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INFLUENCE OF INITIAL TEMPERATURE OF FRESH CONCRETE ON COMPRESSIVE STRENGTH OF CONCRETE

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ABSTRACT: This paper aims to evaluate the influence of initial temperature of fresh concrete on compressive strength and degree of reactions of binder in concrete with and without fly ash. The aggregates are cooled before being used to mix the concrete to achieve the temperatures of fresh concrete of 18°C, 25°C, and 30°C. After 24 hours in the mould, the concrete specimens are continually cured in water at 28 ± 2°C. Test results indicate that the compressive strength of the concrete at an early age decreases when the initial temperature of the fresh concrete decreases. However, the compressive strength of concrete at 91 days increases in the case of low initial temperature of fresh concrete. The effect of initial cooling is more obvious in concrete with higher fly ash content. The bound water, degree of reactions, and C-S-H content, the paste samples were analyzed by TGA. The lower initial temperature of fresh concrete leads to a lower rate of the degree of reaction and produces less amount of C-S-H at an early age. The degree of reaction of the binder at an early age affects early strength and long-term pozzolanic reaction that causes long-term strength. A lower initial temperature of fresh concrete reduces the early hydration of cement and delays the start of the pozzolanic reaction, resulting in an enhancement of the compressive strength at later ages. The degree of reaction and C-S-H content correlated well with the compressive strength of the concrete at early and long-term ages.

Keywords: Initial temperature, Compressive strength, Hydration degree, Thermogravimetric analysis

1. INTRODUCTION

Factors, such as ambient temperature, curing temperature, and especially the initial temperature of fresh concrete play important roles in affecting the properties of concrete. Casting and curing temperatures are the external factors considered as the environmental conditions. In tropical regions, high ambient temperature and large temperature differences between nighttime and daytime may cause thermal cracking, especially in mass concrete. The upper limit of 35°C is specified for concrete under hot weather conditions according to ACI Committee 305 for Hot Weather Concreting [1]. High ambient temperature, especially in tropical countries, leads to a faster setting and a higher water demand for concrete. The slump loss of fresh concrete occurs faster. The rate of evaporation of the water from the concrete surface in hot and dry conditions is significantly higher than that in cold and moist conditions [2]. Curing temperature histories affects the strength development of high strength concrete as well as normal concrete [3]. Therefore, the curing condition in the initial stage, especially fresh concrete temperature affects the rate of compressive strength development [4-5]. Several methods can be used to reduce the initial temperature of fresh concrete, such as: using chilled water, ice, chilled air, liquid nitrogen, and aggregate cooling. Although the methods to cool the ingredients are costly, they demonstrate high efficiencies to reduce the temperature of concrete. Decreasing the initial temperature of fresh concrete is an effective method to reduce the maximum temperature in the core and the temperature difference between the surface and interior of mass concrete so that the risk of thermal cracking can be minimized. However, there has been no study to identify the effects of fresh concrete temperature control on strength development in long term of mass concrete. Aggregate cooling is simple and effective to control mass concrete temperature and to retain the concrete strength in hot weather regions [6]. When the ambient temperature increases, the interfacial transition zone (ITZ) between aggregate and paste is not temperature-resistant and becomes a weak zone, therefore, the compressive strength of the concrete decreases [7].

Fly ash is a by-product of the coal combustion process. This material is abundantly available and cheap in many countries, especially in Southeast Asia. The use of fly ash not only reduces CO_2 emission but also effectively increases some properties of concrete. Fly ash is widely used as a supplementary cementitious material (SCM) in concrete due to its pozzolanic reaction. Higher workability of concrete mixture with a higher volume of fly ash was reported in many previous studies [8-12]. The compressive strength of fly ash concrete increases in the long term when compared to that of conventional concrete due to the pozzolanic reaction generating denser pore structure in concrete [13-15]. Higher curing temperature leads to faster onset and rate of main reactions. The pozzolanic reaction of fly ash is strongly temperature dependent. The onset of the pozzolanic reaction appears earlier at a higher curing temperature. It is approximately 12 hours at 50°C, 72 hours at 35°C, and 672 hours at 20°C curing [16]. At elevated temperature, consumptions of portlandite, releases of Al and Si into the pore solution, and so the formation of additional C–S–H by the pozzolanic reaction are accelerated [17].

