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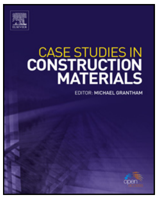

Short communication

Waste polymers and gamma radiation on the mechanical improvement of polymer mortars: Experimental and calculated results

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ABSTRACT

In this work, the effects of waste polymer particles and gamma radiation on the mechanical properties of polyester mortars were studied. Control mortar was elaborated with polyester resin (20%), and silica sand (80%). This last was partially substituted by each waste polymer (1, 2 and 3 wt. %), namely, i) PET from beverage water bottles, ii) Polycarbonate from computer monitors and displays, and iii) Waste tire rubber from automotive tires. A post-curing process was applied to polyester mortars by using gamma rays (at doses of 100 and 200 kGy). Analysis of the results were made according to irradiation dose and the particles concentration. We reminded that such polymer mortars are used in applications where high mechanical and chemical attacks resistance are required, moreover they are friendly to the environment. The results show, that the effect of the ionizing radiation was predominant, because higher percentages of improvement on the mechanical properties were obtained, up to 46% for irradiated mortars with PET particles, and up to 37% for those with polycarbonate particles, respect to that for control mortar. Respect to the waste particles concentration, a general behavior was obtained: mechanical properties decrease gradually with increase of particles concentration. Nevertheless, it was remarkable to use only 1% of waste particles concentration, for to obtain the highest values for both kind of mortars, non-irradiated and irradiated. The experimental results were simulated by Finite Element Method (FEM), both were in good accordance, having minimal difference between them. In addition, morphological modifications of each waste polymer after irradiating, were analyzed by scanning electron microscopy (SEM) and related to mechanical behavior of polyester mortars.

The improvements in the mechanical properties of the composites, as well as the use of waste polymers, make these polymer mortar environmentally friendly construction materials that can be used in applications that require high mechanical resistance.

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1. Introduction

Incorporation of synthetic polymers into commercial products is a common practice. Polymer wastes generated are gradually accumulating into environment, and there are not successes on their degradation due to their high resistance. It is estimated a 60% of plastic wastes per year of the total production, which is approximately 200 million tons per annum [1].

One of the common strategies for dispose of petroleum-based plastics is incineration, but this is highly polluting and causes negative effects on the environment, such as increased CO_2 in the atmosphere and the release of very dangerous chemical compounds, such as dioxins, chloride and hydrogen cyanide. Another strategy is recycling, which consists of collection, reprocessing and remarketing of plastic products considered as waste. Plastic recycling has several advantages, including: a) conservation of non-renewable fossil oils. Plastic production uses 4% of the world oil production; b) reduced consumption of energy, c) reduced emissions of carbon dioxide, sulfur dioxide and nitrogen oxides; and d) reduction of the solid waste amounts going to landfill [1].

Some of the drawbacks for plastic recycling are an appropriate plastic handling, not only in their collection and processing, but also cleaning, selection and adequate separation of them. In addition, recycling of synthetic polymers depends on the physical and chemical properties after processing. Additionally, not all plastics are recyclable. Thermoplastics are recycled, while thermosetting plastics (those that after molding undergo irreversible modifications), do not.

A novel approach that reduces processing and recycling costs of synthetic polymer materials is based on their use as fillers in concrete. It is well known that fillers (fibers or particles), modify the mechanical properties of cement concrete, including: a) compressive and bending strength, b) elasticity modulus, c) deformations due to cracks, and d) ductility [2–5]. For example, tire rubbers are used for their low density, low thermal conductivity, high bulk permeability, high durability, and low cost, when they are comparing with other filler materials. Nevertheless, high concentrations of tire rubbers into concrete decrease unit weight, compressive strength and elasticity modulus, but improve ductility [6].

There are few studies concerning to mechanical improvement by using fibers or particles in polymer concrete. As it is known, polymer concrete is a composite material elaborated with a thermoset resin and mineral aggregates. Which is commonly used for manufacturing precast products (manholes, sewage pipes, and building walls), and for repairing existing concrete pavements and bridge decks. Polymer concrete has special properties such as short curing time, high mechanical and bond strengths, as well as high chemical and freeze-thaw resistance, higher than that for the cement concrete [7,8].

In some studies, synthetic fibers or particles have been added for improvement on the mechanical properties of polymer concrete. For example, the incorporation of both Al2O3 and Fe2O3 nanoparticles into the polymer mortar (epoxy matrix + sand), improved its modulus of elasticity, fracture toughness and fracture energy. Highest mechanical values were obtained with 3.0 wt.% of nanoparticles [9]. Low compressive strength values were obtained, due to the limited interaction forces, between tire rubber particles and polyester resin matrix. Additionally, high porosity of tire rubber particles, generated during vulcanization process. Its cross-linked structure restricts the movement of the molecular chains. It is well known, that more concentration of tire rubber into concrete generate more voids and in consequence, compressive strength is modified [10].

Different polymers have been used to improve the mechanical properties of mortars. For example, waste polyethylene-terephthalate (PET), was used as reinforcement in a siliceous sand composite. The results showed diminution on the compressive strength as well as decrease in the penetration of chlorine ions, from 90 to 40% [11]. In other study, polyvinyl chloride (PVC) was used as reinforcement in light mortars. The results showed that reduce the specific weight of the composites and improve their thermal insulation. Nevertheless, the mechanical properties decreased, namely, dynamic modulus of elasticity and compressive and bending strength [12].

Senhadji et al also proposed to use waste polyvinyl chloride (PVC) as an alternative fine aggregate in eco-friendly mortars. Silica sand was replaced by PVC particles (10, 30, 50 and 70% by weight). The density, compressive and flexural strengths, ultrasonic pulse velocity, and thermal conductivity were determined. The results showed that flexural and compressive strength decreased at high concentrations of PVC (50 and 70%), but the resistance to chemical attacks increased considerably [13].

