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Characterization of recycled polycarbonate from electronic waste and its use in hydraulic concrete: Improvement of compressive performance

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Abstract. Transparency, excellent toughness, thermal stability and a very good dimensional stability make Polycarbonate (PC) one of the most widely used engineering thermoplastics. Polycarbonate market include electronics, automotive, construction, optical media and packaging. One alternative for reducing the environmental pollution caused by polycarbonate from electronic waste (e-waste), is to use it in cement concretes. In this work, physical and chemical characterization of recycled polycarbonate from electronic waste was made, through the analysis by Fourier transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), energy dispersive spectroscopy (EDS) and scanning electron microscope (SEM). Then cement concrete was made with Portland cement, sand, gravel, water, and this recycled polycarbonate. Specimens without polycarbonate were produced for comparison purposes. The effect of the particle sizes and concentrations of recycled polycarbonate within the concrete, on the compressive strength and density was studied. Results show that compressive strength values and equilibrium density of concrete depend on the polycarbonate particle sizes and its concentrations; particularly the highest compressive strength values were 20% higher than that for concrete without polycarbonate particles. Moreover, morphological, structural and crystallinity characteristics of recycled polycarbonate, are suitable for to be mixed into concrete.

Keywords: polycarbonate; recycling; electronic waste; cement concrete; compressive strength

1. Introduction

Transparency, excellent toughness, thermal stability and a very good dimensional stability

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make Polycarbonate (PC) one of the most widely used engineering thermoplastics. According to IHS Chemical (2013), the polycarbonate highest consume is reported in the electrical/electronic industry. Global demand for polycarbonate exceeds 4.2 million tons per year. Unfortunately, such material is part of the so-called “electronic-waste” being México the major producer of Latin America with one million tons per year. In México, 70% of the solid urban waste is accumulated in controlled sites; however, less than 35% comply with environmental regulations; the remaining solid waste, is going to open sky dumps. One additional problem is that polycarbonate is mixed with other solid municipal waste, as reported the Organization for Economic Cooperation and Development (2013).

The rapid development in the Electric and Electronic Equipment (EEE) technology, combined with a short life cycle and a variety of uses, at least for most of the products like polycarbonate, poses a significant issue as far as their disposal is concerned. This has resulted in a continuous increase of Waste EEE, with some representative numbers: in the EU only, 9.5 million tons have been disposed in 2008 and this is expected to increase to 12.3 million tons in 2020.

Polycarbonate waste recycling involves two different kinds of processes: 1) Mechanical processing, which consist of separation, washing and pelletizing; through which the produced particles can be directly employed for elaboration of novel products by using extrusion or injection methods; 2) Chemical processing, for production of monomers, obtained from waste polycarbonate of optical discs, sheets or water bottles.

The main problems concerning to recycling of polycarbonate from EEE waste, including, which do not allow their large-scale applications are the variability of the product composition, the presence of polymers mixtures and the use of additives. The separation and the mechanical recycling of the EEE waste components contains a series of technical and economic challenges, for example they contain flame retarders.

Recycling of plastic wastes to produce new materials like concrete appears to be one of the best solutions, due to its economic and environmental advantages. Early investigations have been performed on cement composites containing different types of plastic waste as aggregates like polyethylene terephthalate (PET), polyvinyl chloride (PVC) and high-density polyethylene (HDPE). For example, has been described by Saikia and de Brito (2014) that porous and flaky plastic aggregates decrease the slump of fresh concrete while spherical shaped plastic increase it Moreover, plastics as aggregates can reduce the density, improve the thermal insulation and permeability properties, as well as reduce chemical attack, than conventional concrete. Concerning to mechanical properties. Saikia and de Brito (2012) have reported that the reduction in compressive, tensile splitting and flexural strength are observed in concrete when adding plastic aggregates.

