Construction and Building Materials 64 (2014) 208–214

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental study on the development of compressive strength of early concrete age using calcium-based hardening accelerator and high early strength cement

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HIGHLIGHTS

- This paper focused on developing compressive strength without steam curing of precast concrete.
- Calcium-based hardening accelerator for C_3S was used for early-stage strength.
- Compressive strength of concrete was more than 10 MPa after 9 h of curing at 20 °C experimentally.
- Hardening accelerator 1–3% of cement mass is proper for setting time and compressive strength.

ARTICLE INFO

Article history:
Received 26 January 2014
Received in revised form 1 April 2014
Accepted 2 April 2014
Available online 4 May 2014

Keywords:
Hardening accelerator
High-early-strength cement
Tricalcium silicate
Precast concrete
Compressive strength
Microanalysis

ABSTRACT

Steam curing is necessary to be used in the manufacturing of precast concrete, thus, a large amount of energy is consumed and the turnover of forms is low. This practice leads to reduction in productivity. This paper focuses paper focuses on developing early stage strength for precast concrete of more than 10 MPa after 6 h of curing at room temperature without steam curing. Various micro-analysis tools such as TG/DTA, Conduction Calorie Meter, XRD, SEM and MIP were conducted on concrete and cement paste with the amount used of calcium-based hardening accelerator (CHA) for tricalcium silicate (C_3S). Results show that the reaction effect of the CHA was terminated before reaching 12 h, the initial setting of concrete was in 80 min with 3% of CHA. The rate of heat evolution is increased in the mechanism of developing the compressive strength in early age and the yield of Ettringite, $Ca(OH)_2$ and C–S–H is increased at early age due to the fact that the CHA stimulates tricalcium aluminate (C_3A) and C_3S in high early strength cement when using calcium-based hardening accelerator into high early strength cement. Additionally, the pore volume of range of 20–100 nm decreased with the CHA content.

1. Introduction

Precast concrete being extended its application to construction and civil structures has advantages of improving the quality of concrete, shortening of construction work, reducing the use of temporary materials and reducing waste. Until now, however, studies on precast concrete have been mainly conducted in structural and constructional aspects such as to improve the structural performance in junction, to introduce prestress, to adopt half precast concrete, to improve the efficiency of lifting, and studies in material aspects of concrete is very lacking relatively [1–5].

Meanwhile, steam curing is widely used in construction site and this method in particular is mainly used to speed up the curing process to achieve early strength of concrete in the production of precast concrete and is done for 12 h per day, thus the problem that a large amount of energy is consumed is raised. This practice leads to reduce productivity in terms of low turnover of forms and one day cycle [6–8]. Additionally, the production of precast concrete member needs expensive steel forms to use in an efficient and fast procedure so as to reduce the initial cost of production generally. Because of this, it is necessary to develop a technology to increase the number of use of the forms if steam curing is

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http://dx.doi.org/10.1016/j.conbuildmat.2014.04.053
0950-0618/© 2014 Published by Elsevier Ltd.

performed [9–11]. It is urgently required to improve the use of steam curing method. Existing studies using high early strength cement and early-strength type agents are conducted to reduce production energy and to increase the number of use of the molds [12–15]. Besides, a curing method using CO_2 instead of steam curing is developing to solve this problem, however, it does not reach commercialization stage yet due to the fact that it is still being in the initial stage [16,17].

However, the previous studies are limited in the sense that they were mainly focused on mechanical material properties like compressive strength of concrete but the microanalysis for the mechanism of compressive strength was not well covered [18,19]. This study focused on the development of compressive strength of concrete without steam curing. Various experiments were conducted to produce more than 10 MPa as early-stage strength at age of 6 h curing at room temperature without steam curing using hardening accelerator and high early strength cement. Therefore, concrete tests using the combination of tricalcium silicate (C_3S) rich high early strength cement and calcium-based hardening accelerator at room temperature without steam curing were conducted. Also, microanalysis of the cement paste using developed materials to determine the mechanism of compressive strength development at early age was conducted.

2. Overview

Two types of concrete and cement paste tests were conducted in this study. For concrete tests, condensation and expression appearance of concrete depending on the amount used of hardening accelerator were evaluated. For cement paste tests, the mechanism of compressive strength development at early age by hardening accelerator through microanalysis for hydration of cement paste depending on the amount used of hardening accelerator was determined.

