Construction and Building Materials 182 (2018) 561–572

Contents lists available at ScienceDirect

Construction and Building Materials

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

Characterization of concrete composites with recycled plastic aggregates from postconsumer material streams

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HIGHLIGHTS

- Optical sorting allowed to reduce the impurity of sorted plastic to about 5%
- A fifth of the aggregate of concrete can be replaced with plastics from postconsumer material streams.
- Comparing different plastics, PVC allowed the lowest reduction of compressive strength.
- PAG allowed to increase thermal insulation of 5% and reduce water adsorption.
- The seasonal variations had an acceptable impact on concrete performances.
- The presence of surface contamination and entrapped air are critical factors to consider.
- Correlation analysis showed the importance of bulk density and PAG shape.

ARTICLE INFO

Article history:
Received 26 April 2017
Received in revised form 9 June 2018
Accepted 9 June 2018

Keywords:
Plastic
Concrete
Recycling
Recycled aggregates
Waste stream characterization
Post-cracking strength
Thermal conductivity
Water absorptivity

ABSTRACT

Plastic waste is today an crucial environmental issue for which innovative recycling techniques are needed. This research aims at investigating the feasibility of replacing fine aggregate in concrete by recycled plastics from real post-consumer streams. Different kind of plastics were sorted in Material Recovery Facilities (MRF) to realize different Plastic Aggregates (PAG) at different seasonal time. The concrete composites were characterized in terms of compressive strength, post-cracking compressive strength, toughness indeces, thermal conductivity, density, and water absorptivity. Correlation tables were used to understand the key material parameter of PAG governing concrete properties. The effects of the replacement percentage, the PAG kind, the level of impurity, and the time-related variations on the quality of the concrete are discussed. The presented results indicate that concrete composite with PAG from postconsumer waste is a promising research direction for developing eco-responsible construction materials with enhanced thermal insulation and water absorptivity.

1. Introduction

Worldwide plastics production reached 322 million metric tons (MT) and an average yearly growth rate of nearly 4% in 2015, and the associated environmental pressure has reached a critical point [1]. Despite persistent efforts by governments, businesses and individuals to increase plastic recovery and recycling rates, it is estimated that between 5 and 13 million metric tons end up as debris in rivers and oceans [2]. Even in regions with a developed waste management infrastructure, the global recycling rate is still limited. For instance, postconsumer plastic recycling rates are below 40% in all European countries [1]. In Quebec province (Canada) household plastics recovery rate is below 32%, although the actual recycling rate is expected to be even lower as only 17% of postconsumer plastics have been reportedly sold for recycling [3,4].

There exist several challenges to recycle postconsumer plastic waste [5,6], e.g.: the wide variety of polymer resins found in

Abbreviations: PAG, Plastic aggregates; PET, Polyethyene Teraphtalate; PE, Polyethylene; PVC, Polyvinyl chloride; PP, Polypropylene; PS, Polystyrene; PLA, Polylactic acid; PC, Polycarbonate; PU, Polyurethane; MRF, Materials recovery facility; MT, metric ton; E, Young's modulus; f_c, compressive strength; f_t, tensile strength; λ, thermal conductivity; TGA, Thermogravimetric analysis; EOL, End of linearity; W_e, Elastic toughness; I_3, Toughness index at 3 time linear deformation; I_5, Toughness index at 5 times linear deformation; PCS, Post-cracking strength.

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https://doi.org/10.1016/j.conbuildmat.2018.06.083
0950-0618/

municipal recyclable streams; the general mechanical incompatibility of molten plastics, the high levels of impurities requiring extensive sorting, conditioning and upgrading processes [7]. At Material Recovery Facilities (MRF), different kinds of plastics are generally sorted manually (based on packaging visual appearance) or with optical sorting units [8–10]. The sorted plastic streams are then granulated, washed and often pelletized by conditioners to obtain an easily marketable commodity [11]. Door-to-door collection programs are generating increasing volumes and kinds of plastic [5]. There is today a critical need for recycling technologies that can process large volumes of plastic at low cost with minimal prior conditioning, as an alternative to landfilling or incineration of plastic. In this context, concrete offers a promising opportunity for recycling postconsumer plastic waste due to its extensive worldwide volume production of about 10 km^3/y, which is about 5, 7.7 and 10 times more than the yearly use of fired clay, timber, and construction steel, respectively [12]. It is worth mentioning that recycled construction and demolition concrete waste are already used as aggregate for structural concrete [12,14]. Recycling PAG in concrete may help tackle three major environmental issues: (i) the ever-increasing amount of anthropogenic waste in landfills and the environment [13]; (ii) the concerns associated with extracting limited natural resources; (iii) improving the ecological footprint of concrete. A "systematic reuse of anthropogenic materials from urban areas" may result in a successful urban mining application [15].

