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Mechanical properties of polypropylene-fiber reinforced concrete after gamma irradiation

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ABSTRACT

Fiber reinforced concretes (FRCs) exhibit property improvement caused by the fibers. By using gamma radiation we have further improved mechanical properties of hydraulic concretes elaborated with Portland cement, water, silica sand, marble and polypropylene (PP) fibers. Compression strength, compression modulus, impact strength and dynamic elastic modulus were determined. Impact fatigue testing is a convenient way to evaluate non-irradiated concretes. We find improvement of the strength and elastic modulus – dependent on PP fiber concentration, marble particle sizes and the applied dose. Both the compressive strength and the elastic modulus are the highest for concrete with 1.5 vol% of PP fibers. The compressive strength value at that PP fibers concentration, the average marble size of 1.4 mm and irradiated at 50 kGy is higher by 19% with respect to non-irradiated concrete. For 9.5 mm marbles the analogous improvement amounts to 25% but for the dose of 10 kGy.

1. Introduction

Fibers are used for polymer reinforcement [1,2] – also in fiber reinforced concretes (FRCs) [3–7]. Various fibers such as those made from polypropylene (PP) have been applied. PP fibers can be produced as monofilaments or as collated fibrillated fiber bundles; their properties are related to the degree of crystallinity. PP is a linear hydrocarbon, although in some cases methyl side groups are attached to alternate carbons to improve oxidation resistance [4].

Commercial success of polypropylene fibers as a filler material in Portland cement concrete (PCC) is due to their advantageous properties. The fibers are chemically inert, have hydrophobic surfaces, are very stable in the alkaline environment of concrete and resist plastic shrinkage cracking. Nevertheless, they also have some disadvantages – including poor fire resistance, sensitivity to sunlight and oxygen, a low modulus of elasticity, and poor bonding with the concrete matrix [5,7].

The use of relatively low-modulus PP fibers does not yield substantial improvement of the tensile strength – but does significantly improve the flexural strength, toughness and ductility. Concrete reinforced with collated fibrillated PP-fibers (at relatively low volume fractions <0.3%) are used for: secondary temperature-shrinkage reinforcement, overlays and pavements, slabs, flooring systems, crash barriers, precast pile shells and shotcrete for tunnel linings, canals and reservoirs [3].

Initial bonding between the fibers and the concrete can be attributed to physical adhesion – and also to static friction caused by the surface finish of the fibers. Chemical bonding (sometimes referred to as elastic bonding) between the fibers and the matrix is not strong in comparison to frictional resistance along the debonded segment against pull-out. Fiber pull-out is a distinct problem. In general, friction plays an important role in confining stress – increasing with the fiber size. In addition, most fiber deformation processes lead to local mechanical interactions between fiber and matrix - involving a typical distribution of the load by the matrix.

Some controversy seems to exist because fibers can reduce crack propagation but poor adherence of the fibers to the cement paste can furnish a passage for the penetration of external agents. Fibers act as cracks arresters through the initial loading stages, and

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increase the energy required for crack propagation – what provides an increase in the strength. During the later stages of straining, the fibers distribute the microcracking, thus increasing toughness and apparent strength [5,7]. Splitting cracks follow the reinforcing fibers, and the bond transfer drops rapidly unless reinforcement is provided to restrain the opening of the splitting crack. The eventual failure of the fibers as well as of concrete is brittle; concrete disintegrates into pieces in a rather sudden way, while the fibers largely still preserve their original size [8]. We recall that brittleness is inversely proportional to the elongation at break in tensile testing [9–11].

Techniques employed to modify interfacial bonding between polymeric fibers and cementitious matrixes include fibrillation and twisting deformation of the fibers. The fibrillation increases the surface contact area and enhances mechanical anchoring to the matrix – as well as improves the fiber modulus. Both techniques are particularly suitable for polymeric fibers due to their low strength and large strain capacity [8].

Dynamic elastic modulus E_d can be obtained in a non-destructive way by measuring the pulse velocity along the composite using electrical transducers located on the opposite sides of cylindrical specimens of concrete. The energy supplied to the material by ultrasonic waves depends of how compact the composite is – including the voids if any. The relation is:

$$E_d = V^2 \rho (1 + v)(1 - 2v)/(1 - v) \tag{1}$$

Here V is the pulse velocity; ρ is the density of the concrete specimen and v is the Poisson ratio. The dynamic elastic modulus depends on the component properties of the aggregates and their interactions with the cement. In general, the pulse velocity is faster through the coarse aggregate than through the cement paste.

