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# Green lightweight ferrocement incorporating fly ash cenosphere based fibrous mortar matrix

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ABSTRACT

This paper presents an experimental assessment on the suitability of fly ash cenosphere (FAC), a waste residue from coal fired power plants, for use in lightweight ferrocement construction. Ferrocement is a special type of thin walled reinforced concrete constructed of hydraulic cement mortar and closely spaced layers of steel wire mesh. In this study, the mortar mix was prepared by replacing the sand (a typical ingredient of ferrocement matrix) with FAC at 40 %, 50 % and 60 % FAC weight fractions in mortar. Single and double layers of galvanized iron welded wire mesh were used as the main reinforcement while small volume fraction (0.50 %) of PVA fibers was also added as a discontinuous reinforcement resulting in a hybrid composite. The mortar mixes were tested for mechanical strength including compressive strength, elastic modulus and Poisson's ratio whereas the ferrocement composites were evaluated for flexural performance. The ferrocement composite properties were compared with high strength quartz sand mortar matrix as well. FAC was found to be excellent in producing structural lightweight ferrocement composites (density 1332.09–1457.89 kg/m$^3$) with excellent mechanical properties. The PVA fibers helped improve the inherent brittleness of FAC composites. Thus, lightweight ferrocement elements with higher specific strength (18.39–26.65 kPa/kgm$^{-3}$), flexural strength (14.47–28.13 MPa), and tensile strength (5.69–11.06 MPa) can be produced, with utilizing FAC waste residue. The use of such composites in construction can promote sustainable development by minimizing waste.


## 1. Introduction

Ferrocement is a distinctive type of thin-walled reinforced concrete constructed of hydraulic cement mortar (ACI 549R-97, 1997) in which the main reinforcement is single or multiple layers of wire mesh, unlike the conventional reinforced concrete where steel reinforcing bars are used as reinforcement. It was invented by Joseph Louis Lambot in 1848 (Naaman, 2000) and originally conceived for boat construction. However, it gained wide acceptability as a construction and building material in the mid-20th century, and since then its use in the construction industry has been ever increasing because of the advantages it offers over conventional reinforced concrete. Some of the advantages are:

i. Ease of construction due to less skill required in fabrication
ii. Cost effectiveness due to the lower cost of raw materials and labor
iii. Better flexural performance due to higher specific surface of reinforcement
iv. Ability to be cast in a variety of shapes, like domes, shells, cylinders, and likewise
v. Suitability as repair and retrofitting material for existing concrete structures
vi. High tensile strength to weight ratio due to its lighter unit weight
vii. Superior cracking behavior, particularly suited for liquid retaining structures
viii. Greater impact resistance and toughness

Due to its advantages over traditional reinforced concrete, ferrocement finds wide applicability in low-cost modular housing, water tanks, swimming pools, silos, roof shells, foot bridges, partitioning structures, and so forth. The use is common throughout the world but it is more popular in developing countries due to its

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cost-effectiveness and requires less labor skills. Various ferrocement applications include boats (Suleiman et al., 2013), water tanks (Guerra et al., 1978; Watt, 1978), structural retrofitting (Shannag, 2009, 2002), roofing elements (Ahmad, 2010a, 2010b; Hago et al., 2005), floors (Fahmy et al., 2012), permanent formwork for concrete members (Krishnan and Abraham, 2016), and typical building structural elements (Wang et al., 2004).

In the past, much of the research work on ferrocement was conducted with a cement binder and sand used for matrix formulation. Studies on lightweight ferrocement and efficient utilization of waste materials for producing structural ferrocement are sparse. A few studies have been conducted utilizing industrial waste as partial replacement of cement, for instance, Yerramala et al. (2013) incorporated metakaolin in ferrocement as a replacement for cement (5%–25% by binder weight) and evaluated the flexural behavior of the resulting composites, and an optimum value of 10% for replacing cement with metakaolin was proposed. In another study, ground granulated blast furnace slag was used to replace 50% and 60% of cement binder in ferrocement (Memon et al., 2007a), and it was concluded that ferrocement with higher slag amounts had adequate workability and flexural strength for the construction of thin ferrocement sections to withstand structural loading.

Additionally, some experimental findings focused on producing lightweight ferrocement. (Desayi and Reddy, 1991) replaced sand (in the range of 20%–100%) with foamed blast furnace slag, in the mortar matrix of ferrocement. Lightweight ferrocement was achieved at 80% and 100% dosages of foamed blast furnace slag, but the corresponding mechanical properties were too low (compressive strength 9.7 MPa and 13.5 MPa) to be classified as structural concrete (minimum compressive strength of 17 MPa as defined by (ACI 213, 2003)). Similarly, (Memon et al., 2007b) tried a rather innovative approach where the sandwich construction methodology was employed with ferrocement as the encasement and aerated concrete as the core. Although this novel approach led to produce exceptionally lightweight composites, the poor ultimate flexural strength discouraged its applicability for structural components.