In the last decades, numerous research on the use of PAG as sand replacement in concrete mixes have been undertaken [16–18], which demonstrated their potentially beneficial effect on concrete properties, such as: ductility, flexural toughness, density and thermal resistance [19–21]. Table 1 summarizes some results available in open literature on the effect of PAG on concrete properties. In particular, Table 2 reports typical Young's modulus (E), tensile strength (f_t) and thermal conductivity (λ) of the polymers considered in this study along with typical concrete raw materials such as aggregates, sand and cement paste. The introduction of PAG in concrete usually negatively affects the Young's modulus E and the compressive strength (f_c). It has been reported that E decreases proportionally with PAG volume [17], e.g., Correira et al. [22] found that E decreased by 13–31% for mixes where sand was substituted by polyethylene terephthalate (PET) aggregates at 7.5% volume. This is somehow expected as PET aggregates have a much lower E value than those of typical mineral aggregates (Table 2). It is also worth mentioning that the range in results was due to the variation of the water-to-cement ratio as the mix-designs were formulated to have a similar workability in terms of slump. Notably, contrarily to round sand particles or pellet-shaped PAG, more angular PAG decreased the workability of fresh concrete [22]. Moreover, PAG size can significantly impact fresh concrete workability, and thus porosity, compaction and mechanical performances in hardened concrete [17,23]. For the compressive strength f_c, previous studies have found that replacing sand by PAG also leads to a significant strength loss. Hannawi et al. [24] reported a decrease in f_c of respectively 30% and 28% by replacing 10% of fine aggregate volume with PET and polycarbonate (PC) aggregates. The loss of f_c was well correlated with the loss of E, hinting to similar degradation mechanisms. Visual inspections of the interface zones under an electron microscope showed large gaps around hydrophobic PAG, which weakens the bond with the cement paste [24–26]. The interface zones between PAG and the surrounding cement matrix resulted to be more porous than that of a cement-mineral aggregates interface [24]. Compressive Post-Cracking Strength (PCS) of concrete has several beneficial effects

Table 2
Some properties of high volume polymers, and concrete materials. 1 column width.

Material	E (GPa) [29,31]	f_t (MPa) [29]	λ (W/mK) [30,31]
PET	2.1–3.1	55–80	0.15
PE	0.6–1.4	18–30	0.33–0.52
PVC	2.7–3.0	50–60	0.17–0.21
PP	1.3–1.8	25–40	0.12
PS	3.1–3.3	30–55	0.105
Quartzite sand	70	–	4.45
Limestone gravel	70	–	2.29–2.78
Cement paste (w/c = 0.5)	36–40	–	1

Table 1
Summary of the reported effects of PAG on key material parameters.

Polymer used for PAG	Size[1]	PAG volume[2]	f_c loss[3] (%)	E loss[3] (%)	λ loss[4] (%)	Slump loss (%)	Reference	Notes
PET	<8 mm	7.5	31	31		8	[22]	e
	<4 mm	7.5	14	13		0		
RPOMIX (compound)	<2 mm	10	48.5				[21]	a
		20	75.7		50			
PET	<10 mm	10	30.5				[24]	e
		50	69	68.4				
PC	<5 mm	10	27.2				[24]	e
		50	63.9	61.9				
PET	<11.4 mm	20	49	48		100	[23]	e
	<2.6 mm	20	38	45		44		
PVC	<5 mm	15	18.6	13.8			[20]	b
		30	21.8	18.9				
PU	<4 mm	13.1	56		55	-14	[27]	c
		33.7	94		85	57		
PET	<2.5 mm	10	0		10.3		[28]	d
		30	0		20.6			
		100	86		73.8			

[a]Hydraulic lime mortars.
[b]Lightweight concrete with expanded clay aggregates.
[c]PUR foam lightweight mortars.
[d]Mortars.
[e]Concrete.
[1] Estimated from a 95% passing value from size analysis curves.
[2] Expressed as % of fine aggregates in concrete, and as % total volume in mortars.
[3] Under wet curing conditions, when specified.
[4] Dried specimens.