Construction and Building Materials 44 (2013) 757–764

Contents lists available at SciVerse ScienceDirect

Construction and Building Materials

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

Development of green engineered cementitious composites using iron ore tailings as aggregates

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HIGHLIGHTS

- Iron ore tailings (IOTs) were used as aggregates to prepare green ECC.
- Influences of IOTs size on fresh properties of ECC mortar were investigated.
- Influences of IOTs size on tensile properties of ECC were studied.
- The mechanical properties of ECC with IOTs are comparable to that with silica sand.

ARTICLE INFO

Article history:
Received 22 January 2013
Received in revised form 15 March 2013
Accepted 22 March 2013
Available online 24 April 2013

Keywords:
Engineered cementitious composites
Aggregate
Iron ore tailings
Fiber dispersion
Tensile ductility

ABSTRACT

Micro-silica sand is often used as fine aggregate in the production of Engineered Cementitious Composites (ECC), which is a class of ultra-ductile fiber-reinforced cement-based structural materials. However, high cost and limited availability of micro-silica sand creates an obstacle for widespread application of ECC in civil infrastructure. To overcome this limitation, the present study explores the feasibility of using iron ore tailings (IOTs) as cheaper and more environmentally friendly alternative aggregates without sacrificing the ductile mechanical performance of standard ECC. Influences of the size of IOTs on plastic viscosity of fresh ECC mortar, and on tensile properties and fiber dispersion in composites were experimentally investigated. At two levels of fly ash/cement ratio, performance of ECC with IOTs under direct tension and compression was investigated. The results show that ECC with IOTs as aggregates can attain tensile and compressive properties comparable to ECC with typically-used micro-silica sand, provided that the size of IOTs used is in the appropriate range which facilitates good fiber dispersion. Thus, the feasibility of using industrial solid waste-iron ore tailings as aggregates in the development of highly ductile and green ECC was established.

1. Introduction

Engineered Cementitious Composites (ECC) designed through micromechanical principles are a special generation of high performance fiber reinforced cementitious composites, which are characterized by ultra-high tensile ductility and tight crack width [1]. ECC with 2% volume fraction of Poly-Vinyl Alcohol (PVA) fibers demonstrates a tensile strain capacity of 3–5%, which is two orders of magnitude higher than that of normal concrete and fiber reinforced concrete (FRC) [2]. Such high ductility is a result of tensile strain hardening behavior through multiple cracking. The inherently small crack width is typically below 100 μm even at large imposed tensile deformation [2]. Due to such high tensile ductility and tight crack width, ECC exhibits superior durability compared to normal concrete and FRC under various mechanical and environmental conditions [3], making it a promising material to enhance safety, serviceability, and sustainability of civil infrastructure.

Aggregates in cementitious materials have a significant impact on material workability, strength, stiffness, shrinkage, and cost. Specifically, in ECC, aggregates influence the material's tensile performance mainly through alterations in matrix fracture toughness and fiber dispersion. The matrix fracture toughness tends to increase with larger aggregate size due to increase in tortuosity of fracture propagation. However, according to the micromechanical design principles of ECC, matrix fracture toughness has to be limited for attaining strain hardening behavior of the composite [1]. For this reason, coarse aggregate is not used in the standard ECC mixture [4]. Additionally, with the presence of PVA fibers in ECC, aggregates with size larger than average fiber spacing can

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0950-0618/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.conbuildmat.2013.03.088

cause fiber clumping and poor fiber dispersion [5]. Fiber clumping becomes more pronounced with increase in aggregate size. Poor fiber dispersion leads to a reduction in the number of effective fibers at the failure crack, which causes a decrease in tensile strength and tensile strain capacity [6]. Therefore, in the design of ECC, the use of fine aggregate is needed to maintain low fracture toughness of the matrix and uniform fiber dispersion in the composite, both of which are crucial for achieving good tensile performance of ECC.

Due to the above considerations, micro-silica sand (SS) with an average diameter of approximately 110 μm is frequently used in various ECC compositions [7–11]. However, the manufactured micro-silica sand is relatively expensive and is less widely available than common sand, which leads to higher initial cost of ECC. In addition, the initial energy consumption and CO_2 emissions associated with the manufacture of silica sand creates larger environmental burdens than coarser aggregates used in concrete. These initial economic and environmental costs limit large-scale application of ECC, despite the fact that replacement of a conventional material such as concrete with ECC in an infrastructure reduces the life cycle costs and environmental impact due to enhanced durability and less frequent maintenance [12]. Therefore, it is imperative to seek cost effective and environmentally friendly alternative aggregate in the production of ECC without sacrificing its mechanical properties.

This paper explores one of the several feasible approaches for promoting greenness and lowering cost of ECC by replacing micro-silica sand with iron ore tailings (IOTs). Iron ore tailings (IOTs) are waste ground rocks generated during the beneficiation process of iron ore concentration. In developing countries, IOTs are mainly stockpiled as waste and are often underutilized. For instance in China, the annual generation of IOTs increased from 137 billion ton in 2000 to 536 billion ton in 2009, and the total accumulation of IOTs from 2000 to 2009 exceeded 2.8 billion ton [13]. However, the current utilization rate of IOTs in China is less than 10% [14]. Due to the economic concern and environmental awareness, the reuse of IOTs is an urgent need. Utilization of IOTs in the production of ECC can potentially provide significant benefits in sustainability of both construction and mining industry, specifically, in terms of reductions in natural resource use, energy consumption, ECC cost, land use, and IOTs management cost.