It is well known that gamma radiation induces alterations of the polymer structure via three main processes: scission, crosslinking and grafting of chains; each process depends on the applied dose. It has been claimed that chain scission occurs either in the amorphous region or inside the crystals, and both process begin with the formation of free radicals [12]. The advantages of high-energy irradiation is the capability to work in the solid state and to reduce the cost and time-in contrast to other procedures used such as chemical attack or thermal treatment [13].

It would be advantageous if concrete could be designed to support an increasing load after cracking of the matrix. As we know, the added fibers have very little effect on tensile or bending strength. However, is possible to improve the stress transfer between fibers and the matrix by modifying the fiber properties by gamma irradiation. Modifications in the chemical structure and the control of the recrystallization process can be important areas for developing improved fibers with potential application in the concretes [3].

Using gamma radiation, isotactic polypropylene (iPP) shows a lowering by 17% of the tensile stress when irradiated at 25 kGy, this with respect to non-irradiated value (33.4 MPa) [14]. In the case of irradiated homo-polypropylene (HP) and random copolypropylene (CP), the tensile strength at break decreases when increasing the radiation dose. The HP has a diminution of 18 and 42% for 10 and 50 kGy, respectively with respect to the non-irradiated value (40 MPa); further lowering for CP of 2 and 37% for 10 and 50 kGy, respectively, are found with respect to non-irradiated material value (38 MPa) [15]. The lowering is attributed to plasticization by lower molecular weight chains formed by main chain scission. The result is a decrease in the average molecular weight by cleavage of molecular chains.

Earlier we have argued that gamma irradiation generates more contact points on the fiber surfaces and in consequence a larger contact area between the fibers and the concrete phase. Moreover, the highest compressive values for concrete are obtained for the highest strain values of the fibers. Thus, a mechanism of external load transfer between the concrete and fiber is seen [16,17].

In the present work we have studied gamma irradiation effects on the strength and the elasticity modulus of polypropylene-fiber reinforced concrete. The strength was studied by two methods, by compression testing and by impact testing. The elasticity modulus was determined by compression testing and by ultrasonic measurements.

2. Experimental

2.1. Specimen preparation

Before preparing the concrete specimens, one set of polypropylene atactic fibers (CONSA™, Distrito Federal, Mexico) whose diameters vary from 30 to 40 μm were cut to 10 mm length on the average. The fibers so obtained were mixed into the concrete at 1.0, 1.5 or 2.0% by volume. The concrete was elaborated with Portland cement (Tolteca™, Monterrey NL, Mexico) and silica sand and marble from a local company (GOSA™, Atizapan, Mexico).

The proportions of components in the concrete were 1/2.75 for cement/aggregates, and the water/cement ratio was 0.485 according to ASTM C-305. The average size of silica sand particles was 150 μm (mesh 100); for marble 1.4 mm (mesh 14) and 9.5 mm (mesh 3/8 in).

For compressive strength evaluation of the FRCs, different lots were elaborated on different days, each one containing six samples. That is, for each PP-fiber content 18 concrete specimens were elaborated. For the evaluation of strength (compression or impact), and the elastic modulus (static and dynamic), 12 lots were elaborated, each containing six samples. After mixing, the concrete cylindrical specimens (2.0″ diameter and 4.0″ long) were placed in a controlled temperature room at 23.0 ± 3.0 °C, with the surface exposed to moisture in air and no less than 50% humidity according to ASTM C-511.

2.2. Irradiation procedure

The concrete specimens were exposed to varying gamma radiation at different doses (5, 10, 50, 100 and 150 kGy) in air at room temperature. A dose rate of 3.5 kGy/h was applied by using a Transelektro irradiator LGI-01 provided with a ^{60}Co source manufactured by IZOTOP Institute of Isotopes Co. Ltd., Budapest, Hungary, and located at the Instituto Nacional de Investigaciones Nucleares in Mexico.