The research studies conducted so far are insufficient to decide on a suitable material for producing structural lightweight ferrocement which also has a positive impact on sustainability. Therefore, there is a need for such a lightweight material which can be used to replace sand in the mortar matrix so as to achieve the desired strength and density targets for ferrocement applications. One such suitable candidate is the fly ash cenosphere (FAC) which has been studied, in the recent years, for its suitability as a filler aggregate in cement-based composites (Hanif et al., 2017c).

FACs are lightweight hollow spherical particles obtained as waste residue from coal fired power plants (Diamond, 1986). Their composition is somewhat similar to regular fly ash, with the particle size relatively larger (Hanif et al., 2017a). Utilization of FAC in cement-based material dates back to 1984 in the work of (Montgomery and Diamond, 1984). Early on, it was used for partial replacement of cement due to its chemical reactivity in cementitious systems. Later, the beneficial effects in producing lightweight composites were determined (Blanco et al., 2000) and, since then, researchers have been investigating the various properties of cement composites incorporating FAC as filler material (Hanif et al., 2017d). (Wang et al., 2014, 2012) carried out in-depth study on cementitious composites incorporating FAC filler and concluded that due to the lower density (600–800 kg/m$^3$) and pozzolanic activity, FAC could be successfully employed for structural lightweight concrete applications. In some other studies on fiber reinforced composites (Hanif et al., 2016; Wang et al., 2013), it was proposed that FAC could be well bound in a fibrous matrix, with the fiber inclusion compensating for the inherent brittleness of lightweight concrete by enhancing the corresponding strain capacity. FAC incorporation as lightweight filler in reinforced concrete elements was studied by Yan et al., in which the flexural (2016a) and punching shear behavior (2016b) of such concretes was analyzed. The useful applicability of FAC was further confirmed in their findings.

The chemical composition of FAC is somewhat similar to fly ash as the source for both is the same; i.e. residue from coal fired power generation plants (Blanco et al., 2000). Due to this reason, FAC possesses some degree of pozzolanic reactivity in cementitious systems (Hanif et al., 2017b). The reactivity not only depends on the amounts of lime and amorphous silica present in the FAC particles, but also it is affected by the FAC particle size (Wang et al., 2012). Hence, although the FAC exhibits reactivity, its larger particle size hinders the extent of reactivity in relation to typical fly ash. The key advantage of using FAC is its lightweight, relatively larger size, and hollow spherical morphology as shown in the SEM image (Fig. 2 (b)). These characteristics of FAC lead to increased total air content within the cementitious system thus reducing the unit weight of resulting composite.

### 1.1. Research significance

The behavior of FAC in cementitious systems has already been studied, both for plain and reinforced concrete structures. However, findings on ferrocement fabricated from FAC incorporated mortar matrix are lacking. The present study was conducted to fill this research gap. In this experimental study, the aforementioned shortcomings have been addressed by developing lightweight ferrocement composites from FAC and evaluating their flexural performance in comparison with typical ferrocement with sand mortar. FACs were used as replacement for sand in hydraulic cement mortar while small amounts of poly-vinyl alcohol (PVA) fibers, as discontinuous fibers, were also added for improved flexural performance. PVA fibers were selected because of their ease of dispersion in the mortar mix and their hydrophilic nature (Yang et al., 2009). Such study would provide useful information for the development and application of green lightweight ferrocement while minimizing rather efficiently utilizing, the waste residue of coal fired electricity producing plants.

## 2. Materials and experimentation program

### 2.1. Materials

Ordinary Portland cement conforming to ASTM type I (Type 52.5 supplied by Hong Kong Green Island Cement) was used as a binder for the ferrocement matrix. Fly ash cenospheres (FACs), incorporated as lightweight filler material in the matrix, were acquired from Zhen Yang Mineral Powder Processing Plant, Hebei, China. The bulk density and surface area (as determined by Brunauer-Emmett-Teller Analysis (Brunauer et al., 1938)) was 720 kg/m$^3$ and 6.02 m$^2$/g. The materials characterization comprised both physical and chemical tests to ascertain the suitability of using the materials in the ferrocement composites. The chemical composition of the powders (cement and FAC) was determined by X-Ray fluorescence spectroscopy (XRF) which provided the mass fractions of the oxides. The XRF results are tabulated in Table 1. The cement composition conformed to the minimum requirements of (ASTM C150-04, 2004). The XRF results indicated that the FAC belongs to Class ‘F’ of coal fly ash as defined by (ASTM C618-01, 2001). The presence of amorphous silica and lime in FAC indicates its pozzolanic activity which may be useful in attaining a higher strength activity index of the resulting cement composite (Wang et al., 2012). The particle size distribution of the powders was done by laser granulometry (using Coulter LS230) which can indicate the particles sizes for