Construction and Building Materials 38 (2013) 181–187

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Mix proportion of eco-friendly fireproof high-strength concrete

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HIGHLIGHTS

- ► The optimum mix proportion for eco-friendly fireproof high-strength concrete was derived.
- ► Derived mix proportion was reduced CO2 emitted/ton in 34.6% compared with using Type I cement only.
- ► The eco-friendly fireproof high-strength concrete is considered to be environment friendly.

ARTICLE INFO

Article history:
Received 30 April 2012
Received in revised form 13 June 2012
Accepted 21 July 2012
Available online 21 September 2012

Keywords:
Alkali-activated slag
Eco-friendly fireproof
High-strength
Porcelain

ABSTRACT

The optimum mix proportion for eco-friendly fireproof high-strength concrete was derived in this study. The mixture of the concrete was evaluated by thermal performance through a fire-resistance test. To derive the optimum mix proportion, ground granulated blast-furnace slag and porcelain were substituted, and a 0.1 vol.% fraction of polypropylene fibre was added to prevent spalling. Porcelain was used, as it is effective in improving residual strength. The RABT curve was adopted as the heating time–temperature curve for the fire-resistance test. The derived optimum mix proportion can contribute to ecological friendliness, as it produced up to 34.6% CO_2 savings compared with the mixture using conventional cement. Furthermore, improvement in the characteristics of concrete was shown after exposing this mixture to high temperature following the addition of porcelain.

1. Introduction

Severe economic and social damage has resulted from the collapse of recent structures in large-scale fire accidents due to the use of high-strength concrete [1]. When fire comes in contact with high-strength concrete structures, it causes reduction in structural strength. Concrete has been widely used as an excellent fire-resistant material, and no review of spalling during fire has been made because there were no serious worries about spalling during fire in normal-strength concrete. However, high-strength concrete is different from normal strength concrete. Exposure to abrupt high temperatures caused spalling with a blast, with delamination and exfoliation of the internal and external structure. Spalling in high-strength concrete reduces the strength of reinforced concrete structures due to cracking and reduction in covering depth [1]. Accordingly, studies are being performed to understand and prevent this brittle behaviour of concrete and to inhibit the creation and growth of cracks with the aim of preventing loss of concrete bearing capacity [1].

Up to now, studies to improve the fire resistance of high-strength concrete have concentrated on methods of reducing internal steam pressure and aiding movement of moisture by adding synthetic fibre such as polypropylene in concrete mixtures [5,6]. Studies on inhibiting temperature increases on concrete surfaces have addressed covering-material replacement technologies, such as fireproof board, paint, spray painting, and mortar, as well as the problems of reduction of construction efficiency when adding synthetic fibre [4,7]. One way to protect scattering of concrete due to spalling is through reinforcement with wire mesh and steel panels. However, such a method only supplements the weak fire resistance of high-strength concrete. It does not inhibit the reduction of bearing capacity from direct spalling in case of actual fire [6]. The unit quantity of cement used in concrete making was increased to strengthen the concrete. About 870 kg of CO_2 is said to be emitted in the production of 1 ton of Portland cement [15]. The production of ordinary Portland cement (OPC), which is the main material of concrete, consumes a lot of resources and energy and also results in the emission of greenhouse gases such as CO_2, SO_2, and NO_x, which cause global warming, and it has the additional problem of depleting resources. Especially, the cement industry generates 4.4% of global CO_2 emission, and it is a main target for reduction of greenhouse gases [2].

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http://dx.doi.org/10.1016/j.conbuildmat.2012.07.103

OECD member countries are committed to reduce greenhouse gases under the Kyoto Protocol that went into effect in 2005. According to the Bali road map, the extension of Kyoto Protocol, the target for greenhouse gas reduction was set at "considerable reduction (deep cuts)," without specific targets [17].

For this reason, the construction industry is studying alternative materials to replace OPC. Adding furnace slag to the mixture reduces the need for OPC and therefore the emission of carbon dioxide, and it both reduces the heat of hydration and improves water tightness [2]. Additionally, ground granulated blast-furnace slag is more environmentally friendly than OPC because energy consumption is less and a burning process is not required.

The optimum mix proportion for eco-friendly, fireproof high-strength concrete with improved fireproof characteristics was derived in this study by substituting a part of the OPC with ground granulated blast-furnace slag and porcelain.

2. Materials and mix proportion

Ground granulated blast-furnace slag was used in this study to reduce the production of carbon dioxide, and porcelain and polypropylene fibre were used to improve fireproof characteristics.

2.1. Cement and aggregates

The cement used in this study was type I Portland cement, which has a specific gravity of 3.15. Crushed stones of 2.70 specific gravity and 19 mm maximum size were adapted for coarse aggregate, and river sand with a specific gravity of 2.60 was used for fine aggregate.

2.2. Polypropylene fibre

Polypropylene fibre is believed effective in inhibiting spalling because it reduces internal steam pressure as it dissolves upon exposure to high temperature because it has a low melting point of 160 °C, which is lower than 190 °C, the spalling temperature of concrete [9]. Fibrillated-type polypropylene fibres, 35 μm in diameter and 6 mm long were used in this study.

