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A novel polymer concrete made with recycled glass aggregates, fly ash and metakaolin

Kou Shi-Cong [a,b], Poon Chi-Sun [a,*]

[a] Department of Civil and Structural Engineering, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong
[b] Guangdong Provincial Key Laboratory of Durability for Civil Engineering, College of Civil Engineering, Shenzhen University, China

HIGHLIGHTS

- ▶ The study reveals a polymer concrete made with recycled glass, fly ash and metakaolin.
- ▶ The mechanical and the durability properties of the PC were investigated.
- ▶ Results indicate that all compositions assessed display high strength and *E*-values.
- ▶ MK and FA have a significant effect on the strengths and *E*-values of the PC.
- ▶ We conclude that a fast cured PC can be synthesized with recycled waste glass.

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ABSTRACT

A novel polymer concrete (PC) was synthesized by mixing epoxy resins and waste glass as aggregates. In this study, metakaolin (MK) and fly ash (FA) were used as filler and compositions with 0%, 10% and 15% by weight of recycled glass sand (<2.36 mm) were prepared to investigate the mechanical and durability properties of the PC. The results indicated that all compositions assessed in this study display high strength and modulus of elasticity values. MK and FA have a significant effect on the compressive strength, the flexural strength and the modulus of elasticity of the PC. Moreover, the PC made with recycled glass aggregate, MK and FA has good chemical resistance for 20% Na_2CO_3, 10% NaOH, tap water, and sea water. Besides the acceptable chemical resistance, the prepared waste glass PC shows low apparent porosity and low water absorption.

1. Introduction

As landfill space in Hong Kong is running out, the high waste generation rate is becoming a major concern. In 2009, there were about 27,400 tonnes of waste required to be landfilled per day, of which about 40% was construction and demolition (C&D) waste. In order to reduce the waste, the Hong Kong government implemented a charging scheme on C&D waste at the end of 2005 [1]. The reuse and recycling of solid waste has raised great concern to reduce waste disposal. Glass, being one of the major solid wastes in Hong Kong, has been investigated as to its ability to be recycled, reproduced and reused [2]. It is known that most recycled glass collected, especially beverage glass bottles, are used to reproduce new glass bottles. However, not all the waste glass is suitable for new glass production because most waste glass is contaminated with paper and other substances, colour mixes and is broken, which make the glass unfavorable for glass bottle production. Hence, researchers have been looking for another outlet for this waste glass. As glass is basically similar to sand, which is one of the major elements in concrete, research experts have been trying to use recycled glass in concrete to replace aggregate. If glass is proved to be feasible and workable in concrete, the recycling and reuse of this waste can be improved and hence the volume of wastes disposed of in landfills can be reduced.

A number of studies have been carried out for use recycled glass in civil engineering. Wartman et al. [3] reported that the crushed glass can be classified as well graded sands with gravel (SW) and exhibited excellent strength and workability characteristics. The low specific gravity (2.49) contributed to crushed glass having compacted maximum dry densities on the order of 16.6–16.8 and 17.5–18.3 kN/m^3 by the standard and modified proctor compaction tests, respectively. Direct shear friction angles were measured between 47° and 62° at normal stresses ranging from 0 to 200 kPa. Friction angles obtained by drained triaxial shear were on the order of 48° for similar stress ranges. Measured hydraulic conductivities

* Corresponding author. Tel.: +852 2766 6024; fax: +852 2334 6389.
E-mail address: cecspoon@polyu.edu.hk (C.-S. Poon).

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were on the order of 1–6 × 10^{-4} cm/s. Their results indicate that crushed glass is a readily available, freely draining, environmentally clean, relatively low cost material whose engineering performance properties generally equal or exceed those of most natural aggregates. Disfani et al. [4,5] reported that laboratory testing results indicated that medium and fine sized recycled glass sources exhibit geotechnical behavior similar to natural aggregates. Coarse recycled glass was however found to be unsuitable for geotechnical engineering applications. Shear strength tests indicate that the fine and medium glass encompass shear strength parameters similar to that of natural sand and gravel mixtures comprising of angular particles. Environmental assessment tests indicated that the material meets the requirements of environmental protection authorities for fill material. Landris [6] indicated that the recycled glass can be used in the US Army constructions after special treatment.

It has been known for a while that glass and cement are chemically incompatible. The alkali in the cement paste and the silica in the glass react in the presence of moisture [7–9]. Alkali–silica reactivity (ASR) is a chemical reaction between Portland cement concrete and certain aggregates. Shayan and Xu [10] indicated that glass is unstable in the alkaline environment of concrete and could cause deleterious alkali–silica reaction (ASR) problems. This property has been used to advantage by grinding it into a fine glass powder (GLP) for incorporation into concrete as a pozzolanic material. In laboratory experiments, it can suppress the alkali reactivity of coarser glass particles as well as that of natural reactive aggregates. It undergoes beneficial pozzolanic reactions in the concrete and could replace up to 30% of cement in some concrete mixes with satisfactory strength development. The drying shrinkage of the concrete containing GLP was acceptable. The drawback limits the utilization of recycled glass waste in cement concrete. However, there is no concern of ASR when recycled glass aggregate is used in polymer concrete.

