International Journal of GEOMATE, July 2023, Vol. 25, Issue 107, pp.141-148
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2023.107.3840
Geotechnique, Construction Materials and Environment

STUDY ON EFFECT OF PREVENTING EARLY AGE FROST DAMAGE USING ADDITIVE FOR SETTING TIME ADJUSTMENT

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ABSTRACT: An advanced concrete finish (ACF) construction method has been developed to shorten the setting time of concrete in low-temperature environments using an additive for setting time adjustment. This paper aims to investigate the effectiveness of the prevention method for early age frost damage using ACF additive and to recommend an appropriate program to utilize it. This study measures various tests such as slump, air content, setting time, and compressive strength. The results show that the use of ACF additive unaffected the slump and air content of fresh concrete. The setting time of concrete was significantly shortened with an increase in the amount of ACF additive, and this effect can be observed even at low temperatures. Additionally, the ACF additive can improve the early age strength within 24 hours. However, there is no difference between ACF concrete and plain concrete in compressive strength at 7 and 28 days. Adding 4 and 6 kg/m^3 of ACF additive successfully prevented early age frost damage. Frozen concrete samples developed the same degree of compressive strength compared to non-frozen concrete samples after recovery curing. Therefore, 4 and 6 kg/m^3 of ACF additive can be used in cold weather concreting to prevent early age frost damage.

Keywords: Cold weather concreting, Early age frost damage, Additive for setting time, Compressive strength

1. INTRODUCTION

Cold weather concreting is a vital technology for construction in cold regions, as it allows for year-round work and significantly improves construction project progress and quality. It plays a crucial role in the economic development of these regions by promoting the efficient use of related facilities and providing permanent employment opportunities [1, 2]. However, early age frost damage is a frequently encountered problem in cold weather concreting. It usually happens when there are sudden drops in temperature, and insufficient curing or temperature control of the concrete makes the situation worse. Early age frost damage can weaken the concrete, cause structural damage, and lead to the formation of internal or external cracks [3-6]. To prevent early age frost damage in cold weather concreting, a widely adopted method is to use air-entrained (AE) concrete and conduct early age curing primarily through heating and insulation until the concrete reaches a compressive strength of at least 5.0 MPa [7-10].

Recently, with the development of studies on early age frost damage, it has been clarified that the duration of curing before exposing concrete to freezing temperatures has a significant effect on the properties of fresh concrete. It is known that the timing of freezing could significantly impact the performance of concrete [11]. Concrete that has undergone hydration and completed its final setting stage can better withstand the impacts of freezing. However, if freezing occurs before the concrete reaches its final setting time, it can result in more serious damage. In addition, according to Yamashita [12], the strength development of concrete with an AE agent at early ages is not affected by freezing after the final setting time. Therefore, it is believed that if the concrete can complete its final setting during the initial hardening stage, it can resist freezing at an early age. Shortening the setting time of concrete during cold weather concreting is possible to help prevent early age frost damage.

However, it is widely recognized that low-temperature environments can lead to delays in the setting time and strength development of concrete [13]. An additive has been developed to reduce the setting time, improve work efficiency, and enhance concrete quality to address this issue. This additive is recommended for finishing work during the cold season, and Advanced Concrete Finish (ACF) Construction method was named using this additive. Previous studies [14, 15] have investigated the effects of mixing a predetermined amount of ACF additive into concrete to shorten the setting time and reduce bleeding. The results showed that compared to concrete without the ACF additive, the fresh properties were maintained, bleeding was reduced, and the setting time was accelerated in temperatures below 10℃. Tests conducted at construction sites also revealed that adding 2.5 to 4 kg/m^3 of the ACF additive reduced working time by approximately 3 to 5 hours. Therefore, it is determined that the ACF additive is highly effective in reducing the setting time of concrete in low-temperature environments, providing a possible method to protect concrete from early age freezing. However, there is still a lack of investigation into the effectiveness of preventing early age frost damage using the ACF additive.

Therefore, the objective of this study is to investigate the effectiveness of ACF additive in preventing early age frost damage and propose a suitable program for its use. In addition, in this study, the effect of varying amounts of ACF additive on the setting time and strength development of concrete at room temperature and low temperature was also examined.

