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Research Article

Polypropylene Fibers as Reinforcements of Polyester-Based Composites

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Effects of gamma radiation and the polypropylene fibers on compressive properties of polymer concrete composites (PC) were studied. The PCs had a composition of 30 wt% of unsaturated polyester resin and 70 wt% of marble particles which have three different sizes (small, medium, and large). The PCs were submitted to 200, 250, and 300 kGy of radiation doses. The results show that the compressive properties depend on the combination of the polypropylene fiber concentration and the applied radiation dose. The compressive strength value is highest when using medium particle size, 0.1 vol% of polypropylene fibers and 250 kGy of dose; moreover, the compressive modulus decreases when increasing the particle size.

1. Introduction

Polymer concrete (PC) is a composite material formed by combining mineral aggregates with a thermoset resin. In its elaboration several parameters must be taken into account, such as resin type, initiator, and accelerator concentrations. The unsaturated polyester resin (UPR) is the most widely used due to their balanced mechanical and chemical characteristics, its ease of handling, and low cost; for its polymerization, 2 wt% of methyl-ethyl-ketone peroxide (MEKP), as initiator, and 0.5 wt% of cobalt naphthenate as accelerator are normally used, with at least 40 wt% of styrene.

The composition of polymer concrete is determined by its applications especially loading stress levels and ability to resist corrosive environment. PC is increasingly being used as an alternative to ordinary Portland cement concrete (PCC) in many applications, such as finishing work in cast-in-place applications, precast products, highway pavements, bridge decks, waste water pipes, and even decorative construction panels. In the last 40 years polymer concrete has made tremendous progress and continues to be very promising materials for a wide range of new and innovative applications. Moreover, the use of polymers should be well considered to guarantee better performance and improved sustainability [1–3]. Improvement on mechanical strength and chemical resistance is basic advantages of polymer concrete in comparison to ordinary Portland cement concrete (PCC). Three to five times on the compressive strength, high values for tensile strength (20 MPa), and flexural strength (50 MPa) are still an outstanding advantage of polymer concrete [3, 4].

Mechanical properties of polymer concrete depend on the type of resin and mineral aggregates. In the case of the last, higher specific surface means higher mechanical values, for example, (a) polymer concrete with clean sand have higher values than those with foundry sand [5]; (b) for concrete elaborated with epoxy resin, silica sand, hematite, and colemanite, the mechanical properties depend on the resin and hematite-colemanite concentrations; larger improvement for hematite is done [6]; (c) for concrete with waste marble as aggregate the splitting tensile strength decreases, and improvement on the elasticity modulus is produced [7].

Polymer concrete has relatively low tensile strength compared to its compressive strength. This limits its usefulness for load-bearing applications. Sudden and brittle failures occur in planes where tensile stresses exceed the tensile strength of the polymer concrete. Thus, reinforcement either by synthetic or natural fibers is one option to increasing its strength capacity, ductility, and toughness [5]. For example, glass fibers have been used for reinforcement of polyester polymer concrete, particularly for increasing flexural strength and strain at peak stress. An improvement of 80% in the flexural strength is obtained with respect to unreinforced polymer concrete. The toughness is increased by more than 1440% when 6 wt% of glass fibers is added. The glass fibers were 3 mm long and 0.013 mm of diameter, with a tensile strength of 2.5 GPa and a modulus of 70 GPa [8].

Carbon and glass fibers (1% and 2%, resp.) added to epoxy polymer concrete showed different behaviors. The carbon fibers increase the fracture energy by 340% while glass fibers by 140% when comparing to plain polymer concrete. Nevertheless, the fibers induce failure due to poor adhesion between them and polymer resin including the break of the fibers when compressive test is evaluated [9]. Chopped glass fibers were with random size, while chopped carbon fibers (made from a poly-acrylic-nitrile precursor material) were on average 6 mm.

The fracture behavior of concrete elaborated with polyester resin (18%) and sand and glass fibers (82%) was studied. Stable crack growth prior to peak load was found when adding 4% of glass fibers (13 mm long) [10]. In the case of polymer concrete with polypropylene fibers the compressive strength, splitting tensile strength, and especially flexural strength and elasticity modulus increase while the weight diminishes [11].

