Construction and Building Materials 99 (2015) 1–10

Contents lists available at ScienceDirect

Construction and Building Materials

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

Influence of limestone powder on mechanical, physical and self-healing behavior of Engineered Cementitious Composites

Hocine Siad [a,b,*], Ahmed Alyousif [a], Ozlem Kasap Keskin [c], Suleyman Bahadir Keskin [c], Mohamed Lachemi [a], Mustafa Sahmaran [d], Khandaker M. Anwar Hossain [a]

[a] Department of Civil Engineering, Ryerson University, Toronto, ON, Canada
[b] Laboratory of Materials and Sustainable Development, Bouira University, Bouira, Algeria
[c] Department of Civil Engineering, Mugla Sitki Kocman University, Mugla, Turkey
[d] Department of Civil Engineering, Gazi University, Ankara, Turkey

HIGHLIGHTS

- Effects of replacing limestone powder with cementitious material were studied.
- Mechanical, physical, self-healing properties and microstructure of ECC's were investigated.
- All mixtures exhibited self-healing even with high limestone powder content.
- The presence of monocarboaluminate in healed cracks of ECC with LP was confirmed.

ARTICLE INFO

Article history:
Received 15 July 2015
Received in revised form 27 August 2015
Accepted 8 September 2015

Keywords:
Engineered Cementitious Composites (ECCs)
Limestone powder (LP)
Self-healing
Mechanical properties
Physical properties

ABSTRACT

Environmental considerations have led to a global trend of using blended cements instead of ordinary Portland cement; cements containing limestone powder (LP) have recently entered the market. This research focuses on the effect of replacing LP content with cementitious material on the performance of Engineered Cementitious Composite (ECC) containing high-volume fly ash (FA). For this purpose, ECC mixtures were created in which cement and FA were partially replaced by 5%, 10% and 20% of LP and ECC mixture without LP (as control). The samples were precracked at the age of 28 days and left under continuous water curing (CW) for recovery of their properties. Compressive strength, modulus of rupture (MOR), mid-span beam deformation capacity, rapid chloride penetration testing (RCPT) and resistivity testing were used to assess the mechanical, physical and self-healing capability of ECC mixtures. Experimental results show that all mixtures exhibited self-healing with slight differences. Microstructure was also assessed using SEM–EDS and XRD analysis. The microstructural analysis of healed cracks in LP-incorporated ECC mixtures showed the presence of calcite, portlandite and C–S–H gels as well as monocarboaluminate, which confirmed a possible reaction between FA and LP. Due to self-healing, the recovery in mechanical and durability performance of the mixtures proposed in this research is anticipated to positively affect life cycle costs and lead to increased civil infrastructure sustainability.

1. Introduction

Engineered Cementitious Composite (ECC) is a special type of concrete material capable of high performance, and is an outcome of research into the enhancement of brittle behavior of conventional concrete. Design based on micromechanics underpins the development of fiber-reinforced ECC characterized by high ductility [1]. The fiber content of this material, which has high-tensile ductility and tight crack width, is moderate at no more than 2% by volume [2]. Furthermore, regardless of applied deformation, the width of tight cracks in ECC does not exceed 100 μm, in contrast with other concrete materials [3]. These singular characteristics are the source of the chemical and physical properties that make ECC an appropriate self-healing material.

Like the healing behavior of all types of concrete, the extent of self-healing in ECC is determined by the matrix [4,5]. The ECC

* Corresponding author at: Department of Civil Engineering, Ryerson University, Toronto, ON, Canada.

E-mail addresses: hsiad@ryerson.ca, hcine_siad@yahoo.fr (H. Siad).

http://dx.doi.org/10.1016/j.conbuildmat.2015.09.007
0950-0618/

matrix consists of cement and various mineral admixtures including FA and slag [6]. Some studies suggest that augmenting FA and/or slag to cement ratio would enhance tensile ductility and self-healing capacity [5,7–10]. ECC has been successfully developed in a few studies that employed different admixtures such as palm oil, fuel ash [11], metakaolin [12], nanomaterial additives [13], silica fume [14], and hydrated lime [15].

In view of global sustainable development, there is a growing trend toward using natural materials to produce different types of concrete mixtures. Using LP powder in mortar and concrete is a common practice in many countries. It could substantially reduce the cost and environmental impact of cement manufacturing, and improve early age compressive strength. According to European standards, CEM II/B type cements can be produced with up to 35% LP [16], while the Canadian Standards Association [17] states that 15% LP can be used in four types of Portland Limestone Cement: General Use Cement (GUL), Moderate Heat of Hydration Cement (MHL), Low Heat of Hydration Cement (LHL) and High Early Strength Cement (HEL). This situation necessitates research into limestone use in cement and concrete.