The use of polycarbonate from electronic wastes is a viable alternative for substituting aggregates in cement concrete. Hannawi, Kamali-Bernard and Prince (2010) reported the compressive strength of 28-day cement mortar containing polycarbonate waste as aggregates in substitution of sand, which was replaced from 3% to 50%. The results show progressively decrement in compressive strength when plastic aggregates are added; up to a maximum decrement of 63.9% when 50% of polycarbonate is added. In terms of the concrete densities, the results show a decrement in the fresh and dry densities as the plastic aggregates concentration increase. The dry density decreased from 2173 kg/m^3 to 1643 kg/m^3, for mixes containing 50% of polycarbonate; such diminution is attributed to the lower specific weight of the polycarbonate in accordance with Saikia and De Brito (2012); such densities are comparable with those for lightweight concrete (1120-1920 kg/m^3) reported by ACI 213R (2003). The primary use of structural lightweight concrete as described by the National Ready Mixed Concrete Association (2003) is to reduce the dead load of a concrete structure, which allows reducing the size of columns, footings and other load bearing elements. Moreover, the architectural and functional design can be achieved more readily employing structural lightweight concrete instead of other kinds of concrete as suggested by ACI 213R (2003).

In order to show the importance of the use recycled materials in concrete, in this work physical and chemical characterization of recycled polycarbonate from electronic waste, and its effects of the particle sizes and concentrations within the concrete, on the compressive strength and density were studied. Polycarbonate was used as aggregate in partial substitution of sand in cement concrete specimens.

2. Materials and methods

2.1 Polycarbonate

Polycarbonate particles were obtained by extrusion from electronic waste, with size a) 1 mm of diameter and 3 mm length (1 mm×3 mm). One part of them was then cut in half to obtain the size b) 1 mm of diameter and 1.5 mm length (1 mm×1.5 mm). Polycarbonate particles are from waste electrical outlets, and they were donated by Polyvima Company (located at San Lorenzo Tepaltitlán, Toluca, Mexico). In Table 1, typical physical and mechanical properties of polycarbonate (from Clear Resin Pellets) presented in accordance with Covestro (2015), and Professional Plastics (2017).

Table 1 Typical physical and mechanical properties of Polycarbonate

Property	Values
Specific Gravity	1.2
Water Absorption**,** %	0.15
Light Transmission, Clear @0.118”%	86
Compressive Strength, MPa	86.1
Flexural Strength, MPa	93.0
Tensile Strength Ultimate, MPa	65.5
Tensile Modulus, MPa	2378.6
Izod Impact Strength, J/cm	6.4-8.5
Rockwell Hardness	M70/R118
Elongation, %	110

2.2 Physical and chemical characterization of polycarbonate particles

The morphological characterization of polycarbonate particles was evaluated by scanning electron microscopy (SEM), in a JEOL-JSM-6510 LV, located at Joint Center of Research in Sustainable Chemistry (CCIQS) of the Autonomous University of the State of Mexico (UAEM). Samples were observed in secondary electron mode at 5 kV.

The crystallinity of polycarbonate particles was evaluated by X-ray diffraction (XDR), by using a Siemens D-5000 diffractometer coupled to a copper-anode X-ray tube. The diffraction patterns were scanned from 5° to 70° 2θ angles.

The elemental quantification at microscopic level of polycarbonate particles were analyzed using scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) in a JEOL-JSM-5900 LV located at National Institute of Nuclear Research (ININ). Samples were observed with at 20 kV.

Fourier transform infrared spectroscopy (FT-IR) studies were performed to the polycarbonate waste particles, with a scanning range of 4000–500 cm^{-1} and using a spectrophotometer IR Prestige-21.

2.3 Sand and gravel aggregates

Sand and gravel aggregates were donated by Comercializadora Trimar (located at Toluca, México). Sieve analyses of sand and gravel aggregates are shown in Tables 2-3.

