Construction and Building Materials 189 (2018) 253–264

Contents lists available at ScienceDirect

Construction and Building Materials

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

Fresh state, mechanical & durability properties of strain hardening cementitious composite produced with locally available aggregates and high volume of fly ash

Mohamed A.A. Sherir *, Khandaker M.A. Hossain, Mohamed Lachemi

Department of Civil Engineering, Ryerson University, 350 Victoria Street, Toronto, ON M5B 2K3, Canada

HIGHLIGHTS

- Engineered cementitious composites with local aggregates and high volume fly ash.
- Assessment of fresh state, mechanical and durability properties of new composites.
- Influence of fly ash contents and aggregate types (silica sand and mortar sand).
- Recommendations on feasibility of using local aggregates.

ARTICLE INFO

Article history:
Received 3 April 2018
Received in revised form 4 August 2018
Accepted 30 August 2018

Keywords:
Engineered cementitious composites
Mortar sand
Silica sand
High volume of fly ash
Fresh properties
Mechanical and durability properties

ABSTRACT

This paper presents the effect of locally available mortar sand (MS) instead of Silica Sand (SS) and high volumes of Class-F fly ash with 55% and 70% cement replacement rates on the properties of engineered cementitious composite (ECC). ECC is a mortar based composite with a strain capacity of 300–500 times higher than normal concrete by using only 2% of fiber content. The ability of ECC to achieve strain hardening behaviour with closely spaced multiple microcracks can enhance the ductility and durability of concrete structures as well as increase their service life. In this study, the performance of ECCs made with MS and SS with high volumes of fly ash (HVFA) was judged based on the heat of hydration, slump flow, flexural and compressive strengths, ultrasonic pulse velocity, linear expansion/drying shrinkage, sorptivity and frost resistance characteristics in an attempt to produce cost-effective, sustainable and greener ECC mixtures (especially with mortar sand) for different construction applications. Replacing the silica sand by mortar sand at the same HVFA content in ECC mixtures, decreased slump flow and flow velocity, did not have a significant influence on strength (compressive and flexural) or bending capacity and reduced drying shrinkage and expansion properties by about 5% and up to 30%, respectively. Overall, the more or less similar fresh state, mechanical and durability properties confirmed the viability of producing ECC mixtures with mortar sand instead of silica sand in combination with high volumes of Class-F fly ash.

1. Introduction

Engineered cementitious composite (ECC) is a special type of high performance fiber-reinforced cementitious composites featuring high tensile ductility [26–27]. ECC is distinguished from the conventional fiber reinforced concrete (FRC) by attaining tensile strain capacity in excess of 4% by using only 2% of polyvinyl alcohol (PVA) fiber content [15]. In addition to PVA fibers, polyethylene (PE) fibers have also been used to obtain a strain capacity far beyond 3–5% [53,57]. The addition of oil coated PVA fibers can reduce the fiber/matrix frictional and chemical bonds (preferred property of fiber pull-out) which results in enhancing the fiber bridging of ECC [25]. This might result in keeping the crack opening constant by maintaining the equilibrium between the transferred stresses across the crack and the externally applied loads; or the unique multiple cracking behaviour of ECC might end earlier by forming a localized macro crack [22,34]. By doing so, ECC can attain a strain capacity of 300–500 times greater than normal concrete, enhance its ductility through achieving the unique behaviour of multiple cracking and improve its long-term durability and sustainability. In contrast, the mix design of FRC depends on

* Corresponding author.
E-mail address: msherir@ryerson.ca (M.A.A. Sherir).

https://doi.org/10.1016/j.conbuildmat.2018.08.204
0950-0618/

densifying the matrix tightly with aggregate by leaving as little voids as possible along with the help of fibers to delay the initiation of the cracks significantly. However, once the cracks have formed, they will continue to expand with ultimately negative consequences. Even though the mix design of ECC is almost similar to FRC, still ECC can achieve the distinctive strain-hardening behaviour through tailoring ECC microstructure [27].

Aggregates are originally used in concrete throughout the cement paste for economic reasons. This is because the cost of aggregate is much cheaper than cement and therefore, at least three-quarters of the concrete volume is occupied by aggregate. Although the economy has a significant role in putting more aggregate in cement-based materials, aggregates also have a significant technical advantage as they lead to higher volume stability and enhanced durability than cement paste alone [35]. The physical characteristics of aggregate such as volume, size and distribution of pores usually have a significant effect on concrete properties by providing crack bridging through aggregate locking action. Among others, using larger aggregate size will weaken the aggregate-cement paste interfacial bond and easily expose it to microcracking which adversely affect the mechanical and durability properties of concrete. Therefore, the addition of fibers to concrete might add more bridging action and superimpose the aggregate bridging effect to increase the stresses carried across the crack [29,30].

The design approach of ECC is based on maximizing the interaction between the fiber-matrix interfacial bond and improving the tensile ductility of ECC through applying strength and energy criteria to achieve the unique strain hardening and multiple cracking behaviours. The strength criterion will always keep the applied stresses below the maximum capacity of fiber bridging to form additional cracks in the crack plan while energy criterion is responsible for switching the crack type in ECC to a steady-state flat-crack propagation mode [30]. However, the addition of larger aggregate size throughout ECC pastes will increase their fracture toughness and reduce their ductility by increasing the tortuosity of the crack path and hence, prevent the steady-state flat-crack propagation mode in ECC [41]. In addition, when the size of aggregate is larger than the average distance between fibers in conventional fiber-reinforced concrete (FRC), fibers will clump together in balls (fiber balls) and this will negatively affect the distribution of fibers in paste which may have a negative impact on concrete properties [15]. Therefore, to maintain the unique ductile behaviour of ECC, the use of aggregate in ECC mixtures has been limited to be a fine aggregate with smaller particle size as in the case of micro-silica sand.