The effects of casting and curing temperatures on the properties of concrete have been well studied, mostly in constant temperature regimes. However, the influences of the initial temperature of fresh concrete on the compressive strength and the hydration of fly ash concrete have not been adequately indicated. Hence, the objectives of this study are to investigate the effects of different initial temperatures of fresh concrete on the compressive strength development and the degree of reaction of binders. The method of cooling aggregates was used to obtain different initial temperatures of fresh concrete at 30°C, 25°C, and 18°C. The compressive strength of the concrete was tested on concrete specimens at different ages. The degree of reaction of binders was measured using paste mixtures. The fly ash replacement percentages in the total binder were 0%, 30%, and 50%. The degree of reaction of binders and C-S-H content of pastes were examined by thermogravimetric analysis.

2. RESEARCH SIGNIFICANCE

The effects of the initial temperature of fresh concrete on long-term compressive strength and the degree of reactions of binder in the concrete with and without fly ash are clarified. It is confirmed that lowering the temperature of fresh concrete benefits the long-term compressive strength of the concrete. The compressive strength improvement by lowering the fresh concrete temperature is an additional benefit for the mass concrete practice where the concrete temperature should be minimized to control maximum temperature and temperature gradient.

3. EXPERIMENTAL PROGRAMS

3.1 Materials and Mix Proportions

In this study, an ordinary Portland cement type I (OPC) and a low CaO fly ash (FA) are used as the binders. The chemical compositions of the binders, as shown in Table 1, were determined by X-ray fluorescence (XRF) spectroscopy. The loss on ignition (LOI) content of 9.7 % of the fly ash was quite high but it was still lower than the limitation of 12 % for class F fly ash, in the case that the freezing and thawing problem was not a concern, according to ASTM C618 [18].

Table 1 Chemical compositions of the binders

Component	Quantity (% by weight)	
	OPC	FA
SiO_2	15.28	50.26
Al_2O_3	3.25	22.51
Fe_2O_3	3.83	6.96
CaO	71.52	2.58
MgO	1.36	1.17
Na_2O	0.07	0.31
K_2O	0.72	3.98
SO_3	3.18	0.55
LOI	-	9.70

Crushed limestone and natural river sand, which satisfied the requirements of ASTM C33 [19], were used as coarse and fine aggregates, respectively, for the concrete mixtures. The values of specific gravity of the crushed limestone and sand were 2.92 and 2.85, respectively. To study the influence of the initial temperature of fresh concrete on the degree of reaction of the binders and the compressive strength of the concrete, the aggregates for mixing the concrete were cooled before the mixing. By using aggregates at three different temperatures, the initial temperatures of fresh concrete were controlled at 30°C, 25°C, and 18°C. The temperature conditions of the used raw materials achieved in the study are described in Table 2.

Table 2 Temperature conditions of used materials

Initial temperature (°C)	Condition of Materials
30°C	Aggregates and water were kept at ambient temperature.
25°C	Crush limestone was kept cold by ice water submergence while sand and water were kept at the ambient temperature.
18°C	Aggregates were kept cold by ice water submergence while water was kept at the ambient temperature.

The percentages of fly ash replacement are 0% and 50% by weight of the total binder. A controlled water to binder ratio of 0.5 is used. The mix proportions of the tested concretes and pastes are presented in Table 3.

Table 3 Mix proportions of the tested pastes and concretes

Mixtures	FA/b	w/b	s/a
Concrete			
100OPC	0		
70OPC	30	0.50	0.40
50OPC	50		
Pastes			
100OPC	0	0.50	-
50OPC	50		

Remarks: FA/b is fly ash to binder ratio by weight, w/b is water to binder ratio by weight, s/a is sand to total aggregate ratio by volume.

3.2 Test Methods

The influence of the initial temperature of fresh concrete on the compressive strength of concrete with and without fly ash was studied. The degree of reaction of binders was evaluated using thermogravimetric analysis (TGA) of paste samples.

Cubic concrete specimens with dimensions of 100 x 100 x 100 mm were used to test compressive strength. After mixing, the initial temperature of the fresh concrete was measured immediately. The concrete specimens were demoulded 24 hours after mixing, and then kept in water at 28 ± 2°C. The compressive strength of the concrete was determined at 1 day, 3 days, 7 days, 28 days, and 91 days of age after casting.

