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Influence of steel fibers on the mechanical properties and impact resistance of lightweight geopolymer concrete

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HIGHLIGHTS

- Effect of uncrushed and crushed OPS on mechanical properties reported.
- Impact behavior of geopolymer concrete is investigated.
- Significant improvements in tensile and flexural strengths of FROPSGC observed.
- Uncrushed OPSGC has better impact resistance compared to crushed OPSGC.
- Significant improvement in impact energy of FROPSGC.

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ABSTRACT

The influence of fiber on the mechanical properties and impact resistance of oil palm shell geopolymer concrete (OPSGPC) prepared with ground granulated blast-furnace slag (GGBS) and palm oil fuel ash (POFA) as binders is reported. The mechanical properties of OPSGPC, namely compressive, flexural, splitting tensile strengths, and modulus of elasticity were investigated; impact resistance was found through drop hammer test. The addition of 0.5% steel fibers enhanced the splitting tensile and flexural strengths of fiber reinforced OPSGPC (FROPSGPC) by about 19–38% and 13–44%, respectively compared to the non-fibrous OPSGPC. The FROPSGPC with uncrushed OPS developed higher initial and final impact resistance compared to specimens with crushed OPS. With the addition of 0.5% steel fiber, the first crack load of the geopolymer concrete increased by 1.5–3.5 times compared to the corresponding mixes of OPSGPC without fiber. The ultimate impact energy of most of the OPSGPC and FROPSGPC with uncrushed OPS was found 15–152% higher compared to the corresponding mixes with the crushed OPS aggregate.

1. Introduction

Rapid industrialization during the last 100 years brought remarkable changes to method of construction and in materials; over 11 billion tons of concrete are being used annually [1] making it as one of the most widely used construction materials. However, the developmental activities were accompanied by exploitation of natural resources in the production of concrete. The realization of overuse of natural resources as construction materials in concrete production had alarmed the entire world to minimize the exploitation of natural materials and this led to search for alternate construction materials towards achieving sustainability. In relation to this, the usage of recycled aggregates is vital in developing sustainable concrete through effective inclusion of industrial by-products considered as waste materials and this in turn would reduce the exploitation of natural resources. The optimum usage of recycled aggregate was found 30% with 0.6% steel fiber in terms of strength and cost benefit analysis [2]. One of the major constituent materials in concrete is cement and its production and energy demand is well established. The emission of carbon dioxide (CO_2) during cement production is a major concern and pressurized researchers to look for alternative of binding material in concrete. Geopolymer concrete, which excludes conventional cement as binder, is considered as one of the potential alternatives to cement based concrete. The use of industrial by-products such as fly ash (FA), slag (GGBS), rice husk ash (RHA), metakaolin (MK), palm oil fuel ash (POFA), etc. as partial and whole cement replacement in conventional and geopolymer concrete has been reported [3–6]. In addition, another industrial by-product from

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palm oil industry, known as oil palm shell (OPS) was used as whole replacement for conventional crushed granite aggregate as sustainable material in lightweight concrete and geopolymer lightweight concrete production and owing to its ductility and energy absorbing characteristics OPS has been successfully tested for blast loads [7,8]. In Malaysia, 4.5 million tons of OPS and 0.516 million tons of POFA are produced annually from the palm oil industry as waste material [9].

The replacement of conventional aggregate by OPS and usage of POFA in geopolymer concrete (GPC) would reduce the environment pollution as these two materials are dumped in the factory yards causing land and air pollution. Thus, this work focusses on the use of POFA and GGBS as binding materials and OPS as whole replacement for crushed granite aggregates in the development of geopolymer concrete.

Fibers are usually used in concrete to control cracking due to plastic and drying shrinkages; they also reduce the permeability of concrete by reducing bleeding water. Bernal et al. [10] carried out a study on the effect of steel fiber on the mechanical properties of slag-based GPC and reported that utilization of steel fiber reduces the compressive strength but largely improve splitting tensile and flexural strengths. They reported that alkali-activated fiber reinforced slag concrete shows better mechanical performance than Portland cement concrete. Aldahdooh et al. [11] investigated that the ultrafine POFA with micro steel fiber significantly improve the compressive strength of mortar. In their study, they used micro-steel fibers (6 and 13 mm) with diameters of 0.16 mm and tensile strength of up to 2850 MPa and achieved the compressive strength up to 158 MPa, a direct tensile strength of 13.78 MPa.