Table 2 Sieve analysis of sand (Fineness modulus: 1.62)

Size (μm)	Retained weight (g)	Retained weight (%)	Retained accumulated weight (%)
595	186	28.88	28.88
247	155	24.07	52.95
149	178	27.64	80.59
74	73	19.41	91.93
Pan	52	8.07	100

Table 3 Sieve analysis of gravel

Size (mm)	Retained weight (g)	Retained weight (%)	Retained accumulated weight (%)
9.5	8	0.8	0.8
4.76	457	45.9	46.7
2.36	398	39.9	86.6
1.18	132	13.3	100.0

Table 4 Components of the concrete with recycled polycarbonate.

Concrete (Code)	Polycarbonate (g)	Cement (g)	Gravel (g)	Water (g)	Sand (g)
PC0	0	297	508	233	460
PC1	1.94	297	508	233	455
PC3	5.81	297	508	233	446
PC6	11.61	297	508	233	432

2.4 Preparation of concrete test specimens

Cylindrical specimens of concrete were elaborated with Portland cement (CPC 30R RS), sand, gravel and water, they were denominated as control concrete. Modified concrete was elaborated by partial substitution of sand by recycled polycarbonate, as it is shown in Table 4. Polycarbonate concentrations were 0%, 1%, 3% and 6% by volume. The specimens were placed in a controlled temperature room according to ASTM C192/C192M-16a standard (2015).

2.5 Density of concrete specimens

Fresh density was calculated according to Eq. (1).

$$Fc = (Mdf + Mdc + Mw + Mct)/V \tag{1}$$

where Fc is the calculated fresh density in batch (kg/m^3), Mdf is the mass of dry fine aggregate in batch (kg), Mdc is the mass of dry coarse aggregate in batch (kg), Mw is the mass of water in batch (kg), Mct is the mass of cement in batch (kg), and V is the volume of concrete produced by the batch (m^3).

In the case of moisture contents, if these are known for the batch of concrete, a calculated oven-dry density in batch can be determinate according to the Eq. (2), established in the ASTM C567 standard (2014).

$$Oc = (Mdf + Mdc + 1.2Mct)/V \tag{2}$$

where Oc is the calculated oven-dry density in batch (kg/m^3), Mdf is the mass of dry fine aggregate in batch (kg), Mdc is the mass of dry coarse aggregate in batch (kg), 1.2 is the factor to account for water of hydration, Mct is the mass of cement in batch (kg), and V is the volume of concrete produced by the batch (m^3).

By using the oven-dry density values, the approximate equilibrium density in batch is determinate according to the Eq. (3), established in the ASTM C567 standard (2014).

$$Ec = Oc + 50kg/m3 \tag{3}$$

where Ec is the calculated equilibrium density and Oc is the calculated oven-dry density in batch (kg/m^3).

2.6 Compressive strength of concrete

Compressive strength of concrete specimens was carried out in a Forney Universal Testing Machine (according to ASTM C39/C39M-15a standard) located at Laboratory of Materials of the Faculty of Engineering of the Autonomous University of the State of Mexico (UAEM). For each trial formulation, three specimens were tested after 28 days (±20 h) of curing process, under water at 23.0±2.0°C.

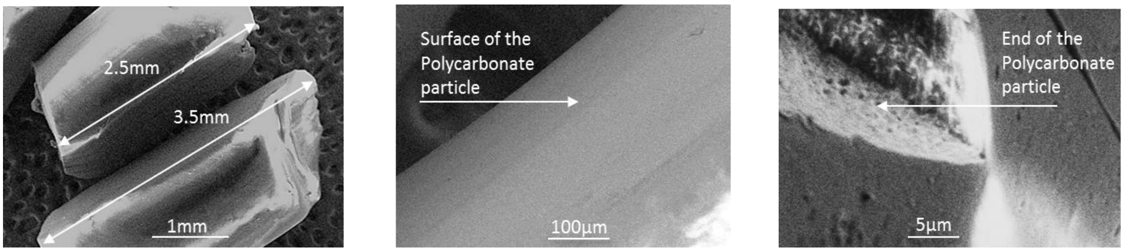
3. Results and discussion

3.1 Morphological characterization of recycled polycarbonate

Morphological characteristics of recycled polycarbonate surfaces are shown in Figs. 1(a)-(b)-(c). SEM images reveals cylindrical particles, with sizes varying from 2.5 mm to 3.5 mm (Fig. 1(a)); with smooth and glossy surface (Fig. 1b), and rugose and rough texture at the ends (Fig.

