Construction and Building Materials 30 (2012) 406–412

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Eco-friendly fireproof high-strength polymer cementitious composites

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ARTICLE INFO

Article history:
Received 17 March 2011
Received in revised form 17 November 2011
Accepted 4 December 2011
Available online 2 January 2012

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

ABSTRACT

The cementitious fireproof material is widely used to protect concrete structures against fire. However, there has lately been interest in developing more environmentally friendly construction materials that have lower cement content, since cement manufacture has a large carbon footprint. One approach, formulated here, makes use of eco-friendly fireproof high-strength polymer cementitious composites made from blast furnace slag (an industrial by-product). And we were used the activator which is necessary to function as a catalyst to induce the hydration of blast furnace slag. In addition, we were used the polypropylene fibre, and porcelain to improve the fire-resistance. To evaluate the properties of eco-friendly fireproof high-strength polymer cementitious composites, we tested mechanical properties in laboratory experiments such as compressive strength and fire-resistance. The tested composite performed just as well as conventional fireproof cement material, and notably had high residual strength.

1. Introduction

Tunnels and their associated underground structures are steadily growing in size [1]. Because of this, the use of high-strength concrete, which improves the physical and mechanical performance of concrete, has been increasing. In addition, traffic volume has increased greatly due to population increase and industrial development, leading to an increased risk of fires occurring as a result of traffic accidents. A tunnel and its underground structure are an enclosed space, rendering extinguishing a fire and evacuating people very difficult. Aside from the loss of life, potential long-term disruption of the traffic network is another issue [2–4,11].

The best countermeasure technology to prevent damage to a tunnel and its underground structure in a fire, to enable safe evacuation of people, and to recover traffic flow after a fire, is fireproofing [2,11]. In Europe and Japan, fireproof countermeasures have recently been applied, depending on the risk of fire in the tunnel or underground structure. Research on fireproof materials and construction methods has been advancing [2,11]. The most general way to fireproof a structure is to apply a fireproof covering, such as fireproof panels attached with fireproof mortar. However, these fireproof materials use cement as the main component, which is not in accord with the global desire to reduce carbon dioxide emissions. Carbon dioxide is the main cause of global warming. About 1 ton of carbon dioxide is created from the production of 1 ton of cement [5,15]; hence, there is great interest reducing the cement content of fireproof coatings.

Previous investigations have focused on developing more environmentally friendly mortars and concretes by using industrial by-products, e.g., pozzolans such as fly ash or blast furnace slag, instead of cement [5–7,12,13]. In this study, we optimised the formulation of an eco-friendly fireproof high-strength polymer cementitious composite suitable for various concrete structures.

2. Materials and formulation

In this study, the use of cement was minimised by adding blast furnace slag (an industrial by-product), porcelain (which forms a dense structure at high temperature), and polypropylene fibre.

2.1. Cement and aggregate

Type I cement was used in this study. The fine aggregates were quartz sand and expanded perlite having a specific gravity 0.15. Expanded perlite is an aggregate with 90% porosity and low weight (density of 0.05–0.30 g/cm^3), and provides thermal insulation (thermal conductivity of 0.03–0.05 kcal/h m K). In addition, since the material is a non-flammable inorganic substance [10], there is no risk of poisonous gas creation during a fire.

2.2. Polypropylene fibre

Polypropylene fibre reduces mortar cracking and explosive spalling by melting during a fire, thereby reducing the vapour pressure inside the mortar. Fibrillated bundle polypropylene fibres, 35 μm in diameter and 6 mm long, were used in this study.

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doi:10.1016/j.conbuildmat.2011.12.034

2.3. Blast furnace slag

The blast furnace slag used was an industrial by-product of the manufacture of pig iron; about 300 kg is produced per ton of pig iron. Pulverised furnace slag is ground granulated blast furnace slag and has angular particles. Sufficient quantities of OH^- or SO_4^{-2} ions are required for ground granulated blast furnace slag to be hardened inside a cement composite because of its latent hydraulic activity [6,7].

The main components of the ground granulated blast furnace slag used in this study were CaO, SiO_2, and Al_2O_3. It had hydraulic activity like cement due to stimulating material [5]. It caused a pozzolan reaction that created the insoluble hardening material when it reacted with the $Ca(OH)_2$ created during the hydration reaction. The blast furnace slag was a pozzolan admixture having similar chemical elements as cement, and could be regarded as a more environmentally friendly material since an industrial by-product was being used as a substitute for cement.

Accordingly, blast furnace slag was used in this study to develop an environmentally friendly fireproof material having a reduced carbon footprint. The characteristics of the ground granulated blast furnace slag used in this study are given in Table 1.