2. RESEARCH SIGNIFICANCE

To prevent early age frost damage of concrete during cold weather concreting, it is standard practice to ensure that the strength development of early age concrete reaches 5.0 MPa before exposing it to freeze-thaw cycles. This research aims to develop a new prevention method using the ACF additive for early age frost damage. The findings from this research show that shortening the setting time of concrete can protect it from early age frost damage, which has practical value for actual construction in cold weather.

3. EXPERIMENTAL PROGRAM

3.1 Materials and Mix Proportion

Table 1 shows the material properties. In this study, concrete samples were manufactured using tap water, ordinary Portland cement (OPC), fine and coarse aggregates, as well as an ACF additive (sulphonate type). To regulate the workability and air content of the concrete mixture, both an AE water-reducing agent and an AE agent were added. Table 2 provides the concrete mix proportions used in this study, with a water-to-cement (w/c) ratio of 0.5 and a sand-to-aggregate (s/a) ratio of 47.1%. The ACF additive was added in varying amounts of 0, 2, 4, and 6 kg/m^3.

3.2 Experimental Design

As shown in Table 3, the experimental design involved mixing four distinct concrete types, each with a unique amount of ACF additive. Concrete samples were poured into cylindrical plastic molds with dimensions of Ø100 × 200 mm and cured under sealed conditions. The fresh concrete was required to exhibit a slump of 18 ± 2.0 cm and an air content of 4.5 ± 1.5%. The experimental measurements encompassed the slump test, air content test, setting time test, and compressive strength test.

Fig. 1 shows the flowchart of the experiments. Concrete samples were placed in both a 20℃ temperature room and a 5℃ temperature room and cured in a sealed condition at early ages. A setting time test was conducted on non-frozen (N) concrete samples from each concrete designed in this experiment after placement. The compressive strength tests were conducted at 1, 3, 7, 28, and 31 days. For frozen concrete, the samples were pre-cured for 6, 12, and 24 hours. Frozen concrete samples were transferred to an adjustable temperature chamber and exposed to 3 freeze-thaw cycles in air, with each cycle consisting of 12 hours at -20 °C followed by 12 hours at +5 °C. Fresh concrete is highly susceptible to frost damage under these freeze-thaw conditions due to excess free water in the concrete. After undergoing freeze-thaw cycles in air for 3 cycles, the samples were returned in a room with a temperature of 20℃ and a relative humidity of 60% to carry out the recovery curing until 31 days.

Table 1 Material properties

Materials	Symbol	Properties
OPC	C	Density: 3.16 g/cm^3
ACF additive	ACF	Sulphonate type; Powder solid; Density: 2.55 g/cm^3; Al_2O_3: 28-30%, SO_3: 68-70%;
Fine aggregate	S	Density: 2.64 g/cm^3; Absorption: 1.75%
Coarse aggregate	G	Density: 2.66 g/cm^3; Absorption: 1.71%
Water	W	Tap water
Admixtures	Ads	①: AE water-reducing agent ②: AE agent

Table 2 Concrete mix proportions

w/c	s/a (%)	Unit Weight (kg/m^3)				Ads		ACF (kg/m^3)
		W	C	S	G	① (C × wt.%)	② (C × wt.%)	
0.5	47.1	175	350	832	941	0.55	0.004	0, 2, 4, 6

Note: W: water; C: cement; S: sand (fine aggregate); G: coarse aggregate

Table 3 Experimental design

Symbol	Cement	Additive	Addition amount (kg/m^3)	Slump (cm)	Air content (%)	Experimental items
P	OPC	ACF	0	18 ± 2.0	4.5 ± 1.5	Slump, Air content, Setting time, Compressive strength
A2			2			
A4			4			
A6			6			