1(c)).

The specific density of recycled Polycarbonate is 1.1.



(a) Cylindrical Particles (b) Smooth and glossy surface (c) Rugose and rough texture

Fig. 1 SEM images of recycled polycarbonate particles

3.2 Crystallinity characterization of recycled polycarbonate

Crystallinity characteristics of recycled polycarbonate are shown in Fig. 2. The X-ray diffraction pattern shows several diffraction peaks, corresponding to polycarbonate and Rutile, the most common natural form of Titanium (IV) oxide (TiO_2), as it is possible to appreciate in Pondé Weber, Vecchio and Miguez Suarez (2010) and Shi, Li and Zhang (2012). For polycarbonate one peak is observed (17.2°), and for Rutile eight peaks are predominates.

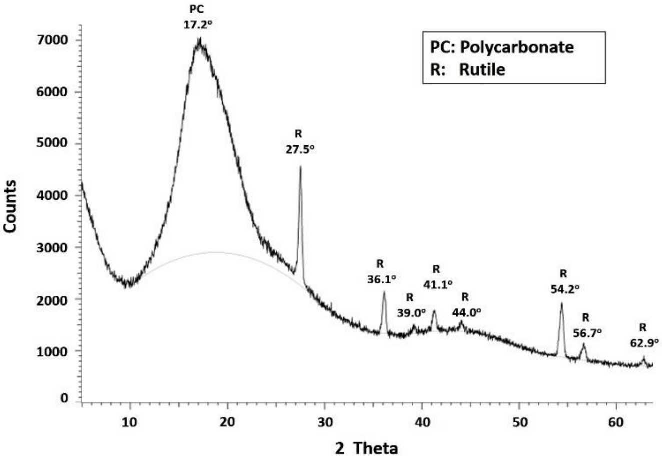


Fig. 2 X-ray spectrum of recycled polycarbonate particles

3.3 Elemental detection of recycled polycarbonate particles.

Elemental detection of recycled polycarbonate particles is shown in Fig. 3. The spectrum shows the presence of carbon, oxygen and titanium elements in atomic proportions, as it can be inferred of Tunçkan, Salge and Terborg (2010). Additionally, no impurities were detected that would be attributable to contamination of recycled process (pelletization). Concentrations of Ti element are attributable to Rutile, a white pigment that is commonly used in plastics, paints and paper. The experimental results agree with the theoretical stoichiometric chemical composition values of polycarbonate: $C_{81.75}O_{17.96}$ ($C_{16}O_3$ stoichiometry), as it can be interpreted of Saraiva Ramos, Baldan and Angelo Nunes (2013).