2.3. Ground granulated blast-furnace slag

Ground granulated blast-furnace slag is an industrial side product created from the manufacturing of pig iron. It may improve the long term strength and durability of concrete and reduce the emission of carbon dioxide in the production of standard Portland cement by using slag instead of cement. Ground granulated blast-furnace slag creates similar hydrates to cement, but the hydration reaction mechanism differs. The hydration reaction of the ground granulated blast-furnace slag is processed with the collapse and decomposition of the glass structure by hydroxyl ions (OH^-) derived from released portlandite ($Ca(OH)_2$) during the hydration of cement [10]. Accordingly, consistent consumption of $Ca(OH)_2$ and the supply of OH^- are necessary for hydration of the furnace slag and the creation of calcium silicate hydrate (C–S–H). Using an alkali activation method that consists of adding alkali material with OH^-, the hydration reaction of the ground granulated blast-furnace slag is accelerated [10,11]. As previously explained, the ground granulated blast-furnace slag is an environmentally friendly substitute for cement in terms of using an industrial side product as well as reducing CO_2 emissions while making a similar hydration reaction to cement.

Accordingly, the ground granulated blast-furnace slag was used to develop the eco-friendly, fireproof, high-strength concrete used in this study. Its chemical characteristics are shown in Table 1. The optimum mix proportion was derived by testing mixtures with 50%, 70%, 90, and 100% substitution by weight of cement.

Table 1
Chemical components of ground granulated blast-furnace slag.

SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	TiO_2 (%)	K_2O (%)	Na_2O (%)	Ig. loss (%)
66.1	22.4	0.18	0.13	0.04	0.07	3.39	1.73	5.56

2.4. Alkali activator

The ground granulated blast-furnace slag is non-crystalline and vitreous. It has a latent hydraulic property of hardening with an alkali stimulant, as the vitreous slag is not structurally stable. When the ground granulated blast-furnace slag contacts water, the water cannot penetrate into the centre of the particles because the silicates create a condensed gel-type membrane on the exterior of the particle. The condensed silicate gel is changed into a loosened structure by adding alkali stimulant to elute silicate and aluminate and react by hydration to produce C–S–H and calcium sulfoaluminate (C–S–A) with $Ca(OH)_2$ [11,13].

Consequently, the alkali activator, which is called water glass, a powder-type anhydrous meta-sodium silicate with 0.92 specific gravity and 1.063 M ratio (Na_2O/SiO_2), was used in this study for the hydration reaction of the ground granulated blast-furnace slag. However, we can know that it was possible the hydration reaction without alkali activator in the case of 70% substitution by cement weight to ground granulated blast-furnace slag through the pilot experiment. Therefore, the alkali activator was used 10% addition by ground granulated blast-furnace slag weight in the case of over 90% substitution by cement weight to derive actual optimum mix proportion.

2.5. Porcelain

Porcelain, a ceramic, was used to improve the residual strength of concrete exposed to high temperature in this study. Porcelain has a firm vitreous surface formed by combining silica ions with melted alkali elements of K_2O and Na_2O in exposure to temperatures over 1000 °C [12,18]. Accordingly, residual strength when exposed to high temperatures can be improved by using porcelain. Clay-type porcelain was fully dried in the drying oven at 110 °C and processed into powder by passing a no. 16 (1.18 mm) sieve through a pulveriser, and the amounts of 5%, 10%, and 20% substituted weight of ground granulated blast-furnace slag were used.

2.6. Mix proportion

High-strength concrete with 180 ± 20 mm of target slump and 45 MPa of design strength was adapted for the plain mixture in this study. The experimental parameters to derive the optimum mix proportion of the eco-friendly fireproof high-strength concrete were the substitution ratios of the ground granulated blast-furnace slag and porcelain. The substitution ratio of ground granulated blast-furnace slag used for the development of environment-friendly material was set at 50, 70, 90, and 100 wt.% cement. The substitution ratio of porcelain to acquire the residual strength after the fireproof test was set for 5, 10, 20 wt.% ground granulated blast-furnace slag weight. Additionally, a 0.1 vol.% fraction of polypropylene fibre was used to inhibit concrete spalling in case of exposure to high temperatures. A 38% water–binder ratio was adopted, and a superplasticizer was used by controlling its quantity so that each mixture could acquire the target slump of 180 ± 20 mm. Table 2 shows the experimental parameters and mix proportions adapted to this study.

3. Experimental

3.1. Slump test

The experiment of slump and mixing time for the eco-friendly fireproof high-strength concrete was performed according to ASTM C 143 [8].

3.2. Compressive strength

Three cylindrical-type specimens were made at ∅100 × 200 mm for each material age of 7, 14, and 28 days, nine specimens in total, according to ASTM C 39 to evaluate eco-friendly, fireproof, high-strength concrete compressive strength, and the test was performed twice [3]. Initial curing for the specimens was performed for 24 h in a curing room at 23 ± 2 °C and 50 ± 5% relative humidity in a constant-temperature water tank at 23 ± 2 °C, and then the compressive strength test was performed.

3.3. Fire test

After measuring the internal temperature of concrete and performing the fireproof test on the concrete exposed to high temperature, the residual compressive strength was measured to evaluate the fireproof characteristics of eco-friendly fireproof high-strength concrete. The time–heating temperature curve adapted to the fire test is the RABT ZTV heating curve with a good reflection of the fire aspect on the concrete structure, and it is shown in Fig. 1 [4].

The 100 × 200-mm cylindrical-type specimen, made using the same method as the above test specimen, and a beam-type