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Effect of marble particle size and gamma irradiation on mechanical properties of polymer concrete

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Abstract: Effects of gamma radiation and the marble particle size on compressive properties and the dynamic elastic modulus of polymer concretes (PCs) were studied. The PCs had a composition of 30 % of unsaturated polyester resin and 70 wt. % of marble as aggregate. Different types of PC were developed with the combination of one, two or three marble-particle sizes. The materials were submitted to 5, 10, 50, 100 and 150 kGy of radiation doses. Both the compressive properties and the dynamic elastic modulus values depend on the combination of the marble-particle sizes and the applied radiation dose. Higher numbers of dispersed particles per unit volume provide more resistance to crack propagation. On the other hand, longer particles give more reinforcement. As a result of these two competing effects, medium size marble particles provide the highest compression modulus.

Keywords: polymer concrete, gamma radiation, marble, compressive strength, dynamic elasticity modulus.

Introduction

Polymer concrete (PC) is three to five times stronger than Portland cement concrete (PCC), but its brittle failure characteristics have limited its usefulness for load-bearing applications. Thus, improvements in its toughness and post-peak stress-strain behavior are necessary for specific applications. Moreover, the versatility in formulating and processing with rapid setting and high strength properties have resulted in the use of PCs in diverse applications including structural civil engineering, automotive and high temperature corrosive environments [1, 2]. Such applications are maintained by a balance between performance and reliability; in other words, we deal with dependability and with absence of breakdowns and failures [3].

Different PC formulations have been developed, such as a mix of foundry sand (80 wt. %) and an unsaturated polyester resin (20 wt. %); a viscous liquid with a styrene monomer content of 44 %. The methyl ethyl ketone peroxide (MEKP) 2 phr has been used as an initiator [4, 5]. Other formulations include an isophthalic unsaturated polyester resin, containing 36 % styrene and MEKP initiator (50 % in dimethyl phthalate) [6].

There is limited information for PC systems as to how the material heterogeneity is revealed in test results and how those results are related to the kind of aggregate (mineral type, grain grade - natural and crushed) as well as the maximal grain diameter [3]. Thus, more knowledge of the optimal compositions and mechanical properties including stress-strain relationships are necessary to enable appropriate design, production, and quality control.

The choice of the fine aggregates is very important in order to achieve the best workability of the PCs; moreover, the mix design of PCs typically involves an aggregate gradation to provide the lowest possible void volume. Thus, a minimum polymeric binder contents necessary to coat the aggregates and to fill the voids has to be defined. For example, a PC with 15 wt. % of resin and 85 wt.% of siliceous sand with grain size of 0.245 or 0.342 mm is nearly void-free [2, 4]. Sand can have a variety of grain size distributions [7, 8]. Some PCs have more than one type of fine aggregate, for example those with basalt, granite, crushed quartzite and natural sand.

Different mechanical features found in polyester-based PCs have been related to the type of thermosetting resin or mineral aggregates, as well as to their concentrations in the composite. The tensile strain at break ε_b values increase when the polyester resin contents increases [9]. We recall that ε_b is inversely proportional to the material brittleness [10 – 12]. Another pertinent mechanical property of PCs is the elasticity modulus in compression E_c. For polyester-based PCs, E_c also increases when the resin content increases, varying from 3.5 to 7.1 GPa for resin contents from 10 to 18 wt.%, respectively [9].

Other kinds of PC systems show similar behavior; for example, PC elaborated with epoxy resin (80 wt. %) and foundry sand (20 wt. %) shows 11.3 GPa as the maximum E_c value [2]. In a polyester mortar, the flexural modulus increases first with increasing polyester content but then passes through a maximum [13]. Moreover, for polyester-based PCs containing two aggregates (fly ash and river sand), the strength values are improved by increasing the resin content in the mix and show synergism in strength behavior up to 75 wt. % of fly ash content. However, at higher fly ash contents the properties decline as the mix becomes unworkable [6].

Improvements of the PCs are based on taking into account physicochemical properties of both the resin and the mineral aggregates. An alternative is the use of gamma radiation - more advantageous compared with thermal processes or chemical attack. The advantages include: curing at ambient temperature, no need for additives, a tighter control of part dimensions and elimination of internal stresses which reduce material strength. Further, curing times are shorter and there is no emission of volatiles into the environment [14].

When the polymeric resins are irradiated, chain scissions result in formation of free radicals. For example, both radical and cationic cross-linking mechanism can occur in irradiated-composites of an epoxy resin and aromatic polyamide [14]. Moreover, impregnation and curing of different substrates with polyester resins at high temperatures does not require initiators [15].

Gamma radiation produces high rates of radical formation, in general some orders of magnitude higher than with classical initiators. Radiation initiation does not require any activation energy and the termination reaction is practically always diffusion controlled. Higher viscosity causes higher activation energy of the termination reaction, decreasing the overall activation energy. When using chemical initiators, a decrease of the overall activation energy (by a few kJ/mol) does not compensate for increased radical concentration and poorer heat transfer [16].

