- Technical Paper -

IMPROVEMENT OF WATER AND CHLORIDE PENETRATION RESISTANCE OF SLAG CONCRETE BY USING HIGH ALITE CEMENT

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ABSTRACT

In this research, the effectiveness of high alite cement (HAC) in improving the quality of covercrete of slag concrete was investigated by Surface Water Absorption Test (SWAT) and penetration depth tests. It is found that water absorption rate at ten minutes, which was obtained from SWAT, had a good correlation with penetration depth of water regardless of the type of binder. It was also revealed that HAC improved water penetration resistance of slag concrete due to its less sensitivity to curing condition. HAC slag concrete could also enhance the resistance against chloride ingress.

Keywords: SWAT, high alite cement, slag concrete, water/chloride penetration, covercrete quality

1. INTRODUCTION

Durability of concrete structures is always one of the most concerns of civil engineers, remarkably for the structures that are constructed in very cold area. These structures will suffer from severe condition such as freezing and thawing. Moreover, the excessive use of deicing agent in winter may lead to severe scaling and chloride-induced corrosion. ASR may be activated due to the supply of alkali from the deicing agent.

Especially, the deterioration of concrete slabs due to fatigue under the effects of deicing agent is severe. The upper slabs of PC box girders are important targets to be made more durable, because it is almost impossible to replace severely deteriorated slabs. To improve the resistance against chloride penetration, utilizing mineral additives such as slag and fly ash is effective. It is also well known that concrete with slag needs appropriate curing to show its full performance. It has been pointed out by many researchers that slag concrete is more susceptible to poor curing condition than OPC concrete.

In this paper, Surface Water Absorption Test (SWAT), a method developed by Hayashi and Hosoda [1], and penetration depth tests were applied to clarify the effectiveness of HAC in improving the resistance against water and chloride ion penetration. The other objective was to confirm that SWAT could be utilized as an effective technique to evaluate microstructure of concrete. SWAT was employed because it is very sensitive to covercrete quality, which is much affected by concreting works. Fundamental researches on SWAT [1-3] have shown that several indices from SWAT measurement have good correlation with concrete properties related to durability. Moreover, it is a simple, nondestructive, and rapid method in actual site.

2. EXPERIMENTAL PROGRAM

2.1 Materials and mix proportions

Three types of binders were used in this research: ordinary Portland cement (OPC), high alite cement (HAC), and ground granulated blast furnace slag (GGBFS). HAC is newly developed cement with high alite content and almost no belite [4]. It is found that HAC can improve bond strength between aggregates and slag mortar due to the formation of CSH from secondary reaction between active silica in slag and calcium hydroxide [5]. Chemical composition and physical properties of the binders are presented in Table 1. Concrete with OPC only was the control mix. In other mixes, the cements were replaced by slag with the replacement ratios of 40%. W/B ratios were 0.4, 0.5, and 0.6. Coarse aggregate of andesite with maximum particle size of 19 mm was used. Air content of the concretes was controlled at 6 ± 0.5% to give higher resistance against scaling under freeze/thaw cycles. For this purpose, air-entraining agent was utilized. Ten cylindrical specimens of 100 mm diameter and 200 mm height for each type of concrete were placed. Mix proportions of concrete are given in Table 2.

2.2 Curing conditions and experimental process

Ten specimens of each type of concrete were cured in five different conditions covering from very good to very poor curing condition as shown in Fig. 1. Two specimens were prepared for each condition and SWAT indices were obtained from both of them. In this study, only one specimen was investigated to obtain penetration depth at the age of six weeks after immersing it into salt water. The other one was remained for long-term observation. The detailed information of SWAT and penetration test is explained in section 2.4 and 2.5.

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Table 1 Chemical composition and physical properties of binders

Binder	Chemical composition (%)								Density (g/cm^3)	Specific area (cm^2/g)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O		
OPC	20.36	5.33	3.04	64.09	1.50	2.13	0.28	0.36	3.16	3310
HAC	18.76	5.18	2.85	64.16	1.88	3.97	0.42	0.38	3.11	5480
GGBFS	32.3	14.2	0.31	43.4	5.7	1.93	0.26	0.27	2.90	4030

Table 2 Mix proportions of concretes.