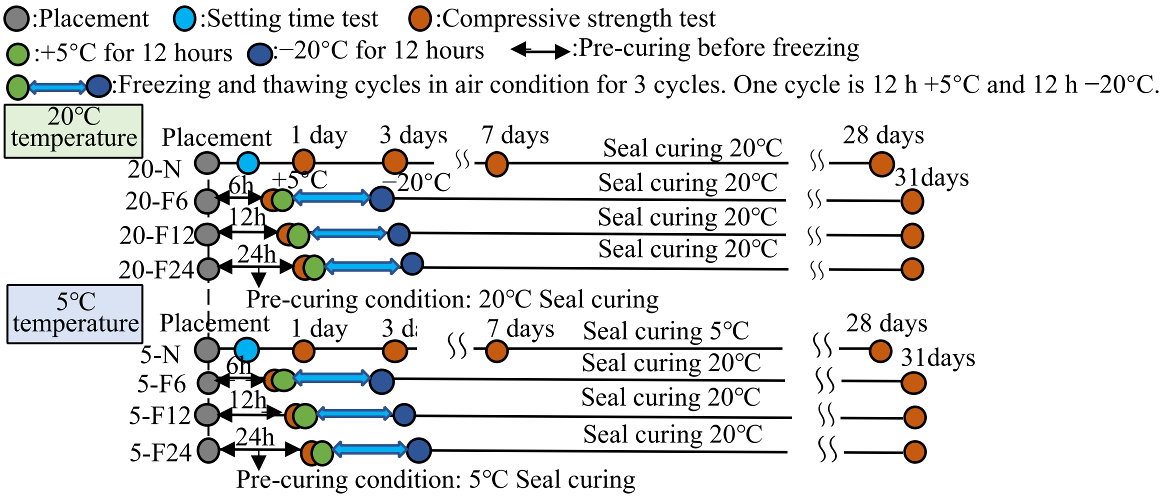

Fig.1 Flowchart of the experiment

3.3 Test Methods

3.3.1 Fresh Properties

The concrete slump was measured according to Japanese Industrial Standards (JIS) A 1101 [16], which is the JIS created based on International Organization for Standardization (ISO) 1920-2 [17]. The clean slump cone and flat plate were kept horizontal. Concrete was filled into the cone in 3 layers, evenly stabbed 25 times per layer, and pulled up to 300mm within 2-3 seconds. The descent height of the concrete center was recorded as the slump.

The air content of freshly mixed concrete was determined by means of a pressure method using an air content measuring instrument in accordance with JIS A 1128 [18], which is based on ISO 1920-2 [17].

The setting time of the concrete was determined according to JIS A 1147 [19], using the penetration resistance value of the mortar. Specifically, the initial and final setting times were defined as the time elapsed from the moment of water injection when the penetration resistance values reached 3.5 N/mm^2 and 28.0 N/mm^2, respectively.

3.3.2 Compressive Strength Test

The compressive strength of the concrete samples was determined in accordance with JIS A 1108 [20], which is based on ISO 1920-4 [21]. Cylinder specimens with a diameter of 100mm and height of 200mm were used for the tests, and they were cured at a temperature of 20℃ and a relative humidity of 60%. The measurements were taken at 1, 3, 7, 28, and 31 days after seal curing.

4. RESULTS AND DISCUSSION

4.1 Fresh Concrete

Fig. 2 shows the slump test results of the fresh concrete samples. It is apparent from the figure that the slump values for all types of concrete samples fell within the target range of 18 ± 2.0 cm. This finding suggests that the ACF additive did not cause a significant impact on the slump of the concrete immediately after placement.

The data illustrated in Fig. 3 reveal that the air content of all concrete sample types met the target range of 4.5 ± 1.5%. It indicated that the use of the ACF additive did not exert any discernible influence on the air content of the fresh concrete. Accordingly, the air content of the fresh concrete can remain stable and consistent even using the ACF additive.

Fig. 4 presents the setting time durations of all concrete types investigated in this study. Notably, the setting time duration differences between all types of ACF concrete and the P sample were smaller in 20℃ temperature conditions than in 5℃ temperature conditions. This finding suggests that the ACF additive is more efficient in reducing the setting time of concrete in low-temperature conditions, particularly in the case of the A6 concrete sample, which exhibited a notably shorter setting time than other concrete samples. These results highlight the potential benefits of incorporating ACF as an additive for concrete production, particularly in situations where low-temperature conditions may impact the setting time of concrete.