The elastic modulus is the most often used characteristics of composites. In the case of building structures, the non-destructive tests (NDTs) take into account the acoustic impedance of the system components - important factors influencing ultrasonic wave propagation [17]. The dynamic elastic modulus is determined by measuring the pulse velocity along the composite and using electrical transductors located on the opposite sides of the cubic specimens of concrete. The energy supplied the ultrasound depends on how compact is the composite, including the void presence and sizes. One thus obtains the dynamic elastic modulus E_d:

$$E_d = V^2\rho(1 + \nu)(1 - 2\nu)/(1- \nu) \quad (1)$$

Here V is the pulse velocity; ρ is the mass density of the concrete specimen; and ν is the Poisson ratio. E_d necessarily depends on the component properties and their interactions with the matrix.

Ultrasonic methods have been applied to non-destructive evaluation of different parameters such as defect detection, layer thickness or delaminations. It is recommended to develop a reference adhesion curve (similar to the ISO curve for concrete compressive strength evaluation) for a given type of polymer coating. One needs to take into account the kind and content of binder and filler as well as content of pores to increase accuracy of the regression function.

Results and discussion

Compressive strength

We have developed PCs containing one, two or three different marble-particle sizes. The selection of the particle sizes was in function of the availability of the commercial mesh (sieve), in our case 8, 14 and 25, which correspond to 2.36, 1.4 and 0.71 mm, respectively. Thus, we have approximately 1:2:3 as the ratio. Below we shall use the terms small, medium or large size respectively for 0.71, 1.4 and 2.36 mm.

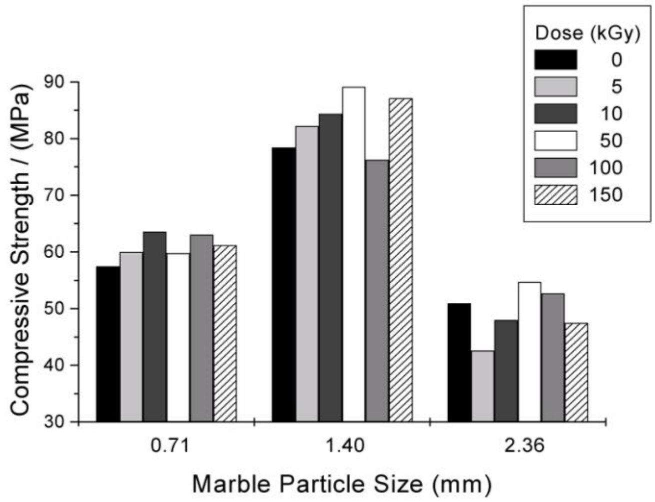


Fig. 1. Compressive strength of PCs with different marble particle sizes irradiated at several doses.

In Figure 1 we show the compressive strength σ_c values for PCs elaborated with different particle sizes. The σ_c values are highest when using the medium particle size and lowest for those with large size. The highest σ_c values are located between 76.2 and 89.1 MPa; these values are comparable to those for polyester-based PCs reported (70 - 80 MPa) before [18].

The effect of gamma radiation is minimal when comparing the σ_c values for non-irradiated and irradiated PC. For the former, the σ_c values are in the range from 50.9 to 78.4 MPa while for irradiated PCs from 42.6 to 89.1 MPa, thus 13 % difference. According to the irradiation dose, the σ_c values are increasing from non-irradiated up to 10 kGy (for PC with small-particle size) or up to 50 kGy (for the medium particle size) (Figure 1). The maximum value is achieved at 50 kGy of radiation. Thus, there is optimal radiation dose to obtain the maximum σ_c value.

For non-irradiated PCs, a maximal difference of 54 % is observed when comparing the highest σ_c value (for medium particle size) and the lowest value (for PC with the large particle size). The difference is larger for irradiated-PCs, namely 62 %. In terms of compression strength, more stable after irradiation is the PC with small particles because only 9 % of difference exists among the respective σ_c values.

We have developed three different combinations of PCs containing two different marble-particle sizes: a) small + medium; b) medium + large; and c) small + large. In Figure 2 we show the σ_c results for PCs with two particle sizes. The highest σ_c values are seen for PC with small + medium particle sizes, namely from 65 to 75 MPa (Figure 2). These values are 16 % lower with respect to the highest σ_c values achieved for a PC with one particle size; see again Figure 1.

