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Polymer concretes improved by fiber reinforcement and gamma irradiation

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Abstract: The well-known key problem with concrete is that its compressive strength and the compression modulus are insufficient for a variety of applications. Our polymer concrete (PC) consists of an unsaturated polyester resin as the polymeric matrix, silica sand as the inorganic aggregate, plus atactic polypropylene (PP) fibers. A further property improvement can be achieved by gamma irradiation and we apply here two methods. The first method consists in irradiation of PP fibers first and then adding them to the PC. The second route consists in irradiation of PC after inclusion of PP fibers. Along both routes we have applied the radiation at dosages ranging from 5 to 150 kGy. In the second route irradiation of silica sand results in larger contact areas of surfaces with PP fibers and with the polyester resin—as seen in scanning electron microscopy. The second route provides compressive properties which is better by a factor of two or three (depending on the irradiation dose) than the first one.

Introduction

Engineers use more and more polymer concrete (PC) that consists of a polymeric matrix and dispersed particles of strengthening phases. The polymer constitutes the continuous phase; hence the composite behavior is largely determined by the properties of the polymer - which are dependent on time, structure and temperature. PC shows a longer maintenance-free service life than Portland cement concrete (PCC), because of its durability and physical properties superior to those of PCC, fast setting times (curing within 1 or 2 h) and low permeability. Moreover, improved mechanical strength (compressive and flexure) and better chemical resistance are also advantages of PC in comparison to ordinary PCC [1, 2].

The composition of polymer concrete is determined by its applications. In general, when adding polymer it is desirable to obtain high compressive and flexural strength, high impact and abrasion resistance, service possible in adverse environments (wind,

moisture, etc.), lower weight and lower costs. PC is in use in a variety of applications: a) in highway pavements; b) as underground wastewater pipes; c) for manufacturing thin overlays (since it has the advantage of providing light weight); d) precast components for bridge panels, buildings, machine bases and transportation components; e) in high pressure and temperature environments such as the utilization of geothermal energy due to its durability in hot acidic springs. This last application is increasing in its importance.

The composition of PC typically involves an aggregate gradation to provide the lowest possible void volume that will require a minimum polymeric binder concentration necessary to coat the aggregates and to fill the voids [1]. Fine and coarse aggregates in PCs have been used, including fly ash, river sand, silica sand, crushed sand or gravel. Other kinds of aggregates are $CaCO_3$, bentonite or barite ($BaSO_4$). Barite is used in concrete shielding against radiation since it contains high concentration of soft barium sulfate particles. Kilincarslan and his colleagues discuss how open cracks can be filled with barite, iron oxide and clay particles [3]. As for bentonite, it consists of montmorillonite and small amounts of fragments that include plagioclase group, silica group (quartz and its polymorphs tridymite and cristoballite) and calcite, and sometimes volcanic glass [4].

As already noted, a polymer is the continuous phase in PCs. Curing of polyester resins must be well controlled in order to obtain good workability and to avoid the presence of water. In general, the resin is pre-accelerated by the manufacturer, and different initiators and promoters have been used to begin the free-radical polymerization process; an example is methyl ethyl ketone peroxide (MEKP).

Some reinforcements such as glass or organic fibers have been added to PCs with a polyester resin as the matrix. These reinforcements have little effect on the pre-cracking behavior but do substantially enhance the post-cracking response, improving the toughness and the ductility as well as the tensile, flexural and impact strength.

Compressive strength values for a number of glass-fiber-reinforced-PCs (G-FRPC) have been reported [5]. The polyester resin content was typically in the range 10 - 18 wt. % while the fiberglass was 2 - 6 vol. %. The resulting compressive strength values are between 33 and 83 MPa - and as expected depend on the fiber and the polyester resin content. The maximum compressive strength value (83 MPa) has been found for 4 % of the fibers and 18 % of resin content. Thus, there is an optimal fiber content (based on maximum strength) for each resin content.

Another important mechanical property is of course the modulus of elasticity in compression E_c. For G-FRPCs, the values decrease when the fiber content increases (from 0 to 6 % in volume) [5]. Moreover, for each fiber content the E_c increases along with an increase of the polyester resin concentration (from 10 to 18 wt. %). The modulus of elasticity values range from 3.5 to 7.1 GPa. Variations of E_c are probably due to entanglements of some glass fibers, resulting in pores and causing a decrement in the stiffness. Sometimes silane as a coupling agent is added to the monomer to improve the bond strength between the resin and the aggregates. However, the main problem arises from the viscoelastic properties of the resin; the polymers usually have a low modulus of elasticity, are flexible and exhibit creep behavior [6].