2.3. Mechanical tests

The strength evaluation of the concrete cylindrical specimens was carried out with two different techniques: (a) by compression employing an Instron Universal Testing machine Model 1125, according to the ASTM C-109 M standard; and (b) by using a hammer impact fatigue machine model 58-C1081/N (Controls™, Cernusco, Italy), which quantifies the number of rebounds supported in the specific area of each specimen. The testing allowed tolerance for the specimens was 28 days ± 12 h.

The compression modulus of elasticity of the concrete cylindrical specimens was evaluated by using a Instron Universal Testing machine Model 1125; and the dynamic modulus of elasticity according to Eq. (1) by using an ultrasonic testing equipment for construction materials: Ultrasonic Pulse Velocity Tester model 58-E0048 (Controls™, Cernusco, Italy), with an ultrasonic resolution of 0.1 ms. The equipment measures the ultrasonic propagation through the concrete specimens.

2.4. Morphological characterization

After mechanical testing, some fractured concrete pieces were dried in a rotovapor for 24 h; then their surfaces were analyzed by scanning electron microscopy (SEM) in a JEOL model JSM-5200 machine, in the secondary-electron mode.

3. Results

3.1. Compressive strength as a function of the fiber concentration

Two general types of behavior are observed for concretes elaborated with marble of 1.4 mm of average size and different concentration of polypropylene fibers (Fig. 1). The first one is related to the PP-fiber content in the concretes: the compressive strength increases for 1.5 vol% of fibers and then decreases for 2.0 vol% of fibers. This behavior is seen for non-irradiated and irradiated concretes from 5 to 100 kGy. This is in contrast to concretes irradiated at 150 kGy, where the compressive strength diminishes with the fiber contents increase.

The compressive strength values show minima. In the case of non-irradiated concretes there is ≈ 8% of variation (from 21 to 22.7 MPa); for irradiated concretes the differences range between 4 and 12% and are most notable for concretes irradiated at 50 kGy (12%).

The second general observation concerns the applied dose for each fiber content: the compressive strength values increase according to the radiation dose until a certain dose and then for higher doses go down. For concretes with 1.0 or 1.5 vol% of fibers, the compressive strength values increase until 50 kGy where a maximum lies. Similar behavior is observed for concretes with 2.0 vol% of fiber, but now the maximum is at 10 kGy (Fig. 1).

We find the maximum compressive strength value for concretes with 1.5 vol% of PP fibers and irradiated at 50 kGy (25.1 MPa); this constituted an improvement of 19% with respect to non-irradiated concrete.

We now compare the compressive strength values of non-irradiated concretes with those elaborated with the same marble size but *nylon* fibers instead of those made from PP. We find similar values: from 21.0 to 22.7 MPa for the present study, and from 19.2 to 21.9 MPa when nylon fibers are used. In the case of irradiated concrete, similar behavior is seen, with values from 21.3 to 25.1 MPa for PP – comparable to concretes with nylon fibers (18.5 to 27.5 MPa) [18]. Thus, we find that comparable results have been obtained for two different kinds of fibers. To explain this, we note that apart from the nature of the fibers also other parameters play a role, particularly interphase adhesion, fiber diameters and fiber lengths. Here the fiber diameters are the same for PP and nylon fibers: 30–40 μm. The fiber length is 10 mm for PP fibers, and 5 mm for nylon fibers, comparable again. We infer that the strength of the interphase interactions is similar.

We further infer that such mechanical behavior is clearly a consequence of morphological changes of the components (silica sand, marble and PP fibers) caused by irradiation [6,15,17]. In the case of silica sand, for non-irradiated samples homogeneous surfaces are seen. Applying low irradiation doses, some grooves and several separated particles (less than 5 μm in diameter) are observed. For the higher dose of 150 kGy, the number and size of the crazes increases (100 μm long) and certain "branching" tendency appears, causing fiber deterioration [17].

3.2. Compressive and impact strength as a function of the marble particle size

As noted in the previous section, the compressive strength values of concrete with 1.5 vol% of fiber are always maxima – except when irradiating at 150 kGy. To explore a different dimension of the problem, we have decided to maintain the same fiber concentration and silica sand size but to vary the marble size. We have studied the concrete strength by two different techniques: compression testing and impact testing. In the compression test the specimen is subject to load in an usual 'universal' testing machine. In impact testing, the specimen hit by a hammer does not necessarily disintegrate. The latter test allows easy transport (out-of-laboratory test), lower weight, and lower time required.