Mix proportion	W/B (%)	s/a (%)	Mix compositions (kg/m^3)							
			Water	Binder			Sand	Coarse aggregate	Admixture	
				OPC	HAC	GGBFS			Air-entraining	AE
O-40				413	-	-	750	927	1.24	5.0
O-40-S	40			248	-	165	745	921	1.24	2.1
H-40-S				-	248	165	744	920	1.44	2.5
O-50				330	-	-	780	965	0.99	2.1
O-50-S	50	45	165	198	-	132	776	960	0.99	0.7
H-50-S				-	198	132	776	959	0.99	-
O-60				275	-	-	801	990	0.83	0.6
O-60-S	60			165	-	111	798	986	0.83	-
H-60-S				-	165	111	797	986	1.38	-

AE: water-reduction admixture

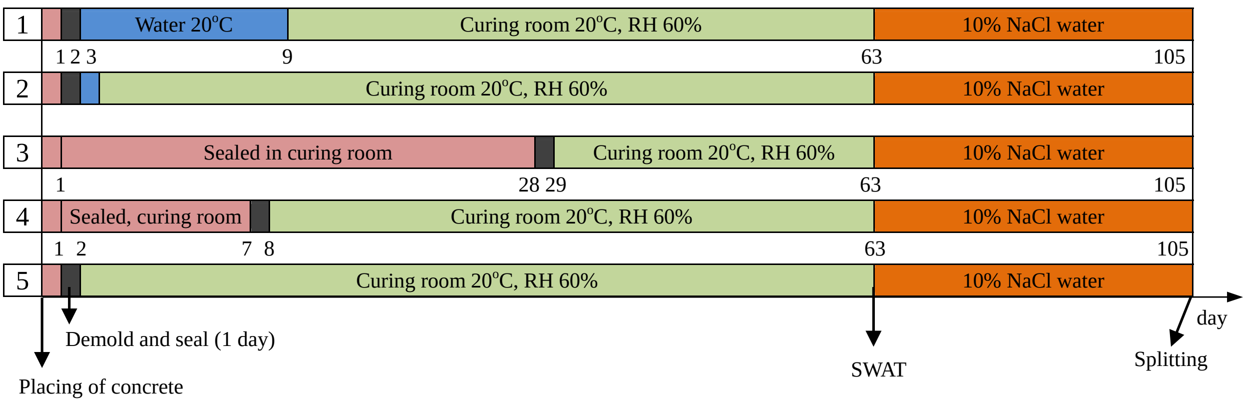

Fig. 1 Curing conditions and experimental process.

2.3 Sealing method

Right after demolding, the top surface and the side of the specimens were sealed (the bottom was opened) to ensure that evaporation or permeation of water is caused only in one direction, i.e., moisture was evenly distributed in the specimen. The specimen was wrapped by alumina tape firstly and then coated by epoxy resin (Fig. 2). It took one day for hardening of epoxy resin. After that, the curing process was continued.

2.4 Surface water absorption test (SWAT)

After the curing process, all the specimens were dried in a room with the temperature of 20°C and relative humidity of 60%. Because the moisture content of concrete is the most influential factor on water absorption of concrete [6], the specimens were dried until the water contents reached stable situations. According to ASTM C140-11a [7], the stable situation can be determined when two successive weighings at intervals of 2 hours show an increment of water loss not larger than 0.2% of the last previously detected weight of the specimen. In this study, all the specimens have reached the stable situation at the age of 63 days. Before conducting Surface Water Absorption Test (SWAT) measurement, the moisture content of concrete was measured at the surface by moisture tester HI-520. Initial weight of the specimens was measured, and then SWAT using pure water was applied to obtain water absorption rate at ten minutes [2, 3]. For cylindrical specimens, a frame was employed to fix the water cup to the surface of the specimen (Fig. 3). For each kind of concrete in each curing condition, water absorption rate at ten minutes was measured in two specimens and then the mean value was taken.