Polyamides such as nylon provide a different class of polymeric fibers. Their commercial success is due to their good properties and economical advantages. A

relatively low concentration of nylon fibers substantially improves the impact resistance of composites due to stretching and resistance to pull-out of the fibers [7]. Large strains are needed to cause failure. Nevertheless, the added fibers have very little effect on tensile or bending strength. Thus, it would be advantageous if composites could be designed to support an increasing load after the cracking of the matrix. This problem can be solved by improving the stress transfer from the matrix to the fibers - in particular after matrix failure. The transfer will depend on the aspect ratio of the fibers and the interfacial shear strength. Thus, there are possibilities for improving these parameters by modifications of the fiber surfaces and/or of the polymeric matrix surface [8].

In some composites, chemical bonding between the fibers and the matrix is relatively weak in comparison to frictional resistance along the debonded segment against pull-out. In general, friction plays a role proportional to the increasing fiber size in confining stress. Moreover, most fiber deformation processes lead to local mechanical interactions between fiber and matrix and, therefore, may be regarded as a macroscopic "roughening" effect [9].

Another important class of synthetic fibers are those based on polypropylene (PP) [10, 11]. They are chemically inert, have a hydrophobic surface, good to fair water resistance and good alkali resistance. Their mechanical performance includes tensile strength varying from 310 to 760 MPa, elastic modulus from 3.5 to 4.9 GPa and elongation at break, ε_b = 15 %. Moreover, they are currently manufactured in a variety of geometries and configurations and can be produced as monofilaments, collated fibrillated fiber bundles or continuous films.

PP fibers can be incorporated into Portland cement concrete (PCC) at relatively low volume fractions (below 0.3 %) merely to control temperature and shrinkage cracking. Also they can improve the post-crack energy absorption capacity, the flexural strength, toughness and ductility of reinforced PCC. Another kind of reinforced-PCC are those involving textile reinforcements as rovings (a bundle of a very large number of continuous filaments). Here the failure mechanisms are quite complex. In general, for low loadings the final failure occurs due to the breaking of the rovings [12]. We would like to point out that a large amount of information has been generated on fiber-reinforced PCC but very little on polymer concrete (PC).

Spatial arrangement of micro-cracks is important. Thus, Richter and Zastrau have modeled textile reinforced concrete at two levels taking into account cracking [12]. Their model deals with interactions between rovings and micro-cracks. As for fiber-reinforced concrete (FRC), a model has been developed for light concrete as the matrix filled with polyester fibers [13]. Aggregation of the fibers is taken into account in a 3-dimensional model. Output includes optimized densities of the components and as well as optimized volumetric concentration of the fibers.

Experiments show that the compressive strength of PP-fiber PCC decreased by approximately 20 % when curing took place in air - compared with the corresponding results for specimens cured under water. Moreover, the fracture toughness decreased 8 % when cured in air, and the shear strength decreased 15 % [9]. Of course, the fact that the more water present improves PCC properties has been known for a long time.

Physicochemical modifications of the polymer concrete components (polymeric matrix and the mineral aggregates) by using chemical attack or thermal processes are consuming time and money. An alternative is to use ionizing energy to improve compatibility between them by means of structural and surface modification of both components.

It is well known that gamma radiation causes structural modifications of polymers via three main processes: scission, crosslinking and grafting of chains involving generation of free radicals [14 - 17]. Moreover, the process has several advantages: curing at ambient temperature; no need for additives; better solvent resistance of the polymer and its improved shape stability with respect to aging and to high temperatures and shorter curing times [18, 19].

If completion of the polymerization process of the resin is not achieved (when the catalyst does not complete its function), applying gamma radiation can solve that problem [19, 20]. The radiation initiation does not require any activation energy; the termination reaction is practically always diffusion controlled. We note that the required doses for total cure strongly depend on the composition used; it is necessary to evaluate the rate of cure progress [21].

In gamma irradiated unsaturated polyester resins the reaction runs smoothly and the product is flawless - unlike badly foamed products obtained when using catalysts. Around 3 kGy the samples behave as fairly elastic gels, and there is a monotonous increment in the conversion percentage up to about 8 kGy; at this stage a gel fraction and the styrene monomer are present. Multiple-phase products are formed in that stage when the glass-rubber transition is below the reaction temperature (the curing temperature = 35 ^{o}C) [22]. Moreover, impregnation and curing of different substrates with polyester resins at high temperatures are safer in the absence of initiators [23].

A few studies have been carried out on effects of gamma radiation on mineral aggregates or on formation of chemical links between filler particles and polymer chains [24]. Kilincarslan and coworkers have shown that using barite one can obtain heavyweight concrete with a high density and adequate structural strength [3]. This is important since barite can provide radiation protection for concrete. In composites such as silica + polysiloxane-rubber the induced crosslinking enhances crystallization rates and thus improves mechanical properties at high strains. At the same time, a reduction in polymer-filler interactions at interfaces in silica + siloxanes composites is seen; the silica was modified by irradiation and a high surface area obtained [25].