Puertas et al. [12] conducted a study on polypropylene (PP) fiber reinforced GPC and found no reduction in compressive strength. In their study, different types of source materials such as slag, fly ash and slag/fly ash combination were used. The polypropylene (PP) fibers of 0.5% and 1% by volume of mortar were used. The addition of 0.5% and 1% PP fiber did not affect the compressive strength of slag based FRGPC at 2- and 28-day. Though, in fly ash based FRGPC the 2-day compressive strength was increased due to increase of PP fiber contents but a slight reduction was observed at 28 days in the same composite. In the case of combined slag/fly ash based FRGPC, slight increase in compressive strength was noticed by increasing the PP fibers from 0.5% to 1.0% at both ages. Shaikh and Hosan [13] studied the mechanical properties of steel FRGPC at elevated temperatures. In their study, they investigated two types of alkali activators (Na and K-based), and reported that Na-based activators showed much higher compressive and indirect tensile strengths in steel fiber reinforced GPC. Another study [14] conducted on the effects of micro steel fibers on the mechanical properties of fly ash based geopolymer composites and reported that addition of micro steel fibers significantly improve flexural strength and energy absorption capacity. On the contrary, Yu et al. [15] investigated the effects of single sized and hybrid steel fibers in the ultra-high performance conventional concrete and reported that the hybrid steel fibers is more efficient for improving the energy dissipation capacity of concrete under impact load.

It is reported [16] that the addition of GGBS improves the quality of OPS concrete (OPSC) by reducing water absorption and the use of 40% GGBS performed the best due to decrease in permeable pores. Another study shows [17] that even though an increase in slag content led to the reduction in the strength, the OPSC with GGBS as high as 60% cement replacement satisfied the minimum stipulated strength required for structural lightweight concrete (LWC). Ahmmad et al. [18] carried out a study by using two industrial wastes from palm oil mill, OPS and palm oil clinker (POC) and reported that the replacement of OPS by POC as coarse aggregate has positive impact on the compressive strength. A review [19] on green concrete for the potential usage of waste materials in the form of cement replacement, aggregate replacement as well as fiber reinforcement reported that if proper treatments and selection of materials are accomplished, these waste materials could be incorporated in concrete to improve mechanical and durability performances. A recent microstructural analysis has been investigated for the potential usage of POFA and the specimen contained POFA showed less surface water absorption and higher durability under acid and sulfate attack [20]. Islam et al. [21] reported that the OPSC with POFA as a 10% cement replacement exhibited the most optimum sustainability performance in terms of both cost and eco-efficiency of OPSC. Apart from this, another study [22] shows the comparison of chemical composition in geopolymer mortar among the binders GGBS, POFA and FA in terms of strength; this study also reported a possible estimation of the concrete strength by modifying the chemical composition and varying binder content.

In another study reported the early improvement of compressive strength of PP based FRGPC compared to plain concrete [23]. The source material used in that study was FA and calcined kaolin. The compressive strength of FRGPC containing 0.5% PP fiber (by wt.) reached about 52 MPa at the age of 3 days and fiber content beyond 0.5% reduced the compressive strength. Yap et al. [24] performed a study on the torsional behavior among the normal weight concrete and OPSC using steel fiber and reported that the additional of steel fiber reduces crack width of both the normal weight concrete and OPSC specimens by about 30–43% and 42–60%, respectively. In their investigation it was also reported that the OPSC is more ductile than normal weight concrete. Yoo et al. [25] carried out a study on concrete beam to enhance its energy absorption capacity under impact load by incorporating steel fiber. Yoo et al. [25] conducted drop-weight impact test to evaluate the impact capacity of fiber reinforced concrete beam and reported that the first crack was mainly influenced by the matrix cracking rather than the fiber bridging effect but the final crack is strongly influenced by the fiber content.

This research focusses on the development of sustainable GPC using POFA and GGBS as binders and OPS as whole replacement of conventional coarse aggregates. In order to enhance the impact resistance of POFA-GGBS based lightweight OPS geopolymer concrete (OPSGPC), steel fibers were added and the impact resistance of the OPSGPC was investigated by drop-hammer method.

2. Experimental program

The main objective of the experimental study was to evaluate the impact resistance of steel fiber reinforced OPSGPC. The other tests include compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity.

2.1. Materials

2.1.1. Binder

POFA with a specific surface area and specific gravity of 1720 m^2/kg and 2.14, respectively, was used in this investigation. GGBS was used along with POFA as the source material in the development of GPC. The specific surface area and specific gravity of GGBS were 3200 m^2/kg and 2.9, respectively. The binder contents for normal weight geopolymer concrete (NWGPC) and lightweight geopolymer concrete (OPSGPC) were 308 kg/m^3 and 400–454 kg/m^3, respectively.

2.1.2. Fine and coarse aggregate

Manufactured sand (MS) with specific gravity and fineness modulus of 2.60 and 3.19, respectively, was used as fine aggregate. The fine aggregate content for NWGPC was kept constant at 618 kg/m^3, while it varied from 998 to 1134 kg/m^3 in case of OPSGPC.

Conventional crushed granite aggregate as shown in Fig. 1 (a) was used for comparison purpose. The other coarse aggregate, OPS used in this study was collected from the local palm oil factory with maximum size of 14 mm (Table 1). Generally, the raw OPS collected from the factory had oily surfaces that could hamper the