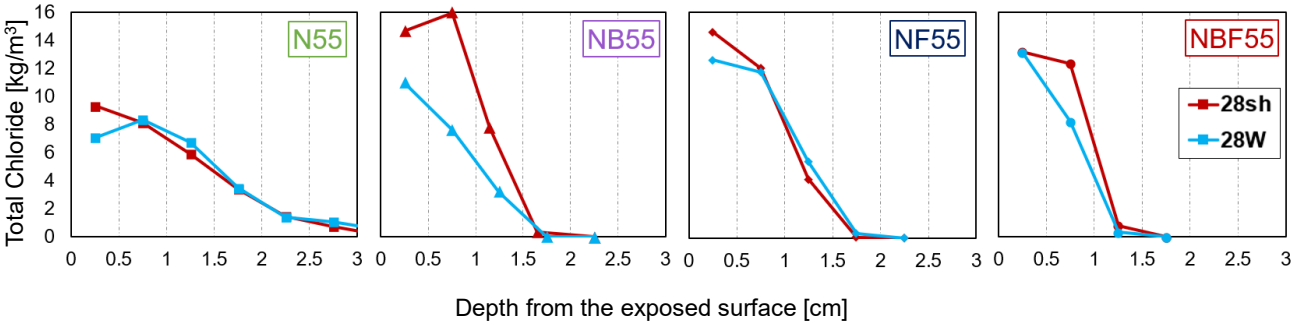

Fig. 14 Comparison of chloride ingress between sheet and water curing for the same curing time

For the N series, however, carbonation resistance is improved by the sheet curing but chloride ingress still proceeded. On the other hand, when using the sheet with SCMs, the higher resistance against both chloride and carbonation can be observed. It can be indicated that longer curing by the sheet is very effective in the NB and NF type binder, whereas it provides less effect on chloride resistance in the case of N type binder.

3.4 Sheet curing and Water curing

From the construction standpoint, curing concrete structures with water tends to be difficult for some parts like walls or bottom surfaces of slabs, and beams. This section examines the applicability of the sheet curing. Fig. 14 and Fig. 15 shows the comparison results of 3.5-year exposure of M1_55_(28sh and 28W) specimens on chloride ingress and carbonation, respectively. For the carbonation test, no significant difference between the 2 curing methods was observed. However, NB_28W shows better performance on chloride resistance than NB_28sh, as the latent hydraulic property can be more active during the initial curing period. Nevertheless, the chloride ingress stopped between 1.5 – 2.0-cm portion, despite NBF where it stopped between 1.0 – 1.5-cm portion. It can be concluded that similar qualities between sheet curing and water curing at the same curing time can be observed for N, NF, and NBF specimens. In the future, sheet curing can be an alternative curing method compared to water curing due to the relative ease of implementation in huge infrastructure or high-rise building projects.

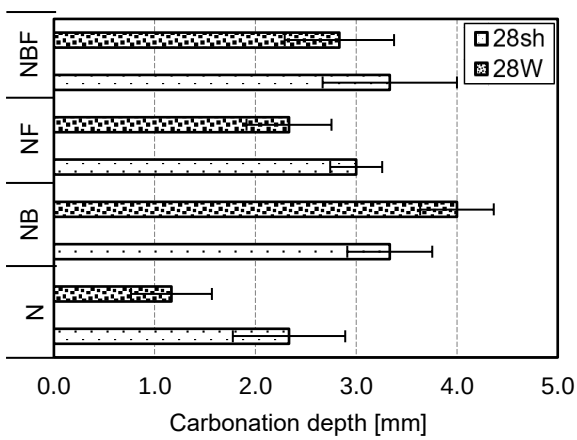

Fig. 15 Carbonation depths of M1 series

4. CONCLUSIONS

(1) SCM-containing mortar and concrete can suppress chloride ingress for long-term exposure. The total chloride content barely increased from time to time. The performance of each series from the best is NBF > NF ≈ NB >> N. However, an effective-adequate curing condition (in general, at least 91 days for FA to ensure the pozzolanic reaction sufficiently proceeds) should be used to exploit the better durability performance.