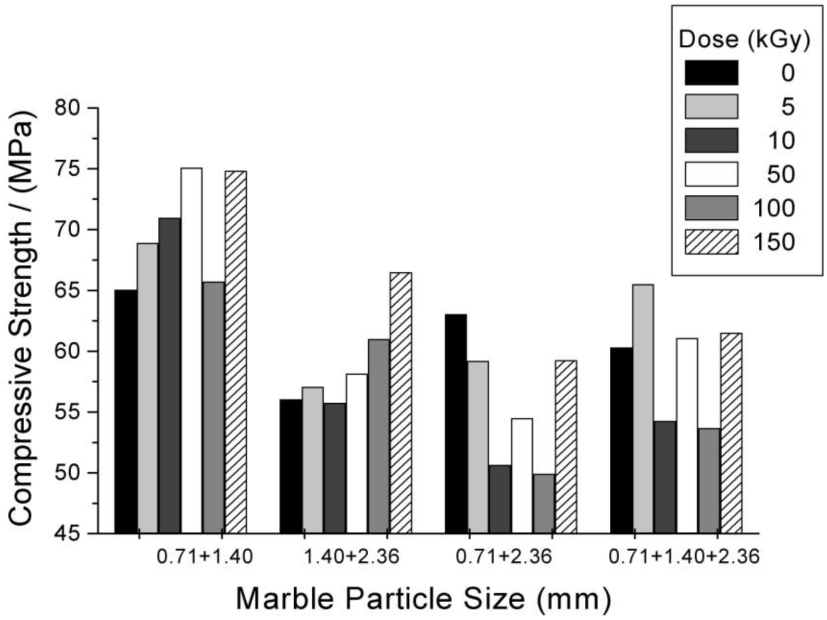


Fig. 2. Compressive strength of PCs with different combinations of marble-particle sizes irradiated at several doses.

The effects of irradiation are significant. We see in Figure 2 large differences in the σ_c values for the three different combinations. There is a sequence in the σ_c values according to the particle size combination as follows: (small + medium) > (medium + large) > (large + small). Thus, we recommend combining small and medium sizes to obtain the highest σ_c values.

According to the increment of the radiation dose, various types of behavior are observed. In the case of PC with small + medium sizes, we have identified a periodic behavior [the increment-decrement-increment etc. sequence of σ_c values], including three stages: i) σ_c increases when the radiation dose increases up to 50 kGy; ii) the values decrease at 100 kGy, and iii) they increase again at 150 kGy. Periodic behavior has been observed for PC containing one mineral aggregate such as SiO_2 [18] or $CaCO_3$ [19]; or two minerals such as SiO_2 + $CaCO_3$ [20] or marble + calcium bentonite [21]. An explanation of the periodical behavior seems related to the multiple 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.

For PCs with medium + large particle sizes, the evolution of σ_c values involves two stages: i) little change up to 10 kGy, ii) an increase of σ_c along with an increase in the radiation dose. Finally, for PC with small + large sizes, more stages are observed: i) the σ_c values decrease up to 10 kGy, ii) there is an increase until 50 kGy, iii) a decrease at 100 kGy, and finally iv) an increase at 150 kGy, see Figure 2.

Clearly, the σ_c values of the PCs depend on the marble-particle sizes and their combinations. The combination of small + medium particle sizes provides the best results; conversely the worst results involve the small + large sizes combination. Apparently the use of large particle size causes detrimental results due to poor adhesion between the polyester resin and the marble particles. We recall the role of interfaces in material properties discussed by Kopczynska and Ehrenstein [22]. We also recall one of the basic tenets of materials science: defects in structure cause crack bifurcation or even crack arrest. With the concentration of marble particles in all our concretes fixed at 70 wt. %, smaller size marble particles provide more such obstacles to crack propagation in a given amount of concrete.

For PCs containing together all three particle sizes we find a periodic behavior containing five stages (see Figure 2). The σ_c values are in the range from 53.6 to 65.5 MPa, higher than the values achieved for PCs with small + larger particle sizes but lower than PCs with small + medium particle sizes. These facts reinforce our interpretation that the number of marble particles per unit volume is important.

When comparing the σ_c values for non-irradiated PCs with others PCs containing different mineral aggregates, we can see the advantages of using marble as the aggregate. The present σ_c values are between 50.9 and 78.4 MPa, thus higher than for PCs with two aggregates, marble and calcium bentonite; the respective values is 45.8 MPa [21]; or for PC with silica sand (49.7 MPa) [18]. Nevertheless, the present values are lower than for a PC with $CaCO_3$ (86.4 MPa) [19], or for a PC with silica sand + $CaCO_3$ (106.9 MPa) [20].

In the case of irradiated PCs there are significant differences. The present values are from 42.6 to 89.1 MPa, higher than for PC with two aggregates marble and calcium bentonite (47.8 - 55.9 MPa) [21] or for PC with silica sand (62.2 - 86.2 MPa) [18]; Thus, higher compressive strength values can be achieved by using marble particles instead of silica sand or marble and calcium carbonate particles. Nevertheless, the present values are lower than for PCs with silica sand + $CaCO_3$ (104.0 - 112.4 MPa) [20] or for PCs with $CaCO_3$ (126.9 - 135.0 MPa) [19].

Compressive strain at yield point

In Figure 3 we show compressive strain values at yield point. The values are decreasing when the marble particle size increases. Thus, the highest values from 0.017 to 0.024 mm/mm are for PCs with the small particle size. These values contrast with those for PC with large particle size (0.007 - 0.014 mm/mm). We recall that the highest values are comparable to those obtained for pure-polyester resin (0.021 to 0.026 mm/mm) obtained in earlier work [20]. Thus, small marble particles do not cause much perturbation as compared to the neat polymer. Larger particles disturb the matrix and cause a decrease in the compressive strain. We find here a different advantage in the use of small particles than that discussed in the preceding section.