The relationship between the addition amounts of ACF additive and final setting times is shown in Fig. 5. The data indicate that as the addition amounts of ACF additive increase, the final setting time of concrete exhibits a decreasing trend under both 20°C temperature and 5°C temperature conditions. Furthermore, the R2 values for 20°C temperature and 5°C temperature conditions were greater than 0.8, indicating a high correlation between the addition amounts of ACF additive and the setting time of concrete. These findings demonstrate the potential of the ACF additive in effectively reducing the setting time of concrete, particularly under low-temperature conditions. Additionally, the strong correlation between the addition amounts of ACF additive and setting time indicates the potential for precise control of the setting time of concrete through the use of ACF additive.

Based on the results presented in Fig. 4 and Fig. 5, it has been confirmed that using ACF additive in concrete has a significant practical effect on reducing its setting time. Furthermore, it indicates that the ACF additive significantly accelerates the setting time of concrete, even in low-temperature environments.

4.2 Compressive Strength

4.2.1 Compressive Strength of Concrete at Early Ages

The compressive strength results of all concrete samples at early ages in both 20°C and 5°C temperature conditions are shown in Fig. 6. It has been observed that there is little strength development in all concrete samples within the first 6 hours. As shown in Fig. 4, the samples were still in the process of setting, making it difficult to determine the strength development of the concrete at 6 hours. The compressive strength increases as the amount of ACF additive increases within 24 hours, both in 20℃ and 5℃ temperature conditions. It is evident that using ACF additive can enhance the compressive strength of concrete compared to that of concrete without ACF additive within 24 hours. Therefore, there is a difference in strength development during early ages up to 24 hours. As for the compressive strength results of 7 days, at 20 ℃ temperature, the compressive strength results of ACF concrete samples were slightly higher than those of the P sample. In contrast, at 5℃ temperature, there were no noticeable differences in compressive strength between the ACF concrete samples and the P sample on 7 days. Fig. 4 indicates that ACF concrete samples had shorter setting time durations than the P sample at 20℃ temperature, allowing them to progress into the hardening stage rapidly. This faster hardening is thought to account for the higher compressive strength values observed in the ACF concrete samples at early ages. In the case of the 5℃ temperature condition, it was suggested that the low-temperature

