Construction and Building Materials 137 (2017) 208–215

Contents lists available at ScienceDirect

Construction and Building Materials

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

Use of ternary blended concrete to mitigate thermal cracking in massive concrete structures—A field feasibility and monitoring case study

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HIGHLIGHTS

- We evaluated the field feasibility of a newly developed ternary concrete mix.
- The ternary mix diminished variations in temperature and strain in the test member.
- The ternary mix reduced the extent of thermal cracking and tightened crack widths.
- The ternary mix can be used to control thermal cracks in mass concrete structures.

ARTICLE INFO

Article history:
Received 9 November 2016
Received in revised form 11 January 2017
Accepted 26 January 2017

Keywords:
Mock-up test
Strain
Temperature
Ternary blended concrete
Thermal cracking

ABSTRACT

This study aimed to evaluate the field feasibility of a newly developed ternary blended concrete mix and its effect on mitigating thermal cracking in massive concrete structures. Four mock-up test members were cast using different types of cementitious binders, and variations in temperature and strain with time were monitored for these members. Results showed that reduced heat of hydration in the ternary mix significantly diminished variations in temperature and strain in the test member. A crack survey revealed that the ternary mix reduced the extent of thermal cracking and tightened crack widths, indicating that it can be used to effectively control thermal cracks in massive concrete structures.

1. Introduction

Massive cast-in-place concrete structures are known to suffer from thermal cracks, which generally develop early on in the life of the structure [1]. These thermal cracks occur over time when the thermal stresses that develop in the structure's materials exceed those materials' strength [1]. Different elements in a concrete member or structure have different heat dissipation rates that depend on the rate of heat exchange between the element's boundary and the environment. Typically, this produces both nonlinear temperature differentials within sections and temperature differences between members in a structure [1,2]. These nonlinear temperature differentials and temperature differences are responsible for thermal stress development in the internally and/or externally restrained concrete members in a structure [1–3]. These thermal cracks should be controlled because they reduce the durability and service life of concrete structures [4].

A number of approaches have been developed to prevent or control thermal cracks. These approaches have focused on materials, design, and construction [1,3,5]. One approach is to reduce the heat of hydration for the binders in the concrete; type IV low-heat Portland cement has been widely for this purpose. Compared to normal type I Portland cement, type IV cement has smaller amounts of C_3S and C_3A, which are primarily responsible for heat production in cement hydration. As a result, type IV cement has been effectively used to control thermal cracks in massive concrete structures [6]. The production of type IV cement, however, results in high CO_2 emissions. Recently, sustainability concerns in the cement and concrete industry have received more attention [7]; new eco-friendly cementitious materials are needed that can provide heat of hydration levels as low as that of type IV cement-based materials while minimizing CO_2 emissions.

A ternary blended concrete mix was successfully developed by Korea Conformity Laboratories [8] with the aim of providing a low-

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http://dx.doi.org/10.1016/j.conbuildmat.2017.01.108
0950-0618/

heat concrete with lower CO_2 emissions, as an alternative to type IV cement-based concrete. The binder in the new ternary blended concrete consisted of type IV cement, fly ash, and ground granulated blast furnace slag (GGBFS). Existing experimental studies [9–14] indicate that this ternary concrete mix, which possesses the required properties and performance needed for its use as a construction material, is expected to have the potential to reduce the risk of thermal cracking in massive concrete structures. Most existing studies [9–14], including the preliminary [8], however, has focused on investigating the material properties of ternary blended concrete; in these studies, the concrete's application was limited to a laboratory testing scale. The field feasibility and performance of ternary concrete has not been adequately addressed. To use the newly developed ternary blended concrete mix for actual field construction, its field performance must be verified.

The purpose of this study was to investigate the field applicability of a newly developed ternary blended concrete mix and its effect on controlling thermal cracks in massive concrete structures. Four massive mock-up plain concrete members were cast, each consisting of a cube-shaped block placed on top of a base slab. Each member was cast using different concrete mixtures. Different cementitious binders were used in the concrete mixtures, including type I normal cement, type IV low-heat cement, and a ternary blended binder. Histories of temperature and strain in each member over time were measured and compared. Crack indices for each member were determined based on the members' measured temperature histories. Additionally, a crack survey was performed, and the widths and lengths of cracks were compared.