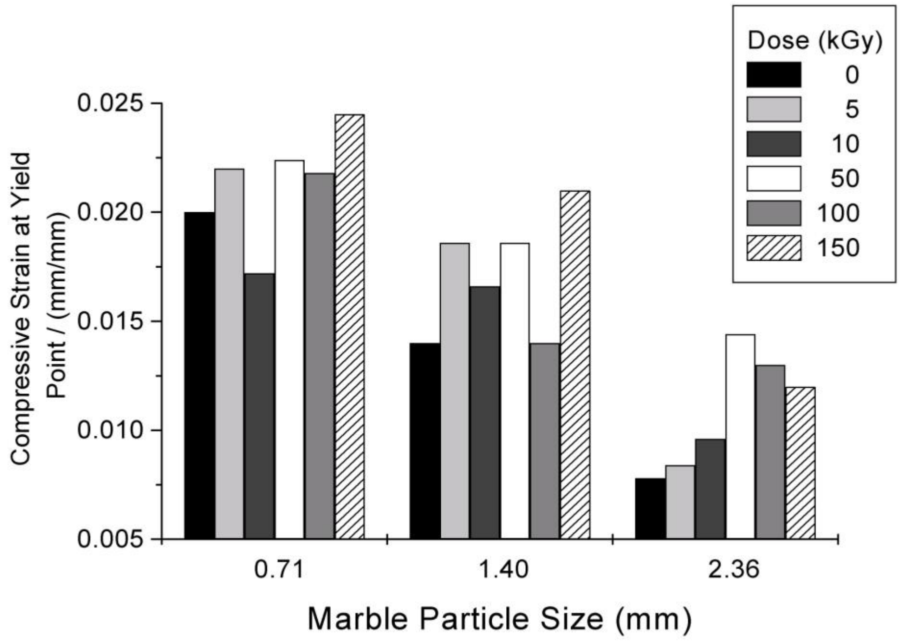


Fig. 3. Compressive strain of PC with different marble-particles sizes, irradiated at several doses.

Consider now the effects of the irradiation dose. Periodical behaviors are observed for each particle size. In the case of PCs with small particle five stages are seen, including the maximum value at 150 kGy, an improvement of 145 % in the compressive strain with respect to the standard values for a polyester-based PC reported as 0.01 mm/mm [16].

For PCs with medium particle size, five stages are observed, with a minimum value at 100 kGy and maximum at 150 kGy. Detrimental results are observed for PCs containing large particles, with two stages: i) the compressive strain increase up to 50 kGy; and ii) afterwards a decrease is seen, but with the strain values still higher than for the un-irradiated material.

Similar behavior is observed for PCs with two particle sizes, see Figure 4. In general, the compressive strain decreases with the radiation dose increase. In the case of PC with small + medium sizes, the values decrease when increasing the radiation dose, they show almost-constant values between 10 and 100 kGy (only 0.001 mm/mm of variation between them), and a decrease at 150 kGy. For the case of PC with medium + large sizes two stages are seen: i) from non-irradiated to 100 kGy the values go down; and ii) they increase towards 150 kGy. Similar behavior is seen for PC with small + large sizes. Thus, we can argue that the use of two particle sizes lowers the compressive strain values below those for PCs with one particle size.