To study the effects of the initial temperature of fresh concrete on the bound water, degree of reactions, and C-S-H content, the paste samples were analyzed by TGA. As the concrete specimens were cured in the moulds for 1 day and continually cured in water at 28 ± 2°C, the paste samples used in TGA were selected at 1 day and 91 days of age to represent early and long-term ages, respectively. After mixing, the paste samples were kept in sealed foam boxes at 18°C, 25°C, and 30°C for 1 day to simulate the curing condition of the concrete specimens during the first day of age. Then, the paste samples were continually cured in water at 28 ± 2°C until 91 days. The selected paste samples at 1 day and 91 days of age were submerged in an acetone solution for 24 hours to stop the hydration before the TGA. Then, the paste samples were continually dried in the oven at 105°C for 24 hours to remove free water from the samples. The dried samples were ground into very fine powders that passed through sieved No. 100 (150 µm) before conducting thermogravimetric analysis. The test temperature of the furnace was increased with a heating rate of 20°C/min up to 1000°C. The test was conducted under N_2 atmosphere.

During the thermogravimetric analysis process, the decomposition reaction can be generally divided into three major stages which are dehydration, dihydroxylation, and decarbonation [20]. The temperature boundaries for phase decomposition in Table 4 are considered.

Table 4 Temperature range for phase decomposition of paste samples considered in TGA

Decomposition Phase Temperature	Boundaries (°C) [20]
Dehydration (Ldh)	105–400
Dehydroxylation (Ldx)	400–600
Decarbonation (Ldc)	600–1000

In this study, the degree of reaction (α) of a sample is obtained by dividing the amount of non-evaporable or chemically bound water (w_b) by the amount of non-evaporable water in the same sample when it is fully hydrated (w_b^o), as seen in Eqs. (1). The amount of chemically bound water (w_b) can be determined from Eq. (2) as indicated by Bhatty [20].

$$\alpha = \frac{w_b}{w_b^o} \times 100 \tag{1}$$

$$w_b = Ldh + Ldx + 0.41(Ldc) \tag{2}$$

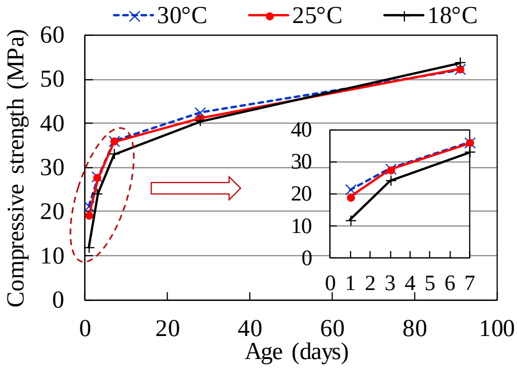
where Ldh, Ldx, and Ldc are the mass losses caused by the dehydration, dehydroxylation, and decarbonation, respectively.

The quotient w^o_b/c varies in the range of (0.18-0.26) in the case of cement paste. The value of 0.24 is typically used in many studies [20-22]. The quotient w^o_b/c depends on the type and percentage replacement of fly ash. In this study, the value of w^o_b/c is assumed of 0.19 in the case of blended paste including cement and fly ash [23]. C-S-H content is simply determined by mass loss of paste between 140°C and 400°C [24-25].