We present the compressive strength values in Fig. 2. We see a maximum of the strength at 10 kGy. Concretes with marble size of 9.5 mm (mesh 3/8 in.) have higher strength values than those containing 1.4 mm size particles – this for non-irradiated samples and those irradiated at 5 and 10 kGy. The opposite behavior is seen at higher irradiation doses.

For non-irradiated concrete an improvement of 6% in the compressive strength is seen for larger 9.5 mm marbles. The extent of improvement increases for irradiated concretes and reaches a maximum of 25% at 10 kGy. In terms of stability against gamma radiation, smaller differences (up to 14%) are seen for the smaller marble size. By contrast, when using the larger marble size 46% of variation is found.

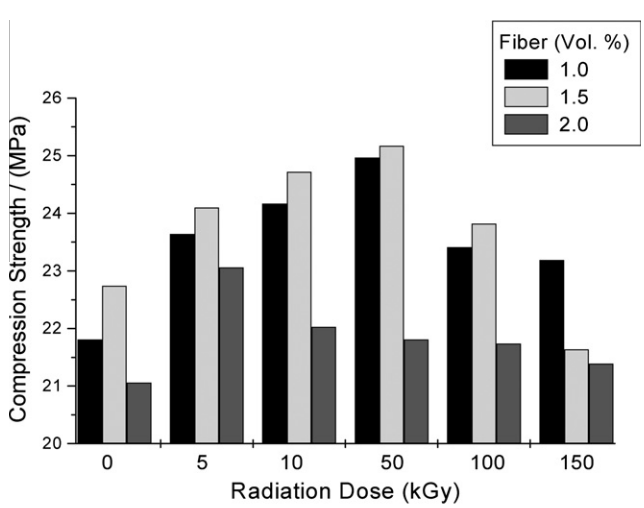

Fig. 1. Compressive strength of polypropylene-fibers reinforced concretes at several irradiation doses for three PP fiber concentrations.

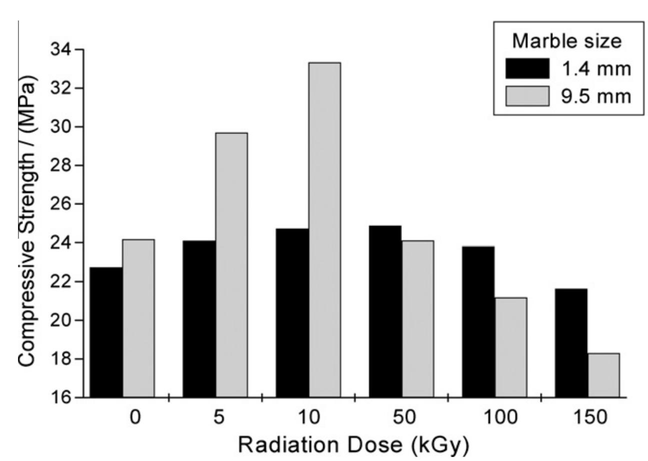

Fig. 2. Compressive strength of polypropylene-fibers reinforced concretes at several irradiation doses; 1.4 and 9.5 mm pertain to average marble particle diameters.

Earlier we have argued that morphological modifications of marble after irradiation tend to lower the compressive strength [18]. We have observed then homogeneous surfaces on marble particles for non-irradiated samples. When increasing the dose to 50 kGy, scraped particles are generated; for the highest dose of 150 kGy a partial destruction of the marble with the presence of still bigger size particles is seen [18]. These findings are corroborated in Figs. 2 and 3 by the gradual lowering of the compressive strength when increasing the applied dose and the deterioration of structure seen in Fig. 3c.

We now turn to impact testing results: (a) the strength increases according the radiation dose up to 10 kGy; (b) for higher doses (from 50 to 150 kGy) the impact strength decreases; (c) concretes with marble sizes of 9.5 mm have higher impact strength than those containing 1.4 mm marble particles – this for non-irradiated and irradiated concretes at 5, 10 and 50 kGy. For concretes irradiated at 100 and 150 kGy the opposite behavior is seen (Fig. 4).

