Study on Performance of Self-healing and Water Leakage Channel-Blocking Admixture for Mortar and Concrete

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Abstract. In recent years, there has been growing demand for sustainable concrete structures. One line of research is the addition self-healing properties to concrete. In this study, a natural pozzolan material known as "Bestone", the product of a mine in Japan, is used as an admixture that blocks water leakage channels formed by cracking in concrete structures. It has previously been shown that when concrete including Bestone in the mix is applied to an underground structure, water leakage through microcracks decreases over several months until it stops entirely. In this study, in order to evaluate this water shutoff performance of Bestone mortars and concretes, a crack about 0.2 mm wide is artificially introduced into concrete specimens and changes in water leakage through the crack are measured. From the results, the water shutoff performance of Bestone is demonstrated. In order to investigate the mechanism of this behavior, SEM observations and X-ray diffraction analysis are carried out hydrates formed in the crack, clarifying that the pozzolan reaction occurs in the crack and that this leads to water shutoff. The effects of adding Bestone on the fresh properties and compressive strength of concrete are also evaluated.

Keywords: Self-healing Performance · Water Leakage · Performance evaluation

1 Introduction

Bestone is, an admixture made from natural pozzolan and produced in Nagano Prefecture, Japan, as shown in Fig. 1. It is a pure inorganic high-performance concrete frame waterproofing admixture without polymers and other substances. Its chemical composition is shown in Fig. 2. Bestone adsorbs calcium hydroxide, which is liberated as the cement hydrates to produce an insoluble calcium silicate gel in what is considered a kind of pozzolanic reaction. The calcium silicate gel fills micro voids in the concrete, making the concrete itself waterproof and impermeable. Further, if water leaks through part of a crack caused by external forces induced by contraction or temperature stress, calcium silicate gel is formed in the crack, keeping water shutoff performance and filling the crack. In fact, a structure with Bestone in the concrete has been shown to become impervious to water performance about one to three months after the initial occurrence of

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water leakage. Figure 3 shows an underground structure that has cracked and is leaking water from the cracks, but the influx of water came to a half after several weeks because the concrete was mixed with Bestone. The estimated reserves of Bestone are about 18 million tons, making it possible to supply it as a product semi-permanently, and it has been applied in the construction of various underground structures in Japan.

This study is an experimental evaluation of the water shutoff performance of Bestone. In order to carry out the evaluation, a water leakage test method is developed and a simulation is carried out of external underground pressure affecting a large subsurface structure including Bestone.

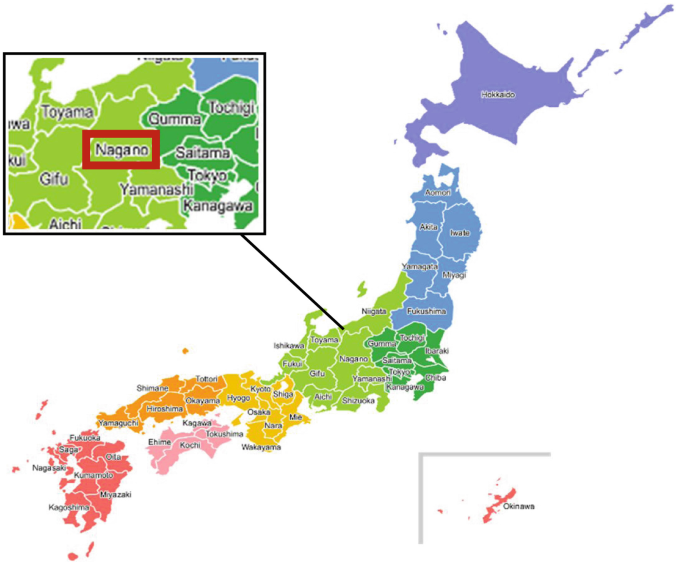


Fig. 1. Bestone-producing area.

