Construction and Building Materials 31 (2012) 105–111

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Production of waste bio-fiber cement-based composites reinforced with nano-SiO_2 particles as a substitute for asbestos cement composites

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ARTICLE INFO

Article history:
Received 25 November 2010
Received in revised form 26 December 2011
Accepted 27 December 2011
Available online 21 January 2012

Keywords:
Asbestos fiber
Waste bio-fiber
Green cement-based composites
Silica nano-particles

ABSTRACT

The environmental impact of asbestos fibers on human health and their consequent safety-related problems indicate that there is a significant need to replace this material in all asbestos-containing products. Many different types of fibers have been introduced to replace asbestos fibers.

In this study, the performance of silica nano-particles combined with waste paper pulp fibers (sulfite fibers) has been investigated. Different mechanical (compressive and flexural strengths and bending performance), durability (water absorption), physical (bulk density and flowability), and microstructural (scanning electron microscopy) tests were conducted to examine the properties of manufactured green composites.

The results reveal that the mechanical properties of cement-based composites containing a ternary system of "natural waste fiber–silica nano-particle cement" have been enhanced. Adding silica nano-particles allows the development of green cement-based composites and movement toward sustainable development in the concrete industry.

1. Introduction

Asbestos had numerous applications in many different countries during previous decades due to its reinforcement, thermal and electrical insulation, and heat resistance properties. Moreover, it had been widely used in the textiles industry because of its high flexibility and strength. It had also been used in packaging, joints and seals. In the early 20th century, thin sheets of a combination of Portland cement and asbestos fibers were produced, and many remarkably durable and flexible asbestos products, such as asbestos cement particles, asbestos yarn cord and fabric, asbestos joint and millboard, and water and sewage pipes were introduced [1]. Asbestos is a collective term given to a group of minerals whose crystals occur in fibrous forms and includes two types, serpentine and amphiboles [2]. In a general consensus among scientific communities, different types of asbestos were classified as carcinogens, and it was declared that these fibers can cause lung cancer if they are inhaled. Chrysotile asbestos, which is a type of serpentine asbestos, was introduced as a carcinogenic factor for the human body. Inhaling the chrysotile asbestos odor damages lung tissue [3].

Previous studies on workers showed that chrysotile in several sections of a factory broadly contributed to terrible diseases. In addition, air movements were shown to promote the movement of asbestos fibers through different parts of a factory [4]. This event proved that inhaling the air containing asbestos particles leads to extreme respiratory problems. This disease was referred to as asbestosis [2].

Given the hazards of asbestos, researchers introduced appropriate replacements for these fibers. Although a material with similar effectiveness and an acceptable price, such as asbestos, has not been found, cellulose fibers have been introduced as an alternative for some applications of asbestos. In addition to cellulose, resistant-to-alkali fiber glass performs acceptably to improve the strength and other qualities of cement products [5]. However, among various types of existing cellulose fibers, paper pulp fibers produced by a sulfite process are crucial. They are used commercially as sheets with different thicknesses, which are applicable for manufacturing tissues, print papers, and hygienic products [6]. In contrast with the environmental compatibility of cellulose fibers, their reinforcing capability is lower than that generated by applying carcinogen asbestos fibers in a cement-based matrix.

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doi:10.1016/j.conbuildmat.2011.12.102

Currently, the application of reinforcing particles at the nano-scale is very common when fabricating cement-based composites. Among different available nano-particles, silica nano-particles are more useful for the fabrication of cement-based composites due to their amorphous structure, SiO_2 content (more than 99% purity in most products), and highly specific surface area (which leads to the super pozzolanic property) [7].

By reacting with calcium hydroxide ($Ca(OH)_2$) crystals located in the interfacial transition zone, silica nano-particles contribute to the formation of a calcium-silicate-hydrate (C–S–H) dense gel. Consequently, the dimensions and quantity of $Ca(OH)_2$ remarkably decrease, and the strength of the hardened cement increases [8–11].

Moreover, silica nano-particles enhance the strength of cement paste in four ways [7,11]: (1) *nucleus-like action:* they are highly capable of forming bonds due to their highly specific surface; (2) *controlling crystallization:* they prevent the crystallization of weak crystals, such as $Ca(OH)_2$ and ettringite; (3) *production of a strong C–S–H gel:* they change the weak crystals ($Ca(OH)_2$) into a high strength gel; (4) *microfilling effect:* because of their small size, they are located between small voids and fill empty spaces. The addition of colloidal silica nano-particles in the matrix of mortars for ferro-cement panels showed that any increase in silica nano-particle content, even at low replacement percentages, enhanced the microstructure and mechanical strengths of specimens [11].

Based on the issues mentioned above, this study aims to produce green composites by presenting a hybrid composite system of waste bio-fiber and silica nano-particles as an alternative for carcinogenic asbestos fibers in the matrix of cement-based composites.

2. Experimental methods

2.1. Materials

The cement used in this study is ASTM type II Portland cement, and its physical and chemical properties are shown in Table 1. Tap water was used. The natural fibers used in this investigation were classified into the two categories of sulfite pulp fiber (SPF) and chrysotile asbestos fiber. Commercial SPF possesses the basic properties presented in Table 2.