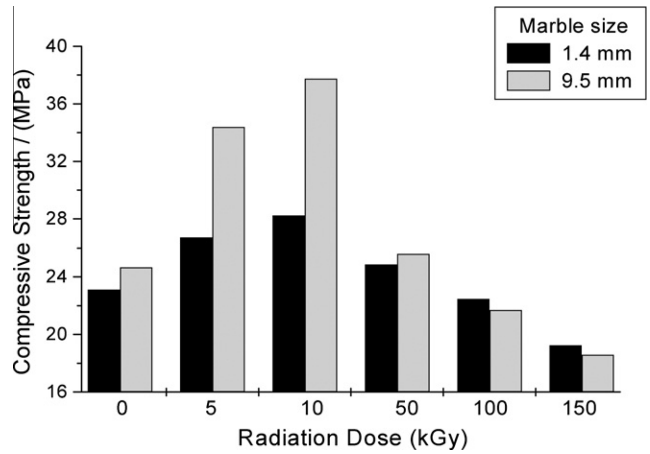

Fig. 4. Compression strength determined by impact testing as a function of the irradiation dose for two marble sizes.

When comparing the strength values obtained by both techniques (compression and impact) similar values are found. For non-irradiated concretes with 1.2 mm marble size a value of 22.7 MPa was obtained by compression while the impact result was 23.1 MPa that is 1.7% difference. For the case of concrete with 9.5 mm a similar difference is found, namely 2.0% (see Figs. 2 and 4). We note that the standard strength values (in kg/cm^2) reported in the Concrete Hammer Manual (Controls™, model 58-C1081/N), are obtained from measurements made on a large number of specimens which were subsequently broken under compression on a test machine. Moreover, under the same analysis the differences for irradiated concretes evaluated by compression have a maximum difference of 14%; and for those evaluated by impact 15%.

In both kind of measurements (compression and impact) the maximum strength values are achieved at 10 kGy, this for both sizes of marble. For concrete with smaller marbles there is an improvement of 22% and larger ones of 53% with respect to non-irradiated concrete. Conversely, at 150 kGy we find lowering of 20% for smaller marbles and 34% for large ones with respect to non-irradiated concrete.

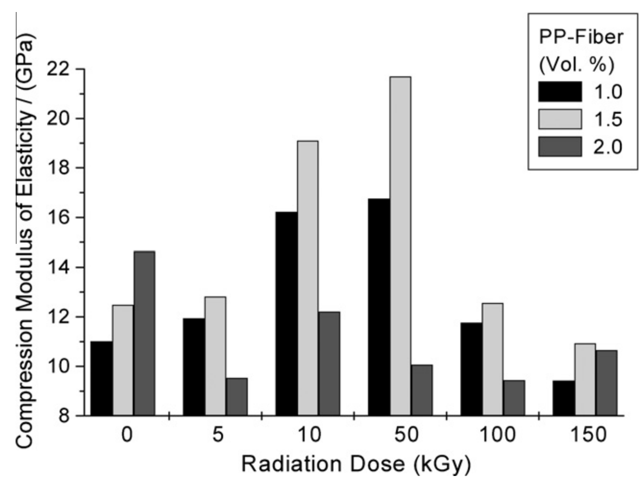

Fig. 5. Compression modulus of elasticity as a function of the irradiation dose for several PP fibers concentrations.

3.3. Compression modulus of elasticity as a function of fiber concentration

In Section 3.1 we have evaluated the compression strength according to fiber contents. We now consider similarly the compression modulus E_c. In Fig. 5 we see that E_c has a maximum at 50 kGy for 1.0 and 1.5% fibers. For 2.0% fibers we have increment–decrement behavior, apparently a consequence of increased interaction of fibers with the matrix on one hand and deterioration of fibers on the other – seen before [16,17,19]. Putting non-irradiated concretes aside, for irradiated ones the highest E_c values are those for 1.5 vol% of fibers.

For non-irradiated concretes the maximum improvement caused by the fibers amounts to 32% for 2.0 vol% of fibers. For irradiated concretes the largest improvement of 73% is achieved for concretes with 1.5% of fibers and irradiated at 50 kGy.

Whether we prefer a soft or hard concrete depends on the application. As expected, E_c depends on the irradiation dose and the fiber concentration. If we desire to have a soft concrete, we need to put in 2.0% of fibers and to irradiate at 5 kGy. By contrast, for obtaining a hard concrete it is necessary to add 1.5% of fibers and to irradiate at 50 kGy.