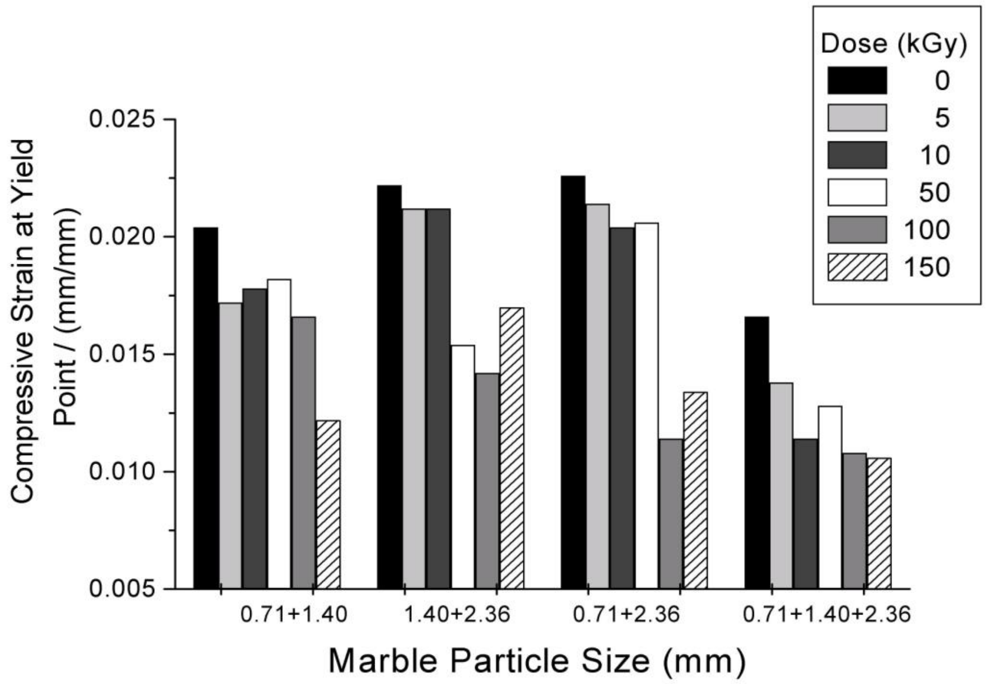
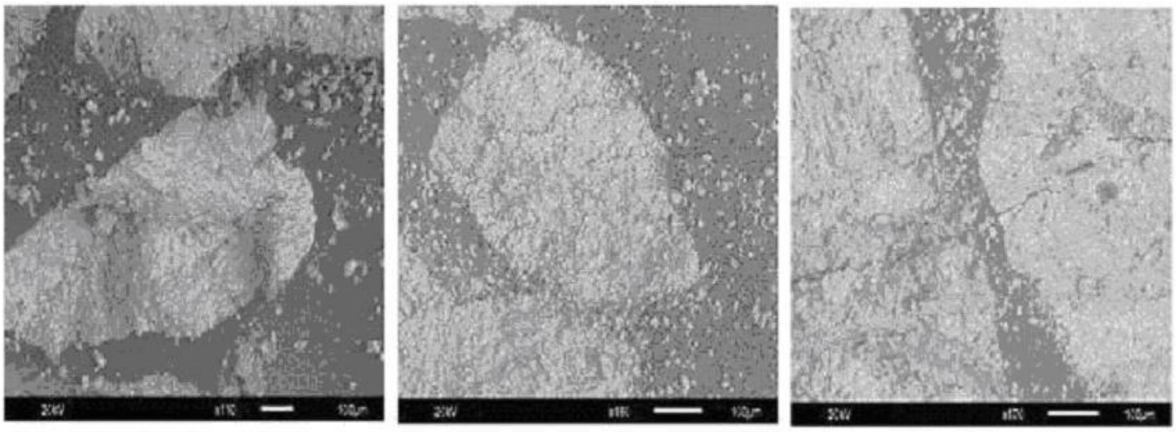


Fig. 4. Compressive strain of PC with different combinations of marble-particle sizes, irradiated at several doses.

The compressive strain values can be related to the morphology of the PC surfaces fractured after testing. Consider PCs with medium + large particle sizes irradiated at several doses (Figure 5). Values are the same for 5 and 10 kGy (0.021 mm/mm), but lower by 29 % at 50 kGy. At low doses the marble particles are covered by the polyester resin; several scrap particles (produced by the compression force) smaller than 10 μm are seen (Figures 5a and 5b). When increasing the applied radiation dose, a larger number of scrap particles and cracks passing through the marble particles are seen (Figure 5c). A large number of such cracks provide more ductile PC. The cracks are a consequence of the polyester constraints resulting from crosslinking of the chains in the polyester resin.

Finally, the compressive strain behavior of PCs with three-particle sizes, has three stages: a) a decrease from non-irradiated to 10 kGy; b) an increase up to 50 kGy; and iii) a decrease at higher doses (100 and 150 kGy). Thus, the combination of three different particle sizes results in a harder material. Values from 0.01 to 0.016 mm/mm of the compressive strain are lower than those for PCs with two particles sizes. These values are comparable to the standards for polyester-based PC reported (0.01 mm/mm) [16].

We conclude that PCs with a combination of two or three different particle sizes generate a harder material - instead of a ductile material created when only one particle size is used.



a) b) c)

Fig. 5. SEM Micrographs of irradiated PC with medium + large particle sizes at several irradiation doses: a) 5 kGy, b) 10 kGy, and c) 50 kGy.

When comparing the compressive strain values for non-irradiated PCs with other PCs elaborated with different mineral aggregates, we can see the advantages of using marble as the aggregate. The present values are in the range from 0.007 to 0.022 mm/mm, higher than for PC with one mineral aggregate such as silica sand (0.010 mm/mm) [18] or with $CaCO_3$ (0.012 mm/mm) [19]; or PC with two aggregates such as PC with marble and calcium bentonite (0.011 mm/mm) [21], or PCs with silica sand + $CaCO_3$ (0.017 mm/mm) [20].

In the case of the compressive strain for irradiated-PC, there are major differences. The present values are from 0.008 to 0.024 mm/mm; they are larger than for PCs with one mineral aggregate such as silica sand (0.006 - 0.013 mm/mm) [18] or with $CaCO_3$ (0.010 - 0.016 mm/mm) [19]; or for PCs with two aggregates of silica sand + $CaCO_3$ (0.014 - 0.017 mm/mm) [20] or for marble and calcium bentonite (0.013 - 0.020 mm/mm) [21].

Compression Modulus of Elasticity

The compression modulus of elasticity E_c exhibits similar behavior as the compressive strength values. That is, the highest values are obtained for PCs with medium particle size, and lower values for the other particle sizes (Figure 6). The highest values are from 9.6 to 11.7 GPa. Thus, an optimal particle size is necessary to achieve the highest strain values. Apparently small particles - while providing good protection against crack propagation - provide less reinforcement than the medium ones. We have here a result of two competing effects. A higher number of reinforcing particles per unit volume is preferred. On the other hand, smaller particles provide less reinforcement. This is why the medium size particles give us the highest modulus.