In the last decades, treatment of polymers by gamma radiation has been increasing due to modifications and improvement on their physical, chemical, electrical, optical and structural properties. Such changes depend on the specific polymer. Radiation processes are preferred more than conventional ones, due to many advantages. For example, no catalyst or additives are required to initiate chemical reaction. Scission of polymer chains occurs at low radiation dose; and for high dose, free radicals are generated in the polymer chains, which produce cross-linking of the same [14].

Gamma irradiation produces electrons and low energy photons in polyethylene terephthalate (PET), they are responsible for its structural modification. Moreover, free radicals produce scissions of polymer chains and can recombine to create cross-linking with adjacent molecules. Irradiation cause changes in the degree of crystallinity as well as in the physical, electrical, and chemical properties. In a study, polyethylene terephthalate (PET) was irradiated with gamma rays, and its structural changes were analyzed by X-ray diffraction (XRD) and UV–vis spectroscopy. It was observed that the degree of crystallinity as well activation energy increases with increasing irradiation dose, but optical band gap (Eg) decrease with increasing dose [15]. Similar studies for PET from beverage bottles show increment of the crystallinity (analyzed by XRD), but decrease in the direct and indirect band gap, when gamma radiation dose increase [16]. In other study, raw and waste PET was irradiated with gamma rays and their changes were evaluated by IR spectroscopy, thermogravimetric analysis and differential scanning calorimetry. The results show improvement of the thermal stability for both raw and waste PET, after gamma irradiation [17].

In the case of polycarbonate (PC) irradiated with gamma rays, physicochemical changes are produced. For example: a) photo-physical changes are produced at doses of 10, 50 and 100 kGy, which are evaluated by their emission and excitation spectra data [18]; b) mechanical properties and molecular weight are modified, in polycarbonate sheets, when gamma irradiation increase (at high doses >50 kGy); both molecular weight and toughness decrease due to scission of polymer chains (mainly of carbonyl groups). Moreover, polycarbonate have a ductile-to-brittle transition as radiation dose increases [19,20]; c) total fracture increase for irradiated polycarbonate sheets (340 kGy) submitted to three-points bend tests [21]; d) gases, mainly CO, CO2 and H2, are produced through the scission of their carbonate groups after irradiating [22].

Different behaviors are observed in gamma irradiated rubber, including: changes of the thermal stability due to cross-linking of polymer chains, as well as improvement of the tensile strength, elongation at break, and hardness. Some investigations show that: a) tensile strength, hardness and gel content increase with increasing gamma dose. Moreover, high thermal stability is due to cross-linking of polymer chains. Such results were obtained for blends of waste tire rubber (WTR) and styrene butadiene rubber (SBR) [23]; b) thermal stability increase, due to increase of the cross-linking density after increment of irradiation dose. High cross-linking density is obtained after aging process. The sulfur could make a further chemical reaction with the C—S—C bonds formed during the thermal aging process. These results are observed for blends of polybutadiene rubber and nature rubber [24]; c) Vulcanization process and the thermal stability are improved by gamma irradiation (up to 250 kGy of dose), for blends of natural rubber (NR) and styrene butadiene rubber (SBR) [25].

Finite Element Analysis (FEA), is a numerical method that emerged on the 60's, and has become one of the most innovative tools at both academic and industrial levels. The main difference between classical and finite element methods, is the perception of the structure along the procedures. The FEA method consider the structure as an assemblage of small particles of a finite size, unlike to the classical methods, where the structure is considered as a continuum; and their behaviors are operated by ordinary differential equations. The FEA method discretizes the object and solves each one of the elements of the equations system, and finally assemble the total solution.

There are different software packages that use the finite element method (FEM) for solving partial differential equations. ANSYS is a program for computational calculation based on finite element analysis, with applicability to a wide variety of common problems in engineering. This software allows static and dynamic analysis in structural calculations, as well as in problems of heat transfer, fluids and electromagnetism.

Several investigations have been carried out to simulate the behavior of composite materials. For example: a) the effect of fibers lay-up on the initiation of the flexural failure of laminated composites, was studied by Finite Element Analysis (FEA), which provided more accurate results; b) the fracture toughness of steel fiber-reinforced aluminosilicate geopolymers was studied, and the experimental results were compared with those obtained by finite element method (FEM). Four different parameters on both experimental and calculated fracture toughness were studied. It was proved that FEM predicted fracture toughness with a reasonable approximation [26,27].

In this work, in a first experimental stage, polymer mortars were elaborated with polyester resin, silica sand and waste polymer particles (PET, polycarbonate and tire rubber) in concentrations of 1, 2 and 3 wt. %. After, polymer mortar specimens were irradiated with gamma rays at dose of 100 and 200 kGy to study the effect on the mechanical properties. Compressive and flexural tests on both non-irradiated and irradiated specimens were made. Subsequently, the compressive modulus of elasticity was calculated. In addition, polymer wastes (PET, polycarbonate and tire rubber particles), were characterized by scanning electron microscopy (SEM). Finally, according to the characteristics of the polymer mortars, their mechanical properties were modeled by Finite Element Method (FEM) using an ANSYS program, and the resulting data were compared those obtained by experimental.

2. Materials and methods

2.1. Materials and specimen preparation

Polymer mortar specimens were elaborated according to the formulations shown in the Table 1. The concentrations of each component were chosen according to the results obtained in a previous work by the authors [28], where it was observed that when exceeding 3 wt. % of waste particles, the mechanical properties decrease considerably. Polyester resin concentration was constant (20%), and silica sand concentration was partially substituted by polymer wastes (1–3 wt. %).

Table 1
Polymer mortar components.