Polymer concrete (PC) is a composite material produced by combining dry aggregates, in which the monomers (binders) undergo polymerization (hardening) after the addition of additives, catalysts and accelerators [11]. Due to its rapid setting, high strength properties and ability to withstand a corrosive environment, Polymer-based building materials have received special attention in many countries all over the world. They are widely used in building foundation walls, small houses and shops [12], as bridge deck overlays [13] waste water pipes, and even structural and decorative construction panels. The widely used materials are: polymer composites [14], nano polymer composites [15], fly ash composites [16] and glass reinforced plastics (GRP) [17]. Coarse and fine aggregates, such as crushed stone, sand, gravel, and fly ash, which result as a waste from thermal power plants, are widely used as inorganic fillers in the production of PC [14–18]. Marble, basalt, and quartz as well as, rice straw, bagasse, and cotton stalk fibres are also used as reinforcing fillers in PC production [19–24].

Good mechanical properties and the excellent chemical resistance of polymer concretes make them cost-effective construction materials for civil engineering applications. These properties of polymer concretes are dependent upon the type of polymeric binder and the filler materials used. The effectiveness of fly ash in PC is well-known. Varuguese and Chaturvedi [25] used fly ash as fine aggregate and observed an improvement in mechanical properties and a reduction in water absorption, with good compatibility between sand and ash [25]. Fly ash improves the workability of fresh PC mortar and the resulting concrete shows excellent surface finish [26]. The small size of spherical fly ash particles also contributes to a better packing of the aggregate materials, which reduces porosity and hinders the penetration of aggressive agents, thus considerably improving the chemical resistance of PC [26]. Rebeiz et al. reported that a replacement of 15% by weight of fly ash improves the compressive strength of unreinforced PC cylinders by about 30% and the flexural strength of steel-reinforced PC beams by about 15% [27].

Metakaolin (MK) is produced from kaolinite clay through a calcining process. Many Portland cement concrete mixing companies already use very successfully the pozzolanic characteristics of MK as a replacement for cement in their mix design (i.e. as a mineral admixture) [28–30]. An advantage of MK over other pozzolans is that MK is a primary product, not a secondary product or by-product. This allows the manufacturing process to be structured to produce the optimum characteristics for MK, ensuring the production of a consistent supply. Another advantage of MK is its colour, which is white and produces much lighter coloured PC for decorative construction panels.

The aim of this work is to study the suitability of PC prepared with recycled waste glass aggregate to be used as polymer-based building material, and to report on the properties such as compressive strength, flexural strength, modulus of elasticity, chemical resistance and water absorption of the PC prepared with MK and FA.

2. Experimental programme

2.1. Materials and specimens preparation

The mix design for the PC systems is optimized for workability, strength and economy, depending on the intended application [27,31]. The epoxy resin system used is based on a diglycidyl ether bisphenol A and an aliphatic amine hardener with low viscosity (500–700 MPa s) and flexural strength of 70 ± 5 MPa, which cluster the waste glass aggregate. In this study, the resin content used was 13% by weight. The coarse aggregate was recycled glass (10–5 mm), whereas the fine aggregates were recycled glass sand (<2.36 mm), fly ash (FA) and metakaolin (MK). The coarse recycled glass aggregate and recycled glass sand was oven-dried for a minimum of 24 h at 120 °C to reduce their moisture content to less than 0.5% by weight, thus ensuring good adhesion between the polymer matrix and the aggregates. The particle size distribution of coarse recycled glass aggregate and recycled glass sand are shown in Table 1. The major trace components of the MK and FA used in this study are also shown in Table 1 and the mix proportions of the PC are shown in Table 2. Mixing was typically done using conventional concrete mixers for a period of about 5 min. Specimens were then cast in steel moulds with 75 × 150 mm cylinders and 40 × 40 × 160 mm prisms.

In order to investigate the affect of casting pressure on the compressive strength of the PC, after control specimens are cast in steel moulds with 75 × 150 mm cylinders, a compression force from 3 to 12 kN/cm^2 was applied for 60 s to allow curing at room temperature.

2.2. Testing

2.2.1. Compressive strength and modulus of elasticity

BS standards applicable to cement-based materials are used as guidelines whenever applicable. PC compression tests were performed on 75 × 150 mm cylinders at the loading rate of 1.25 mm/min according to the ASTM C39-05 [32] standard. The compression specimen was tested in a Denison compression machine with a loading capacity of 3000 kN. Electrical strain gauges bonded to the specimens and connected to a data acquisition system were used to read strains for modulus of elasticity evaluation.

Table 1
Major trace components of MK, FA and particle size distribution of recycled glass (dried at 105 °C).

Component	%		Particle size distribution of recycled glass		
	FA	MK	BS sieve size (mm)	Passing (%)	
				10–5 mm	<2.36 mm
Al_2O_3	28.21	43.9			
SiO_2	56.79	53.2	10	100	–
Na_2O	–	0.17	5	96	100
TiO_2	–	1.68	2.36	38	95.4
CaO	<3	0.02	1.18	5.2	52.3
Fe_2O_3	5.31	0.38	0.6	1.3	23.5
MgO	5.21	0.05	0.3	0.5	12.3
K_2O	–	0.10	0.15	–	8.6
Ignition loss	3.90	0.50	0.075	–	1.5