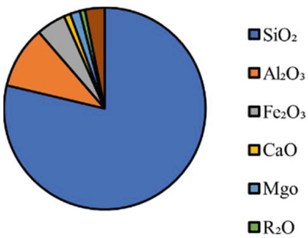


Fig. 2. Components of Bestone

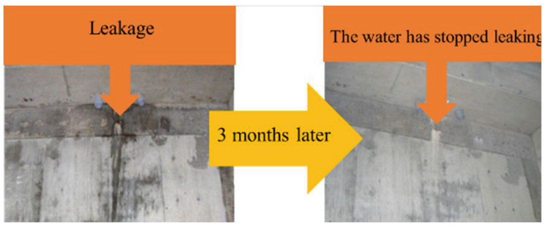


Fig. 3. Concrete mixed with Bestone improves water stopping performance and can be stopped in a few months.

2 Evaluation of Basic Properties and Water Shutoff Performance

In this study, researchers examine water shutoff performance of Bestone with various cement powders is investigated.

2.1 Materials and Mixing Conditions

The materials used in this work are listed in Table 1. In recent years, watertight structures of larger size are being constructed, so the use of moderate heat cement, low heat cement, blast furnace cement, etc. has been increasing to prevent thermal cracking. These cements are used in the experiments carried out here so as to compare any differences in results.

Table 1. Materials.

Material	Symbol	Density (g/cm^3)
Ordinary Portland cement	OPC	3.16
Blast furnace cement type B	BB	3.04
Moderate heat Portland cement	MC	3.21
Low-heat Portland cement	LC	3.22
Tap water	W	1.00
River sand	S	2.63
Silica-based natural mineral fine powder (Bestone)	BE	2.64
AE water reducing agent	AE	1.03
Defoamer	DF	1.00

Table 2 shows the composition of mixes studied. The water-cement ratio was fixed at 50% for all experience and the amount of Bestone was set at 6% by mass of the standard amount of cement powder used. The volume corresponding to the calculated unit volume was replaced with a portion of fine aggregate.

Table 2. Mix proportions.

Mix	W/C (%)	Unit quantity(kg/m^3)								
		W	OPC	BB	MC	LC	BE	S	AE	DF
OPC (BE0%)	50	285	570	–	–	–	0	1355	1.1	3.4
OPC (BE6%)							34	1320	1.2	3.6
BB (BE0%)	50	284	–	567	–	–	0	1342	1.1	3.4
BB (BE6%)							34	1307	1.2	3.6
MC (BE0%)	50	285	–	–	571	–	0	1361	1.1	3.4
MC (BE6%)							34	1326	1.2	3.6
LC (BE0%)	50	285	–	–	–	571	0	1362	1.1	3.4
LC (BE6%)							34	1327	1.2	3.6

2.2 Method of Mixing

Mixing was carried out using a pan-type mixer in batches of 13L. First, the powder and Bestone were added and mixed for 30 s, followed by the water and AE water reducing agent which were mixed for 1 min 30 s. Finally, after scraping off, AE water reducing agent was added in the same way and mixed for 1 min before discharge.

2.3 Tests and Methods

Flow Value Test and Target Values. Flow testing was conducted in accordance with ASTM C1437. The target flow value was 150 ± 30 mm.

Air Content Test. The air content was measured in accordance with BS EN 1015–7. The target value of air volume was set at no more than 1.5% in order to minimize variation in the area of the fracture according to the amount of air appearing on the fracture surface of the specimen in the water leakage test.

Compressive Strength Test. Compressive strength testing was conducted in accordance with BS EN 1015–11 after curing in water for 7 and 28 days. The target value of compressive strength was 45 N/mm^2 at 28 days.

Water Leakage Test. Specimens for the water leakage testing measured 150mm x 150 mm x 400 mm. Two steel reinforcing bars of diameter 5 mm were cast in the axial center to prevent the destruction. Further, four bolts for attaching the water flow device were set into one side of the form before casting. These details are shown in Fig. 4 and Fig. 5. After filling the form with mixed mortar, the cast specimen was removed after 24 h. Following warm-water curing in 60 °C water for 7 days, curing continued in 20 °C water for further 28 days. In order to induce cracking, a slot was cut on the upper and lower faces of the specimen with a concrete cutter. Then a concrete bending test