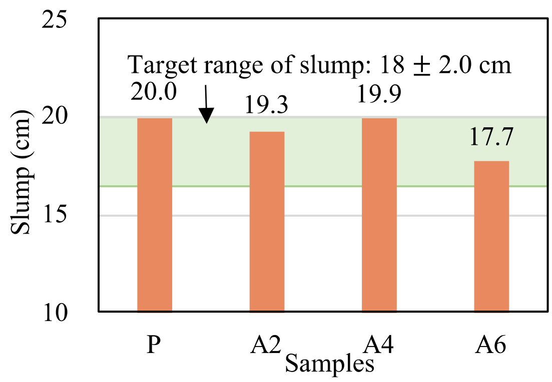

Fig.2 Slump results of fresh concrete

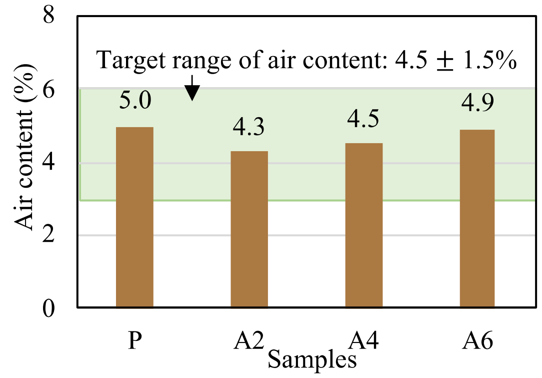

Fig.3 Air content results of fresh concrete

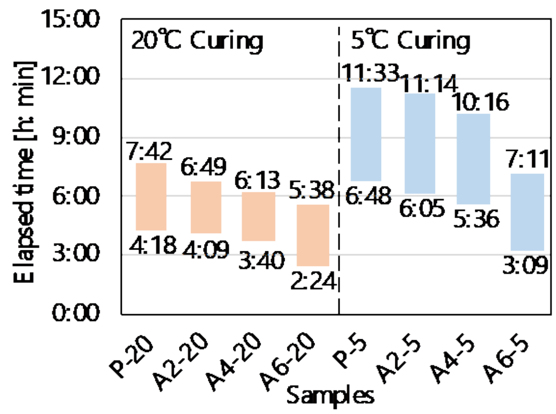

Fig.4 Setting time durations of all concrete types

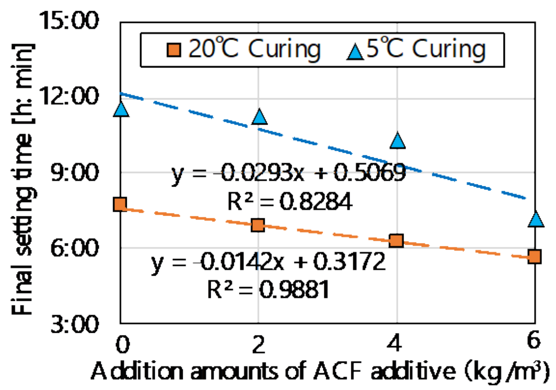

Fig.5 Relationship between addition amounts of ACF additive and final setting times

environment predominantly affects the strength development. As a result, the compressive strength results of the ACF concrete samples and the P sample were not significantly different at 7 days under 5℃ temperature.

3.2.2 Compressive Strength of Concrete at 28 Days

Fig. 7 presents the compressive strength results of all concrete sample types after 28 days of curing at both 20°C and 5°C temperatures. It was found that all concrete samples had similar compressive strength values at both temperatures, but the values were slightly higher at 20°C. It is apparent that curing temperatures affected the compressive strength of concrete, with lower temperatures resulting in lower hydration degrees. The results also demonstrated that ACF additive did not affect compressive strength after 28 days and primarily shortened the setting time of concrete. However, ACF does not significantly increase compressive strength over long curing times. Overall, the compressive strength of ACF concrete after 28 days depends on the concrete mix proportion, materials, and curing temperature.

Fig. 8 displays the relationship between compressive strength development and maturity for concrete samples tested under 20°C and 5°C temperature conditions. The logistic curve is a well-known model used to estimate concrete strength development accurately. The compressive strength values observed in this study coincide precisely with the trend of the logistic curve, suggesting its suitability for modeling the strength development process. Furthermore, the results indicate that adding ACF additive in any amount does not affect the compressive strength development of concrete. It suggests that the strength development of concrete is not related to the use of ACF additive.

3.2.3 Prevention Effectiveness of Early Age Frost Damage Using ACF Additive

Fig. 9 shows the compressive strength results for each concrete sample type after recovery curing. It is well-known that if the compressive strength ratio of frozen concrete samples, based on non-frozen concrete, is less than 90%, it can be determined that the concrete has been subjected to early age frost damage. The red dashed line in Fig. 9 means the compressive strength ratio of 90% based on each N sample. It is evident that for P and A2 concrete samples, the compressive strength ratio of F6 samples was lower than 90% of the N sample, which means F6 samples were subjected to early age frost damage. Conversely, the compressive strength values of the F12 and F24 samples after recovery curing were similar to that of the N sample, indicating the absence of early age frost damage.

According to Fig. 4, the final setting time of P and A2 samples at 20℃ and 5℃ temperatures is more than 6 hours. Therefore, F6 samples were susceptible

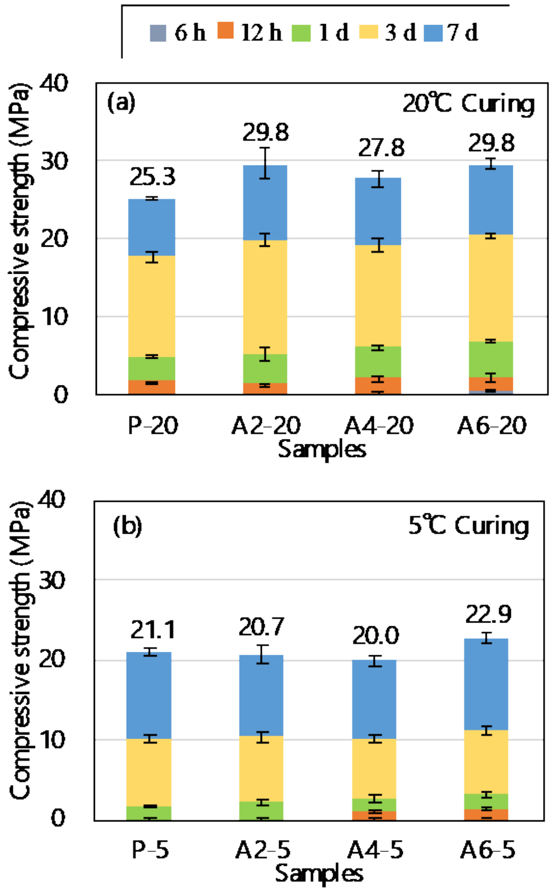

Fig.6 Compressive strength results of all types of concrete samples at early ages