2.5 Penetration test

(1) Immersion of the specimens in salt water

Right after conducting SWAT, the specimens were immersed in 10% NaCl water following JSCE

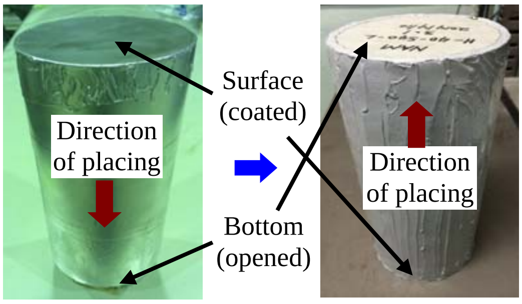

Fig. 2 Specimen was wrapped by alumina tape (left) and then coated by epoxy resin (right).

Fig. 3 SWAT testing.

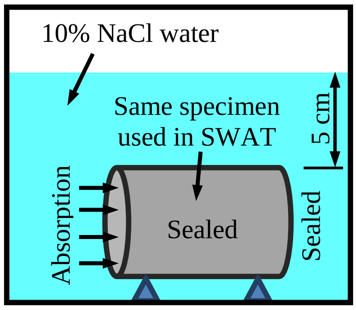

Fig. 4 Specimen was immersed in 10% NaCl water.

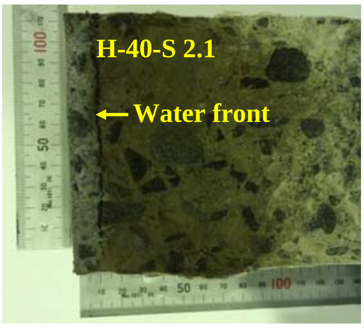

Fig. 5 Water front detected by naked eyes (black line).

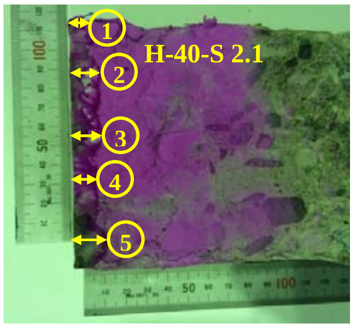

Fig. 6 Water front detected by colored-change agent.

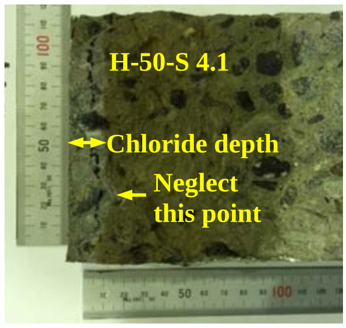

Fig. 7 Chloride front detected by $AgNO_3$.

G572-2010 [8] (Fig. 4) and were continuously weighed as specified in ASTM C1585-04 [9] until their weights became almost stable. Finally, the specimens were split to measure the penetration depth of liquid water in two methods. Furthermore, the penetration depth of chloride ion was also measured.

(2) Splitting of specimen

In order to measure the penetration depth of liquid water, the specimens were split at 42 days after immersing them into salt water.

Normally, a usual concrete cylindrical specimen is easy to split under a small pressure. In this case, the surface of split section is rather flat. Hence, it is not difficult to visually detect the water front. In this study, however, because of the epoxy resin coating, a larger load was needed to split the specimen. Therefore, concrete close to the loaded edges of the specimen was easily damaged, which caused more difficulty in detecting the penetration front due to the rough surface of the split section. To avoid this inconvenience, the loading rate was made very large.

(3) Detection of water front

After splitting, the penetration depth of liquid water was measured in two methods. First, immediately after splitting, the water front was observed in both halves of split specimen by naked eyes to detect the difference of color between the wet part and the dry part. The wet part showed a bit darker color than the dry part. With this visual detecting method, the water front was clearer in the specimen whose inside part was drier, e.g., concrete with low W/B subjected to poor curing. Figure 5 shows the water front detected by naked eyes.

After that, water front was investigated by applying color-change agent to the first half of the specimen (the other half was remained for chloride depth measurement). This agent detects the existence of liquid water sensitively and is usually used for detecting water leakage. The agent was sprayed evenly onto the surface of the section. It also should be noted that if the color-change agent was sprayed too much or too less, the water front would be too unclear. The water front was recorded by a zigzag line at the interface between wet part and dry part, as shown in Fig. 6. In this case, the depth was measured at five points on the front, and then the average value was taken. Compared with the water front recorded by naked eyes (Fig. 5), the water front detected by color-change agent was almost the same. When the line of the water front was not zigzag, the number of measuring points could be reduced.