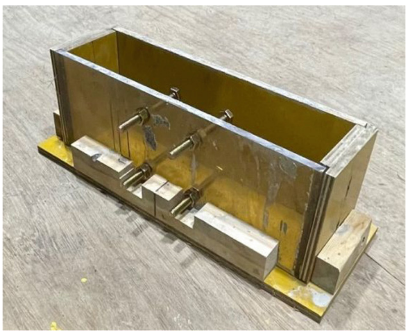


Fig. 4. The specimens of water leakage tests

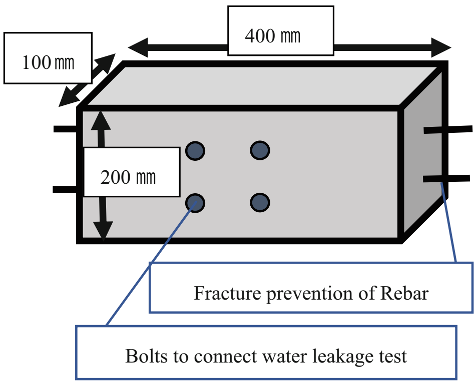


Fig. 5. The detail of the specimen

device was used to form crack of about 0.5 mm through the center of the specimen. The cracking procedure is shown in Fig. 6 and Fig. 7.

Figures 8 and 9 shows the equipment used for water leakage testing. Compressed air pressurizes the water in a tank, forcing it into the water pressurization equipment attached to the test piece. Leakage was measured at 30, 60, 90, and 120 min after the water flow was turned on, then at 3, 6, 12, and 24 h, and then every 24 h after the second day. In principle, the total measurement period was 7 days, but if the water flow rate through the Bestone-blended mortars did not fall below 5% of the peak leakage rate during the first 7 days, the measurement period was extended up to a maximum of 10 days.

All measured values were converted into water flow rates per minute, and were divided by the peak water flow rate to obtain the water flow rate ratio, as follows:

$$Flow\ rate(\%) = \frac{flow\ rate\ at\ time \times after\ start(g)}{peak\ flow\ rate(g)} \times 100 \tag{1}$$

Fig. 6. The state of forming cracks.

Fig. 7. The formed microcrack.

2.4 Results of Fresh Properties and Compressive Strength Testing

Table 3 shows the result of the fresh property tests. The target values were achieved by setting the addition ratio of AE water reducing agent to 0.2% and that of the defoaming agent to 0.6%.

The results of compressive strength tests are shown in Fig. 10. Bestone is a naturally occurring pozzolan-reactive material, so the strength of mixes including Bestone is higher as a result of their porous hydrated structure after aging. The compressive strength of the Bestone mix with blast furnace cement is lower than that of the one made with ordinary Portland cement, because the alkali required by the Bestone reaction is consumed by the latent hydraulic properties of the blast furnace cement fine powder.

Fig. 8. Water leakage test in progress

2.5 Result of Water Leakage Testing

The results of leakage tests in Figs. 11–14 show that the initial water flow rate and the water flow rate ratio decreased earlier in mixes including Bestone for each cement. Further, Bestone mixes with all cements except BB had water flow rates below 5% after 7 or 10 days. This indicates that adding Bestone can be expected to not only to impart water shutoff performance but also to have the effect of early cracks repair.

The OPC, MC and LC mixes contain a large amount of $Ca(OH)_2$ generated by the hydration reaction of cement. This enables the pozzolanic reaction through reaction with SiO_2 contained in the Bestone to form hydrates. This is thought to reduce the amount of water passing through the Bestone mixes compared with the non Bestone mixes.

On the other hand, in the case of BB mixes, blast furnace cement has the property of latent hydraulicity and hardening in the presence of $Ca(OH)_2$ and gypsum produced by the cement hydration reaction. The $Ca(OH)_2$ is consumed in the reaction, which proceeds faster than the pozzolan reaction, leaving insufficient $Ca(OH)_2$ to for the pozzolanic reaction of Bestone. This means the quantity of hydrates formed by reaction with SiO_2 in the Bestone is minimal, so the water flow through Bestone and non Bestone mixes is little different in the BB combinations (Fig. 12 and Fig. 13).