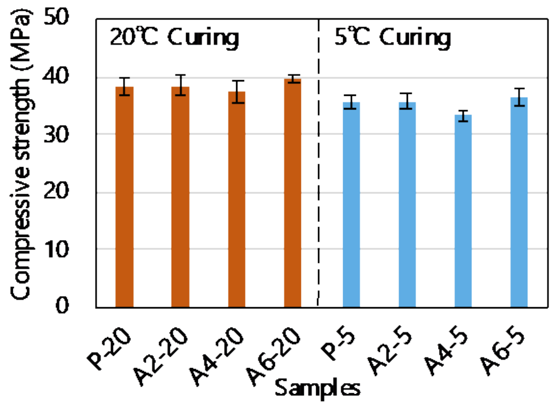

Fig.7 Compressive strength of all types of concrete samples at 28 days

to early age frost damage. However, the freezing time for F12 and F24 samples was after the final setting time. Even though the compressive strength values of F12 and F24 samples were lower than the minimum required compressive strength of 5.0 MPa when early age freezing occurred, the compressive strength ratios of F12 and F24 samples were almost 100% after recovery curing. It indicates that early age freezing did not affect the strength of F12 and F24 samples. It also supports the finding reported by Yamashita [12] that the strength development of concrete at early ages is not influenced by freezing after the final setting.

However, for A4 and A6 concrete samples, the compressive strength values of all frozen concrete samples were similar to that of the N sample after recovery curing. It indicates that all frozen concrete samples were not subjected to early age frost damage since their compressive strength ratios were above 90%.

At 20℃ temperature, the final setting time of the A4 and A6 concrete samples was less than or equal to 6 hours, indicating that the concrete had reached a sufficient level of strength and stiffness. When cured at this temperature, these samples did not suffer from early age frost damage. However, at 5℃ temperature, the A4 concrete samples had an initial setting time of 5 hours and 36 minutes. It means that the cement in the concrete had not fully hydrated, and there was still much free water. When these samples were exposed to freezing at 6 hours (A4-5-F6 sample), the free water in the concrete froze and the hydration reaction of the cement was stopped. It can cause damage to the concrete and weaken its strength. However, when the frozen concrete was subsequently cured under standard conditions, the hydration process resumed and helped to repair the damage caused by early freezing partially.

On the other hand, the A6 samples had a final setting time of 7 hours and 11 minutes at 5℃, indicating that the cement had almost completed its hydration reaction and formed a dense matrix of hydration products. It helped to provide a strong skeleton structure for the concrete, which was able to resist some of the pressure caused by the formation of ice lenses during freezing. When these samples were exposed to freezing at 6 hours (A6-5-F6 sample), the concrete was able to withstand some of the pressure from the ice lenses due to its strong skeleton structure. Finally, it was observed that when the frozen concrete was cured under standard conditions for 31 days, the compressive strength ratio of the samples was above 90% based on the N sample. It suggests that recovery curing can help partially repair the damage caused by early freezing and restore the strength of the concrete.

Therefore, according to the results of compressive strength, it can be seen that early age freezing does not significantly affect the frozen concrete samples under the A4 and A6 concrete conditions.