One important thing affecting the accuracy in water front measurement is the smoothness of the surface of split halves. Because the specimens were coated by epoxy resin, sometimes it they were crumbled near the top of specimen during splitting work. This made the surface of split halves rough that caused different water front between both methods in some cases. The way to select the data obtained from two methods will be discussed in detail in section 3.1.

(4) Detection of chloride front

The penetration depth of chloride ion was measured on the other half of the specimen by spraying 0.1mol/l $AgNO_3$ solution onto the surface. The color change from dark to light indicates the presence of chloride ions (Fig. 7). The silver nitrate solution can record the existence of chloride ions down to a concentration of 60 ppm [10].

Table 3 Penetration depth of water and chloride.

Mixtures	Specimens														
	1.1			2.1			3.1			4.1			5.1		
	Water		Cl^-	Water		Cl^-	Water		Cl^-	Water		Cl^-	Water		Cl^-
	Eye	Agent		Eye	Agent		Eye	Agent		Eye	Agent		Eye	Agent	
O-40	8	8	14	6	5.5?	13.5	4?	7	15	9	3.5?	14	9.5	-	18
O-40-S	8	14?	10	11?	11	10.5	7.5	15?	9	12	6?	10	17	-	15
H-40-S	4.5	10?	9	11	11	11	6	12?	10	8?	12	10	17.5	-	15.5
O-50	14	15	20	16?	10	19	14?	9	18	13	x	18	14	-	21.5
O-50-S	9?	8	9	14	12?	13	8?	8	10	19	12?	12	37	-	20
H-50-S	6	6.5	11	10	x	10	8?	6	10	9?	12	12	20	-	15.5
O-60	8	8	15	18	9?	18	10?	10	18	14	x	18	41?	20	25
O-60-S	10	10	11	21	x	14	11	5?	11	15	15	12	46	x	28
H-60-S	9.5?	12	11	18	x	14	12.5	15?	13	12?	15	13.5	30	x	22

- : agent not used, ? : unclear observation, x : data cannot obtained, number in the red: chosen value

An example for the measurement of chloride front is shown in Fig. 7. It can be seen that the chloride front was almost a straight line but an abnormal point was observed. In this case, the abnormal point was neglected in the measurement. As explained in the measurement of water penetration depth, the chloride penetration depth was also measured at several points when the chloride front was zigzag and the mean value was taken.

3. RESULTS AND DISCUSSION

3.1 Penetration depth of water and chloride

The water penetration depths of the specimens detected by two methods, i.e., naked eyes and color-change agent, and chloride immigration depths are shown in Table 3. Because chloride front was very clear to detect, the discussion in this section only focuses on the measurement of water penetration depth.

Due to some difficulties in detecting water front as aforementioned, the water front was unclear in some cases (for both naked eyes and color-change agent methods). It was impossible to detect the water front in seven cases of color-change agent method. All the specimens were categorized into two groups: the first group included the specimens whose water fronts were clear in both observation methods, and the second group consisted of the specimens whose water fronts were clear only in one method of observation.

The results in the first group specimens (the numbers in the cells with yellow background) show that the both methods gave almost the same values. In this group, the average depths of water penetration recorded by naked eyes and by agent were 10.3 mm and 10.5 mm, respectively. The similar average water penetration depths recorded by the two methods in the first group indicates that water penetration depth can be measured by any of them. In consequence, for specimens in the second group, the water penetration depth was chosen from the clearer value between the two values, represented by the red number.

3.2 Effectiveness of HAC in improving water absorption resistance of slag concrete

The comparisons of water absorption rate at 10 minutes (p_{600}) of slag concretes with OPC and HAC are presented in Fig. 8. In the graph, values of HAC slag concretes are connected by solid lines while those of OPC slag concretes are linked by dash lines.