Polymer Mortar (code)	R3 Mesin (%)	Sand (%)	Waste polymer particles (%)
PC	20	80	0
PC-1	20	79	1
PC-2	20	78	2
PC-3	20	77	3

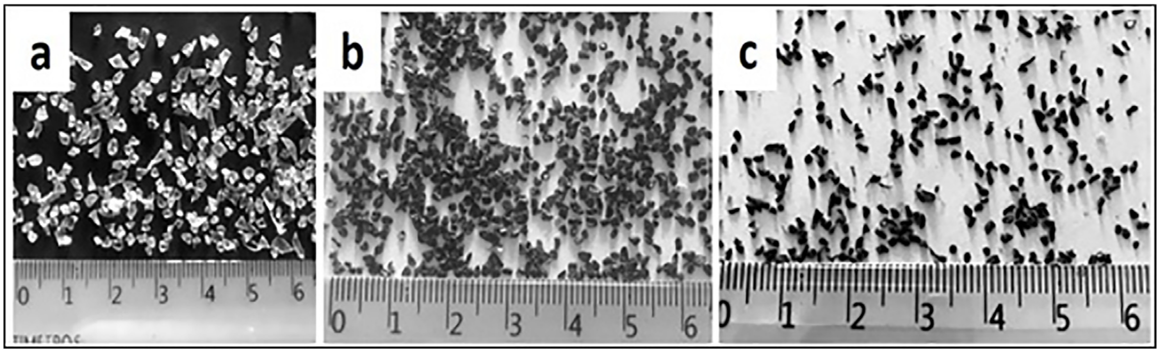

Fig. 1. Waste polymer particles: a) PET, b) polycarbonate, and c) Tire rubber.

Table 2
Mechanical properties of PET and polycarbonate.

Property	PET	Polycarbonate
Tensile Modulus, GPa	2.8–3.1	2.37
Young Modulus, GPa	3.7	2.38
Compressive strength, MPa	76–128	86
Flexural strength, MPa	86	93
Poisson's ratio	0.37–0.44	0.37

Table 3
Polyester resin properties.

Properties	Value
Brookfield Viscosity, LV, 2/60, cPs	100–200
Gel time, min	6–8
Exothermic temperature, °C	145–163
Curing time, min	16
Specific weight, lb/gal	9.10–9.30
Stability @ 105 °C, 4 h	4

The waste polymers shown in Fig. 1, were obtained as follows: a) PET came from beverage water bottles, b) Polycarbonate (PC) from computer monitors and displays, and c) Waste Tire Rubber (WTR) from automotive tires. These waste materials were subjected to washing, grinding and sieving processes; with a final size of 1.4 mm (mesh 14). Mechanical properties of PET and polycarbonate materials are shown in the Table 2.

Silica sand with average diameter of 250 μm (mesh 60) was obtained from a local company (MONCA, Gijón-Asturias, Spain). Polymerization of Unsaturated Polyester Resin (UPR), was made using methyl ethyl ketone peroxide as initiator. UPR was provided by Grupo Químico Industrial^{TM} (code MR-300/75C). Properties of the polyester resin are shown in the Table 3.

Prismatic polymer mortar specimens were elaborated using steel molds (40 × 40 x 160 mm) (Fig. 2). They were initially cured at room temperature (24 h), and then post-cured at 60 °C for 2 h. Six specimens of each formulation were elaborated.

A second post-curing process was applied to polymer mortar specimens by using gamma rays (at doses of 100 and 200 kGy), in an industrial JS-6500 irradiator provided with cobalt-60 pencils. The irradiation process was carried out at room temperature in air atmosphere, at dose rate of 3.5 kGy/h.

2.2. Test methods

Compressive and flexural strength as well as compressive modulus of elasticity of both non-irradiated and irradiated polymer mortar specimens, were carried out using a Universal Testing Machine model 70-S17C2 (Controls^{TM}, Cernusco, Italy), with a load cell of 30 tons. Six specimens of each formulation were tested.

Non-irradiated and irradiated polymer wastes (PET, polycarbonate and tire particles), were analyzed by scanning electron microscopy (SEM) in a JEOL equipment model JSM-6510LV, in the secondary electron mode.

2.3. Finite element model

The commercial finite element package ANSYS 16.0 and the finite element SOLID186 were used for simulating of the mechanical characteristics of the polymer mortars. ANSYS is used for both linear and nonlinear analysis of static and

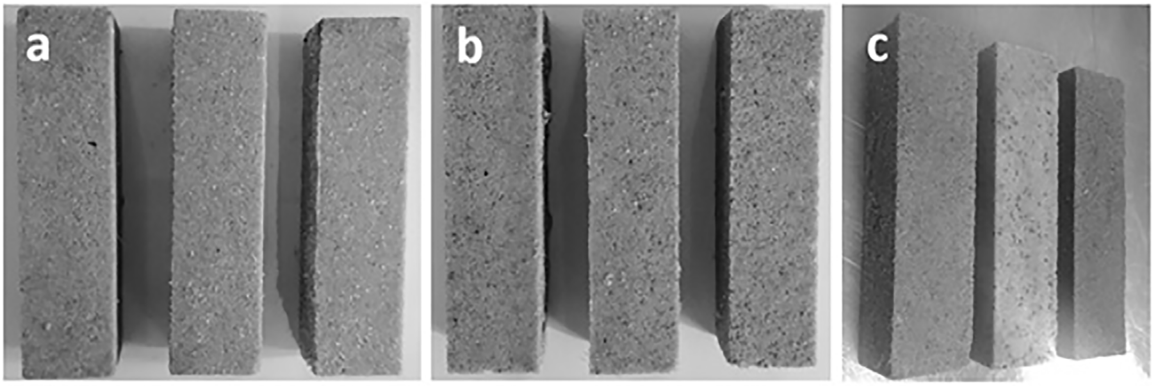

Fig. 2. Polymer mortar specimens with: a) PET particles, b) polycarbonate particles and c) Tire rubber particles.

dynamic problems. This software uses the Newton–Raphson method, where the total load is divided into series of load increments, until the final convergence of the solution. While, the SOLID186 element is a 3-D 20-node that exhibits a quadratic displacement behavior. The element is defined by 20 nodes with three degrees of freedom per node. Moreover, each element supports plasticity, hyper-elasticity, creep, stress stiffening, large deflection, and large strain capabilities.