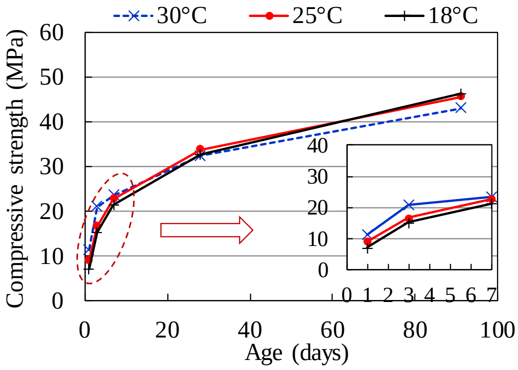
4. RESULTS AND DISCUSSIONS

4.1 Effects of Initial Temperature of Fresh Concrete on Compressive Strength Development

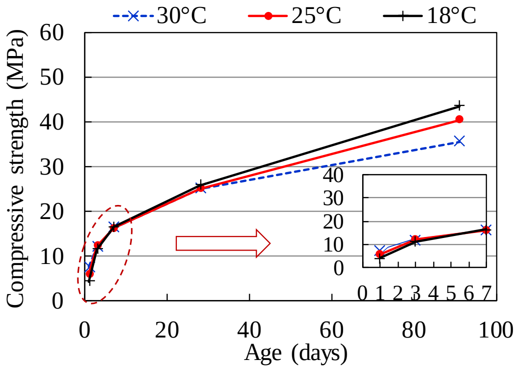
Fig.1 shows the compressive strength development of concrete mixtures at different initial temperatures of fresh concrete. At 1 day of age, the compressive strength of the concrete decreases at a lower initial temperature of fresh concrete, especially in the case of cement-only concrete (see Fig. 1(a)). In the case of 30% fly ash replacement mixtures (70OPC) mixtures), the compressive strength of concrete is lower than that of cement-only. And lower temperature of fresh concrete leads to a lower compressive strength of concrete (see Fig. 1(b).) The decrease of compressive strength due to lower initial temperature is less obvious in concrete mixtures containing fly ash. At 50% fly ash replacement, the compressive strength of concrete at 1 day of age is almost unchanged when the initial temperature of the fresh concrete decreases as seen in Fig. 1(c).



(a) 100OPC



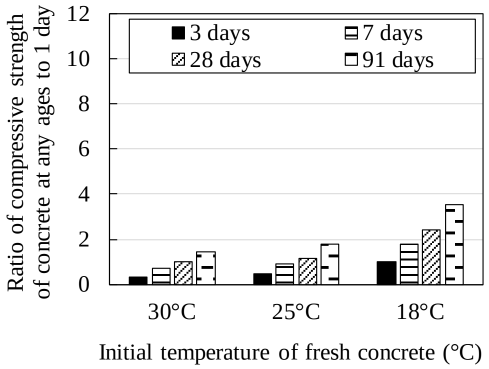
(b) 70OPC



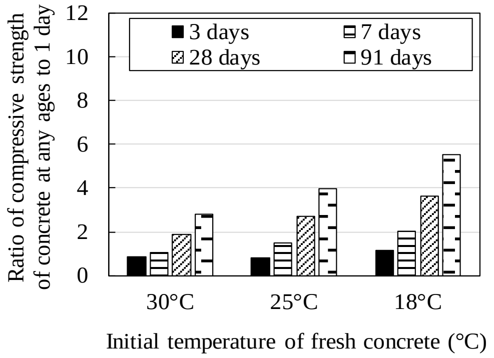
(c) 50OPC

Fig.1 Compressive strength development of concrete mixtures at different fresh concrete temperatures

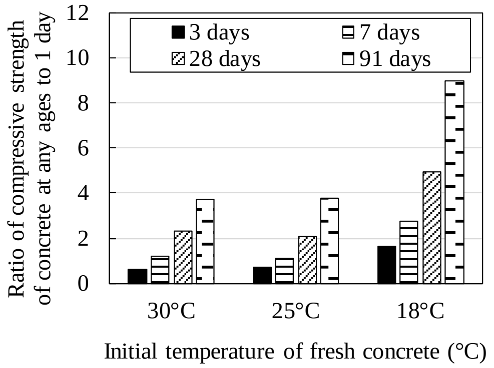
However, the strength development behavior at later ages is the opposite. The compressive strength of fly ash concrete at 91 days is enhanced by reducing the initial temperature of the fresh concrete, especially for the 50OPC concrete mixture. Ratios of compressive strength of concrete at each age to that at 1 day of age are calculated and plotted in Fig. 2.



(a) 100OPC



(b) 70OPC



(c) 50OPC

Fig.2 Ratio of compressive strength of concrete at any age to the 1-day compressive strength

Fig. 2(a) shows the strength development of 100OPC mixtures. The enhanced strength at 91 days of age is higher than that of other ages, especially at the initial temperature of fresh concrete of 18°C. In the case of fly ash concrete in Fig. 2(b) and Fig. 2(c), the ratio of compressive strength of fly ash concrete at 91 days to 1 day is clearly higher than that of cement-only concrete. This ratio is presented obviously in the case of 50% fly ash replacement and the initial temperature of fresh concrete at 18°C. Therefore, the strength development in the long term of fly ash concrete is more dominant than that of the cement-only concrete.