Both types of behavior of E_c, a single maximum and a periodic behavior, can be related to morphology surface changes of the fibers-more than to ceramic components, silica sand and marble.

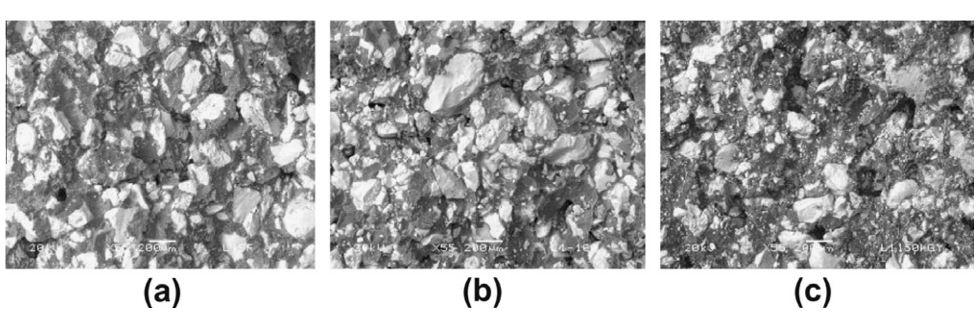

Fig. 3. SEM micrographs of fractured zones of concretes: (a) non-irradiated, (b) irradiated at 100 kGy, and (c) irradiated at 150 kGy.

High stability of ceramic constituents against the ionizing radiation has been reported [20,21].

We have observed earlier smooth and homogeneous surfaces of non-irradiated PP fibers. After applying the dose of 5 kGy, several "wrinkles" appear; and for higher doses wrinkles and small particles are formed on the surface [17]. Such surface changes have been related to the tensile stress changes since an improvement of 14% of the tensile stress is found when irradiating the fibers at 5 kGy. For higher doses (100 kGy) the values decrease up to 40% with respect to non-irradiate fibers [7]. Similarly, a lowering (by 52% at 120 kGy) of the tenacity of PP yarns has been reported [22].

3.4. Compression modulus and dynamic modulus as a function of the marble particle size

We have found above that the compression elastic modulus E_c values are always the highest for 1.5 vol% of fibers-except for non-irradiate fibers. We have now followed the same procedure, using the same fiber concentrations and silica sand size while varying the marble size.

Relevant E_c results are reported in Fig. 6 as a function of the irradiation dose. There is a maximum at 50 kGy for concretes with smaller marbles and at 10 kGy for larger marbles. Notable is the inversion of the values according to the radiation dose: (a) for non-irradiated and irradiated at 5 and 10 kGy specimens, the concretes with larger marbles have higher E_c values than those containing smaller marbles; (b) for higher doses of 50, 100 and 150 kGy an inverse behavior is observed. The maximum modulus value is found for concrete with smaller marbles and irradiated at 50 kGy – an improvement of 73% with respect to non-irradiated concrete.

We now consider in turn the dynamic modulus E_d defined in Eq. (1); the results are presented in Fig. 7. Comparing both Figs. 6 and 7, we find that $E_d > E_c$. the dynamic modulus values are larger than compression modulae. In fact, for non-irradiated concrete with smaller marble size E_d is 8% higher than E_c; for larger marbles the difference amounts to 18%.

When comparing the dynamic elastic modulus values with those for concrete with nylon fibers (instead of polypropylene fibers as present work), we observe higher values: 23.7–25.0 GPa with nylon *versus* 9.4–19.2 GPa with polypropylene [14].

4. Concluding remarks

Fibers are not the only way to reinforce concretes [23–25]. On the other hand, fibers as concrete reinforcement have a strong tradition [26]. Polymer-based concretes are also developed [27].

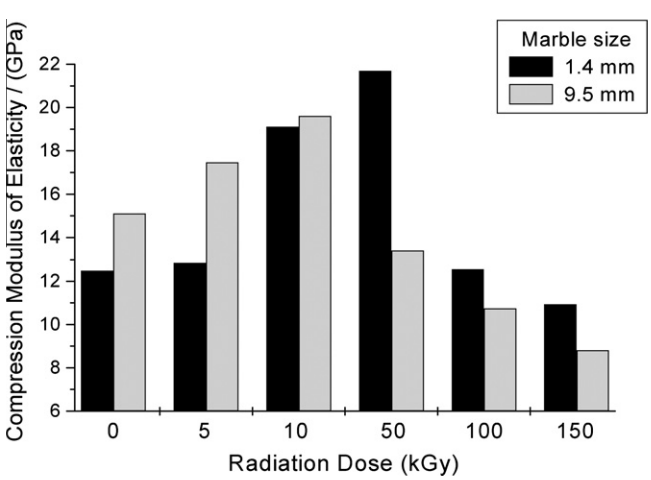

Fig. 6. Compression modulus of elasticity as a function of irradiation dose for two marble sizes.