2.4. Sodium silicate

An activator is necessary to function as a catalyst to induce the hydration of blast furnace slag. The strong base NaOH was used in initial experiments with activated slag, but it was difficult to handle due to its deliquescence [9]. Sodium silicate ($Na_2O{\cdot}nSiO_2$), known as water glass, was considered as an alternative activator; however, there are health hazards associated with SiO_2 [5]. Instead, we used the safer powdered anhydrous meta sodium silicate as an activator. A ratio of 1.0:0.2 of blast furnace slag to meta sodium silicate was used. The shape of the meta sodium silicate is indicated in Fig. 1, and its chemical composition is detailed in Table 2.

2.5. Porcelain

When heated above 1000 °C, concrete and mortar made mainly from cement experiences a great reduction in strength, i.e., its residual compressive strength decreases by more than 80% [8]. A cement composite applied to an underground structure and tunnel must have high residual strength to prevent extensive damage during a fire. Porcelain was used in this study to improve the residual strength of cement composites exposed to high temperature. Porcelain exposed to high temperature over 1000 °C acquires a vitreous structure by combining with silicate ions and melted alkali oxides such as K_2O and Na_2O [16]. The vitreous structure was formed the dense structure within cement matrix like Fig. 6. Therefore the vitreous nature was expected to improve the residual strength of the composite and thereby improve the stability of the structure after exposed the high temperature.

Porcelain in its original form appears as a white clay. But it must be added as a powder in a cement composite. Therefore, the porcelain clay was fully dried in a drying oven at 110 °C, and then crushed into a powder using a pulverizer. The powder that passed through a number 16 sieve (1.18 mm) was accepted for further use. The shape of the porcelain particles used in this study is shown in Fig. 2, and its components are detailed in Table 3.

2.6. Polymer

The polymer was used as an admixture to ensure a sufficient amount of air in the concrete and to improve the bond strength between the cement paste and the aggregate. The polymer was in the form of small spherical particles, 0.5–5.0 μm in diameter, and coated with surfactant. All particles remained in suspension because of the adsorbed surfactant. Using the polymer suspension improved the workability of the unhardened cementitious composite and enabled a reduced water–cement ratio, and this increased the strength. During the hydration reaction, latex particles formed a film and reduced the permeability by filling pores and attaching the hydration products to the aggregate surface. In addition, the latex film increased the tensile strength. Table 4 shows the physical characteristics of the polymer used in this study.

2.7. Mix proportion

Previous work established the optimum formulation for a high-strength fireproof polymer cement mortar [2], and was taken as the basic formulation in the work reported here. This formulation had a compressive strength greater than 40 MPa at 28 days. Light aggregate perlite and polypropylene fibre were used to improve the resistance to high temperature. Finally, the polymer was used to improve the tensile and flexural strengths, which were key mechanical characteristics of the cement composite.

Fig. 1. Meta sodium silicate powder.

Table 2
Properties of meta sodium silicate.

Type	Na_2O (%)	SiO_2 (%)	Na_2O/SiO_2[a]	Specific gravity
Anhydrous metasilicate	50.54	46.03	1.066	0.92

[a] Molar ratio.

The experimental variables were the substitution ratio of blast furnace slag, the addition ratio of porcelain, and the volume fraction of polypropylene fibre. Substitution levels of 0, 50, and 100 wt.% of blast furnace slag for cement were set to evaluate the mechanical characteristics. The porcelain was added at 0, 15, and 30 wt.% to the cement to assess the improvement in residual strength following exposure to fire. In addition, polypropylene fibre was used to inhibit the explosive spalling that can occur with exposure to high temperature; 0.1, 0.15, and 0.25 vol.% of the entire volume was used. A water–cement ratio of 53% satisfied the criterion of 160 ± 5 mm mortar flow for spary-attaching polymer cement. Water–cement ratios of 40% or 39% could also be used, depending on the blast furnace slag substitution ratio. Table 5 indicates the adopted experiment variables and mix proportions.

3. Experimental

3.1. Compressive strength

The compressive strength of the mortar was assessed according to ASTM C109. Three sets of nine 50 × 50 × 50-mm cube specimens were made for testing at each of 7, 14, and 28 days of ageing time in order to evaluate the compressive strength. Each test was repeated twice. The specimens were demolded after initial curing at 23 ± 2 °C and 50% relative humidity for 24 h, and then cured in a constant temperature water tank at 23 ± 2 °C.

3.2. Fire test

The residual compressive strength was measured after the fire test to evaluate the physical and mechanical changes after exposure

Table 1
Properties of blast furnace slag.

Specific gravity	Ig. loss (%)	Blain fineness (cm^2/g)	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	K_2O (%)	Na_2O (%)
2.9	0.48	4530	34.4	12.7	0.5	41.3	5.93	0.5	0.4