Gamma radiation excites electrons sufficiently so that they leave their normal positions (valence to conduction band) producing positive holes and free electrons. Positive holes are electronic defects in the silica O^{2-} matrix created as a result of removal of an electron from the O^{2-} sites, which then become O^{-} sites. The existence of unpaired spins suggests the creation of paramagnetic species which can be trapped in regions of local charge deficit within the silica matrix and can be detected by electron spin resonance (ESR) spectroscopy [26].

At low gamma doses (up to 20 kGy) most of the paramagnetic species are likely to be trapped in the silica matrix. It is possible; however, that any species which are not trapped will migrate to the surface and - together with paramagnetic species created directly on the silica surface - will cause damage to the water/OH phase on the silica surface. At high gamma doses (greater than 30 kGy), it is likely that paramagnetic species created in the silica matrix will not be trapped since the trapping sites will be full. Such species may migrate to the silica surface. A small reduction in polymer filler

interaction (loss in silica reinforcement) is followed by a gradual increase of that interaction at higher doses. The effect may be due to silica-polymer crosslinking effects - probably arising from the reaction of peroxy entities or positive holes on the silica surface with free-radical sites on the polysiloxane chain [26].

Paramagnetic species that are not trapped may recombine or diffuse towards the surface causing the silica surface to become reactive. The sites are chemically active and may interact with surface water or silanol species to liberate hydrogen - whose quantities depend on the silica particle size. The effect is larger for small particles (with larger surface areas and relatively easy diffusion of paramagnetic species to the surface) than for large particles.

The effects of gamma radiation on thermal stability of two systems: a) polyester + styrene resin, and b) polyester + styrene resin + gypsum, show that the glass transition temperatures T_g are higher for the second system. The cross-links built between the polymer chains via irradiation reduce mobility of molecular segments of the chains in the vicinity of the filler particulates. It is for this reason that the glass transition temperature increases [27]. For low irradiation doses there is a slight increase of the glass transition temperature and then that temperature becomes constant. A generally observed behavior is that the filler influences the mechanism of thermal degradation of the polymer, independently of the amount and type of filler. Also in general inorganic particles because of their effective heat transfer decrease the thermal stability of the polymer composites. Then, the decomposition temperature of the polyester + styrene resin + gypsum goes down significantly, a result of the presence of the inorganic filler [27]. In both systems, the compression strength and the tensile stress at break increase with increasing the irradiation dose up to 320 kGy. The improvement of the compression strength is higher for the polyester + styrene resin system than for the composite containing gypsum for an obvious reason: only the polymer chains (but not the inorganic filler particles) can create crosslinks.

Compressive Strength

The compressive strength values are presented in Figure 1; we have identified the results of the two different methodologies as: a) AIF-PC = added-irradiated-fiber PC, for irradiation of PP fibers and then adding the fibers to the PC; and b) DI-PC = directly-irradiated PC for irradiation of the total PC composite already containing PP fibers. The results presented are based each on results for five different lots (labeled as A to E), each lot contained six samples and was prepared on a different day. That is, for each methodology 60 concrete specimens were made.

The first group analyzed consisted of non-irradiated PC specimens; the differences between them amount at most to 0.9 MPa or 1.3 %, as seen in Figure 1 and Table 1.

The second group analyzed was all irradiated AIF-PC specimens; the results are also seen in Figure 1 and Table 1. The compressive strength values for specimens with 0.3 vol. % of PP fibers have the maximum variation of 5.3 % with respect to the average (A-E) value (right extreme column in Table 1), and of 5.5 % for those specimens with 0.4 vol. % of fiber. Both percentage variations are a proof of our consistent control of material preparation.