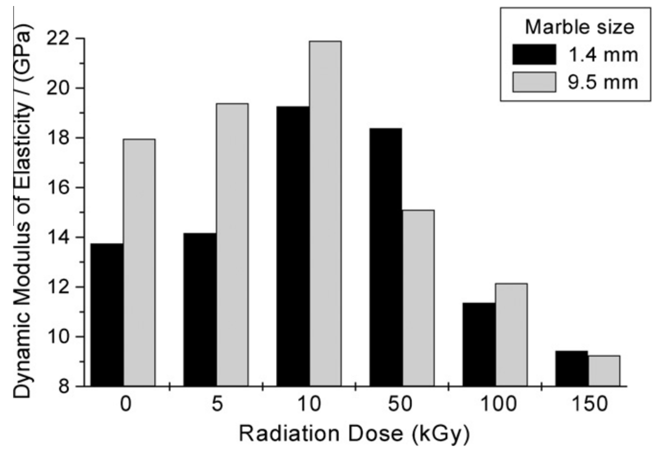

Fig. 7. Dynamic elastic modulus as a function of irradiation dose for two marble sizes.

In this work we have noted major influence of the polymeric component – that is PP-on mechanical properties of concretes, while effects caused by ceramic constituents – silica sand or marble are smaller. In other words: PP fibers can be found inside silica sand cracks; the fibers support loads after disintegration of marble particles, particularly so since more contact points are then present. Our results indicate that interfaces are important for properties of multiphase composites – a fact noted by Kopczynska and Ehrenstein [28].

We find that for non-irradiated concretes it is more convenient to use a non-destructive and portable (hammer) test than a laboratory test; this saves money and time. We recall that Adams and Wu [29] recommended repetitive impact testing leading to fracture by fatigue.

Improvement in the strength and compressive modulus of PP-fibers reinforced concrete has been achieved by gamma irradiation. The extent of improvement depends on polypropylene fiber concentrations, marble particle sizes and applied irradiation dose. Gamma radiation can be a two-edged sword, either improving or worsening mechanical parameters. In our case the first statement applies when applying gamma irradiation doses up to 50 kGy. The ionizing energy generates more surface contacts between the components and the hydrated cement phase. Property worsening appears at higher doses (100 and 150 kGy). In our earlier work using higher doses we have seen more disintegrated particles on marble, more cracks appearing on silica sand and more wrinkles and scrap particles on surfaces of PP fibers at higher doses [8,17,19].

Acknowledgments

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References

[1] Rabello M. Aditivaçao de polimeros. Sao Paulo: Artliber; 2000.
[2] Pisanova E, Zhandarov S. Fiber-reinforced heterogeneous composites. In: Brostow W, editor. Performance of plastics, Munich–Cincinnati: Hanser 2000.[Chapter 19]