Apparently, p_{600} remarkably varied according to curing conditions. The specimens cured for one day in mold presented the highest p_{600}, i.e., the worst quality of covercrete while the specimens cured for 7 days in water or for 28 days in mold showed the best covercrete quality. It can be said that p_{600} can clearly differentiate the effects of curing conditions on the resistance against water absorption.

Considering the type of cement, HAC slag concretes showed smaller p_{600} than OPC slag concretes. The difference in p_{600} was not significant in concretes subjected to good curing but very clear in concretes subjected to poor curing condition. Clearly, the water absorption resistance of HAC slag concretes was less sensitive to curing conditions than that of OPC slag

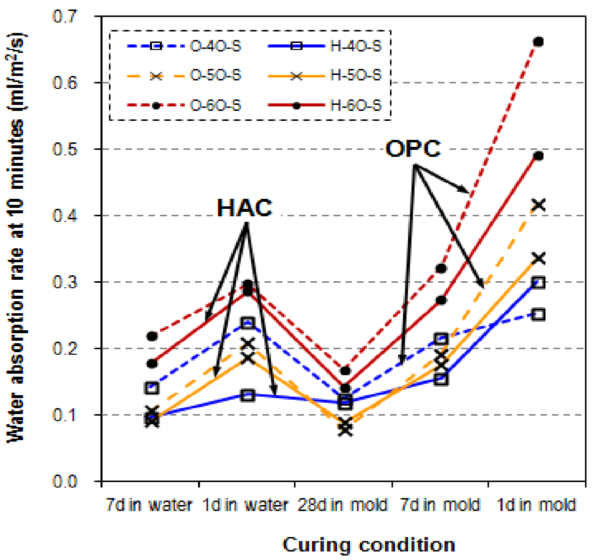

Fig. 8 Water absorption rate at 10 minutes of slag concretes with OPC and HAC.

concrete. This advantage was derived because denser matrix was achieved due to rapid hydration. As pointed out in Nam *et al.* [5], strong bond between aggregate and mortar in the case of HAC slag concrete might have contributed to improve water absorption resistance.

3.3 Relationship between water absorption rate and water penetration depth

Figure 9 exhibits the correlation between p_{600} and penetration depth of water in OPC concrete, OPC slag concrete and HAC slag concrete.

In three concretes, p_{600} had a good correlation with penetration depth of water. Furthermore, the linear relationships of three kinds of concrete were on almost the same line. This implies that water absorption rate and penetration depth of liquid water of concrete were governed by the same factor, i.e., the threshold pore size proposed by Sakai *et al.* [11]. Here, threshold pore size is the minimum pore size which mass should pass to penetrate the objective. They reported that there was a good correlation between threshold pore size and water permeability of concrete [11]. Water absorption resistance and threshold pore size also had a good correlation [12]. It can be said that SWAT can be utilized as an effective technique to examine microstructure of concrete. This is very significant because SWAT is a simple, rapid, and nondestructive method and it is easy to be applied in actual sites.

The tendencies of water penetration in the all concretes were almost similar. The only difference here was the range of values. Apparently, the quality of concrete containing slag (both OPC and HAC) was more sensitive to curing condition than OPC concrete. As a result, water absorption rate at 10 minutes as well as water penetration depth in slag concretes subjected to poor curing were much larger than those in OPC concrete. It implies that appropriate curing is indispensable for concrete containing slag to achieve the durability of concrete structures. Fortunately, HAC slag concrete presented less sensitivity to curing condition than OPC slag concrete. It may be due to the high hydration rate of HAC. Even in a poor curing condition, due to rapid hydration of C_3S, higher resistance against water absorption of HAC slag concrete was observed. Less sensitivity to poor curing is one of the advantages of HAC slag concrete.