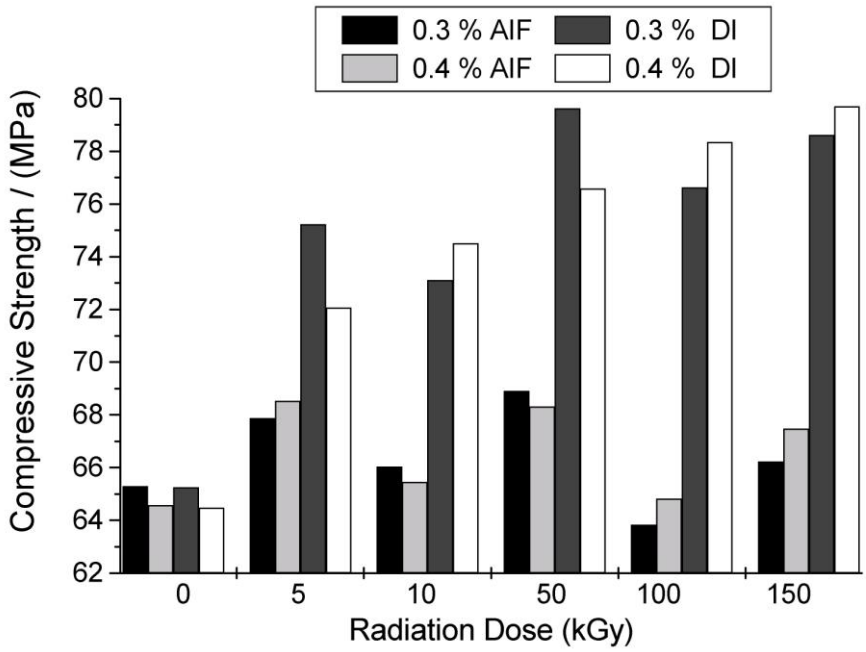


Fig. 1. Compressive strength of the fiber-PCs prepared by two different methods

One can argue that the addition of irradiated PP fibers to improve the compressive strength is hardly worthwhile. For AIF-PC with 0.3 vol. % of PP fibers the maximum compressive strength (68.91 MPa) was obtained when adding irradiated fibers at 50 kGy. For AIF-PC with 0.4 vol. % the maximum value (68.53 MPa) was obtained when adding irradiated fibers at 5 kGy. For both PP fiber concentrations, the best option is the irradiation at a low dose of 5 kGy.

The third group consisted of the DI-PC specimens whose compressive strength values are presented in Figure 1 and Table 2. Two well-defined behavior patterns as a function of the radiation dose are seen. For DI-PC with 0.3 vol. % of PP fibers, the compressive strength values increase along with the radiation dose. We have identified five stages that follow an increment-decrement-increment-etc. behavior. Similar periodic behavior has been observed in other polyester-based PC composites [24, 29, 30]. A different behavior is seen for DI-PC with 0.4 vol. % of PP fiber, where the rule “the compressive strength increases with the applied dose” is followed. We see that here even 0.1 vol. % of PP fibers in the PC change the overall compressive behavior.

The highest compressive strength value for DI-PC with 0.4 vol. % of PP fibers is only 0.08 MPa higher than for DI-PC with 0.3 vol. % of the fibers (see Table 2). For 0.3 % of fibers the maximum value (79.62 MPa) was reached at 50 kGy while for 0.4 % of PP fibers it was necessary to apply a triple dose of radiation (150 kGy) to achieve a similar result. Figure 1, tells us that the combination: low fiber content (0.3 vol. %) and low radiation dose (50 kGy) provides the highest compressive strength.

In general, the compressive strength values go from 64.57 to 68.91 MPa for AIF-PC, and from 64.47 to 79.7 for DI-PC. These values are higher than those reached for polyester-based PCs with nylon fibers and calcium bentonite + marble as aggregates: from 47.3 to 69.6 MPa [30].

Tab. 1. Compressive strength of the fiber-PCs prepared by the AIF method.

Specimen number	Radiation dose / kGy	Vol. % of PP fibers	Compressive Strength/(MPa)					Average A-E
			A	B	C	D	E	
1	0	0.3	68.31	65.20	68.68	62.40	61.92	65.30
2	5	0.3	64.73	65.79	71.31	70.61	66.96	67.88
3	10	0.3	69.87	62.77	68.28	67.05	62.18	66.03
4	50	0.3	72.82	66.19	71.63	67.25	66.66	68.91
5	100	0.3	60.82	63.84	66.37	67.35	60.82	63.84
6	150	0.3	63.19	69.34	67.05	68.39	63.18	66.23
7	0	0.4	61.20	67.39	62.38	63.70	68.18	64.57
8	5	0.4	64.35	67.28	71.18	70.49	69.36	68.53
9	10	0.4	63.47	69.22	68.37	63.25	62.94	65.45
10	50	0.4	65.49	65.28	68.10	71.25	71.43	68.31
11	100	0.4	61.23	66.30	65.12	68.02	63.43	64.82
12	150	0.4	63.75	70.29	70.66	68.39	64.31	67.48

At the same time, the present values are lower than those in polyester-based PCs without fibers and with different mineral aggregates: a) with silica sand (from 49.7 to 86.2 MPa) [29] or with $CaCO_3$ (from 86.4 to 135.0 MPa) [24]. Thus, when using PP fibers in the PCs, it is possible to reach the compressive strength of nearly 80 MPa.

Tab. 2. Compressive strength of the fiber-PCs prepared by the DI method.