The effect of limestone as an inert or reactive admixture has been studied extensively [18–21]. According to Celik et al. [22], chemical interactions during cement hydration take place between the calcite ($CaCO_3$) from LP and various calcium aluminate hydrates from Portland cement to form high and low forms of carboaluminates, hemicarboaluminate and monocarboaluminate, which all belong to a group of AFm phases. Considering the presence of AFm phases and the $CaCO_3$ and calcium hydroxide crystals in the healed cracks of concretes mentioned in several studies [11], it may be advantageous to use LP filler in ECC to gain economic and ecological benefits. The literature has very limited information about the use of limestone in ECC. Türk and Demirhan [23] presented an experimental investigation on the mechanical properties of ECC with LP replaced by 25%, 50%, 75%, and 100% silica sand. Their study showed that greater LP content (instead of silica sand) had a positive effect on flexural strength, increased ductility and decreased crack width. Qian et al. [24] studied the self-healing of cementitious composites containing blast furnace slag as a supplementary material and LP as sand at different water-to-binder ratios between 0.45 and 0.60. The specimens were preloaded at 28 days, and compared to sound specimens, recovered about 65–105% of their deflection capacities after an additional curing of 28 days in water, and 40–60% after further curing of 28 days in air. In the same study, ESEM and XEDS analyses revealed that the healing product was calcium carbonate, which filled cracks from the faces to the middles of the specimens cured in water. In a continuing study, Qian et al. [25] investigated the effect of curing condition (air curing, water curing, 3% CO_2 concentration curing, and wet/dry curing) and preloading time (14, 28 and 56 days) on the self-healing capability of similar mixtures. The effect of nanoclay paired with slag and LP was also studied. Deflection capacities obtained via four-point bending test showed high recovery levels compared to sound specimens at all preloading ages. However, the use of nanoclay increased the recovery level of deflections.

This paper describes an experimental program conducted to test the effect of substituting cementitious materials (cement + fly ash) with LP on the mechanical, physical and self-healing properties of ECC. To better understand the role of LP fly ash incorporated mixtures, ECC mixtures with an FA-cement ratio (FA/C) of 2.2 were prepared, and cementitious materials were partially replaced with 5%, 10% and 20% LP filler. The study investigated compressive and flexural strength change, load–displacement curves in flexure, and self-healing capability of different compositions by assessing chloride ion permeability and electrical resistivity change. Microstructural changes were also analyzed within the cracks using X-ray diffraction (XRD) analyses and scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDS).

2. Experimental study

2.1. Materials

The mineral admixtures employed alongside standard Portland cement (PC) include Class-F FA (FA) (in conformance with ASTM C 618 [26]) and extremely fine limestone powder (LP). ECC mixtures included silica sand with maximum aggregate size (MAS) of 400 μm and 0.3% water absorption capacity, polyvinyl alcohol (PVA) fibers measuring 39 μm in diameter, 1610 MPa nominal tensile strength, 1.3 specific gravity and high range water reducing admixture (HRWRA).

The particle size distributions of solid ingredients are shown in Fig. 1, with chemical and physical properties of Portland cement and mineral admixtures indicated in Table 1.

2.2. Mixture proportions and specimen preparation

Four distinct ECC mixtures were prepared in which LP was substituted for cementitious materials (cement, FA and LP) in different proportions, as illustrated in Table 2.

A planetary-type mixer with a 25 L capacity was used for the production of the ECC mixtures. Casting was conducted with constant water to cementitious materials (W/CM), FA to Portland cement (FA/PC) and sand to fine materials (cement + FA + LP) ratios of 0.27, 2.2 and 0.36, respectively. After casting, specimens were stored in molds for 24 h at a temperature of 23 ± 2 °C and a relative humidity of 50 ± 5%. Subsequently, they were transferred into plastic bags where they were kept for 6 days at a temperature and relative humidity of 23 ± 2 °C and 95 ± 5%, respectively. They were then cured in a laboratory environment for 4 weeks at the same temperature and humidity.

Principal mechanical properties were evaluated by employing 360 × 75 × 50 mm prisms and 50 mm cubic specimens to examine flexural strength and mid-span beam deflection capacity, respectively, under four-point bending load, and to determine compressive strength after 7, 28, 56 and 90 days. Ø100 × 50 mm cylindrical specimens were used to analyze rapid chloride permeability (RCPT) and electrical resistivity. Results derived from the three specimen categories formed the basis of appraisals.

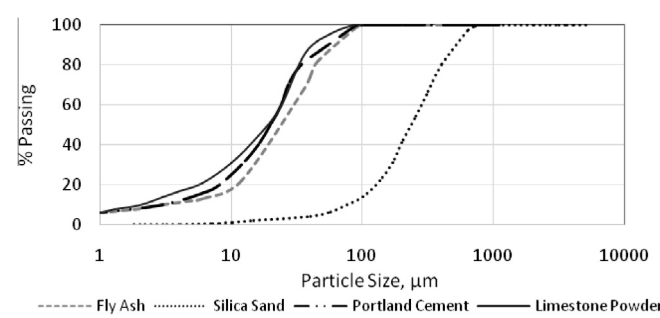

Fig. 1. The article size distributions of silica sand, Portland cement, fly ash, and LP.

Table 1
The chemical and physical characteristics of Portland cement and various mineral admixtures.

Chemical composition (%)	PC	FA	LP
$CaCO_3$	–	–	94
SiO_2	19.5	27	0.4
Al_2O_3	5.1	21	–
Fe_2O_3	2.92	4.2	–
MgO	2.5	1.8	2.5
CaO	61.8	9.8	–
Na_2O	0.30	2.2	–
K_2O	1.11	1.5	–
Loss on ignition	2.5	1.3	–
$SiO_2 + Al_2O_3 + Fe_2O_3$	27.52	82.2	–
Physical properties			
Specific gravity	3.1	2.02	2.71
Blaine fineness (m^2/kg)	408	325	460