This paper aims to investigate the feasibility of using IOTs as aggregates in the production of green ECC with reduced environmental and economic cost. The influences of the size of IOTs on plastic viscosity of fresh ECC mortar, fiber dispersion, and mechanical properties of ECC mixtures are experimentally investigated. The tensile and compressive properties of ECC with IOTs are compared to standard ECC with micro-silica sand at two different fly ash contents. Experimental investigations exploring various effects of IOTs on the mechanical performance of ECC and conclusions therefore are detailed in the following sections.

2. Experiment program

2.1. Materials

The major matrix ingredients of ECC are Type I ordinary Portland cement (C), Class F fly ash (FA), fine aggregate (IOTs or SS), water and High Range Water Reducing Admixture (HRWRA). Chemical composition and physical properties of fly ash are given in Table 1. Poly-Vinyl Alcohol (PVA) fibers are incorporated as reinforcing fibers. The PVA fibers with a length of 12 mm and diameter of 39 μm are coated with 1.2% by weight of oil to control the fiber/matrix interfacial properties. The nominal tensile strength, elastic modulus, and density of the PVA fibers are 1620 MPa, 42.8 GPa, and 1300 kg/m^3, respectively.

IOTs used in this study mainly consist of silica, alumina, and iron oxide, with quartz as the major mineral phase [15]. Four size ranges of IOTs depicted as IOTs-Fine, IOTs-1180, IOTs-600, and IOTs-425 were investigated in this study. During iron ore mining operations, two types of IOTs are generated, fine IOTs and coarse IOTs. The fine iron ore tailings as obtained from the mine without additional processing are named IOTs-Fine in this study. The coarse IOTs are passed through sieves with openings of 1180 μm, 600 μm, and 425 μm (plus bottom pan) and the IOTs passing through sieve are called IOTs-1180, IOTs-600, and IOTs-425, respectively, such that the number in the name of IOTs represents the nominal maximum aggregate size. For comparison purpose, a standard ECC mixture containing micro-silica sand was also prepared. Particle size distributions of IOTs and micro-silica sand obtained through sieve analysis are given in Fig. 1. Particle morphology of micro-silica sand and IOTs-Fine is shown in Fig. 2, which suggests that micro-silica sand has a near-round shape, while IOTs have an angular shape as a result of crushing and grinding.

Table 1
Chemical and physical properties of fly ash (%).

Chemical composition, %	Fly ash
CaO	14.04
SiO_2	44.09
Al_2O_3	23.21
Fe_2O_3	8.39
SO_3	1.46
Moisture	0.05
Loss on ignition	0.56
Available alkalis, as Na_2O	0.99
Physical properties	
Retained on 45 μm, %	16.85
Water requirement, %	97
Specific gravity	2.45

Alkali silica reaction (ASR) is known to cause serious deterioration problems in cementitious materials using aggregates containing amorphous silica, and therefore, the ASR potential of IOTs was determined before using it as alternative aggregate in ECC. Accelerated mortar bar test as specified by ASTM C 1260 was used to measure the ASR potential of IOTs. The mortar bars were immersed in a 1 N NaOH solution at 80 °C for 14 days. Fig. 3 shows the expansion test results of mortar bar specimens containing IOTs-Fine and IOTs-1180 as representatives of fine and coarse tailings, respectively. The expansion rate of these mortar bars measured at 14 days is far below 0.10% (Fig. 3), indicating that IOTs are innocuous aggregates that can be used in cementitious materials without concerns of ASR.

2.2. Mix proportions

Two sets of mixtures were prepared in this study. In the first set (Table 2), four ECC matrix mixtures M1–4 (without fibers, 'M' stands for matrix) with the same constituent proportions but with different IOTs size were prepared to investigate the influence of IOTs size on the plastic viscosity of fresh ECC mortar. The plastic viscosity was measured through Marsh cone flow test. The rheology of the matrix in the fresh state is important for fiber dispersion uniformity [6].

In the second set (Table 2) of mixtures, eight ECC mixtures C1–8 (with fibers, 'C' stands for composites) were prepared to investigate the effects of IOTs size and FA content (FA/C of 2.2 and 4.4 by mass) on the mechanical properties of cured ECC mixtures, while utilizing the knowledge of the influence of IOTs size on the fresh matrix properties from the first set to achieve good fiber dispersion in the second set. For mixtures C1–8, the HRWRA content was adjusted to keep the fresh matrix

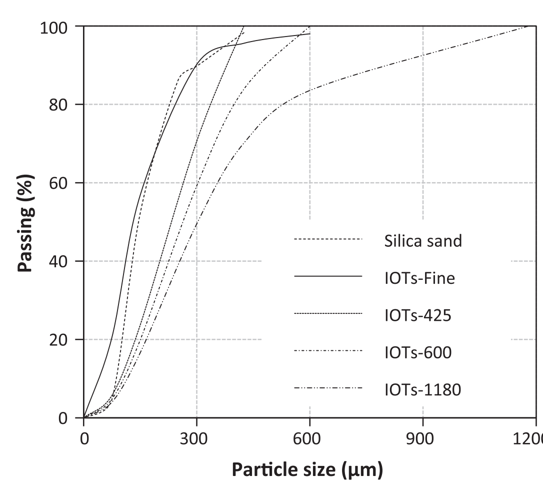

Fig. 1. Particle size distributions of IOTs and micro-silica sand.