Specimen number	Radiation dose / kGy	Vol. % of PP fiber	Compressive Strength / (MPa)					Average A-E
			A	B	C	D	E	
13	0	0.3	66.71	67.56	61.45	63.98	66.50	65.24
14	5	0.3	78.53	71.55	70.95	76.20	78.91	75.23
15	10	0.3	73.34	73.46	77.22	72.54	69.00	73.11
16	50	0.3	82.98	76.09	79.09	79.78	80.15	79.62
17	100	0.3	73.70	80.13	74.51	75.05	79.75	76.63
18	150	0.3	76.25	80.01	76.98	79.60	80.26	78.62
19	0	0.4	61.43	68.84	64.65	60.48	66.95	64.47
20	5	0.4	69.35	68.49	74.58	74.77	73.12	72.06
21	10	0.4	77.43	70.24	71.14	77.88	75.88	74.51
22	50	0.4	73.32	76.84	74.65	79.86	78.29	76.59
23	100	0.4	75.66	75.29	77.62	81.04	82.15	78.35
24	150	0.4	78.40	78.31	76.82	82.58	82.40	79.70

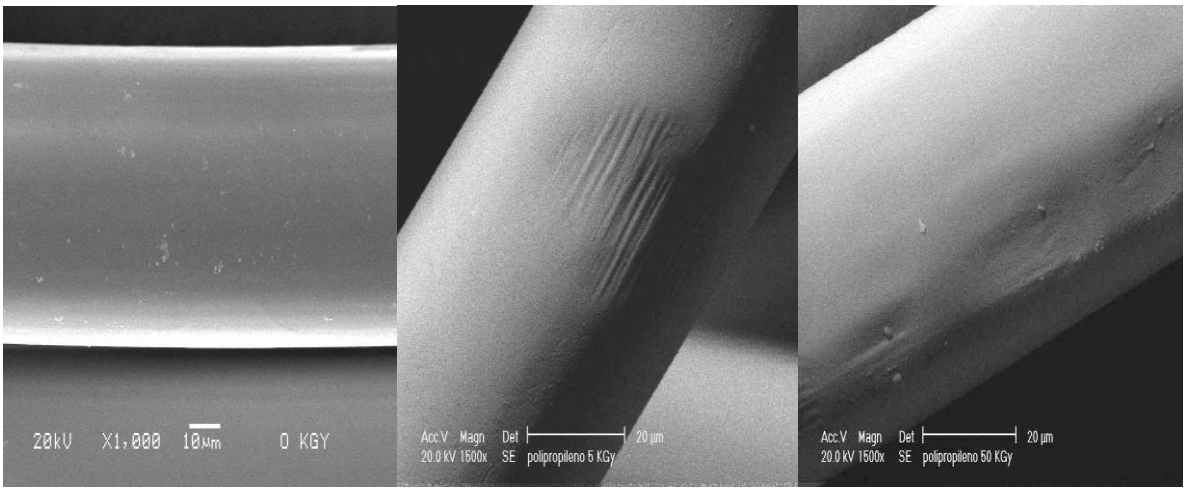
As for mechanical characteristics, earlier work on irradiated PP fibers shows a maximum improvement of 14 % for the tensile stress when irradiating the fibers at 5 kGy. Above that dose the tensile stress values decrease; for fibers irradiated at 100 kGy the tensile stress is 40 % lower than for the raw fibers [31]. Another way to characterize the fibers is tenacity – which is the strength for its given size, it is the

grams of breaking force per denier unit of the fiber size (grams per denier, gpd). The tenacity values decrease dramatically when the applied radiation increases: 4.34 (gpd) for non-irradiated PP yarns and loosing 70 % of that value from irradiation at 180 kGy [32].

We note that the highest compressive strength value obtained at 5 kGy for AIF-PC with 0.4 vol. % of PP fibers corresponds to the maximum tensile stress of the PP fibers irradiated at the same dose. At higher doses both the compressive strength and the tensile stress go down.

Morphology of the Concrete

Changes in surface morphology caused by radiation were studied with SEM. In Figure 2 we display the results for several doses. For non-irradiated fibers a smooth and homogeneous surface is seen (Figure 2a). At 5 kGy several “wrinkles” are observed (Figure 2b). The results reported in the previous Section tell us that the wrinkles contribute to an improvement of the compressive strength (a maximum at that dose). Figure 1 tells us that for fibers irradiated at 50 kGy there is a second maximum. Figure 2c suggests that the maximum is related to a combination of two kinds of morphological changes: wrinkles and small particles formed on the surface.



(a) (b) (c)

Fig. 2. SEM micrographs of polypropylene fiber: a) non-irradiated, b) irradiated at 5 kGy, and c) irradiated at 50 kGy.

The surface morphologies we see are similar to those reported by others for irradiated PP fibers. At 5 kGy small pieces of scrap of material are formed. When increasing the irradiation dose to 50 kGy, small spheres are formed [31].

Kopczynska and Ehrenstein [33] and also Dzenis [34] discuss the importance of interfacial energies for properties of the composites. Along these lines, the ionizing energy generates more contact points and in consequence larger contact areas between the components: fibers, polyester resin and silica sand. 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 a reinforcement is provided to restrain the opening of the splitting crack.

