Cement & Concrete Composites 34 (2012) 975–981

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

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

Performance of cement mortar made with recycled high impact polystyrene

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A R T I C L E I N F O

Article history:
Received 7 October 2011
Received in revised form 8 May 2012
Accepted 22 June 2012
Available online 27 June 2012

Keywords:
Recycled high impact polystyrene (HIPS)
Cement mortar
Strengths
Dynamic modulus of elasticity
Thermal conductivity
Resistance to freeze–thaw cycles

A B S T R A C T

This paper investigates the possibility of utilizing recycled high impact polystyrene (HIPS) as a sand substitute in cement mortar, in order to reduce the solid waste disposal problem and thereby environmental pollution and energy consumption. The results show that the compressive strength and splitting tensile strength of mortar are decreased by replacing sand with HIPS, but the decrease in the splitting tensile strength is much smaller. HIPS makes the mortar become more ductile and increases the energy dissipation capacity. HIPS decreases the dry bulk density, dynamic modulus of elasticity, thermal conductivity, and also water vapor permeability, but does not affect the resistance to freeze–thaw cycles. The use of mortar made with various percentages of HIPS offers promise for applications as medium or light weight concrete, mostly due to its improved thermal isolation, while adding value to a post-consumer plastic material that is now generally treated as solid waste.

1. Introduction

The unabated growth in the use of plastics in recent years is of considerable concern because of the difficulties involved with their disposal. The reduction of solid waste through reuse or recycling calls for appropriate research efforts. The ideal strategy would be to identify characteristics of value-added applications of recycled plastics. One potential use is as an ingredient of concrete which is the most frequently used construction material in the world because of its known advantageous characteristics. However, its drawbacks are well known, such as low tensile strength and brittleness. In comparison, plastic is more flexible, lighter and tougher, and it has the potential of lower thermal conductivity. If it can be shown that plastic improves certain properties of concrete, it adds value to a material that otherwise would contribute to the solid waste disposal problem.

The idea of using plastic as an ingredient of concrete is not new. Several researchers have studied ways to modify plastic such that it improves certain properties of concrete.

Poly-ethylene terephthalate (PET) aggregates manufactured from waste PET bottles were used as substitute for sand in concrete [1–3]. Such concrete was found to have similar workability characteristics, slightly lower compressive strength and splitting tensile strength, and moderately higher ductility than the reference concrete. Mortar containing PET and sand aggregate can fall into the structural lightweight concrete category in terms of unit weight and strength properties; i.e. shredded small PET particles may be used successfully as sand substitute in cement composites.

Fibers manufactured from postconsumer plastic milk or water containers were used as substitute for sand in concrete or as reinforcing material [4–6]. Such fibers were shown to arrest the propagation of micro cracks. The inclusion of high density polyethylene (HDPE) fibers did not noticeably improve the splitting tensile strength, but significantly increased the overall toughness, fracture energy, and postpeak load carrying capacity of the cement composite.

River sand was partially replaced by polyvinyl chloride (PVC) waste granules from scrapped PVC pipes [7]. Two major findings were made. On the positive side, the concrete prepared with partial sand replacement by PVC was lighter, more ductile, and had lower drying shrinkage and higher resistance to chloride ion penetration. On the negative side, workability, compressive strength and splitting tensile strength were reduced. In another study [8], ground plastics and glass were used to replace up to 20% of fine aggregates in concrete mixes, while crushed concrete was used to replace up to 20% of coarse aggregates. The investigation revealed that the three types of waste materials can be reused successfully as partial substitutes for sand and coarse aggregate in concrete mixtures.

Some engineering and thermal-setting plastics such as poly(acrylonitrile butadiene styrene)/polycarbonate (ABS/PC), melamine–formaldehyde (MF) and melamine were ground to be used

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http://dx.doi.org/10.1016/j.cemconcomp.2012.06.014

in concrete as aggregate substitutes [9–11]. The results showed that with 5% addition of ABS/PC plastic granules the mechanical properties of concrete are increased. Replacing sand with MF resulted in a lighter-weight concrete with improved characteristics, and in general the strengths increased as the percentage of MF was increased, up to a maximum value of approximately 30% MF. The melamine not only led to a low dry density concrete, but also a lower strength.