Based on production procedures used in tissue manufacturing industries in Iran, after passing SPFs through a needle mill at 3000 rpm, most fibers were within the favorable range (more than 3 mm), and the remaining were removed as waste. Therefore, waste fibers (SPFs) within the range of 1.2–1.5 mm have been utilized in this study. Chrysotile asbestos fibers were used in the range of 2–3 cm.

The silica nano-particles used in this study are colloidal and have 40% solid content (40% SiO_2 powder and 60% water). The physical properties of these silica nano-particles are presented in Table 3.

2.2. Mixing and testing procedures

In this study, as shown in Table 4, binder (cement and silica nano-particles) and water are considered constant factors (the water to binder ratio is equal to 1), while fibers (asbestos and sulfite) are applied in three percentages (5%, 10%, and 15%, with respect to the total content of binder in each mixture (1500 g)), and colloidal silica nano-particles are added in four dosages (0%, 0.5%, 1%, and 3%, with respect to the total content of binder in each mixture (1500 g)) as variables.

Table 1
Chemical and physical properties of cement (ASTM Type II).

Item	Cement (%)
Chemical composition	
SiO_2	20.4
CaO	63.0
Al_2O_3	4.9
Fe_2O_3	3.9
MgO	1.7
SO_3	2.0
$Na_2O + K_2O$	0.9
Loss on ignition	1.5
Physical properties	
Specific gravity (g/cm^3)	3.12
Specific surface (m^2/kg) (blaine)	295
Average particle size (μm)	26

Table 2
Basic properties of SPFs.

Basic weight (gr/cm^2)	Dry density (gr/cm^3)	Wet (%)	Fine (%)	Brightness (%)	pH	Fiber length (mm)
0.7	0.8	9	12	84	7	<3

Table 3
Physical properties of nano-SiO_2 particles.

Type	Average particle size (nm)	Specific surface area (BET) (m^2/gr)	SiO_2 content (%) (in dry form)	Density in colloidal form (gr/cm^3)
Colloidal	34	135	99.7	1.32

Table 4
Mix proportions in different mixtures (gr).

Mix code	Fiber type	Fiber	Cement	Water	Nano-SiO_2
SF1	Sulfite	75	1500	1500	–
SF2	Sulfite	75	1492.5	1488.75	18.75
SF3	Sulfite	75	1485	1477.5	37.5
SF4	Sulfite	75	1455	1432.5	112.5
SF5	Sulfite	150	1500	1500	–
SF6	Sulfite	150	1492.5	1488.75	18.75
SF7	Sulfite	150	1485	1477.5	37.5
SF8	Sulfite	150	1455	1432.5	112.5
SF9	Sulfite	225	1500	1500	–
SF10	Sulfite	225	1492.5	1488.75	18.75
SF11	Sulfite	225	1485	1477.5	37.5
SF12	Sulfite	225	1455	1432.5	112.5
AF1	Asbestos	75	1500	1500	–
AF2	Asbestos	150	1500	1500	–
AF3	Asbestos	225	1500	1500	–

In the mixing procedure, cement and fibers were first mixed together by hand mixing. Then, water and silica nano-particles in colloidal form were mixed in the mortar mixer at a moderate speed (200 rpm) for 2 min. Finally, all the materials were stirred at a high speed (600 rpm) for 4 min.

The well-mixed cement pastes were then poured into oiled molds to form 50 mm cubes for compressive strength testing at 3, 7, and 28 days and into 40 × 40 × 160 mm prisms for flexural strength testing at 28 days. The samples were de-molded after 24 h and then cured in a water tank (at 20 ± 2 °C) for 3, 7, and 28 days. The compressive and flexural strengths were determined according to ASTM C109-02 and ASTM C 348-02, respectively, at 3, 7, and 28 days.

For the water absorption test (7 and 28 days) different mixtures were casted in 50 mm cubes according to the BS 1881: Part 122-1983 standard. It should be noted that because of the similar performance mechanism of silica nano-particles and the different fiber contents, mixtures including 10% fiber were selected for the water absorption test. Moreover, the water absorption test was conducted to investigate the durability of the specimens. In this test, the specimens were put in oven at 105 °C for 72 h at 7 and 27 days. After a gradual cooling period in an ambient environment (22 ± 0.5 °C), the specimens were immersed in water for 30 min. The absorption was calculated according to Eq. (1) by measuring the dry weight (before immersing in water) and wet weight (after 30 min of immersion) of the specimen. The specimen was dried with a towel before determining the wet weight to achieve a similar saturated surface dried (SSD) condition.

$$WA = \frac{W_w - W_d}{W_d} \times 100 \quad (1)$$

where WA, W_w and W_d are the water absorption percentage, wet weight and dry weight, respectively.

The bending strength of cement sheets was examined in accordance with DIN 68763 in terms of the modulus of elasticity (MOE) and the modulus of rupture (MOR) (Eqs. (2) and (3)). Thus, specimens with dimensions of 15 × 50 × 280 mm were constructed and tested at 28 days.

$$MOE = \frac{P_1 \cdot L^3}{4BH^3Y_1} \quad (2)$$