Compressive Strain at Yield Point

Compressive strain at yield point values ε_y are presented in Figure 3. We begin with the results for PC without fibers. Increasing the radiation dose increases ε_y up to 10 kGy; afterwards a decrease is observed. Zhang, Tasaka and Inagaki [35] have reported increased adhesion (and also higher friction) in polystyrene (PS) caused by decreasing molecular weight and thus appearance of shorter chains. While PS exhibits much higher brittleness than most polymers [36, 37], we presume that effects of formation of shorter chains by scission are similar in polymers in general. Since irradiation causes both chain scission and crosslinking, we infer that up to 10 kGy the scission prevails.

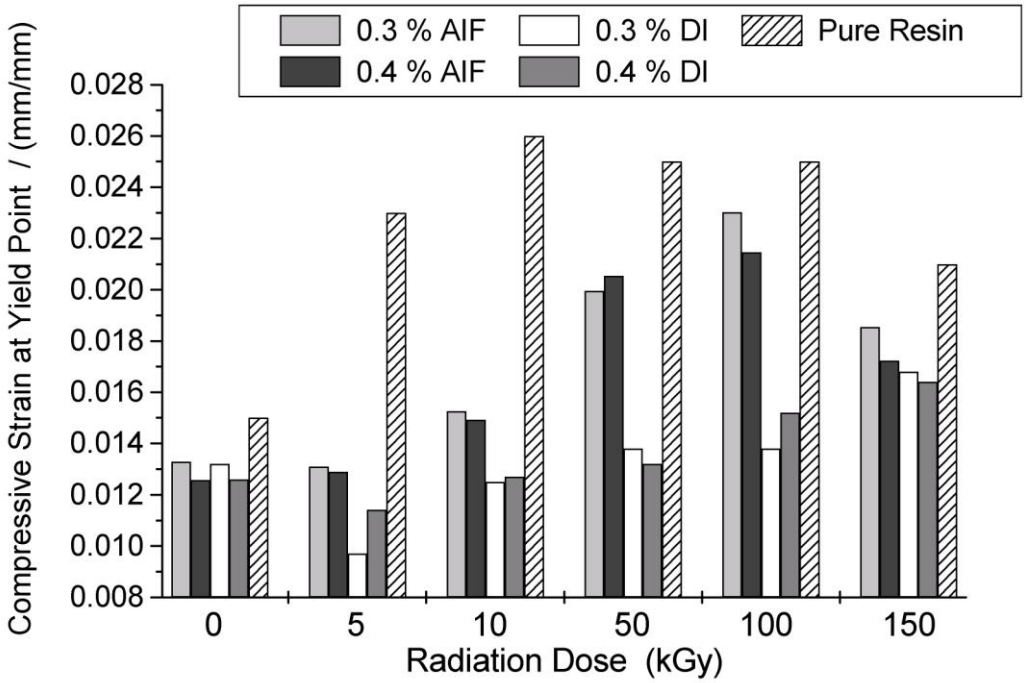


Fig. 3. Compressive strain at yield point results.

As expected, ε_y depends on several parameters, including the applied dose, the volume percentage of PP-fibers and the preparation procedure (AIF or DI). As noted in Section 2, we have prepared five lots for each composition and each procedure. The largest difference in ε_y values between the lots is 4.6 % - testifying to our consistent control of material preparation.

For AIF-PC the compressive strain behavior is very similar for both fiber concentrations. The ε_y values increase from 0 to 100 kGy and then go down for 150 kGy. At 100 kGy we have 84 % higher ε_y with respect to non-irradiated PC. This behavior is similar to that of the composite without PP fibers, except that the maximum value is reached much sooner, already at 10 kGy.

A different behavior is seen for DI-PC; overall, ε_y values are lower than for AIF-PC. For both PP fibers concentrations in DI-PCs we see two well-defined stages: I) from 0

to 5 kGy a decrease; II) from 5 to 150 kGy an increase. Also for both fiber concentrations the highest values are reached at 150 kGy, an improvement of 27 % for 0.3 vol. % PP and 30 % for 0.4 vol. % PP with respect to non-irradiated DI-PC.

When two kinds of polymeric constituents are present: fiber and polyester resin, larger effects on the compressive strain as seen. In Figure 3, large decreases of ε_y are caused by the PP fibers for each irradiation dose. Thus, we conclude that the fibers have more influence on the PC properties than the polyester resin.

In general, the compressive strain values go from 0.012 to 0.023 mm/mm for AIF-PC and from 0.009 to 0.016 mm/mm for DI-PC. These values are lower than those reached for polyester-based PCs with nylon fibers and calcium bentonite + marble as aggregates: from 0.011 to 0.039 mm/mm [30]. Nevertheless, the values are similar when compared with polyester-based PCs without fibers but with various mineral aggregates: a) with silica sand (from 0.006 to 0.013 mm/mm) [29], or with $CaCO_3$ (from 0.01 to 0.016 mm/mm) [24].

Compression Modulus of Elasticity

In general, for both fiber percentages and for the material without fibers, the elastic modulus in compression E_c values show two well-defined stages: I) an increase from 0 to 5 kGy and II) a decrease from 5 to 150 kGy (Figure 4).