Some studies concerned with the use of gamma radiation on polymer/mineral composites have been carried out. The effects of gamma radiation on pure polyester resin and polyester resin/gypsum composites show that the rupture stress is higher for pure resin than that for the composite (6.5 MPa versus 2.0 MPa, at 20 kGy). At highest dose (320 kGy) the values increase up to 9.0 MPa for pure resin and 3.6 MPa for the composite. Such difference is due to the lower tensile strength of gypsum (filler) when comparing to those for resin. Moreover, only the polymer chains (but not the inorganic filler particles) would build cross-links between the chains [12]. In other results, a minimal variation on the hardness is observed at different doses: 91% and 92% for the composite and 89% and 88% for pure resin (at 20 and 320 kGy, resp.) [12].

As it is known, the cross-linking reaction of unsaturated polyester resins (UP) is usually initiated by a thermal or redox initiator, but sometimes the full conversion is not fully achieved, due to the difficulty of mixing with initiators and/or promoters, which reduces the conversion, especially at room temperature [13]. The release of residual styrene of the UP resins creates problems to the environment and is the source of odor in many applications. One alternative route of curing UP resins is by radiation processing [14, 15]. Some differences are found when polyester resin with or without initiators is irradiated. At low dose (11.1 kGy), polyester resin with initiator shows a larger increase in the maximum load (30 N) higher than that for resin without initiator (20 N). Notorious is this value at higher dose (33.3 kGy), 320 N for resin with initiator and 200 N for resin without initiator [16].

2. Materials and Methods

2.1. Specimen Preparation. Before preparing the polymer concrete composites, one set of polypropylene atactic fibers (CONSA, Distrito Federal, Mexico) whose diameters vary from 50 to 60 μm were cut to 10 mm length on the average. For preparing the polymer concrete specimens, marble from a local company (GOSA, Atizapan, Mexico), as the fine aggregate, polypropylene fibers at concentrations of 0.1, 0.2, or 0.3% by volume, and a commercial unsaturated preaccelerated polyester resin (Polylite 32494-00, Reichhold, Atlacomulco, Mexico) were used. The proportion of the polyester resin in the PC was 30% by weight, and the PP fibers were distributed hazardously within the polymer matrix.

Polymer concrete specimens were prepared to be subjected to three different irradiation doses. After mixing, the polymer concrete cubic specimens ($5 \times 5 \times 5$ cm) were placed in a controlled temperature room at $23.0 \pm 3.0^{\circ}$C for 24 hours. Polymer concrete specimens were prepared and subjected to three different irradiation doses (200, 250, and 300 kGy).

2.2. Mechanical Tests. Compressive tests of the polymer concrete specimens were carried out in an Universal Testing Machine model 70-S17C2 (Controls, Cernusco, Italy), located at Laboratory of Research and Development in Advanced Materials (LIDMA) of the Autonomous University of the State of Mexico (UAEM), according to the ASTM C-109M standard.

2.3. Morphological Characterization. First, the fibers were vacuum-coated with carbon (thickness between 3 to 10 nm) with the aid of a Vacuum Evaporator (E. F. Fullam) at 50 mTorr. Then, the fiber surfaces were analyzed by scanning electron microscopy (SEM) in a JEOL model JSM-6510LV microscope in the secondary-electron mode, at 20 keV.

2.4. Irradiation Procedure. Atactic PP fibers and the polymer concrete composites were exposed at various gamma radiation doses using a ^{60}Co source. The fibers were placed in packets of 50 in a capillarity tube. The dosages were 200, 250, and 300 kGy at the dose rate of 3.5 kGy/h; the experiments were performed in air at room temperature. The irradiation was provided by a 651 PT Gammabeam Irradiator manufactured by NORDION (Chalk River, Ontario) and located at the Institute of Nuclear Sciences of the National Autonomous University of Mexico.

3. Results and Discussion

3.1. Compressive Strength. The PCs were fabricated containing different marble-particle sizes and different polypropylene-fiber concentrations. The selection of the particle sizes was in function of the availability of the commercial mesh (sieve), in our case 25, 14, and 8, which correspond to