2.1. Materials

Three types of C_3S rich high early strength cements were used in this study, and their compositions are shown in Table 1. Table 2 shows the characteristic of polycarboxilic ether (PC)-based superplasticizer used in this study. Table 3 shows the characteristic of conventional accelerator and calcium-based hardening accelerator used in this experiment [20]. Using accelerator make the degree of Ca^{2+} saturation surrounding cement particle to be oversaturated and accelerates the generation of $Ca(OH)_2$. Oversaturated Ca^{2+} ion has a characteristic of inducing generation and growth of C–S–H rapidly as bonding with gel generating around C_3S particles. Most conventional accelerators are amine-type. It accelerates cement hydration by accelerating Ettringite to monosulfate reaction in cement hydration product. But, contents of Ettringite and monosulfate are under 10% in cement hydration product. So, it has limitation in strength development [20]. Therefore, calcium-based hardening accelerator is used in this experiment. For experiments, natural aggregates were used and Table 4 shows the characteristic of used aggregates.

2.2. Specimens and measured items

Table 5 shows mix design of concrete and Table 6 shows mix design of cement paste. In concrete test, water cement ratio (W/C) was 32% and the amount used of hardening accelerator was added to 4 levels of cement weight ratio of 0%, 1%, 3% and 5%. Air dry curing was performed as a curing method under the condition of temperature 20 °C and humidity 60% and the testing age was set to 6, 9, 12, 18 and 24 h. In cement paste test, the amount used of hardening accelerator was added to 3 levels of cement weight ratio of 0%, 1% and 3%. And water cement ratio was 20%, curing method was same with concrete test and the age was set to 2, 4, 6, 12 h. Table 7 shows measurement items in concrete test and cement paste test.

For cement paste, setting time, $Ca(OH)_2$ generation, compressive strength, hydration and porosity were measured. To conduct these items, various microanalysis (TG/DTA, Conduction Calorie Meter, XRD, SEM, MIP) were carried out.

Table 1
Chemical compound composition of cement.

Type	Compound composition (%)			
	C_3S	C_2S	C_3A	C_4AF
Ordinary Portland cement	51	26	12	11
High-early-strength cement	58	21	11	10

Table 2
Characteristic of superplasticizer.

Main component	Type	Density (g/cm^3)	Usage (cement × %, mass ratio)
PC (polycarboxilic ether)	Liquid	1.05	1–4

Table 3
Characteristic of hardening accelerator.

Main component	Type	Density (g/cm^3)	Usage (cement × %, mass ratio)
Calcium formate	Powder	2.15	1–5
Amine-type	Liquid additive	1.24	1–5

Table 4
Physical properties of aggregates.

Type	Density (t/m^3)	Absorption (%)	Fineness modulus	Ratio of absolute volume (%)
Fine aggregate	2.60	1.45	2.16	63.72
Coarse aggregate	2.68	1.03	7.05	58.13

3. Experimental results

3.1. Concrete tests

3.1.1. Slump flow of concrete

Slump flow of concrete is shown in Fig. 1. The slump flow of C-A3 (accelerator 3%) slightly increased while the slump of C-A5 (accelerator 5%) sharply decreased. This is caused by quick-setting of concrete with a large amount used of hardening accelerator.

3.1.2. Setting-time of concrete

Fig. 2 illustrated the initial setting time and final setting time of concrete depending on the amount used of hardening accelerator. As the amount used of hardening accelerator increased, initial and final setting time are rapidly shortened. It is considered that this is because the production of hydrates of tricalcium aluminate (C_3A) and C_3S were rapidly started by hardening accelerator. The initial setting time became faster as about 180 min at 1%, 80 min at 3% and 50 min at 5% with increase of accelerator contents.

3.1.3. Compressive strength expression of concrete

Fig. 3 shows the relationship between compressive strength and time with different amount used of hardening accelerator. The more the amount used of hardening accelerator, the stronger the compressive strength. Compressive strength increases as the amount used of hardening accelerator increases up to 9 h. However, there is no change in compressive strength though the amount used of hardening accelerator increases after 12 h and compressive strength of specimen without hardening accelerator is almost similar to that of specimen using hardening accelerator after 18 h. Thus, it is considered that the reaction effect of hardening accelerator is almost taken before 12 h and hardening accelerator is very effective on improving compressive strength in early age before 12 h.

3.2. Cement paste test

3.2.1. Setting-time of cement paste

The setting-time of cement paste is shown in Fig. 4. As the amount used of hardening accelerator increases, both the initial and the final setting time shortened. In the case of P-A3, by using 3% hardening accelerator compared with P-A0 without hardening accelerator, initial and final setting times are 50 min and 125 min, respectively. Thus, it is considered that hardening accelerator shorten setting time by reacting with high early strength cement rapidly.

3.2.2. Compressive strength expression of cement paste

The relationship between compressive strength and time of cement paste with the amount used of hardening accelerator is shown in Fig. 5. The higher the amount used of hardening accelerator, the higher the compressive strength. In particular, compressive strength increases sharply after 6 h of curing. Meanwhile, compressive strength of P-A3 is over 10 MPa at 6 h when 3% hardening accelerator is used.