To demonstrate the influence of the initial temperature of fresh concrete on the compressive strength of the concrete at a later age (91 days), the efficiency of the cooling is defined using Eq. (3).

$$E_c = \frac{f_i^c - f_{30°C}^c}{f_{30°C}^c} \times 100(\%) \tag{3}$$

where E_c is the cooling efficiency, f_i^c is the compressive strength of concrete at 91 days with the initial temperature of fresh concrete of 25°C or 18°C, and $f^c_{30°C}$ is the compressive strength of concrete at 91 days with the initial temperature of fresh concrete of 30°C.

The results of the cooling efficiency of concrete mixtures at 91 days are shown in Fig. 3.

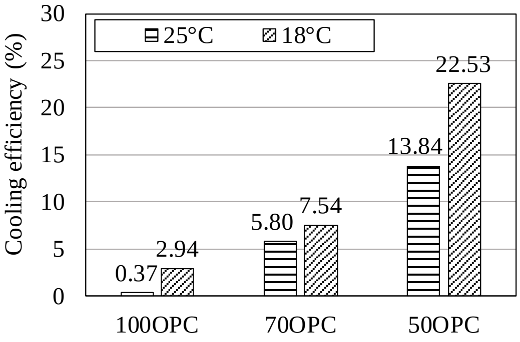


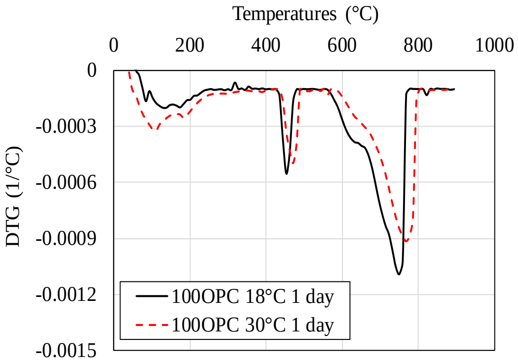
Fig.3 Cooling efficiency for compressive strength of concrete mixtures at 91 days

It is obviously seen that cooling aggregates to reduce the initial temperature of fresh concrete shows a higher effectiveness in the concrete containing a higher fly ash replacement. It is worth mentioning that cooling efficiencies for compressive strength of 50OPC mixture are impressively high at 13.82% and 22.53% with the fresh concrete temperature of 25°C and 18°C, respectively while they are lower than 3% in the cement-only concrete and lower than 7.6% in the mixture with 30% fly ash replacement. For all the tested concrete mixtures, the cooling efficiency of concrete with the initial temperature of 18°C is higher when compared to 25°C. This can be explained by the delayed pozzolanic reaction of fly ash at an early age when the initial temperature is low. At 1 day, when the concrete specimens are still in the mould, the cement hydration and the pozzolanic reaction are affected by the concrete temperature. It has been reported that at 50°C, the pozzolanic reaction of fly ash starts after 1 day of hydration, and when the temperature of concrete decreases from 40°C to 20°C, the start of pozzolanic reaction shifts from 7 days to 28 days [26]. To describe the effect of the initial temperature of fresh concrete on the degree of reaction, thermogravimetric analysis is applied to determine the degree of reactions and hydration products. More details are presented in the next section.

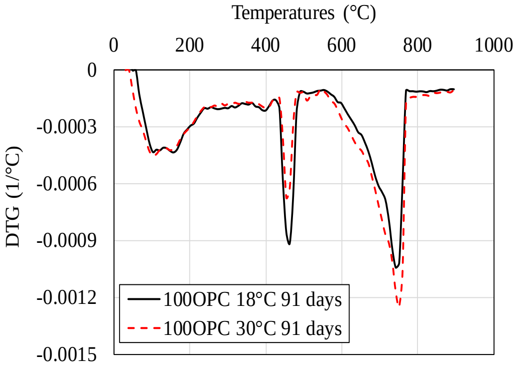
4.2 Effects of Initial Temperature of Fresh Concrete on the Degree of Reaction

Based on the compressive strength results, the cooling efficiency for compressive strength of concrete with lower initial fresh concrete temperature is obvious in the case of 50OPC mixture. Therefore, 100OPC and 50OPC paste mixtures with the initial temperature of 28°C and 30°C were selected for the TGA. The TGA was applied on pastes at 1 day and 91 days of age.