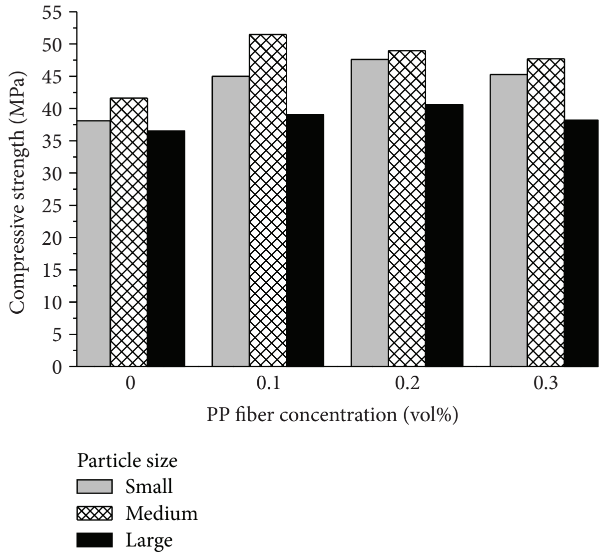

Figure 1: Compressive strength of polymer concrete with different marble particle sizes and fiber concentrations.

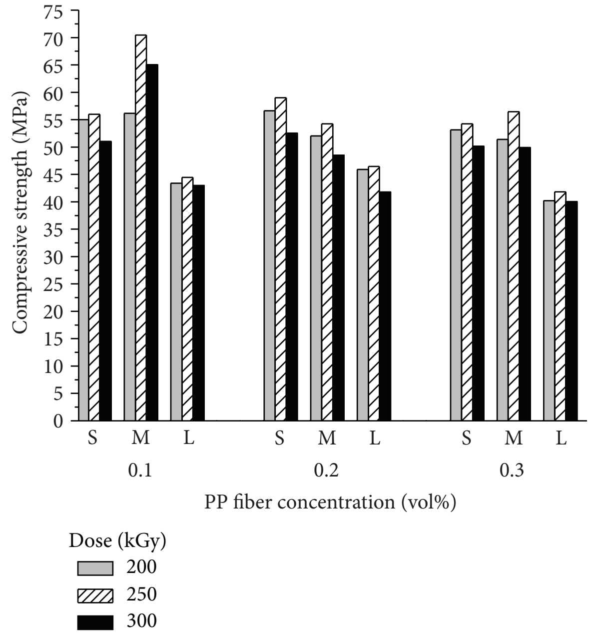

Figure 2: Compressive strength of irradiated-polymer concrete with different marble particle sizes and fiber concentrations.

an average particle size of 0.71, 1.4, and 2.36 mm, respectively. Thus, we have approximately 1 : 2 : 3 as the ratio. Through the article we will use the terms small (S), medium (M) or large (L) size, for 0.71, 1.4 and 2.36 mm, respectively.

It can be seen in Figure 1 the compressive strength (σ_c) values for PC elaborated with different particle sizes and polypropylene-fiber concentrations. The σ_c value is highest when using medium particle size and 0.1 vol% of polypropylene fibers, namely, 51 MPa. Conversely, the lowest value (36 MPa) is for those with large particle size and nonpolypropylene fibers.

For plain polymer concrete (without fibers), the σ_c values are in the range from 36 to 41 MPa, while for fiber-reinforced PCs from 38 to 51 MPa; thus, an improvement of 24% is obtained when using PP fibers. Moreover, a high-to-low sequence in the σ_c values for PC with respect to the particle size is as follows: (medium) > (small) > (large), independent of the fiber concentrations.

When comparing the present σ_c values with other PCs, we can see similar results. The σ_c values of the present communication are from 36 to 51 MPa; similar results were obtained as PC with silica sand (49 MPa) [17], but lower than for PC with $CaCO_3$ (86 MPa) [18], or with silica sand + $CaCO_3$ (106 MPa) [19].

The effect of the gamma irradiation is observed in Figure 2. The highest σ_c value is 70 MPa, that is, 58% of improvement in comparison with plain concrete. The present σ_c values are from 46 to 59 MPa.

According to the irradiation dose, different behaviors are well defined for the σ_c values: (a) the highest σ_c values are always obtained at 250 kGy, for all specimens, independent of the fiber concentration and particle size; (b) two well-defined stages are seen for each particle size; the first one consists of an increase of σ_c according to gamma radiation increase up to 250 kGy; then for higher dose the σ_c values decrease; an explanation for such behavior seems related to the radiation effects on the polyester resin; as already noted, the irradiation causes chain scission, but it also produces some crosslinking, chain relaxation, and cage breaking [20, 21].