2. Mock-up test

2.1. Materials

Table 1 summarizes the proportions of the mixture used in each test member. The normal-strength and high-strength members used type I Portland cement with water-to-binder ratios (w/b) of 0.40 and 0.28, respectively. The low-heat member used type IV cement with a w/b ratio of 0.34. The ternary member also used type IV cement, with mineral admixtures of fly ash and GGBFS, using the amounts shown in Table 1. The fly ash was produced by the Hadong thermal power plant in South Korea. Silicon oxide (SiO_2) and aluminum oxide (Al_2O_3) accounted for 78% of the fly ash. GGBFS was produced by the Dangjin thermal power plant in South Korea; its fineness was 4000 cm^2/g. The fine aggregate included a mix of crushed sand with sea sand and coarse aggregate included crushed stone with a maximum size of 25 mm. Table 2 shows the chemical compositions of the binders used in the test members.

2.2. Mock-up members

Four cube-shaped blocks were constructed over the slab using the mixtures shown in Table 1. Fig. 1(a) shows an overview of concrete casting in the field. The base slabs, which were 10 m long, 10 m wide, and 0.6 m thick, were placed first. After curing the slab concrete for 28 d, the concrete cubic blocks were cast. Each test member was cast at a different instance of time. The compressive strength of the slab was 25.6 MPa after 28 d. Vertical reinforcing bars 19 mm in diameter were placed from the bottom of slab to a block height of 2.5 m at a spacing interval of 300 mm, to allow the development of composite behavior between the slabs and blocks. The cube-shaped block was 4 m long, 4 m wide, and 4 m high, with the base of the block supported by the slab. Fig. 1(b) shows the normal-strength test member cast in the field.

2.3. Measurement

To evaluate temperature variations and distributions, which are closely associated with the risk of thermal cracking, a total of 25 temperature sensors (type T thermocouple) were installed in each test member: 13 along the vertical line passing through the centroid of the block, and 12 along the horizontal line, as shown in Fig. 2(a). The sensors near block surfaces were installed close together, while sensors in the center of the block were installed further apart.

Fig. 2(b) shows the embedded strain gages (Model KM-100B, Tokyo Sokki Kenkyujo) and non-stress cylinders installed in the horizontal direction near the centroids of the members. Thermal stress-related strains and thermal stresses developed when any volume changes in the members due to temperature variation were constrained internally or externally. The strain gages embedded directly in the concrete measured the total strain (which consists of stress-dependent and stress-independent strains) [15], whereas the strain gages installed in the concrete inside nonstress cylinders measure only stress-independent strain components [16]. The stress-independent strain measured by the gages in the nonstress cylinders includes thermal strain, drying shrinkage and autogenous shrinkage [16]. The nonstress cylinders were successfully employed for field monitoring in other studies [16,17], indicating that they effectively eliminate the stress-dependent strain component of concrete inside the cylinder. As total strain consists of elastic strain, creep strain, thermal strain, and shrinkage [15–17], the stress-dependent strain in the test members includes elastic and creep strains before crack occurrence [15–17].

The adiabatic temperature rise of each mix in Table 1 was tested in accordance with ASTM C 186, so that the heat of hydration for each mix could be compared and that its effects on controlling thermal cracking could be quantitatively evaluated. Adiabatic calorimetry (ATR-120HA, TOKYO RICO, JAPAN) was used to measure temperature increases under adiabatic conditions.

The pozzolanic reaction of fly ash and GGBFS is generally considered to slowdown the early-stage strength development of concrete [6,9,14], which may limit the field applicability of the developed ternary concrete. In order to assess the strength development of the ternary concrete, the compressive strength of each mix was tested in accordance with ASTM C 39 starting from an early stage in the process.

Table 1
Mixture proportions of mock-up members.

Member	Water (kg/m^3)	Cement (kg/m^3)	Fly ash (kg/m^3)	GGBFS (kg/m^3)	w/b[*] (–)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	S.P.[**] (kg/m^3)
Normal-strength	170	430 (Type I)	–	–	0.40	770	930	3.01
High-strength	165	585 (Type I)	–	–	0.28	702	874	7.02
Low-heat	180	530 (Type IV)	–	–	0.34	742	881	3.71
Ternary	135	226 (Type IV)	87	134	0.30	820	937	3.58

[*] w/b: water-to-binder ratio.
[**] S.P.: superplasticizer.