3.4 Effectiveness of HAC in improving resistance against chloride penetration of slag concrete

Regarding to chloride penetration, there were two

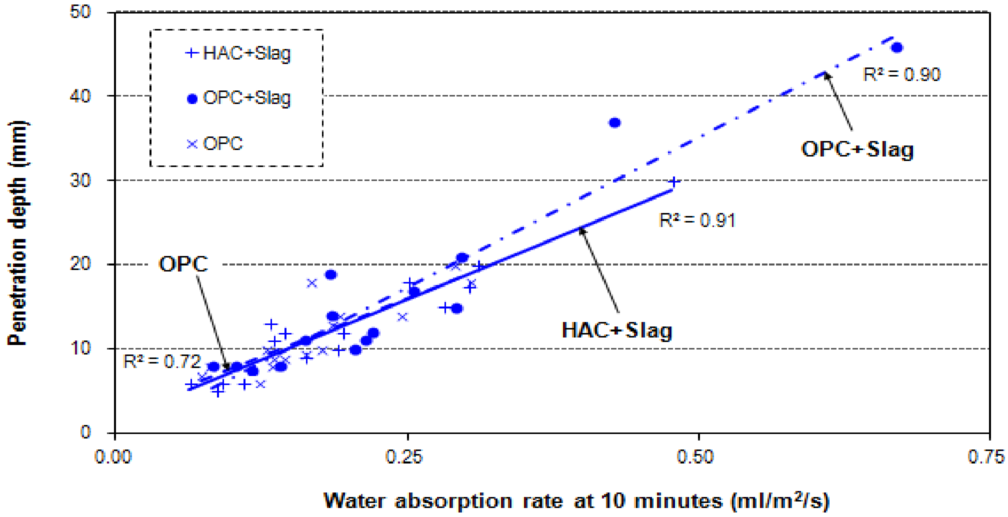

Fig. 9 Relationship between water absorption rate at 10 minutes and water penetration depth.

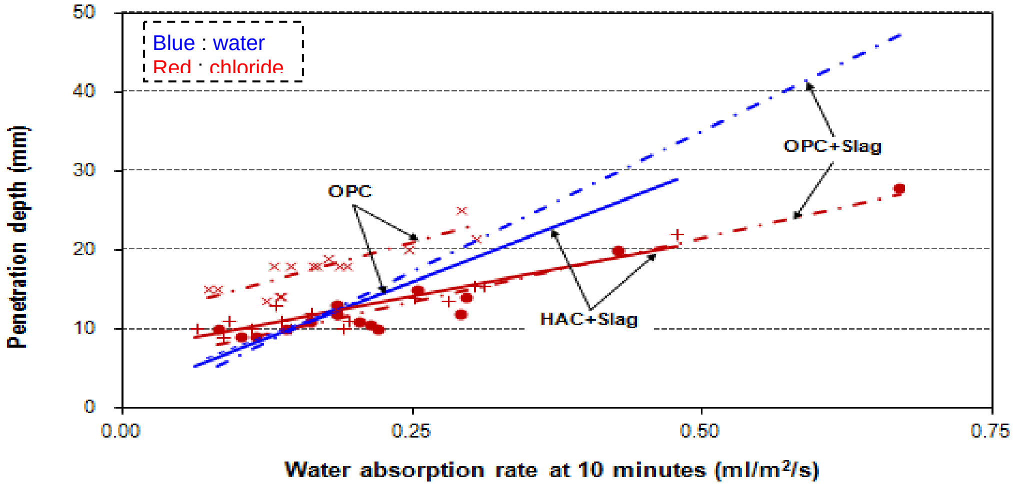

Fig. 10 Comparison between OPC, OPC slag, and HAC slag concretes.

clearly distinct tendencies between concrete with and without slag (Fig. 10). In OPC concrete, chloride ions penetrated more deeply than water. This result can be explained by the distinction in transportation mechanism of liquid and ion. The main mechanism of liquid water movement is absorption due to capillary suction force. Absorption becomes stagnant when covercrete reaches near to its saturated situation. Whereas, the main mechanisms of chloride ion transfer are not only absorption but also diffusion [13].

On the other hand, in both concretes containing slag, chloride ions penetrated much shallower than water, especially in very poor quality concrete. It means that chloride movement was restricted in these concretes. It is well known that the rate of chloride ingress into concrete is influenced by the chloride binding ability of the concrete. The chloride binding capacity is controlled by the cementitious materials. Chemically, chloride ions can be bound by C_3A to form calcium chloroaluminate, $3CaO \cdot Al_2O_3 \cdot CaCl_2 \cdot 10H_2O$, sometimes referred as Friedel's salt [14]. Because of rich C_3A content, slag can improve chloride binding ability of concrete. As a result, during the movement of salt water into concrete, chloride ions were bound by slag leading to the shallower penetration of chlorides compared with pure water. In terms of resistance against chloride ion, HAC slag concrete showed almost the same trend as OPC slag concrete.