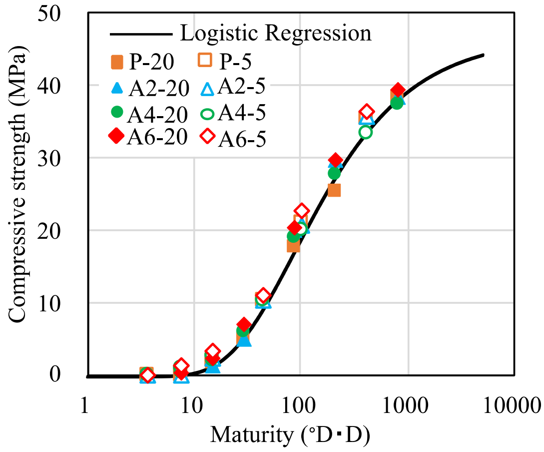

Fig.8 Relationship between the compressive strength development and maturity

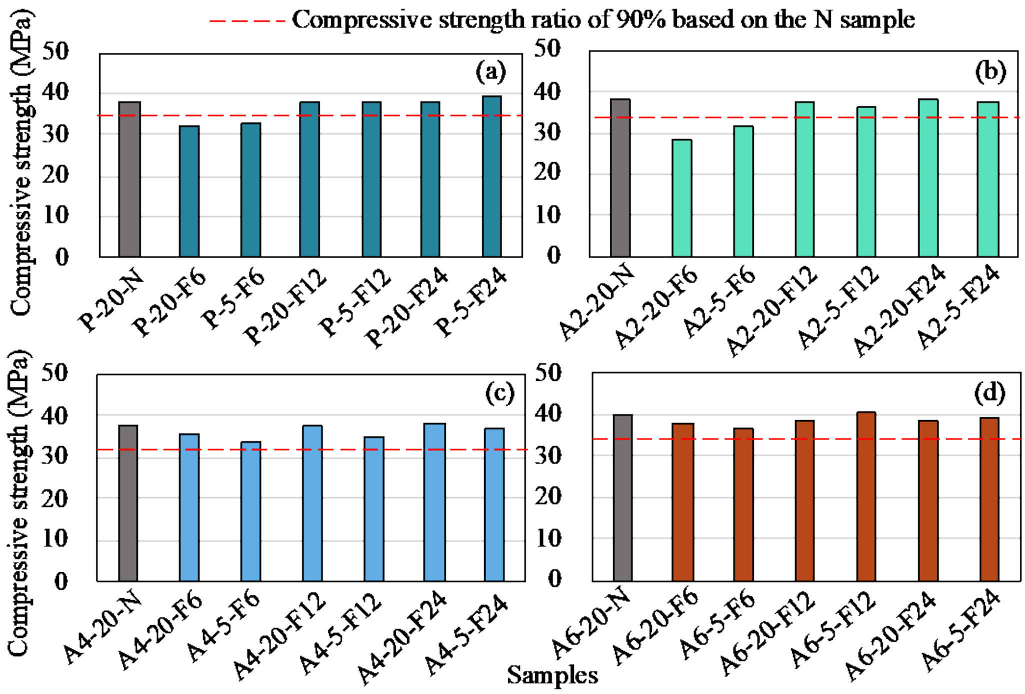

Fig.9 Compressive strength of each concrete sample type after recovery curing

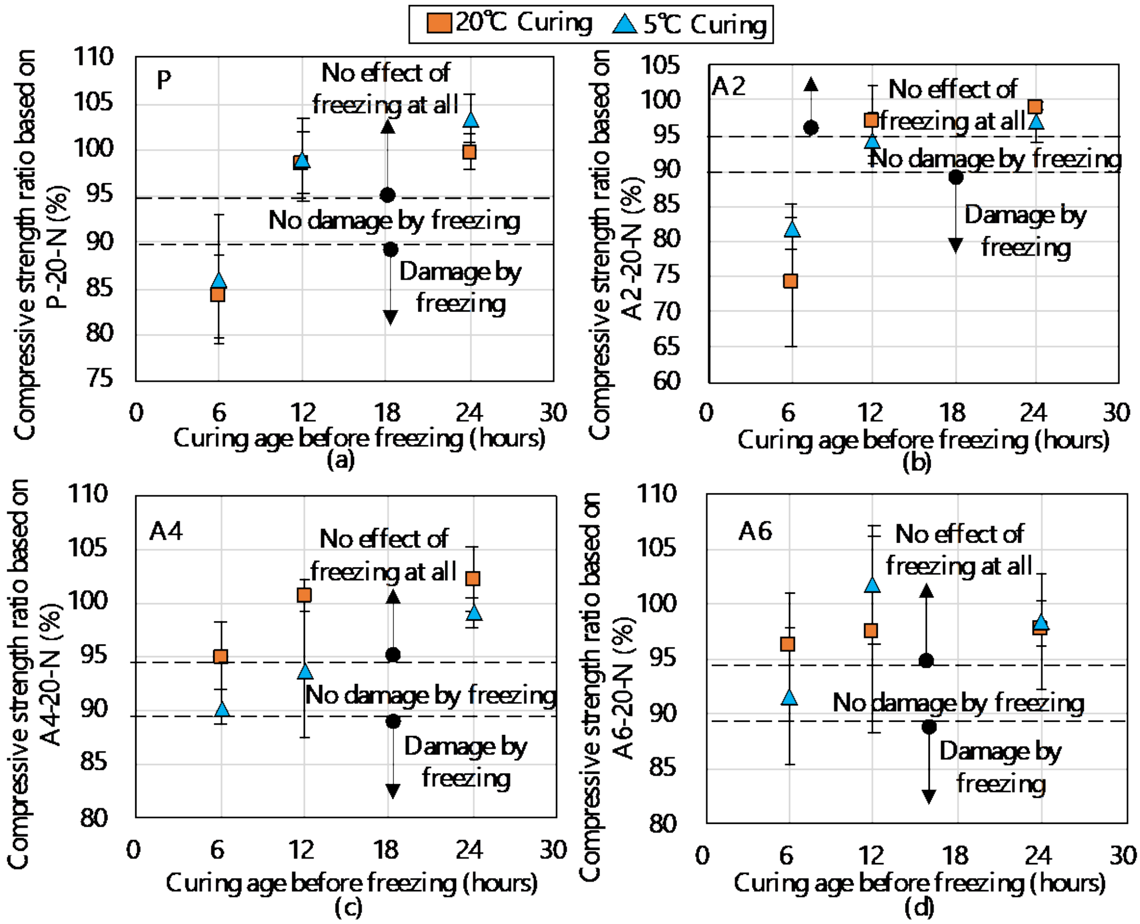

Fig. 10 Relationship between prevention effectiveness of early age frost damage and addition amounts of ACF additive under different temperatures

Fig. 10 illustrates the relationship between the prevention effectiveness of early age frost damage and addition amounts of ACF additive under different temperatures. Based on the compressive strength ratios of each N sample, the following evaluation method for prevention effectiveness can be proposed:
(1) Compressive strength ratio below 90%: Damage due to freezing
(2) Compressive strength ratio above 90%: No damage by freezing
(3) Compressive strength ratio above 95%: No effect of freezing at all

The results show that the addition of 2 kg/m^3 of ACF additive did not significantly improve the prevention effectiveness of early age frost damage. In both 20°C and 5°C temperature conditions, the F6 samples of P and A2 concrete suffered from early age frost damage. However, for A4 and A6 concrete samples in Fig. 10 (c) and (d), the compressive strength ratios of all samples were above 90%, indicating that the concrete was not subjected to early age frost damage. Especially, even the F6 samples did not suffer from early age frost damage. Compared to P concrete samples, adding 4 or 6 kg/m^3 of ACF additive improved the prevention effectiveness of early age frost damage. Additionally, A6 concrete was more effective than A4 concrete in preventing early age frost damage.

5. CONCLUSIONS

This study investigated the effect of using different amounts of ACF additive on the setting time and strength development of concrete, and a suitable use program of ACF additive for preventing early age frost damage was discussed. The following conclusions were drawn:

1) The use of ACF additive did not affect the slump and air content of fresh concrete.

2) The addition of ACF additive resulted in a shorter setting time for concrete, and this effect was more pronounced at low temperatures. The greater the amount of ACF additive added, the shorter the setting time.

3) The ACF additive can improve the early age strength within 24 hours. The early age strength at 7 days and compressive strength at 28 days of ACF concrete were the same as those of P concrete.

4) Adding 4 and 6 kg/m^3 of ACF additive effectively prevented early age frost damage. These

two addition amounts of ACF additive can be used for cold weather concreting due to their outstanding effectiveness in preventing early age frost damage.

To conclude, this study suggests that the addition of ACF additive is an effective method to prevent early age frost damage of concrete while maintaining its strength development. This study provides concrete producers and engineers with practical information to maximize the benefits of ACF additive in cold weather concreting.

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