Polymer mortars were modeled based on the yield stress-strain curves for the multilinear strain. Testing data were used for calibration of the Finite Element Model and the validation of the adopted parameters.

3. Results and discussion

3.1. Compressive strength

Fig. 3 shows the compressive strength values of non-irradiated and irradiated polymer mortars. For a better understanding of the behavior of the polymer mortars with respect to the control polymer mortar (without waste particles and non-irradiated), a straight horizontal line was put starting from the value for control mortar. Moreover, polymer mortars were analyzed according to: I) radiation dose, and II) concentration of waste particles.

In the case of polymer mortars with polyethylene terephthalate (PET). I) according to radiation dose: a) for non-irradiated polymer mortars, highest values are obtained when adding PET particles, such mortars had an improvement of 23% respect to that for control mortar (which had a compressive strength value of 63 MPa). Lower values were obtained for mortars with polycarbonate particles. In addition, mortars with tire rubber particles had values lower than that for control mortar; b) for irradiated polymer mortars, compressive strength values increase when irradiation dose increase. Highest values were obtained for mortars irradiated at 200 kGy: an improvement up to 34% was obtained for those with PET, and of 17% for those with polycarbonate, respect to that for control mortar. II) Respect to particles concentration, a general behavior was obtained for non-irradiated or irradiated mortars: compressive strength values decrease when increasing particles concentration.

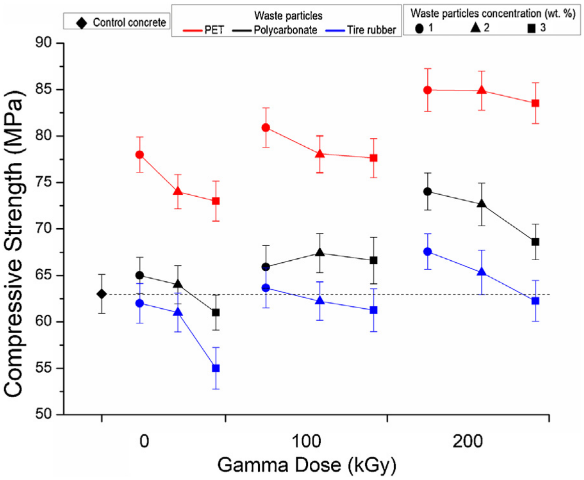

Fig. 3. Compressive strength of non-irradiated and irradiated polymer mortars with waste polymer particles.

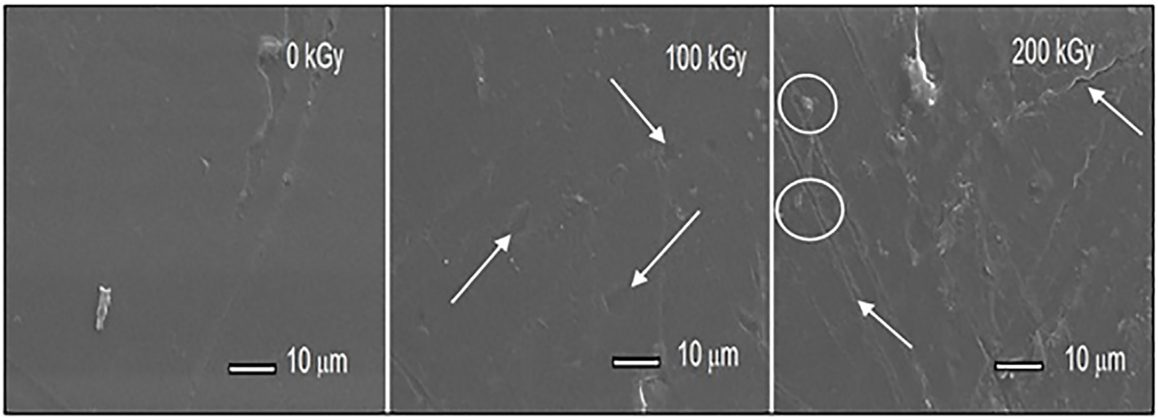

Fig. 4. SEM images of non-irradiated and irradiated waste PET particles.

Compressive strength behavior of polymer mortars with waste PET particles, can be related with the morphological changes of PET particles after irradiating, as can be seen from the Fig. 4. For non-irradiated PET a smooth surface is obtained; however, surface deterioration begins when ionizing radiation is applied. A rough surface, with some cavities (pointed out by arrows) was obtained at 100 kGy. For higher dose (200 kGy), a rougher surface with detached particles and cracks (pointed out by circles and arrows) was obtained. Thus, the degree of crystallinity of PET changes.

The morphological changes are consequence of the scission of polymer chains inside of PET. Moreover, such morphologies develop more contact points and greater superficial area on the PET particles. In addition, it has been reported that polyester resin also shows morphological changes after submitting to gamma irradiation, which improves its mechanical properties [29]. In summary, the modified PET particles interacting constantly with the surfaces of the mortar components (resin and sand), while that polyester resin also have morphological changes. Thus, both irradiated polymers contribute to have higher compressive strength values.

Fig. 5. Compressive stress-strain curves of experimental and simulation data for polymer mortars: control and those with 1% of PET particles and irradiated at different doses.