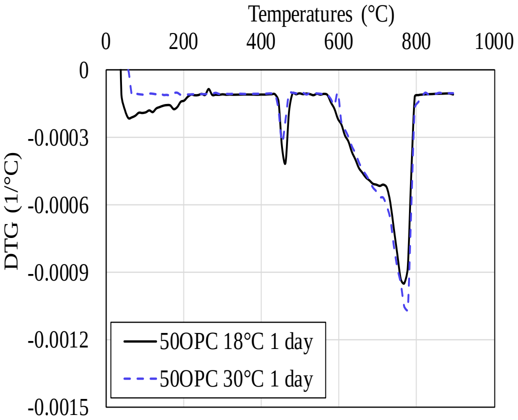
The Derivative Thermogravimetry (DTG) curves with different initial temperatures of paste samples are presented in Fig. 4.



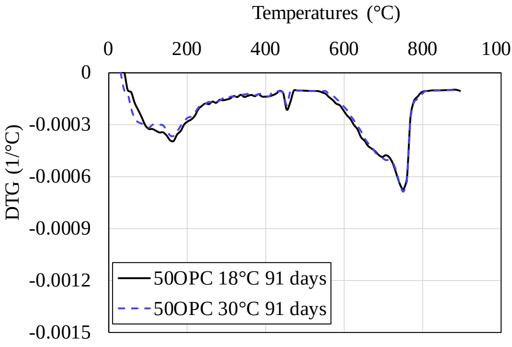
(a) 100OPC at 1 day



(b) 100OPC at 91 days



(c) 50OPC at 1 day



(d) 50OPC at 91 days

Fig.4 DTG curves of pastes with different temperatures of paste samples

A simple view of the DTG curves in Fig. 4 indicates different decompositions. The dehydration, the dehydroxylation, and the decarbonation are shown at the first, the second, and the third peaks, respectively. The calculated values of chemically bound water (W_b), C-S-H content, and degree of reaction (α) are presented in Table 5.

Table 5 Values of chemically bound water (W_b), C-S-H content, and degree of reaction (α) of the mixtures

Mixtures	Age (day)	T (°C)	W_b (mg)	C-S-H (%)	α (%)
100OPC	1 day	30	5.27	2.98	63.40
		18	2.37	2.09	56.86
	91 days	30	2.48	4.44	90.53
		18	2.84	4.41	90.73
50OPC	1 day	30	2.82	1.85	59.29
		18	1.78	1.13	48.51
	91 days	30	2.27	3.24	78.90
		18	2.49	3.95	82.39

The degree of reaction and C-S-H content are plotted against the initial temperature of fresh concrete in Fig. 5a and Fig. 5b, respectively. In the case of cement-only paste, the influence of the initial temperature of the fresh paste is only present at an early age (1day). For both 100OPC and 50OPC mixtures, the higher initial temperature of the fresh concrete leads to a higher degree of reactions and more major product (C-S-H) of the hydration at the age of 1 day, causing higher compressive strength at the age of 1 day. However, the initial temperature shows no effect on the enhancements of the degree of reaction and C-S-H content at 91 days of age. The mixture with combined cement and fly ash shows a different tendency from the cement-only mixture in long term. The results of the 50OPC mixture indicate that the degree of reaction of binder and C-S-H content of the mixture with 18°C of the initial temperature of fresh concrete are higher than those of the mixture with 30°C of the initial temperature of fresh concrete. This confirms that the rate of pozzolanic reaction of fly ash is strongly temperature dependent. It was also found in another literature that elevating the curing temperature from 20°C to 50°C shortens the dormant period and brings about faster onset of the main reaction from 28 days to 12 hours [16].