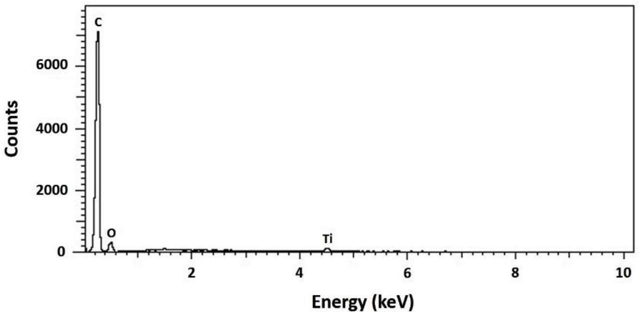


Fig. 3 EDS spectrum of recycled polycarbonate particles

3.4 Functional groups characterization of recycled polycarbonate

Functional groups characterization (FT-IR spectrum) of recycled polycarbonate particles is shown in Fig. 4. Spectrum exhibits characteristic vibration bands at: 2966 cm^{-1} attributed to the stretching vibration of C-H bonds of CH_3 groups (sp^3 C-H), as it can be compared with the Universitat de Barcelona report (2016); 1770 cm^{-1} for carbonate group (C=O) vibration, as it appears in Sweileh, Al-Hiari and Kailani (2010); 1504 cm^{-1} for ring C=C vibration from the two phenol rings, as it is shown in Mayo, Miller and Hannah (2003); bands in 1250-1100 cm^{-1} range corresponding to stretching deformations of asymmetric O-C-O carbonate group; 1080 cm^{-1} attributed to the -CH3 vibrations; a band at 1014 cm^{-1} attributed to a symmetric O-C-O carbonate group in stretching vibration mode, as it appears in Parshin, Gunyakov and Zyryanov (2013), and finally a vibrational band at 829 cm^{-1} for para-substituted phenol rings as it is shown in Hokenek (2009).

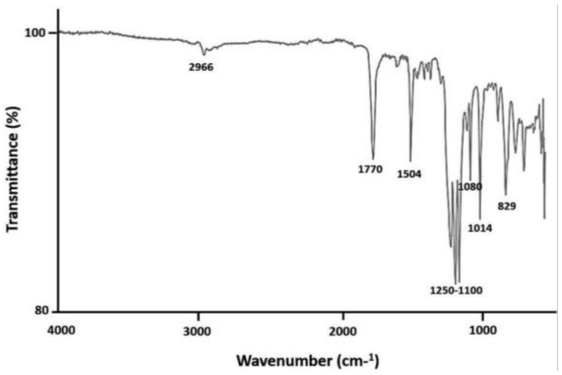


Fig. 4 FTIR spectrum of recycled polycarbonate particles

3.5 Compressive strength of concrete specimens

Compressive strength values of concrete with recycled polycarbonate particles are shown in Fig. 5. The results are discussed in terms of two parameters: size and concentration of polycarbonate particles. According to the particle size, higher compressive strength values are obtained when adding smaller particles (1 mm×1.5 mm); as well as higher values for a concentration of 3% of particles. In the case of concrete with smaller particles, compressive strength values slightly decrease for sand replacement ratio of 1% and increase for ratios of 3% and 6%; although the increase is higher for replacement ratio of 3% than that for 6%. For concrete with bigger particles (1 mm×3 mm) small variations of the compressive values are observed for all particle concentrations. The highest values are for concrete with 3% of particles of 1 mm×1.5 mm length (28.2 MPa), which is 20% higher than the value for concrete without particles.

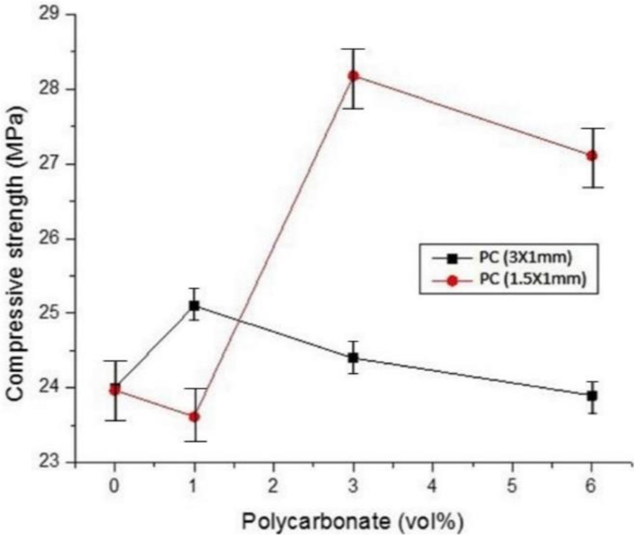


Fig. 5 Compressive strength of concrete with recycled polycarbonate

3.6 Equilibrium density determination

The calculated fresh density and oven-dry density in batch were calculated according to Eqs. (1)-(2). The results are shown in the Table 5.