[3] Zheng Z, Feldman D. Synthetic fibre-reinforced concrete. Progr Polymer Sci 1995;20:185–210.
[4] Laukaitis A. Influence of carbon fibers addition on porous silicate concrete formation and product properties. Mater Sci Medziagotyra 1997;3:42–5.
[5] Kurtz S, Balaguru P. Postcrack creep of polymeric fiber-reinforced concrete in flexure. Cem Concr Res 2000;30:183–90.
[6] Bakis CE, Nanni A, Terosky JA, Koehler SW. Self-monitoring, pseudo-ductile, hybrid FRP reinforcement rods for concrete applications. Comp Sci Tech 2001;61:815–23.
[7] Deng Z, Li J. Mechanical behaviors of concrete combined with steel and synthetic macro-fibers. Int J Phys Sci 2006;1:57–66.
[8] Martínez-Barrera G, Vigueras-Santiago E, Hernández-López S, Menchaca-Campos C, Brostow W. Mechanical improvement of concrete by irradiated polypropylene fibers. Polym Eng Sci 2005;45:1426–31.
[9] Brostow W, Hagg Lobland HE, Narkis M. Sliding wear, viscoelasticity and brittleness of polymers. J Mater Res 2006;21:2422–8.
[10] Brostow W, Hagg Lobland HE. Predicting wear from mechanical properties of thermoplastic polymers. Polym Eng Sci 2008;48:1982–5.
[11] Brostow W, Hagg Lobland HE. Brittleness of materials: Implications for composites and relation to impact strength. J Mater Sci 2010;45:242–50.
[12] Dole M. Radiation chemistry of macromolecules, vols. 1–2. New York: Academic Press; 1973.
[13] Timus DM, Cincu C, Bradley DA, Craciun G, Mateescu E. Modification of some properties of polyamide-6 by electron beam induced grafting. Appl Rad Isotopes 2000;53:937–44.
[14] Denac M, Musil V, Smit I, Ranogajec F. Effects of talc and gamma irradiation on mechanical properties and morphology of isotactic polypropylene/talc composites. Polymer Degrad Stabil 2003;82:263–70.
[15] Thorat HB, Prabhu CS, Kumar KS, Pandya MV. γ–ray-induced degradation: A comparative study for homo- and copolymers of polypropylene. J Appl Polymer Sci 1997;65:2715–20.
[16] Martínez-Barrera G, Brostow W. Fiber-reinforced polymer concrete: Property improvement by gamma irradiation. In: Barrera-Díaz C, Martínez-Barrera G, editors. Gamma radiation effects on polymeric materials and its applications, Kerala India: Research Signpost; 2009[Chapter 3].
[17] Martínez-Barrera G, Martínez-Hernández AL, Velasco-Santos C, Brostow W. Polymer concretes improved by fiber reinforcement and gamma irradiation. e-Polym 2009;103:1–10.
[18] Martínez-Barrera G, Menchaca-Campos C, Vigueras-Santiago E, Brostow W. Post-irradiation effects on nylon-fiber reinforced concrete. e-Polym 2010;042:1–3.
[19] Martínez-Barrera G, Menchaca-Campos C, Hernández-López S, Vigueras-Santiago E, Brostow W. Concrete reinforced with irradiated nylon fibers. J Mater Res 2006;21:484–91.
[20] Akkurt I, Basyigit C, Kilincarslan S, Mavi B, Akkurt A. Radiation shielding of concretes containing different aggregates. Cement Concr Comp 2006;28:153–7.
[21] Vodak F, Trtık K, Sopko V, Kapickova O, Demo P. Effect of γ -irradiation on strength of concrete for nuclear-safety structures. Cem Concr Res 2005;35:1447–51.
[22] Sen K, Kumar P. Influence of gamma-Irradiation on structural and mechanical properties of polypropylene yarn. J Appl Polym Sci 1995;55:857–63.
[23] Kersevicius V, Skripkiunas G. Physical properties and durability of concrete with elastic additive from rubber waste. Mater Sci Medziagotyra 2002;8:293–8.
[24] Hernandez-Zaragoza JB, Caballero-Badillo CE, Rosas-Juarez A, Lopez-Tara T, Hinojosa-Torrez J, Castaño VM. Modification of Portland cement mortars with cactus gum. Chem Chem Technol 2007;1:175–7.
[25] Gencel O, Brostow W, Ozel C, Filiz M. Concretes containing hematite for use as shielding barriers. Mater Sci Medziagotyra 2010;16:249–56.
[26] West HA, Sprecher AF. Fiber reinforced composite materials. J Mater Ed 1991;13:161–72.
[27] Bobadilla-Sanchez EA, Martinez-Barrera G, Brostow W, Datashvili T. Effects of polyester fibers and gamma irradiation on mechanical properties of polymer concrete containing $CaCO_3$ and silica sand. Express Polym Lett 2009;3:615–20.
[28] Kopczynska A. Ehrenstein. Polymeric surfaces and their true surface tension in solids and melts. J Mater Ed 2007;29:325–40.
[29] Adams GC, Wu TK. Materials characterization by instrumented impact testing. In: Brostow W, Corneliussen RD, editors. Failure of Plastics, Munich–Vienna–New York: Hanser; 1986. [Chapter 8]