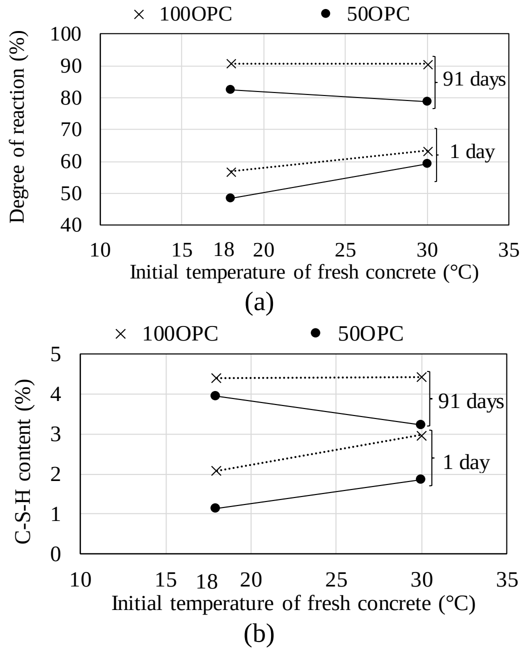


Fig.5 Relationships between initial temperature of the tested pastes and (a) degree of reaction, (b) C-S-H content, at 1 and 91 days of age

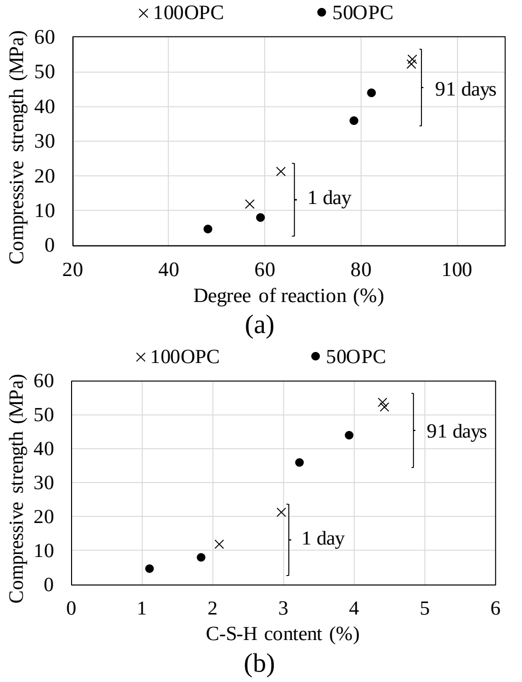


Fig.6 Relationship between (a) compressive strength and degree of reaction and (b) compressive strength and C-S-H content, at 1 and 91 days of age

The strength of concrete is due primarily to calcium silicate hydrate (C-S-H) which is the main product of the hydration of calcium silicates (C3S and C2S). The compressive strength results at both 1 day and 91 days of age show good correlations with the degree of reaction as well as the C-S-H content as seen in Fig. 6a and Fig. 6b, respectively. This proves that lowering the fresh concrete temperature increases the degree of reaction and C-S-H content in the long term, causing the compressive strength improvement in the long term.

The results obtained in this study confirm that lowering the temperature of fresh concrete benefits not only the temperature control in mass concrete but also the long-term strength of the concrete.

5. CONCLUSIONS

The influence of the initial temperature of fresh concrete achieved by the aggregate cooling process on the compressive strength of concrete was examined in this study. The following conclusions can be drawn from the results of the study:

1. Higher initial temperature of fresh concrete leads to a higher compressive strength at early ages, especially in the case of cement-only concrete.
2. The effect of the initial temperature of fresh concrete is more significant on compressive strength in the long term of the concrete mixture containing higher fly ash replacement.
3. Cooling efficiency is more obvious in the concrete mixtures containing higher fly ash replacement.
4. For all tested paste mixtures, the degree of reaction and the C-S-H content of the pastes at 1 day are enhanced when the initial temperature of fresh concrete increases. However, at 91 days, the cement-only mixture shows no increases in the degree of reaction and C-S-H content when cured at a higher initial temperature. On the other hand, the mixture containing fly ash with 18°C of initial temperature shows a higher degree of reaction and C-S-H content compared to that with 30°C of initial temperature of fresh concrete.
5. Compressive strength of concrete at early and long-term ages correlated well with the degree of reaction and C-S-H content.

6. FURTHER RESEARCH

Further research can be considered on the extension of the study to cover the use of fly ash and other SCMs to improve the quality of concrete and control thermal cracking in mass concrete structures.

7. ACKNOWLEDGEMENT

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8. ABBREVIATIONS

CO_2: Carbon Dioxide
DTG: Derivative Thermogravimetry
FA: Fly Ash
ITZ: Interfacial Transition Zone
LOI: Loss on Ignition
OPC: Ordinary Portland Cement
SCM: Supplementary Cementitious Materials
TGA: Thermogravimetric Analysis
XRF: X-ray Fluorescence

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