In Fig. 5 are shown the stress-strain curves obtained by compression tests and by Finite Element Method (FEM) using ANSYS program. Polymer mortars with 1% of PET particles and irradiated at 100 and 200 kGy were taken as example. As it is shown in Fig. 5 and in the Table 4, the simulation results are in good accordance with the experimental data. According to the Table 4, the percentages of difference are minimal. For compressive strength a maximal difference of 2.5% was obtained; in the case of the elasticity modulus was of 3.3%, while for the deformation was of 19%.

Following with the compressive results (Fig. 3), in the case of polymer mortars with polycarbonate two well-defined behaviors are obtained: I) respect to irradiation dose: a) non-irradiated polymer mortars have lower compressive strength values than that for control mortar, such diminution can be related with the compressive strength and elasticity modulus of the polycarbonate, whose values are lower than those for polyester resin; nevertheless, b) irradiated polymer mortars have higher compressive strength values, which increasing for higher irradiation dose. Moreover, an improvement up to 17% was obtained when irradiating at 200 kGy. According to the literature, a ductile-brittle transition happens when high irradiation dose is applied to polycarbonate [16]. While, II) respect to waste polycarbonate concentration, compressive strength values diminish when concentration of polycarbonate increase.

Finally, for polymer mortars with tire rubber particles (Fig. 3). I) according to the irradiation dose: a) non-irradiated mortars have lower compressive strength values than that for control mortar; while b) for irradiated ones, only those irradiated at 200 kGy have values slightly higher than that for control mortar. Diminution of the strength can be attributed to the weak interfacial bonds between polyester resin and tire rubber particles, as well as to the cross-linking of tire particles after irradiation. Higher cross-linking ratio restricts the movement of rubber molecular chains. Thus, there are limited interaction forces between tire rubber particles and polyester resin matrix, and in consequence diminution of strength values. II) Respect to waste tire rubber concentration, compressive strength values diminish when concentration of the waste rubber particles increase.

3.2. Compressive strain at ultimate strength

Deformations of non-irradiated and irradiated polymer mortars are shown in Fig. 6. Control mortar had a value of 0.029 mm/mm.

I) Respect to irradiation dose: a) for non-irradiated polymer mortars, higher deformation values were obtained, they had an improvement up to 20% for mortars with PET, and an improvement of 10% for those with polycarbonate, respect to the values of the control mortar; b) for irradiated ones, deformation increase when irradiation dose increase. High ionizing

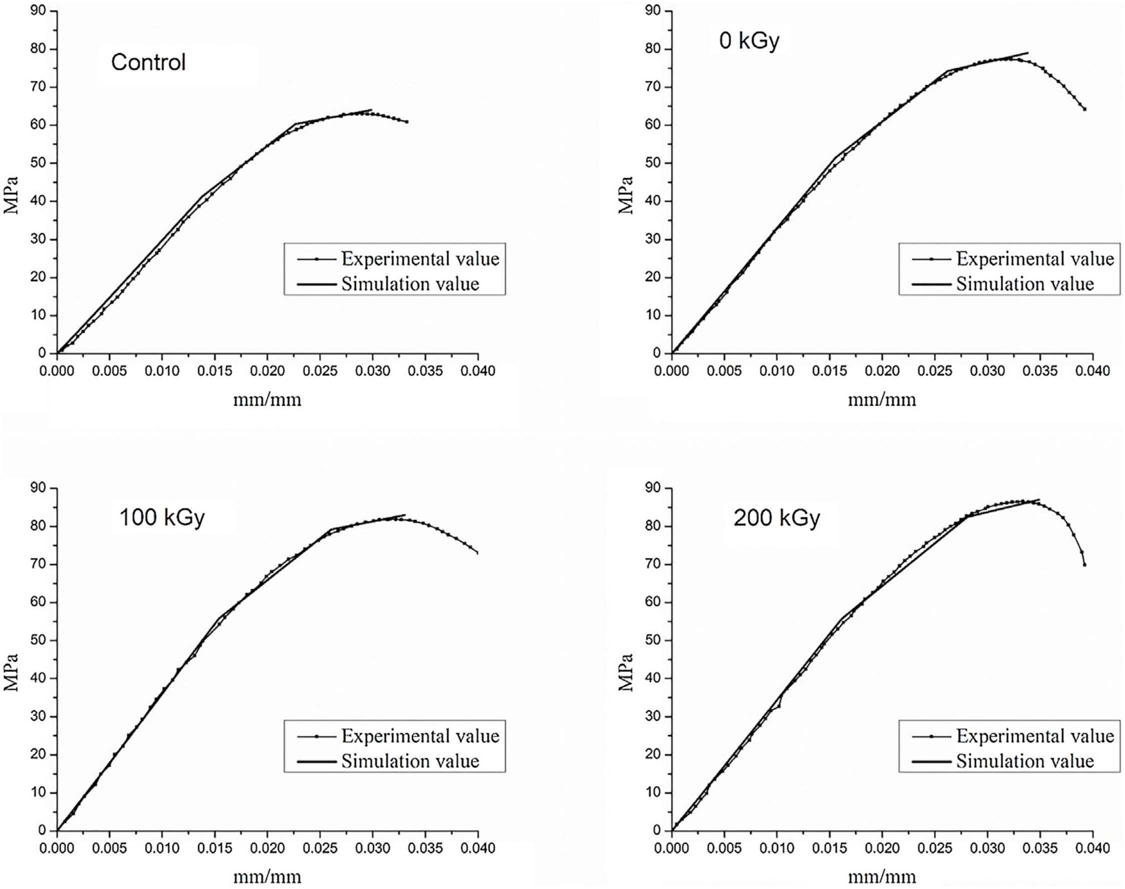

Fig. 5. Compressive stress-strain curves of experimental and simulation data for polymer mortars: Control and those with 1% of PET particles and irradiated at different doses.