Recycled HDPE, PVC and polypropylene (PP) were used as coarse aggregates in concrete mixtures to improve the thermal properties of buildings [12]. Some chemical agents were used to treat waste HDPE or ABS powder to be used as additives in concrete with some positive effects [13,14].

Optimal quantities of plastic label waste collected during the glass recycling process were determined for the production of light weight concrete [15]. Some researchers tried to make synthetic lightweight aggregate using recycled PET with granulated blast-furnace slag (GBFS) [16] or HDPE with fly ash [17]. It was found that the adhered GBFS is able to strengthen the surface of waste PET lightweight aggregate and to narrow the transition zone owing to the reaction with calcium hydroxide. The HDPE-fly ash aggregates were manufactured through thermal processing using plastic to encapsulate and bind fly ash particles. As the fly ash content of the aggregates increased, all properties of the concrete were improved.

Recycled PET [18] or mixed plastic and paper waste [19] were processed into fibers to reinforce structural concrete. Both the compressive strength and elastic modulus decreased as fiber volume fraction increased. Cracking due to drying shrinkage was delayed in the PET fiber reinforced concrete specimens. The discrete reinforcement systems derived from abundantly available waste streams can have positive effects on the reinforcement of concrete. If unsaturated polyester based on recycled PET is properly formulated, it can be mixed with inorganic aggregates to produce polymer concrete or polymer mortar with good mechanical properties and durability performance. However, despite the low manufacturing cost of plastic wastes, precast polymer concrete components are not popular in construction because the time-dependent strength development mechanism and mechanical properties are still far from being fully understood [20,21].

High impact polystyrene (HIPS) is a common component of consumer electronics. With the fast increasing use and replacement of such electronics components, the waste disposal problem of HIPS will increase dramatically. This paper investigates the possibility of utilizing recycled HIPS as a sand substitute in cement mortar. If successful, such an application of recycled HIPS will be a major step towards reducing the solid waste disposal problem and reliance on natural resources, thereby reducing environmental pollution and energy consumption.

2. Experimental program

2.1. Materials and mix design

Type I general-purpose Portland cement according to ASTM C 150/C 150M-09 was used. River sand with a density of 2.44 g/cm^3 and recycled HIPS granules with a density of 1.04 g/cm^3 were used as fine aggregates. The sieve analysis results of the river sand and the ASTM C 33 limits for fine aggregates for concrete are listed in Table 1. The HIPS granules as shown in Fig. 1 were obtained by shredding the HIPS electronics waste to particle size less than 4 mm. Tap water was used in the experiment. The water to cement ratio was 0.55 in all the experiments, the cement to sand ratio is 1:3 for the control, and the mortars with HIPS replacement of sand by volume of 10%, 20% and 50% were also made. The mortar mix designs are listed in Table 2.

Table 1
Sieve analysis results of river sand.

Aperture of sieve (mm)	Passing of river sand (%)	Passing limit in ASTM C 33 (%)
4.75	100.00	95–100
2.36	99.79	80–100
1.18	96.85	50–85
0.84	89.17	–
0.60	79.59	25–60
0.42	62.99	–
0.30	35.78	5–30
0.175	15.66	–
0.150	–	0–10

Fig. 1. Picture of HIPS granules.

2.2. Production and curing of mortar

The mortar specimens were made and cured according to ASTM C 31/C 31M-09. The cement was mixed with water first, and then the aggregates were added. After mixing, the fresh mortar was filled into cylinder forms with the dimension of ϕ 50.8 mm × 101.6 mm for compressive strength, splitting tensile strength and dry bulk density tests, or ϕ 76.2 mm × 152.4 mm for thermal conductivity, water vapor permeability, dynamic modulus of elasticity and resistance to freezing and thawing tests. The specimens were demolded after 24 h and then cured in 23 °C water until the designed ages.

2.3. Test methods

2.3.1. Flow

The flow of the fresh mortar as a measure of workability was determined according to ASTM C 1437-07. The flow value is defined as the average increase in base diameter of the mortar, expressed as a percentage of the original base diameter.

2.3.2. Dry bulk density

The dry bulk density of the mortar was determined according to ASTM C 642-06. The specimens were dried in an oven at a temperature of 105 °C for 72 h before testing. The dry bulk density of the mortar numbers 1, 2, 3 and 4 was 1.98, 1.90, 1.81 and 1.56 g/cm^3, respectively.