According to the radiation dose, periodical behaviors are observed for each PC type with different particle size (five stages for PCs with small or medium particles, and four stages for PCs with large particles). Similar behavior has been observed for polyester-based PCs with one mineral aggregate of silica sand (SiO_2) [18] or with $CaCO_3$ [19]; or for PCs with two aggregates of silica sand + $CaCO_3$ [20] or for marble + calcium bentonite [21]. For each PC with different particle size we have identified a maximum value at a certain radiation dose: at 10 kGy for PC with small particles, and at 50 kGy for PC with medium or large particles sizes. Thus more energy is necessary to obtain the maximum values when a medium or large size is used.

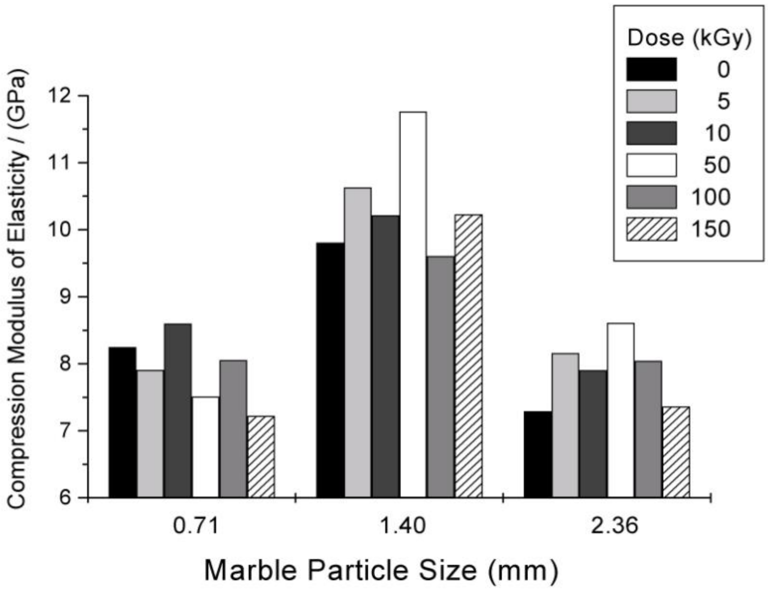


Fig. 6. Compression modulus of elasticity of PCs with different marble-particle sizes, irradiated at several doses.

In general, the E_c values for PCs with two different particle sizes (non-irradiated and irradiated) are lower than for PCs with one particle size. For non-irradiated PCs with two particle sizes, the values are located from 6.6 to 7.9 GPa (Figure 7), thus lower than those for PCs with one particle size (from 7.2 to 9.8 GPa).

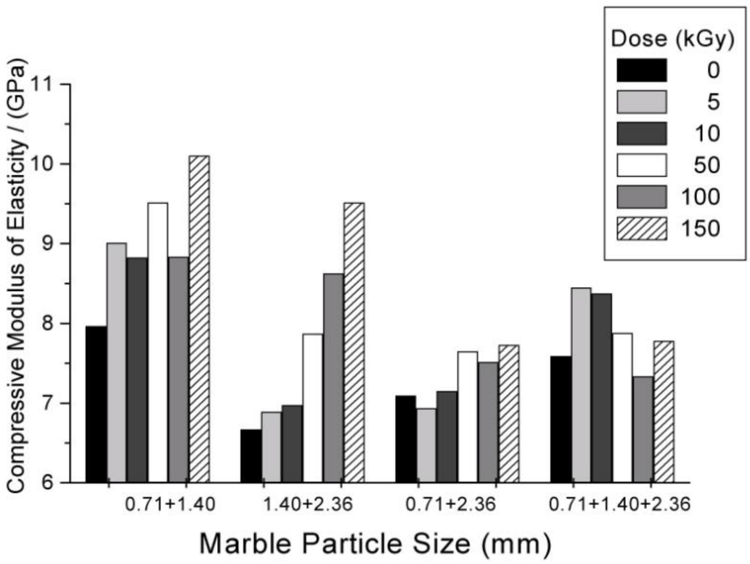


Fig. 7. Compression modulus of elasticity of PCs with different combination of marble-particle sizes irradiated at several doses.

The same situation is seen for irradiated PCs with two particle sizes, where the values (from 6.8 to 10.1 GPa) are lower than those for PCs with one particle size (from 7.2 to 11.7 GPa). Thus, the combination of two particle sizes generates a more ductile concrete.

According to the radiation dose, a variety of behaviors are observed. In general, E_c increases when the radiation dose increase also. PCs with small + medium sizes show five stages and have the highest E_c values (from 7.9 to 10.1 GPa), with the maximum value at 150 kGy. For PCs with medium + large or small + large sizes, E_c increases when increasing the radiation dose, with the maximum value at 150 kGy.

Special attention has to be paid to PCs with small + large particle sizes. On one hand, there is a ductile behavior, seen in the strain at yield point values (from 0.011 to 0.022 mm/mm); see again Figure 4. On the other hand, we find then the lowest E_c values (from 6.9 to 7.7 GPa) (Figure 7). We note that the E_c values are very similar to those obtained in earlier work for an irradiated polyester resin (from 6.2 to 8.2 GPa) [22].