(2) Longer initial sheet curing yield better chloride and carbonation resistance, especially with the SCMs. However, in the case of N series, sheet curing provides less benefit in terms of chloride resistance, whereas It is very compatible with the SCMs.

(3) Curing with the highly water-repellent sheet for at least 28 days yields as good performance as curing with water. Therefore, sheet curing may potentially play an important srole at construction sites due to the relative ease to implement and control the quality than the conventional sealed curing or water curing.

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REFERENCES

[1] Chalee, W., Jaturapitakkul, C. and Chindaprasirt, P. “Predicting the chloride penetration of fly ash concrete in seawater.” Marine Structures, Vol. 22, 2009, pp. 341-353.

[2] Maruya, T., Tangtermsirikul, S. and Matsuoka, Y. "Modeling of chloride ion movement in the surface layer of hardened concrete." Concrete Library of JSCE, No. 32, 1998.
[3] Thomas, M.D.A., and Matthews, J.D. "Perform-" -ance of pfa concrete in a marine environment – 10-year results." Cement & Concrete Composites, Vol. 26, 2004, pp. 5 – 20.
[4] Sakata, N., Watanabe, K., Nukushina, T., Fujioka, A., and Ishida, T. "Development of an innovative curing method to improve cover concrete quality by using high water-repellent sheet." Proceedings of JSCE, 2016. (In Japanese)
[5] Nukushina, T., Watanabe, K., Sakai, G., and Ishida, T. "New curing method using the water repellent sheets for enhanced durability of concrete." Proceedings of Our World in Concrete & Structures, August 2016, Singapore, pp. 227 – 236.
[6] Watanabe, K., Sakai, G., Sakata, N., and Ishida, T. "Concrete surface quality improvement technique using highly water repellent sealing method." Proceedings of JCI, Vol. 54, No. 11, 2016, pp. 1105 – 1100. (In Japanese)
[7] Koyanagi, S., Takahashi, Y., and Ishida, T. "An experimental study on material properties and time-dependent chloride diffusivity of cementitio-us materials mixed with GGBFS and fly ash." Proceedings of JCI, Vol. 37, No.1, 2015, pp. 109 – 114. (In Japanese)
[8] Wattanapornprom, R., and Ishida, T. "Modeling of chloride penetration into concrete under airborne chloride environmental conditions combined with washout effects." Journal of Advanced Concrete Technology, Vol. 15, pp. 126 – 142.
[9] Hosoi, Y., Wattanapornprom, R., Ishida, T., and Takahashi, Y. "Validation of airborne chloride generation and transportation model based on field measurements for 27 months by two methods." Proceedings of JCI, 2017. (In Japanese)
[10] Takahashi, Y., Elakneswaran, Y., Hayashi, M. and Ishida, T. "Chloride diffusion model considering electrokinetic" Proceedings of JCI, Vol. 36, No.1, 2014, pp. 898 – 903 (In Japanese)
[11] Japan Society of Civil Engineers. "Standard Specifications for Concrete Structures-2012, Materials and Construction." JSCE, 2012, pp. 122.
[12] Saeki, T. "Effect of Carbonation on Chloride Penetration in Concrete." The Third RILEM workshop on Testing and Modelling the Chloride Ingress into Concrete, 2002.
[13] Gruyaert, E., Heede, P., and Belie, N. "Carbonation of slag concrete: Effect of the cement replacement level and curing on the carbonation coefficient – Effect of carbonation on the pore structure." Cement & Concrete Composites, Vol. 35, 2013, pp. 39 – 48.
[14] Marangu, J., Thiong'o, J., and Wachira, J. "Review of Carbonation Resistance in Hydrated Cement-Based Materials." Journal of Chemistry, 2019.