Table 4
Comparison of experimental (Exp), and simulation (Sim) results for compression tests.

Polymer mortar	Compressive Strength (MPa)			Compressive modulus of elasticity (GPa)			Strain at ultimate strength (mm/mm)		
	Exp	Sim	Dif (%)	Exp	Sim	Dif (%)	Exp	Sim	Dif (%)
Control	63	64	1.5	2.9	2.8	3.4	0.029	0.029	0
1%PET	77	79	2.5	3.2	3.1	3.1	0.031	0.033	6
1%PET 100 kGy	81	83	2.4	3.3	3.3	0.0	0.041	0.033	19
1%PET 200 kGy	85	87	2.2	3.4	3.3	2.9	0.039	0.034	12

radiation provokes scissions on the polymer chains, and a more flexible polymer is obtained; such characteristics influence to obtain a more flexible polymer mortar. The highest values were obtained for polymer mortar with waste PET particles, and lowest for those with tire rubber particles.

The highest deformations were obtained for polymer mortars with 3% of PET particles irradiated at 200 kGy, meanly 0.0425 mm/mm, which is 46% higher than that for control mortar. In the second place, were located the polymer mortars with polycarbonate particles, which having an improvement of 37%, under the same conditions.

Special attention is observed for polymer mortars with tire rubber particles. When applying gamma radiation, the deformation values increase, then mortar is more ductile; nevertheless, when the tire rubber concentration increase deformation gradually diminish, in consequence mortar is harder. Ionizing radiation cause cross-linking of polymer chains on the tire rubber particles, and in consequence their tensile strength, elongation at break, as well as hardness is increased. Thus, high concentration of tire rubber particles with these features contribute to diminish the deformation. Nevertheless, the highest deformation values for mortars with tire rubber particles were obtained for a concentration of 1% and 100 kGy of dose, namely an improvement of 34% respect to that for control mortar.

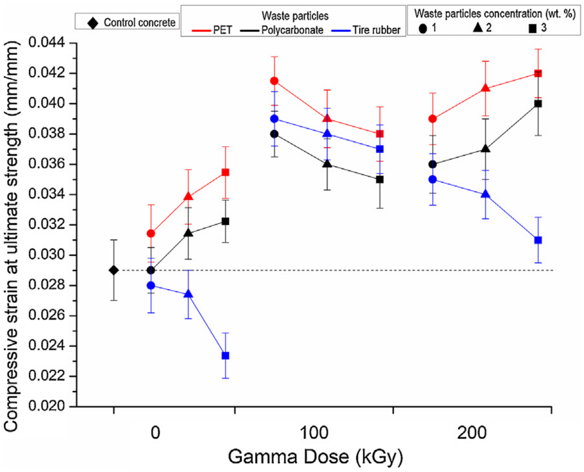

Fig. 6. Compressive strain at ultimate strength of non-irradiated and irradiated polymer mortars with waste polymer particles.

II) Respect to particles concentration, two well-defined behaviors were obtained: a) deformation of polymer mortars increase when particles concentration increases, this for non-irradiated mortars and those irradiated a 200 kGy; b) an opposite behavior is obtained, deformation decrease when particles concentration increases; this for mortars with waste tire rubber irradiated at 200 kGy, and for polymer mortars irradiated at 100 kGy, regardless of the waste particles type.

The morphological changes on the tire rubber surface caused by irradiation can be related with the deformation values of polymer mortars. A slightly rough surface is observed for non-irradiated tire rubber (Fig. 7), which does not produce strong physical interactions with polymer matrix (polyester resin) and in consequence low deformation is produced. Nevertheless, for irradiated particles (at 100 kGy), rougher surface with linear orientation is produced (pointed out by arrows) (Fig. 7), which improving physical interactions and deformation values. Finally, high irradiation dose (200 kGy), produces higher roughness (pointed out by a circle), not recommendable, because the deformation values diminish.

3.3. Compressive modulus of elasticity

Fig. 8 shows the compressive modulus of elasticity of polymer mortars. Control mortar had a modulus of 2.9 GPa. I) Respect to the irradiation dose: a) for non-irradiated polymer mortars, highest values are obtained when adding PET particles, and lowest for tire rubber particles. In addition, only mortars with PET particles had higher values than that for control mortar; b) For irradiated mortars, the elasticity modulus increases when irradiation dose increase; for both irradiation dose (100 and 200 kGy), highest values were obtained when adding PET particles and lowest for tire rubber particles. The highest values were obtained for mortar with 1% of PET particles and irradiated at 200 kGy, namely 3.4 GPa; which is 17% higher than that for control mortar. II) According to the particle's concentration, a general behavior is obtained: the elasticity modulus values decrease gradually with increase of particles concentration.

The advantages of use PET particles over polycarbonate and tire rubber particles are observed in Fig. 8. The elasticity modulus values for mortars with polycarbonate or tire rubber particles are lower than that for control mortar. In addition, the

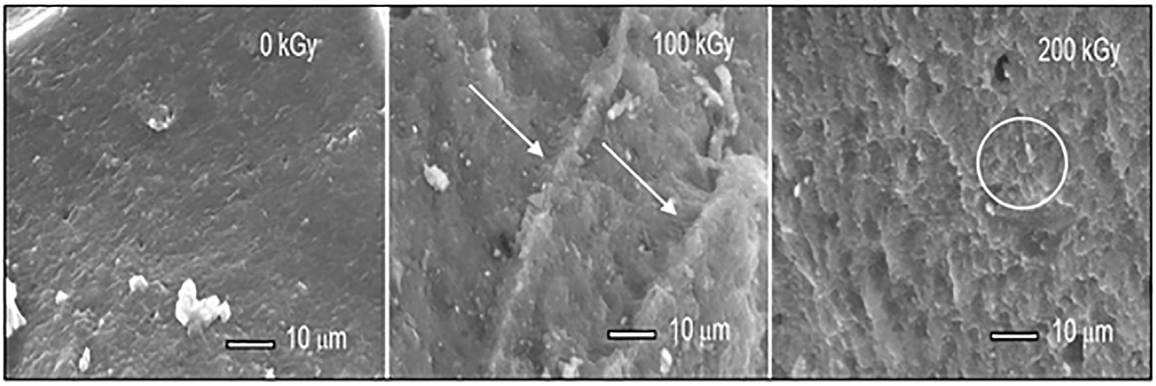

Fig. 7. SEM images of non-irradiated and irradiated waste tire rubber particles.