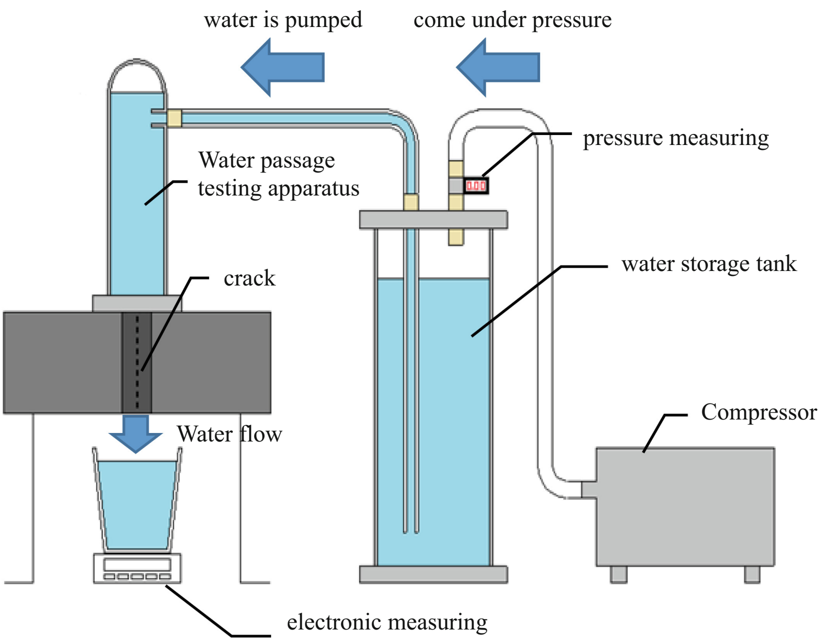


Fig. 9. Overview of water leakage test device

Table 3. Fresh properties of mixes.

Combination	Air volume (%)	15 stroke flow value (mm)	Temperature (°C)
OPC (BE0%)	0.3	165	28
OPC (BE6%)	1.1	170	28
BB (BE0%)	0.6	175	27
BB (BE6%)	1.1	160	27
MC (BE0%)	1.4	155	24
MC (BE6%)	1.2	155	24
LC (BE0%)	1.3	145	24
LC (BE6%)	1.3	145	24

2.6 Discussion

Following the water leakage test, each crack surface was examined by SEM observations and X-ray diffraction. Here, OPC (BE 6%), which showed the greatest decrease in water flow rate, is compared with BB (BE 6%), which showed minimal water shutoff performance. Each surface in contact with water was observed at 1, 3, 7, and 28 day, but results on 1 day and 28 days were excerpted.

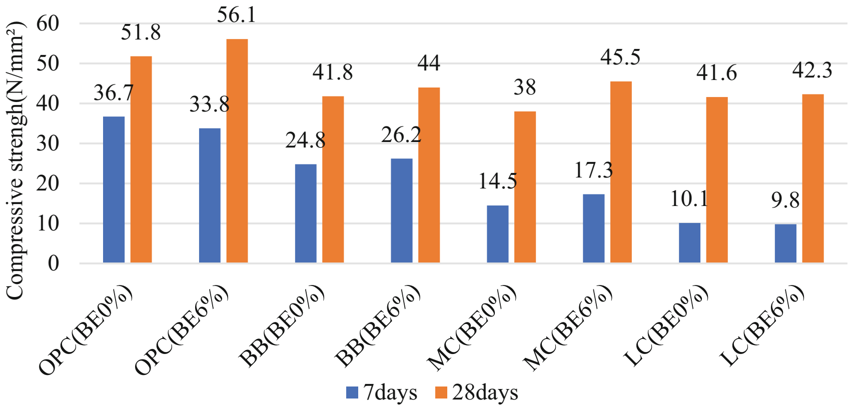


Fig. 10. Compressive strength after 7days and 28 days curing in water.