4. CONCLUSIONS

In this research, the quality of covercrete of OPC and HAC concrete containing slag with W/B of 0.4, 0.5, and 0.6 subjected to five curing conditions was investigated by SWAT (water absorption rate at 10 minutes: p_{600}) and by penetration depth tests. The conclusions can be drawn as follows.

1. There were good correlations between p_{600} and penetration depth of water in all kind of concretes. It means that SWAT can be applied to evaluate the resistance against mass transfer into concrete.
2. Almost same linear relationships were observed between the water penetration depth and p_{600} regardless of the type of binder. This will be because both properties are governed by the same mechanism like the threshold pore size.
3. Owing to the high hydration rate of C_3S, HAC slag concrete was effective to enhance water penetration resistance because it was less sensitive to curing conditions. Therefore, HAC should be utilized with slag in concrete structures subjected to severe conditions. Furthermore, slag could improve the resistance against chloride ingress of concrete remarkably due to the chloride binding ability of C_3A component existing in slag. These results were also indicated in the past studies [14].

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REFERENCES

[1] Hayashi, K. and Hosoda, A., "Developement of Water Absorption Test Method Applicable to Actual Concrete Structures", *Proceedings of the JCI*, Vol. 33, No.1, 2011, pp. 1769-1774 (in Japanese)

[2] Akmal, U., *et al.*, "Evaluation of Covercrete of Expansive Concrete with External Restraint by Surface Water Absorption Test", *Proceedings of the JCI*, Vol. 34, No. 1, 2012, pp. 760-765

[3] Hayshi, K. and Hosoda, A., "Fundamental Study on Evaluation Method of Covercrete Quality of Concrete Structures by Surface Water Absorption Test", *Journal of JSCE*, Ser. E2 (Materials and Concrete Structures), Vol. 69, No. 1, 2013, pp. 82-97 (in Japanese)

[4] Siribudhaiwan, N., *et al.*, "Influence of alite content on the hydration of blended cement", *Proceedings of the 1st International Conference on Concrete Sustainability* (ICCS13), 2013, pp. 447-452

[5] Nam, H. P. and Hosoda, A., "Mechanism of improvement of crack resistance of slag concrete with high alite cement", *Journal of JSCE*, Ser. E2 (Materials and Concrete Structures), Vol. 2, No. 1, 2014, pp. 239-248

[6] Dirh, R. K., Hewlett, P. C., and Chan, Y. N., "Near-surface characteristics of concrete: assessment and development of in situ test methods", *Magazine of Concrete Research*, Vol. 39, No. 141, 1987, pp. 183-195

[7] ASTM International, ASTM C140-11a, Standard test method for sampling and testing concrete masonry units and related units, 2011

[8] JSCE, JSCE-G 572-2010, Test method for apparent diffusion coefficient of chloride ion in concrete by submergence in salt water, 2010

[9] ASTM International, ASTM C1585-04, Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes, 2004

[10] McCarter, W. J., Ezirim, H., and Emerson, M., "Absorption of water and chloride into concrete", *Magazine of Concrete Research*, Vol. 44, No. 158, 1992, pp. 31-37

[11] Sakai, Y., Nakamura, C., and Kishi, T., "Correlation between permeability of concrete and threshold pore size obtained with epoxy-coated sample", *Journal of Advanced Concrete Technology*, Vol. 11, 2013, pp. 189-195

[12] Sakai, Y. and Kishi, T., "Evaluation of the resistance of concrete based on threshold pore radius", *Proceedings of the JCI*, Vol. 36, No.1, 2014, pp. 688-693 (in Japanese)

[13] Neville, A. M., "Properties of Concrete," 5th ed., Prentice Hall, 2011, pp.484-486

[14] Neville, A. M., "Chloride attack of reinforced concrete: an overview", *Materials and Structures*, Vol. 28, 1995, pp. 63-70