Besides the function of oil-coated PVA fibers, fly ash with low calcium content can improve the frictional bond of ECC matrix when act as filler. The addition of fly ash particles featured with a spherical shape and small particle size can enhance the compactness property of ECC matrix and increase the tensile ductility of ECC mixtures [52,56]. Also, using a high volume of fly ash (HVFA) can provide less cracking by reducing the heat of hydration and internal thermal stresses significantly. Hence, adding HVFA to ECC matrix can reduce the matrix toughness which will enhance the multiple cracking formations and reduce the steady-state crack width in ECC to benefit the mechanical and long-term durability properties of the structure [24,52,56].

The addition of locally available aggregates with larger particles size instead of normally used silica sand (SS) and high volume of FA (with spherical and smaller particle size) in ECC mixtures tends to increase and decrease matrix toughness, respectively. Hence, local aggregates in combination of FA can be successfully used in the production of ECC mixtures without affecting the ductility and strain hardening properties. So evaluation of FA contents with local aggregates is important to achieve an ECC with desired strain hardening and multiple cracking behaviour. Very limited research studies taking a holistic approach covering fresh state, mechanical and durability properties of local aggregate based ECCs with varying FA contents are conducted in the past. The previous works focused only on the mechanical properties of ECC produced with local aggregates without doing fresh state and durability studies [41,49]. It is practically not feasible to predict ECC durability from mechanical properties which warrants detailed study on durability properties of such ECCs for practical construction applications. Therefore, the current research was focussed on the fresh state, mechanical and durability properties of ECCs made of local aggregates in combination with FA compared to their silica sand counterparts. The incorporation of local aggregates replacing micro-silica sand in combination with FA will lead to the development of low cost ECC mixtures with satisfactory properties and increase their acceptance in construction industry for production and wider commercialization.

This paper presents the results of a comprehensive experimental investigation with analyses on the effect of silica sand, locally available mortar sand and FA contents on the fresh state, mechanical and durability properties of ECCs such as heat of hydration, slump flow, flexural and compressive strengths, ultrasonic pulse velocity, linear expansion/drying shrinkage, sorptivity and frost resistance. The findings and recommendations of this research will significantly contribute to the existing knowledge of technology by introducing new cost-effective and greener mortar sand based ECC mixtures.

2. Experimental program

2.1. Materials and ECC mixture proportions

The materials used in the production of ECC mixtures were Portland cement (C) Type I general use (GU) and Class-F fly ash (FA) with calcium content 3.55%. Silica sand (SS) with a maximum grain size of 0.40 mm (mean size of 0.30 mm) and mortar sand (MS) with a maximum size of 1.18 mm. The purpose of using locally available mortar sand is to replace relatively costly silica sand [41,49]. Polyvinyl alcohol (PVA) fibers with a length of 8 mm, diameter of 39 μm, tensile strength of 1620 MPa, elastic modulus of 42.8 GPa and maximum elongation of 6.0% were used to meet the requirements of strain-hardening performance of ECCs [29]. Water and a polycarboxylic-ether type high-range water-reducing admixture (HRWRA) were also used in the production of ECC mixtures. The chemical composition and physical properties of Portland cement, Class-F fly ash and silica sand are presented in Table 1. The grain size distributions of silica sand, mortar sand, Class-F fly ash and Portland cement are shown in Fig. 1.

Four ECC mixtures were designed to investigate the influence of aggregate type/size, along with Class-F FA/C ratios on the fresh, mechanical and durability properties of ECC. The first and second ECC mixes (designated as F_1.2_SS & F_2.2_SS) were produced from Class-F fly ash and silica sand with two cement replacement ratios FA/C = 1.2 or FA/binder = 55%, and FA/C = 2.2 or FA/binder = 70%, respectively. The third and fourth ECC mixes were same as the first two mixes except that aggregate type and size were locally available mortar sand and 1.18 mm, respectively.

Table 1
Chemical composition and physical properties of Portland cement and Class-F fly ash.

Chemical composition (%)	Cement (C)	Class-F Fly Ash	Silica Sand
Calcium Oxide CaO	61.40	3.55	0.010
Silicon Dioxide SiO_2	19.60	46.19	99.88
Aluminium Oxide Al_2O_3	4.90	23.39	0.050
Ferric Oxide Fe_2O_3	3.10	21.81	0.015
Magnesium Oxide MgO	3.00	0.82	0.003
Sulfur Trioxide SO_3	3.60	1.13	–
Alkalis as Na_2O	–	0.51	0.007
Loss on ignition LOI	2.30	2.12	0.100
Sum ($SiO_2 + Al_2O_3 + Fe_2O_3$)	27.60	91.39	99.94
Physical properties	Cement (C)	Class-F Fly Ash	Silica sand
Residue 45 μm (%)	3.00	18	–
Density (g/cm^3)	3.15	2.54	–
Blaine fineness (m^2/kg)	410	306	–