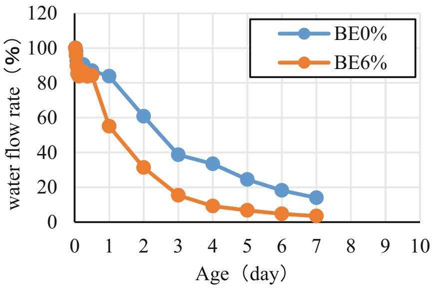


Fig. 11. Influence of water flow rate on using ordinary cement with Bestone.

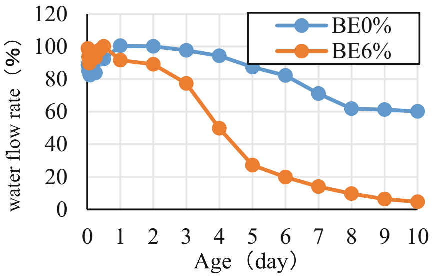


Fig. 12. Influence of water flow rate on using low-heat cement with Bestone.

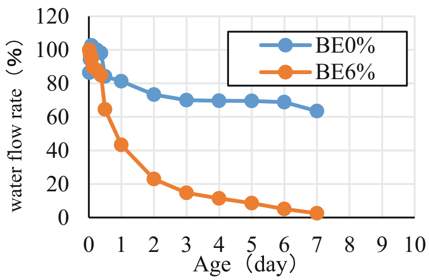


Fig. 13. Influence of water flow rate on using medium heat cement with Bestone.

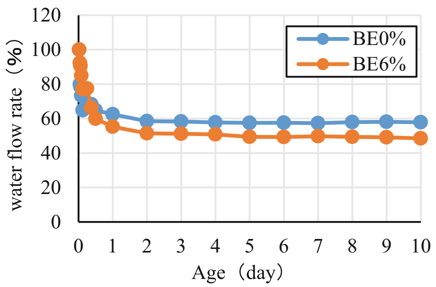
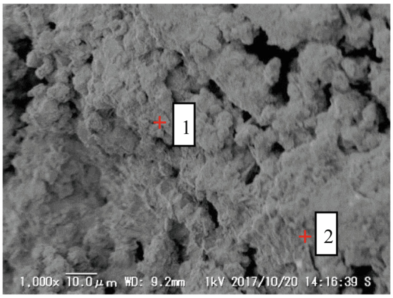


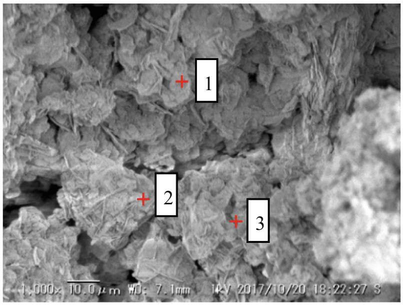
Fig. 14. Influence of water flow rate on using blast furnace cement with Bestone.

The SEM results are shown in the Fig. 15 and 16. Small needle-like crystals and thin plate-like crystals can be observed crack surface before starting water leakage test in the OPC with Bestone combination only. The needle-like crystals are considered to be the cement pore phase or ettringite, while the plate-like crystals are thought to be calcium hydroxide. The number of small needle-like crystals decreased from between 3 days and 7 days of age in the Bestone mix, and needle-like crystals joined together became visible on the 28 days. This is because the insoluble calcium silicate gel formed when Bestone combined with calcium hydroxide in the cement was combined with water, etc., and fine hydrates filled in the gaps. In the BB combination, only the admixed Bestone showed small needle-like crystals on the first day of age. In addition, plate-like crystals were observed in the admixed Bestone and non-admixed Bestone at 1, 3, 7 and 28 days of age.