(c) The maximum values are achieved when using medium particle sizes, and a high-to-low sequence in the σ_c values with respect to the particle size is as follows: (medium) > (small) > (large), independent of the fiber concentrations except for PC with 0.2% of fibers, where (small) > (medium) > (large) sequence is established.

Small size marble particles provide more obstacles to crack propagation in a given amount of concrete. Apparently the use of large particle sizes causes detrimental results due to poor adhesion between the polyester resin and the marble particles. Our PC had 70 wt% of marble particles.

In the case of irradiated PCs, there are significant differences. The present σ_c values were from 40 to 70 MPa and lower than for PC with silica sand (62–86 MPa) [17], with silica sand + $CaCO_3$ (104–112 MPa), [19] or with $CaCO_3$ (126–135 MPa) [18].

Along these lines, the ionizing energy generates more contact points and in consequence larger contact areas between the components: fibers, polyester resin, and marble particles [19, 22]. In turn, an increased number of contact points in the concrete will resist larger loads oriented at various angles relative to the longitudinal axes of the fibers. Eventually, the concrete will split approximately parallel to the dominant axis of the fibers, and the resulting crack will propagate out to the surface. In other words, the energy transfer drops rapidly unless reinforcement is provided to restrain the opening of the splitting crack.

3.2. Compressive Strain at Yield Point. In Figure 3 compressive strain values at yield point are shown. For plain polymer

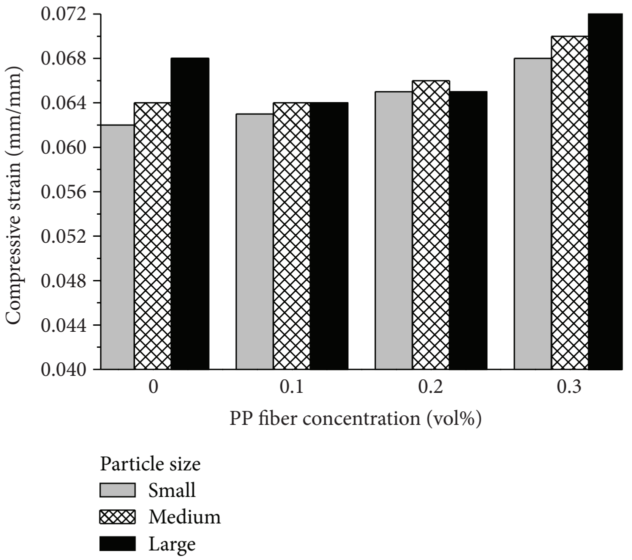

FIGURE 3: Compressive strain of polymer concrete with different marble particle sizes and fiber concentrations.

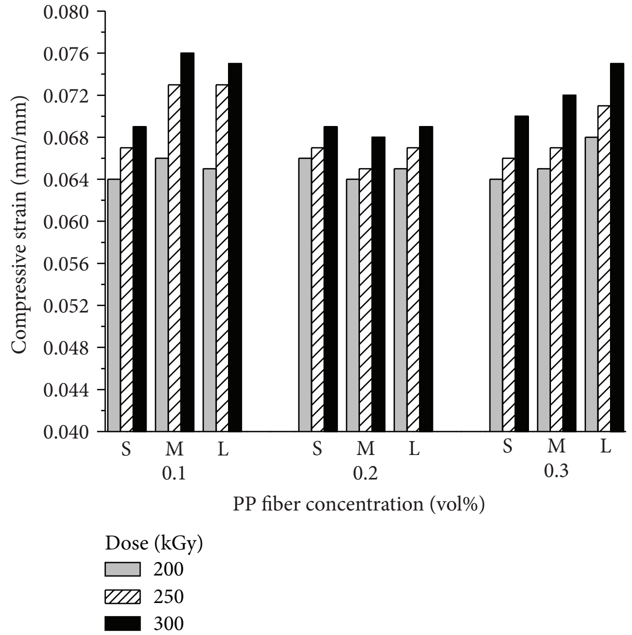

FIGURE 4: Compressive strain of irradiated-polymer concrete with different marble particle sizes and fiber concentrations.

concrete the values vary from 0.062 to 0.068 mm/mm. The highest values are for PC with 0.3 vol% of fibers (0.068 to 0.073 mm/mm); this means a minimal 7% of difference with respect to polymer concrete without fiber.