For PCs with three different particle sizes, three stages are identified for E_c: i) the compression modulus of elasticity increases up to 5 kGy; ii) it decreases up to 100 kGy; and iii) it increases again towards 150 kGy. The respective values are from 7.3 to 8.4 GPa.

Thus, depending on the combination of particle sizes, the PCs need low or high radiation doses to obtain high deformability - and at the same time moderate compressive strength values. In this sense, special attention should be taken to the polyester resin behavior after irradiation, and its effects on the E_c values. In general, non-irradiated resins show homogeneous surfaces. The radiation doses up to 50 kGy result in formation of constraining regions. Thus, the elasticity modulus values increase. For a higher radiation dose of 100 kGy more constrained regions are present, providing the highest elastic modulus [21].

When comparing the E_c values for non-irradiated PCs with others PCs elaborated with different mineral aggregates, we observe that the present values (from 6.6 to 9.8 GPa), are higher than for PC with silica sand + $CaCO_3$ (5.2 GPa) [20] but comparable to those for PC with two mineral aggregates, marble + calcium bentonite (6.8 GPa) [21], or for PC with one aggregate: silica sand (7.3 GPa) [15] or $CaCO_3$ (7.6 GPa) [19]. We recall the standard value for polyester-based PCs, namely 6.7 GPa [1].

In the case of E_c values for irradiated-PCs, the differences are notable. The values are from 6.8 to 11.7 GPa, higher than for PC with two mineral aggregates of marble + calcium bentonite (3.3 - 6.3 GPa) [21], or for silica sand + $CaCO_3$ (5.6 - 8.0 GPa) [20]. However, these values are lower than for a PC with one aggregate of silica sand (7.4 - 16.3 GPa) [18] or with $CaCO_3$ (10.5 - 16.1 GPa) [19]. Thus, more ductility is achieved when using marble particles instead of silica sand or $CaCO_3$ particles.

Dynamic Elastic Modulus

The values for the dynamic elastic modulus, E_d, are similar to those of the compression modulus E_c. Also here the highest values are for PCs with medium particle size (Figure 8). For non-irradiated PCs, the E_d values are in the range from 9.0 to 11.3 GPa, while for irradiated ones from 9.1 to 13.0 GPa.

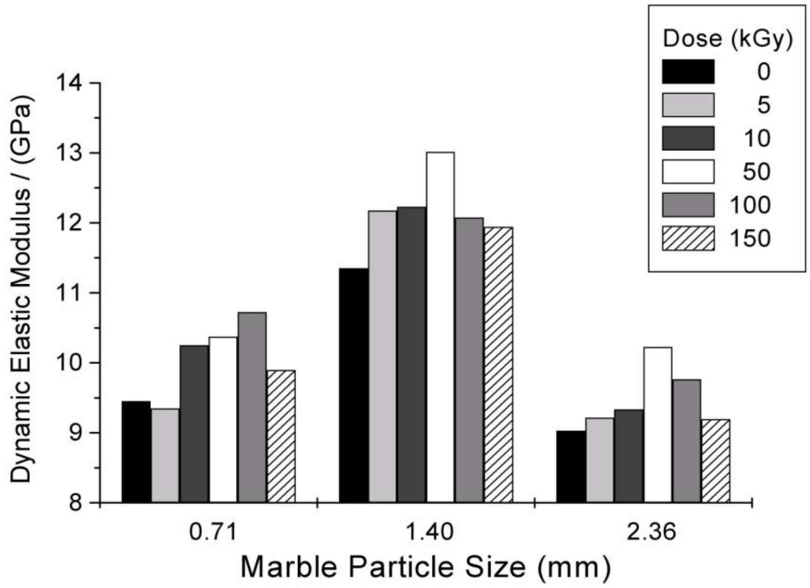


Fig. 8. Dynamic elastic modulus of PCs with different marble-particle sizes, irradiated at several doses.

A difference between both kinds of modulus is that a smaller number of stages of the dynamic modulus change with increasing irradiation dose. Two stages are seen for PCs with medium or large particle sizes: I) an increase up to 50 kGy; and II) a decrease for higher doses (100 and 150 kGy); see Figure 8. Three stages are seen for PCs with small particles: i) a decrease at 5 kGy, ii) an increase up to 100 kGy; and iii) a decrease at 150 kGy. In both cases the E_d values increase until a certain dose, pass through a maximum, and then decrease.