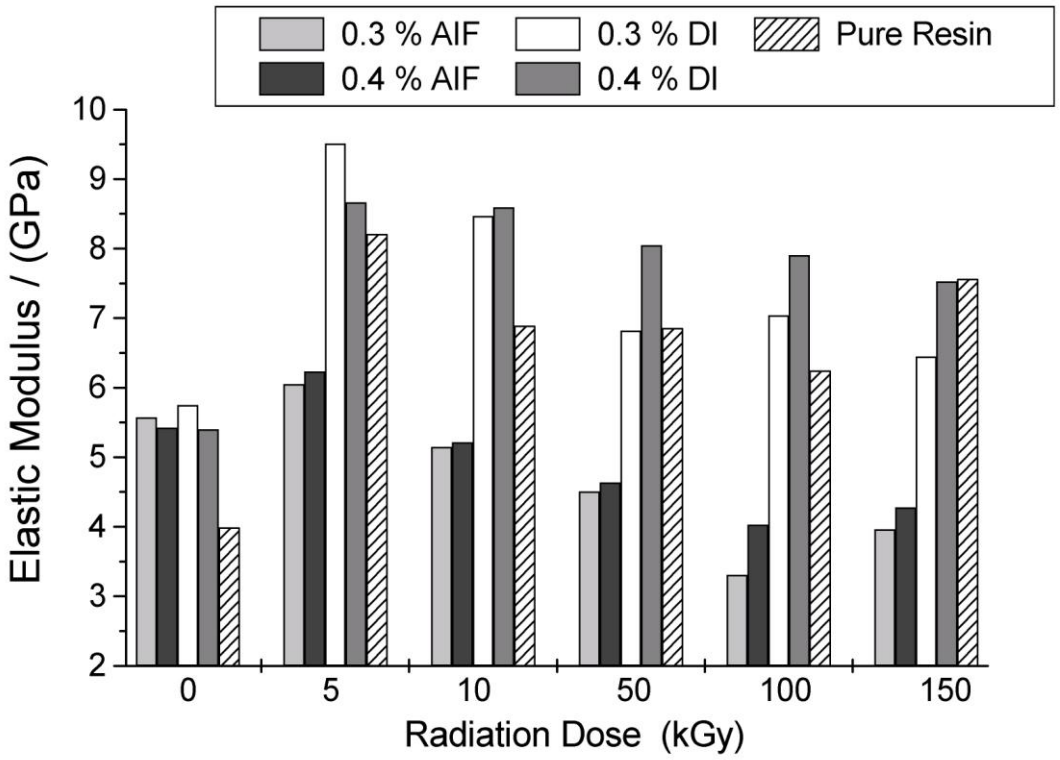


Fig. 4. Compression modulus of elasticity E_c results.

Compression modulus values for AIF-PCs are lower than those for DI-PCs. The highest E_c values for AIF-PCs are found at 5 kGy and the lowest at 100 kGy,

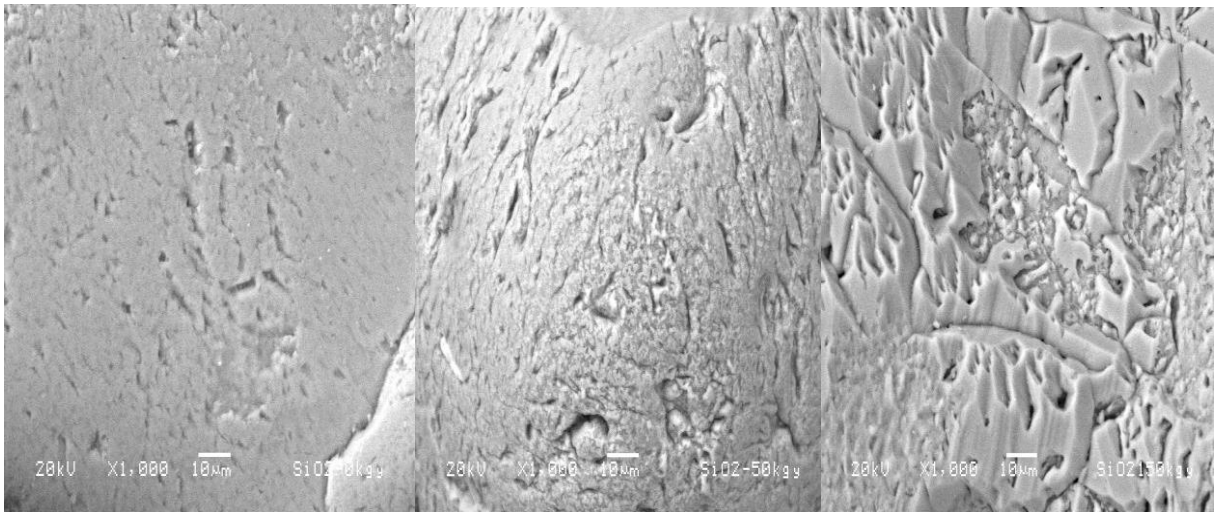
independently of the fiber content. The elastic modulus values for PC with 0.4 vol. % PP are quite close to those with 0.3 % PP.