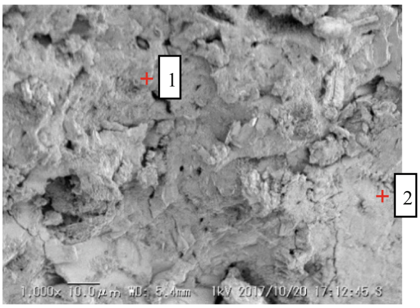
In BB mixes with Bestone, the linear or thin plate-like structure is less prominent and the gap is densified by the latent hydraulic properties of blast furnace slag and the pozzolanic reaction of Bestone. The combinations of the 28 days SEM of OPC and BB admixed Bestone shows that OPC is denser. This is because the latent hydraulicity of



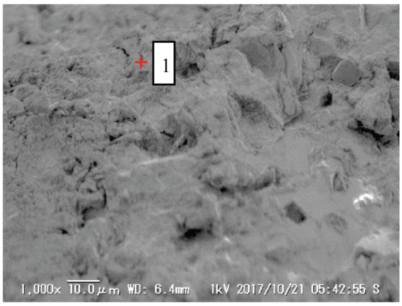
(a) OPC(BE0%)・1day
Needle-like crystals representing the cement pore phase or ettringite (+1,+2)



(b) OPC(BE6%)・1day
Thin plate-like crystals of calcium hydroxide (+1,+2,+3)



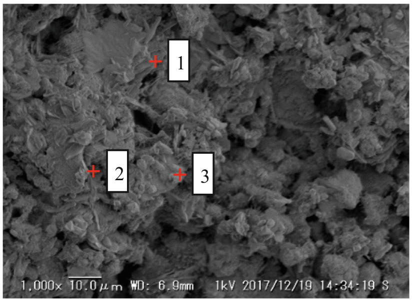
(c) OPC(BE0%)・28days
Fewer needle-like crystals and hydrates fill the gap. (+1,+2)



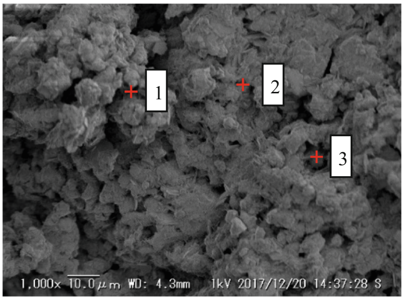
(d) OPC(BE6%)・28days
Fewer thin plate-like crystals and needle-like crystals and hydrate fills the gap. (+1)

Fig. 15. Crack surface in the water leakage test after 1day and 28 days using OPC.

the blast furnace slag fine powder consumes calcium hydroxide, which is necessary for Bestone's pozzolanic reaction. Therefore, Bestone's reactivity is lower in BB cement.



(a) BB(BE0%) · 1day
Thin plate-like crystals of unreacted calcium hydroxide (+1,+2,+3)



(b) BB(BE6%) · 1day
Thin plate-like crystals are almost impossible absent. There are some needle-like crystals. (+1,+2,+3)

(c) BB(BE0%) · 28days
Thin plate-like crystals and needle-like crystals are absent.

(d) BB(BE6%) · 28days
The hydration reaction has advanced and the gap is densely filled.

Fig. 16. Crack surface in the water leakage test after 1 day and 28 days using BB

The X-ray diffraction results are shown in Fig. 16 and 17. The mixes with Bestone show a notable peak of SiO2, while the non-Bestone mixes do not. This is attributable to the high content of active silica in the Bestone. Although not confirmed by X-ray diffraction, previous studies have confirmed the formation of calcium silicate, which is not found in the OPC-only mix. This is because calcium silicate gel is formed when the silica contained in Bestone combines with calcium hydroxide in the cement. The wide distribution of SiO_2 confirms that the pozzolanic reaction takes place with Bestone. In the mix of OPC with Bestone, the SiO_2 peak tends to decrease with age. This suggests that the pozzolanic reaction progress, but further investigation is needed to confirm this.