The compressive strain increases as the fiber concentration increases. Moreover, the sequence of high-to-low values in terms of the particle sizes is: (large) > (medium) > (small), except for polymer concrete with 0.2 vol% of fibers.

Different behaviors of the compressive strain for irradiated-polymer concrete were observed in Figure 4. (a) the high-to-low sequence on the values in terms of the fiber concentration is (0.1% by volume) > (0.3% by volume) > (0.2% by volume). Thus, an optimal concentration is 0.1% by volume for getting a more ductile concrete and 0.2% by volume, for getting a hard concrete. (b) For all specimens the compressive strain increases when gamma radiation dose increases.

The highest value (0.076 mm/mm) was obtained for polymer concrete with medium particle size and irradiated at 300 kGy; this means 11% of improvement with respect to nonirradiated polymer concrete.

3.3. Compressive Modulus of Elasticity. The compressive modulus of elasticity Ec for nonirradiated PCs showed values ranging from 0.71 to 1.26 GPa (Figure 5). Such values exhibit the same behaviour for all specimens: the modulus diminishes as the particle sizes increase, following the sequence: (small) > (medium) > (large); thus a statement can be formulated: the compressive modulus decreases when increasing the particle size. Apparently small particles—while providing good protection against crack propagation—provide more reinforcement than the medium or large ones.

A maximum for PC with small particles size and 0.1 vol% of PP fibers was identified, namely, 1.26 GPa; conversely a minimal value was obtained for PC with large particle size and 0.3 vol% of fibers (0.71 GPa).

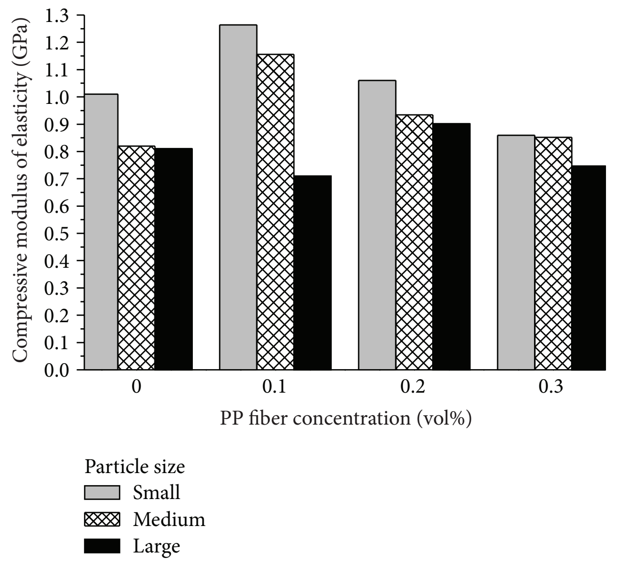

FIGURE 5: Compressive modulus of elasticity of polymer concrete with different marble particle sizes and fiber concentrations.

When comparing the Ec values for nonirradiated PCs with other PCs elaborated with different mineral aggregates, it was observed that the present value 1.88 GPa is lower than for PC with silica sand + $CaCO_3$ (5.2 GPa) [19], or silica sand + polypropylene fibers (5.7 GPa) [23], or PC with marble + calcium bentonite (6.8 GPa) [22], or for PC with silica sand (7.3 GPa) [17], or PC with $CaCO_3$ (7.6 GPa) [18].

In the case of Ec values for irradiated PCs, several behaviors were observed. The present values are in the range from 0.99 to 1.88 GPa (Figure 6); it means 49% of improvement

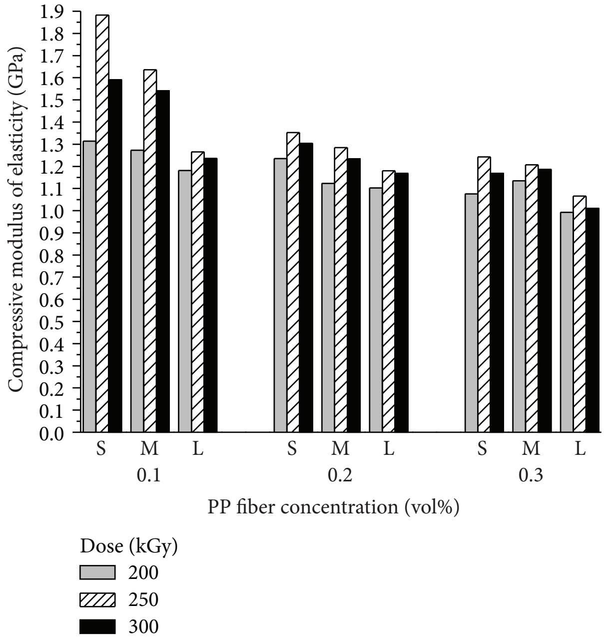

Figure 6: Compressive modulus of elasticity of irradiated-polymer concrete with different marble particle sizes and fiber concentrations.