For DI-PCs the maximum E_c value is found at 5 kGy for both fiber contents. That maximum represents an improvement of 41 and 33 %, for 0.3 and 0.4 vol. % of PP fibers, respectively, with respect to the composite without fibers.

When we follow the AIF method, the values of E_c at any non-zero irradiation dose are lower than for the PC without fibers. Thus, the AIF procedure makes the concrete more ductile. An opposite – and desired – effect is seen when following the DI method.

Morphology of Silica Sand

A literature survey shows that relatively little attention has been paid to the morphology of silica sand and contribution of the sand to mechanical improvement of PC. We have decided to address this issue. The results are presented in Figure 5.
Evident in Figure 5 are morphological changes dependent on the irradiation dose. Crazes and some grooves are observed. The number of the crazes increases with the irradiation dose; the crazes are well developed at 150 kGy, about 100 μm long and a certain “branching” tendency is seen. The wrinkles have more contact points – thus providing stronger adherence of sand to the polymeric components, PP fibers and the polyester resin. Herein lie an explanation of the property improvement resulting from irradiation.



(a) (b) (c)

Fig. 5. SEM micrograph of silica sand: a) non-irradiated, b) irradiated at 50 kGy, and c) irradiated at 150 kGy.

Concrete is one of the oldest materials used by mankind. A large variety of methods of improving it has been developed [38 - 41]. The field is as crowded as it is important. We have succeeded in making progress by our combination of fibers and irradiation.

Given the above results, the question is whether to use the AIF-PC or the DI-PC route. The latter offers higher compressive strength values than the former; apparently the addition of irradiated PP fibers to the PC is not sufficient to improve

the compressive strength. The highest compressive strength is achieved for the DI-PC method at a low fiber content (0.3 vol. %) and a low radiation dose (50 kGy). On the other hand, when ductility is important for the final application, the AIF-PC method is recommended since the compressive strain values are higher (the elastic modulae lower) – a consequence of irradiating the fibers only.

Experimental part

Specimen preparation

Before preparing the polymer concrete specimens, polypropylene atactic fibers (CONSA™, Distrito Federal, Mexico) whose diameters vary from 30 to 40 μm were cut to 10 mm length on the average.

For preparing the polymer concrete specimens, natural silica of a local company (GOSA™, Atizapan, Mexico) was used, as well as commercial unsaturated pre-accelerated polyester resin (orthophtalic), a viscous liquid resin with a styrene monomer content of 30 % (Polylite 32493-00™, Reichhold, Atlacomulco, Mexico). The proportions of MEKP added to the polymer for initiating the free-radical polymerization process were 1 mL/100 g of the polyester. The weight proportions of the components in the polymer concrete were 30 % of the polyester resin and 70 % of silica sand.

Two different methodologies for obtaining the polymer concrete were employed: a) irradiation of PP fibers and then adding the fibers to the PC (added-irradiated-fiber PC, AIF-PC); and b) irradiation of PC already containing PP fibers (directly-irradiated PC, DI-PC). After mixing, the polymer concrete cubic specimens (2”x2”x2”) were placed in a controlled temperature room at 23.0 ± 3.0 °C for 72 hours.

For both AIF-PC and DI-PC specimens, five different lots were prepared, each one a different day. The fiber content was 0.3 or 0.4 % in volume.

Mechanical Tests

The compressive tests of the polymer concrete cubic specimens were carried out in an Instron Universal Testing machine Model 1125. The allowed testing tolerance for the specimens was 4 days and the charge speed was between 91 and 184 kg/s, holding the charge until the maximum value to assure the reliability of the test was reached.

Morphological characterization

First the fibers were vacuum-coated with carbon (thickness between 3 to 10 nm) in a vacuum pump (E.F. Fullam) at 50 mTorr. Then the fiber surfaces were analyzed by scanning electron microscopy (SEM) in a JEOL model JSM-5200 machine in the secondary-electron mode. That mode provides good images of distribution of dispersed phases in a matrix [28].

Irradiation procedure

Atactic PP fibers and the PC cubic specimens were exposed to varying gamma radiation doses using a ^{60}Co source. The fibers were placed in packets of 50 in a capillarity tube. The dosages were 5, 10, 50, 100 and 150 kGy at the dose rate of 6.10 kGy/h; the experiments were performed in air at the room temperature. The

irradiation was provided by a 651 PT Gammabeam Irradiator manufactured by the Atomic Energy of Canada Ltd. (AECL, Chalk River, Ontario), and located at the Institute of Nuclear Sciences of the National Autonomous University of Mexico.

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