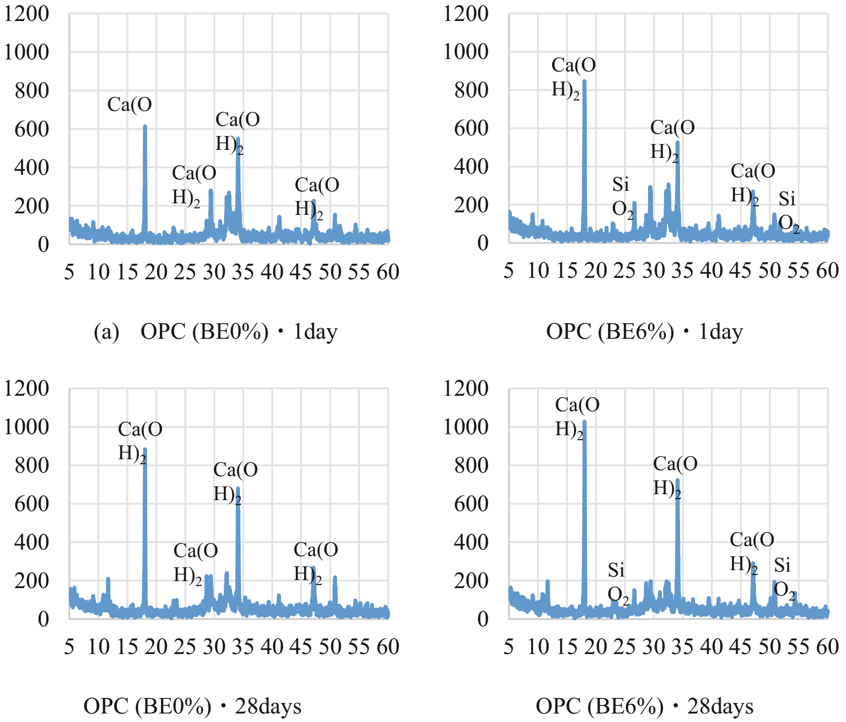
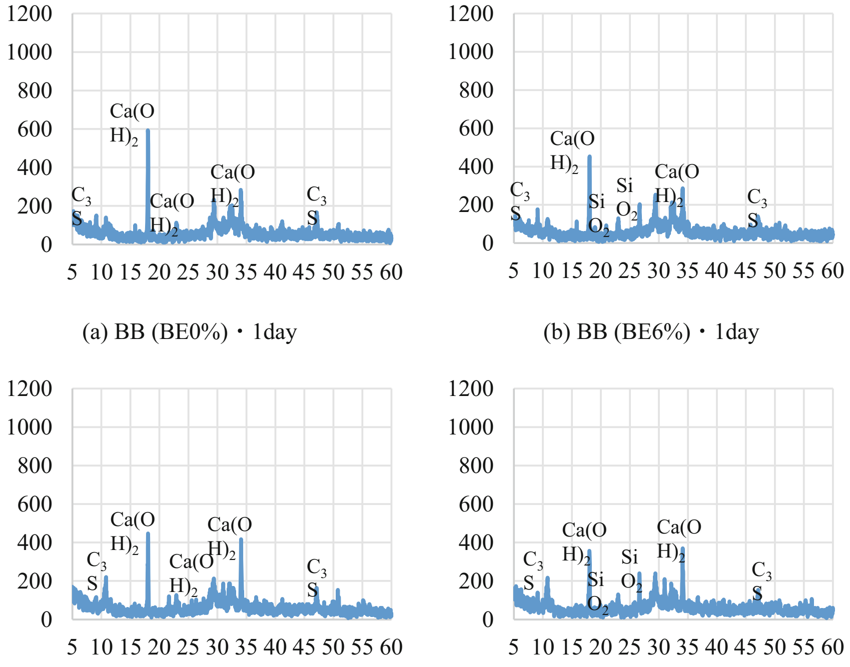


Fig. 17. Result of X-ray diffraction at the crack surface during the water leakage test after 1 day and 28 days using OPC.

3 Conclusions

The findings of this study are as follows:

1. The addition of Bestone does not affect compressive strength.
2. Mixes including Bestone are more effective in terms of water shutoff performance than those with no Bestone as demonstrated by the earlier decrease in water flow rate.
3. The addition of Bestone not only delivers water shutoff performance but also leads to early repair of cracks.
4. Since $Ca(OH)_2$ is consumed by the latent hydraulic property of the slag in BB mixes, Bestone delivers little the water shutoff performance in these cases (Fig. 18).



(a) BB (BE0%)・1day

(b) BB (BE6%)・1day

(c) BB (BE0%)・28days

(d) BB (BE6%)・28days

Fig. 18. Result of X-ray diffraction at crack surface during the water leakage test after 1 day and 28 days using BB.

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