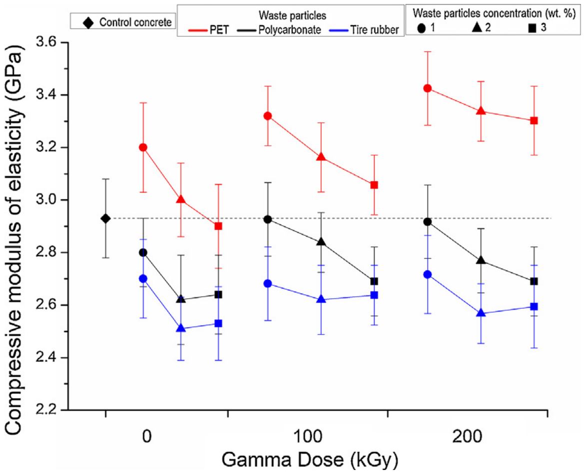

Fig. 8. Compressive modulus of elasticity of non-irradiated and irradiated polymer mortars with waste polymer particles.

high elasticity modulus of mortars with PET are related to the high degree of crystallinity of PET, which is higher than those for polycarbonate and tire rubber. Moreover, changes on the crystallinity modify the mechanical properties.

3.4. Flexural strength

Fig. 9 shows the flexural strength values of polymer mortar specimens. Control mortar had a value of 18 MPa. I) Respect to irradiation dose: a) for non-irradiated mortars, higher values are observed for mortars with PET particles, and lower for those with polycarbonate or tire rubber particles, respect to the value for control mortar; b) For irradiated mortars, the differences on the values are more notable; only the mortars with PET particles had higher values than that for control mortar. The highest values were obtained for polymer mortars with 1% of PET particles and irradiated at 200 kGy, namely 22.5 GPa, which is 25% higher than that for control mortar. In the second position, were located the mortars with polycarbonate, which had an improvement of 8% respect to the values of the control mortar.

Two behaviors are obtained: flexural strength values increase when irradiation dose increase, this for mortars with PET or polycarbonate particles; but not so for mortars with tire rubber particles, which have an opposite behavior. II) According to the particles concentration: a) for non-irradiated mortars with PET particles, flexural strength decreases when increasing PET concentration, b) but not so for polycarbonate particles, which has an opposite behavior, the values increase with concentration increase.

The increment of the flexural strength of the mortars with polycarbonate particles can be related with the morphological changes of the polycarbonate particles after irradiation, as it shown in Fig. 10. Smoother surface is observed for non-irradiated polycarbonate, which allows have similar flexural strength values at different particles concentration (see Fig. 9). Nevertheless, flexural strength values diminish at 100 kGy, because the irradiation cause a ductile-brittle transition on the

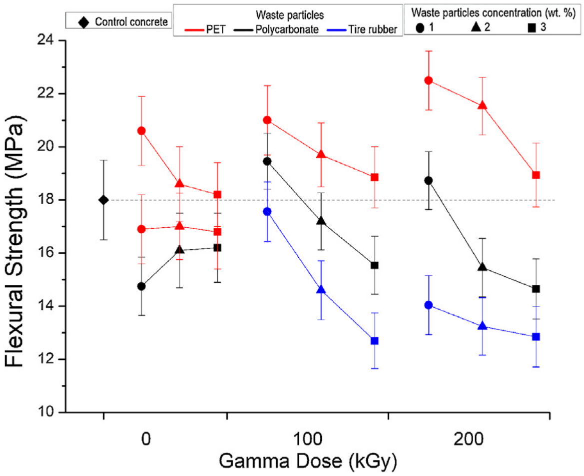

Fig. 9. Flexural strength of non-irradiated and irradiated polymer mortars with waste polymer particles.

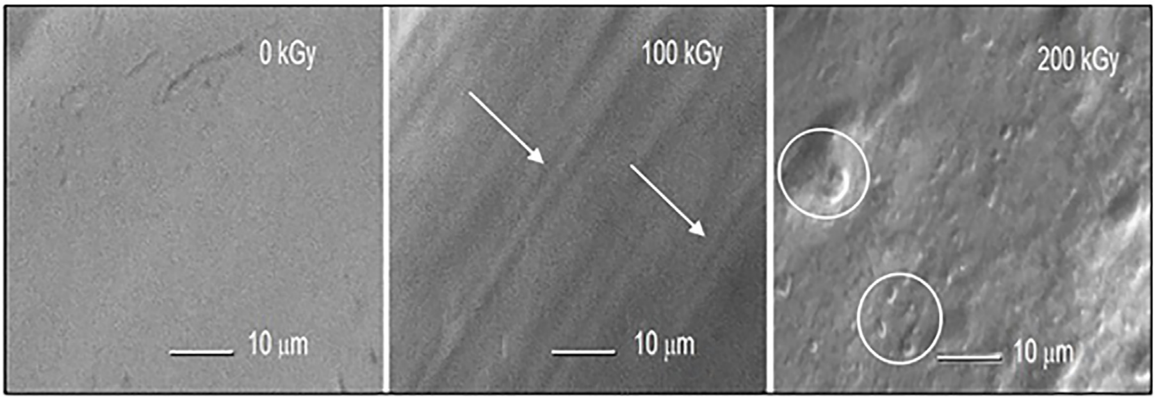

Fig. 10. SEM images of non-irradiated and irradiated waste polycarbonate particles.