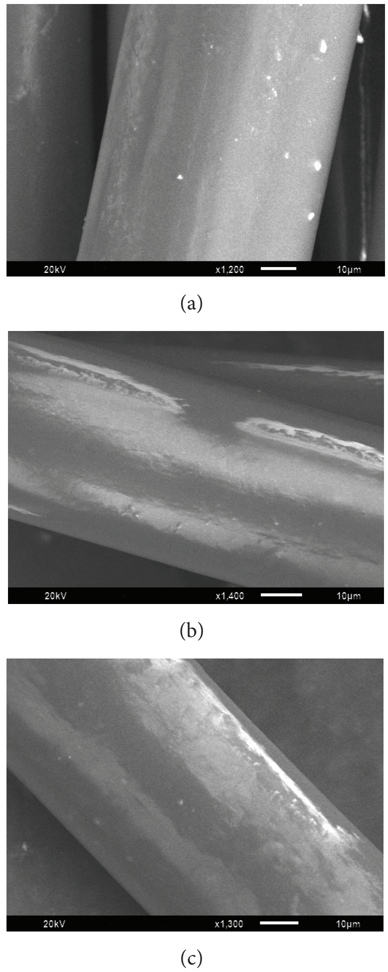

Figure 7: SEM images of irradiated polypropylene fibers at (a) 200 kGy, (b) 250 kGy, and (c) 300 kGy.

with respect to Ec values of nonirradiated PCs. In terms of PP fiber concentration, higher values were observed when adding 0.1 vol% of fibers and lower values when adding 0.3 vol% of fibers. Thus, the values follow the sequence: (0.1 vol%) > (0.2 vol%) > (0.3 vol%), and it is established that the compressive modulus decreases when increasing the PP fiber concentration.

With respect to particles size, the Ec values follow the rule: when increasing the particle size, the compressive modulus diminishes; same behavior was observed for nonirradiated PCs. Finally, following the radiation dose, for each particle size a premise is observed: the Ec values show two well-defined stages; the Young modulus increases when the radiation dose increases up to 250 kGy, and after this dose the Young modulus decreases. At 250 kGy the highest value is obtained.

When comparing with another Ec reported in the literature, the highest Ec value (1.88 GPa) is lower than for PC with two mineral aggregates of marble + calcium bentonite (6.3 GPa) [22], or for PC with silica sand + $CaCO_3$ (8.0 GPa) [19], or for PC with silica sand + polypropylene fibers (9.6 GPa) [23], including PCs with one aggregate: silica sand (16.3 GPa) [17] or with $CaCO_3$ (16.1 GPa) [18].

As it was studied the compressive strength and strain as well as compressive modulus depend on: particle size, PP fiber concentration, and gamma dose. The last one involves the modifications of the surface morphology caused by radiation on the polypropylene fibers. SEM images for irradiated fibers at 200, 250, and 300 kGy are shown in Figure 7. Small pieces of scrap of material and well-defined lines at irradiation dose of 200 kGy (Figure 7(a)) can be seen. When increasing the radiation dose at 250 kGy, roughness and deteriorated regions are observed (Figure 7(b)). Such deteriorated regions increase at 300 kGy dose, and more small particles are formed on the surface.

4. Conclusions

As expected, mechanical behavior depends on the combination of polypropylene fiber concentration and the applied radiation dose. Compressive strength values are higher for polymer concrete with medium particle sizes and irradiated at 250 kGy and the lowest elasticity modulus with large particle sizes. Such last behavior suggests generation of a ductile material. Moreover, depending on the latter combination of particle sizes, the polymer concrete needs low or high radiation doses to obtain high deformability with moderate compressive strength.

Conflict of Interests

The authors declare that none of them have a direct financial relationship with the commercial trademarks mentioned in this paper (CONSA, Controls, and GOSA) that might lead to a conflict of interests for any of the authors.

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