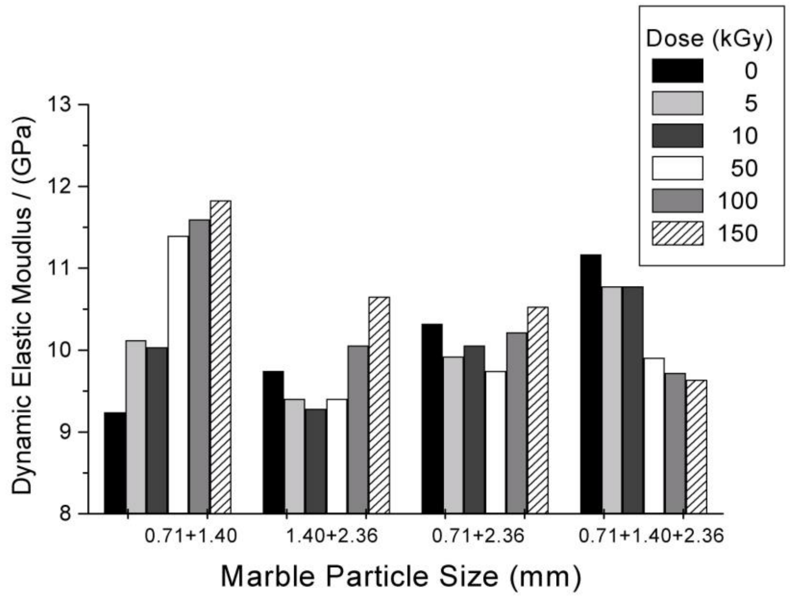


Fig. 9. Dynamic elastic modulus of PCs with different combination of marble-particle sizes irradiated at several doses.

For PCs with two different particle sizes, two tendencies are observed: a) E_d increases when the radiation dose increases, and b) E_d decreases up to a certain radiation dose and increases afterwards (Figure 9). The first case is seen for PCs with small + medium sizes, and the second for the other PCs, with medium + large or small + large sizes. In both cases the maximum value at 150 kGy is seen.

In the case of PCs with three particle sizes, a different behavior is seen: E_d values decrease when the radiation dose increases.

When comparing values of both kind of elastic modulus, we have found certain differences. For example, in the case of non-irradiated PCs, the dynamic values E_d are from 9.0 to 11.3 GPa, higher than compressive modulus E_c values (from 6.6 to 9.8 GPa); there is 36 % of maximal difference. A similar difference (35 %) for irradiated PCs is seen, because the dynamic E_d values go from 9.2 to 13.0 GPa, while the E_c values from 6.8 to 11.7 GPa.

Conclusions

Mechanical properties of composites are in general not additive [11, 12, 24 – 32]. As expected, mechanical behavior depends on the combination of marble particle sizes and the applied radiation dose. Compressive strength values are lower for PCs containing two or three particle sizes. Notable increments are seen for the compressive strain values when using one particle size. Such behavior suggests generation of a ductile material. Moreover, depending of the combination of particle sizes, the PCs need low or high radiation doses to obtain high deformability with moderate compressive strength.

Finally, while in this paper we deal with polymer concretes, activities on inorganic concretes [33] could conceivably also benefit from some conclusions reached here. Maneuvrability of properties by using aggregates of varying sizes is one such conclusion.

Experimental part

Specimen preparation

For preparing the polymer concrete specimens, marble from a local company (GOSA^{TM}, Atizapan, Mexico), was used as the fine aggregate, and mixed with a commercial unsaturated pre-accelerated polyester resin (orthophtalic). The proportion of the polyester resin in the PC was 30 % by weight. The resin is a viscous liquid with a styrene monomer content of 30 % (Polylite 32493-00^{TM}, Reichhold, Atlacomulco, Mexico). The proportions of the methyl ethyl ketone peroxide (MEKP) initiator added to the polymer for initiating the free-radical polymerization process was 1 mL/by 100 g of the resin weight.

Seven different polymer concrete lots were prepared (three for PCs with one particle size; three for PCs with two particle sizes, and one for PCs with three particle sizes). Each lot contained six specimens, to be subjected to six different irradiation doses. Thus, we had a total of 42 PC specimens for each test. After mixing, the polymer concrete cubic specimens (5 x 5 x 5 cm) were placed in a controlled temperature room at 23.0 ± 3.0 °C for 24 hours.

Mechanical Tests

The compressive tests of the polymer concrete specimens were carried out in an Universal Testing Machine model 70-S17C2 (Controls^{TM}, Cernusco, Italy), according to the ASTM C-109M standard. The dynamic modulus of elasticity was measured by using an ultrasonic testing equipment for building materials: Ultrasonic Pulse Velocity Tester model 58-E0048 (Controls^{TM}, Cernusco, Italy), with an ultrasonic resolution of 0.1 ms. Both machines were located at Laboratory of Research and Development in Advanced Materials (LIDMA) of the Autonomous University of the State of Mexico (UAEM).

Morphological characterization

After mechanical testing, some fractured polymer concrete pieces were dried in a rotovapor for 24 hours. Then their surfaces were analyzed by scanning electron microscopy (SEM) in the secondary-electron mode by using a JEOL model JSM-6510LV machine.

Irradiation procedure

The polymer concrete specimens were exposed to gamma radiation at different doses (5, 10, 50, 100 and 150 kGy) in air at room temperature. The dose rate 3.5 kGy/hr was applied by using a 651 PT Gamma beam Irradiator with a ^{60}Co source, manufactured by NORDION (Chalk River, Ontario), and located at the Institute of Nuclear Sciences of the National Autonomous University of Mexico.

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