Table 5 Calculated fresh and oven-dry density in batch of the control concrete.

Polycarbonate (vol %)	Calculated fresh density in batch (kg/m^3)	Calculated oven-dry density in batch (kg/m^3)
0	2111	1866

The fresh concrete density and calculated oven-dry density for each concrete specimen were calculated considering the mass and volume of each concrete specimen after 28 days of curing process as well as the difference between fresh and oven-dry densities in batch of the control concrete. Results are shown in the Table 6, in which increment of the recycled polycarbonate concentration provoke diminution of the calculated oven-dry density. For concrete without polycarbonate density of 1801 kg/m^3 is obtained, while for highest polycarbonate concentration the lowest density is obtained (1775 kg/m^3).

Table 6 Fresh concrete density and calculated oven- dry density for each concrete specimen after 28 days of curing process

Code	Size 1 mm×1.5 mm		Size 1 mm×3 mm	
	Fresh concrete density (kg/m^3)	Calculated oven-dry density (kg/m^3)	Fresh concrete density (kg/m^3)	Calculated oven-dry density (kg/m^3)
PC0	2037	1801	2037	1801
PC1	2033	1797	2031	1795
PC3	2021	1786	2021	1786
PC6	2011	1776	2011	1775

Equilibrium density values are shown in Fig. 6, they were calculated according to Eq. (3). The results are evaluated on the basis of the concentration and size of the polycarbonate particles. In general, when the concentration of recycled polycarbonate increases, the equilibrium density of the concrete diminishes, independently of the particle sizes. This suggests that the equilibrium density depends on the quantity of recycled polycarbonate added. However, at the same polycarbonate concentration, the equilibrium density is slightly higher when the polycarbonate particles are smaller than when they are larger, suggesting that the smaller particles generate a more compact material.

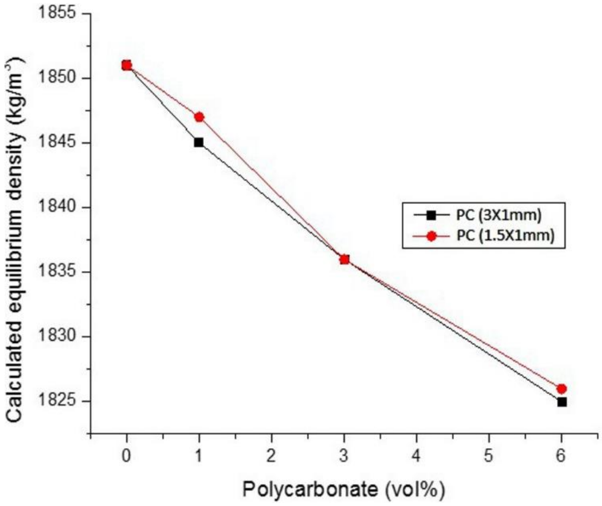


Fig. 6 Equilibrium density of concrete with recycled polycarbonate

4. Conclusions

Morphological characteristics of recycled polycarbonate reveals cylindrical particles, with sizes varying from 1.5 mm to 3.0 mm, smooth and glossy surface as well as rough texture; such characteristics are suitable for polycarbonate to be mixed into concrete. Respect to crystallinity, diffraction peaks are related to polycarbonate and Rutile components; which was corroborated by EDS, which suggest a C16O3 stoichiometry. Moreover, functional groups of waste polycarbonate were detected by FT-IR spectroscopy.

As expected, compressive strength values and equilibrium density of concrete depend on the polycarbonate particle sizes and its concentrations; the highest compressive strength values were obtained for concrete with 3% of smaller particles, these values were 20% higher than that for concrete without polycarbonate particles. Smaller polycarbonate particle sizes create less free space into concrete and in consequence, compressive strength increase. Moreover, when the concentration of recycled polycarbonate increases, the equilibrium density of concrete diminishes, independently of the particle sizes. It is promising that concrete with polycarbonate is consistent with ACI 213R standard.

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