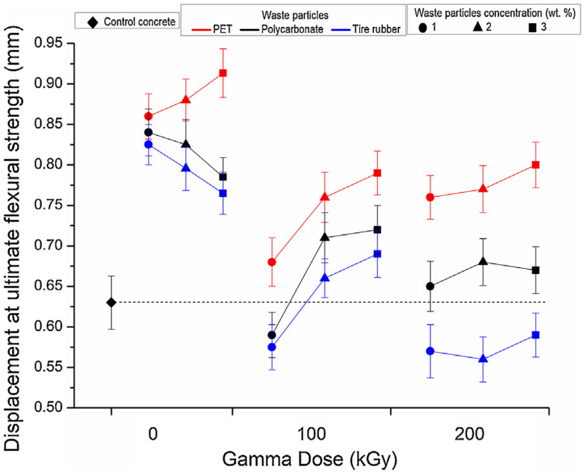

Fig. 11. Displacement at ultimate flexural strength of non-irradiated and irradiated polymer mortars with waste polymer particles.

polycarbonate, which is manifested for the well-defined lines on its surface (pointed out by arrows). At high ionizing radiation, 200 kGy, a rougher surface with some detached particles (pointed out by circles), are produced on the polycarbonate; these features allow more contact points with sand and the polyester resin; thus, flexural strength increase.

As mentioned above, the surface of the waste particles changes when are subjected to gamma radiation, that is, the roughness increases, which improves the mechanical properties.

It is well known that mechanical bonding in a composite depends on the roughness of the components; higher roughness, better interaction at the interface. This type of joint is not very effective for tensile stresses, but very effective for shear stresses. On the other hand, the mechanical properties of the polyester resin also improve when is subjected to radiation [29]. These two phenomena improve the behavior of polymer mortar when is subjected to bending stresses.

3.5. Flexural displacement at ultimate strength

The flexural displacement at ultimate strength values are show in Fig. 11. The control mortar had a displacement of 0.63 mm. I) according to the irradiation dose: a) non-irradiated mortars had higher values than that for control mortar. Mortars with PET particles had a displacement of 0.92 mm, which means an improvement of 46%. Moreover, improvement of 33% were obtained for mortars with polycarbonate, and of 30% for those with tire rubber; b) In the case of irradiated mortars, higher values were obtained; with improvements of 26% for mortars with PET, 15% for those with polycarbonate, and 9% for those with tire rubber; respect to the values of the control mortar; II) Respect to the particles concentration: displacement increase when particles concentration increase, this for non-irradiated and irradiated mortars with PET particles; while for the others mortars (with polycarbonate or tire rubber) two behavior are obtained: a) displacement diminishes when particles concentration increase, this for non-irradiated mortars; b) but for irradiated mortars, the displacements tend to increase as the concentration of particles increases.

Table 5
Percentages of improvement of each mechanical property respect to that for control mortar.

Property	Improvement (%)					
	PET		PC		Tire	
	Non-I	I	Non-I	I	Non-I	I
Compressive strength	23	34	–	17	–	–
Compressive strain	20	46	10	37	–	34
Elasticity modulus	–	17	–	–	–	–
Flexural strength	–	25	–	8	–	–
Flexural displacement	46	26	33	15	30	9

Table 5 shows a summary of the mechanical improvements achieved by the addition of waste particles and the irradiation doses. Those results without improvement are showed by dashed lines. In the case of non-irradiated mortars (Non-I), highest improvements were obtained by adding waste PET particles, followed for those by adding polycarbonate particles, not so for tire rubber. In the case of irradiated mortars (I), the highest improvements are obtained, mainly for mortars with PET particles, followed for those with polycarbonate particles. Thus, the highest improvements on the mechanical features are obtained by mortars with 1% of PET particles and irradiated at 200 kGy; such improvements ranging between 17% and 46%.

It is important to note that the compressive and bending strength and modulus of elasticity decrease when the waste particles concentration increases. This behavior is similar to that reported in previous investigations [11–13] where PET and PVC particles are used as filler in composites.

4. Conclusions

In this work, the mechanical properties of polymer mortars modified with waste polymer particles and ionizing radiation were obtained. Moreover, the experimental results were compared with those obtained by using the Finite Element Model. The analyses of the results were based on the waste particle concentration and the irradiation dose. The main conclusions are as follows:

a) The highest improvements (46%), were obtained for irradiated mortars with PET particles, as well as of 37%, for those with polycarbonate particles. Unfortunately, the effects of gamma radiation were not representative when adding tire rubber particles.
b) Respect to the waste particles concentration, a general behavior was obtained: mechanical properties decrease gradually with increase of particles concentration. Nevertheless, it was remarkable to use only 1% of waste particles concentration, for to obtain the highest values for both kind of mortars, non-irradiated and irradiated.
c) The simulation results evaluated by Finite Element Method (FEM), were in good accordance with the experimental data, having minimal difference between them.

In summary, the highest mechanical results were obtained for mortars with 1% of PET particles and irradiated at 200 kGy. Moreover, future researches will be focused on the treatments with silane for polycarbonate and tire rubber particles to improve the interfacial behavior with the polymer matrix.

Declaration of Competing Interest

The authors declare that none of them has a direct financial relationship with the commercial trademarks mentioned in this paper that might lead to a conflict of interests; moreover, they declare that there is not conflict of interest in order to publish this paper.

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