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Research Article

Recovery and Modification of Waste Tire Particles and Their Use as Reinforcements of Concrete

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Environmental pollution caused by solid wastes is increasing in the last decades; one of these is referred to automotive tires, which are recycled by different methods, including mechanical grinding. One of the most recurrent applications is to use recycled particles as fillers in building materials, as hydraulic concrete. Nevertheless, detrimental values on the mechanical properties are obtained when they are added. For solving these problems, in this work, a novel proposal is to modify the physicochemical properties of the waste automotive tire particles, previously obtained by grinding process, by using gamma irradiation in order to use them as reinforcements of hydraulic concrete. The results show that improvements on the mechanical properties depend of gamma irradiation as well as concentration and size of waste tire particles. Moreover, SEM images are related to mechanical properties; for instance, rough surface of the tire particles changes when applying irradiation; more smooth surfaces are created, due to the cross-linking of polymer chains. Nevertheless, for higher doses, cracks are observed which are produced by scission of the polymer chains.

1. Introduction

One of the major environmental problems around the world is the final disposal of waste of automotive tires. Nevertheless, a lack of information is concerning end-of-life of tire management issues. Innovative solutions are developed to meet the challenge of tire disposal problem. They include update of the life cycles assessments, showing the benefits of the recycling, and recovery actions. Moreover, it is necessary to have in mind how waste tires can be converted into a valuable resource [1]. Recycling of such materials has been carried out by different processes, including (a) landfilling, which diminishes in some countries due to new laws that forbid any new landfill; (b) producing powder richer in carbon compounds by pyrolysis process, which consist in the decomposition of the organic materials by heating at 400°C in absence of oxygen; pyrolysis sometimes is not economically viable due to low quality final products; nevertheless, it is possible to obtain three different phases through all processes, (1): solid black phase composed by ZnO and ZnS; (2): gaseous phase containing aromatic compounds; and (3): liquid phase with heavy and light oils [2–4]; (c) using as fuel in cement kilns, whose cost is lower than raw tire materials, which is an example of downcycling process [4]; (d) recycling by shredding process, where waste tires particles require having certain size for specific applications, varying from 0.15 mm to

19 mm; after shredding an electromagnetic process is applied for separation of rubber particles and steel fibers, for reusing them in several applications, for making rubber products such as floor mats, carpet padding, and plastic products, and as a substitute of fine aggregate in concrete [5, 6].

Recycled waste tires have been used in the construction industry; some examples of their uses are (a) waste steel fibers from recycled tires as mechanical reinforcement of concrete, which makes possible the improvement of mechanical performances of the concrete [7–9]; (b) recovered rubber as replacement of natural aggregates (fine and coarse), in which the elasticity features were improved and a lower diminution on the compressive strength and brittleness values were found; moreover, by adding rubber particles the reduction of the water absorption was possible; thus a better protection of the steel reinforcement against corrosion is obtained, as well as reduction in the structural weight [10–15]; (c) partial replacement, either sand or cement, by crumb rubber or powder rubber in concrete. The fracture characteristics of concrete were improved when adding crumb rubber; nevertheless, flexural strength was diminished. Moreover, light increment is done when adding powder. Other study points out large reductions in the strength and tangential modulus of elasticity as well as in the brittle behavior of the concrete when adding tire chips and crumb rubber particles [16, 17]; (d) recycling tires as foundation pad for rotating machinery and as vibrations damper in the railway station or where impact resistance, energy absorption, or blast is required [18]; (e) the incorporation of crumb rubber aggregates from worn tires as lightweight aggregate in cement based materials which endows enhanced acoustic and thermal conductivity characteristics; moreover, when crumb rubber is used as insulation material allows potential savings on energy [19].

Although some advantages are obtained when adding recycled materials as rubber tire particles for improvement of the toughness of concrete, they present some disadvantages as lower values on the compressive strength, which should be attended. One alternative is the use of gamma radiation. Recent works have studied the effects of gamma radiation on compressive properties of polymer concrete; in one of them, the results show more resistance to crack propagation; moreover, compressive strain and the elasticity modulus depend on the combination of the particle sizes and the radiation dose [20].

The gamma radiation (γ) is a type of high electromagnetic energy radiation, generally produced by radioactive elements or subatomic processes such as the annihilation of a positron-electron pair. One important characteristic is its capacity to penetrate matter deeper than alpha or beta radiation. In general, the gamma rays strike and pass through the material; it depends on the photon energies, thickness, or density of the materials.

Application of gamma radiation in polymeric materials causes three different processes: cross-linking or scission of polymer chains and graft polymerization. The permanence of any of these processes depends on the nature of the radiation, the chemical structure of the polymer, and the applied dose [21]. In general, molecular weight changes are produced after chemical reactions; content of gels with low molecular weight is obtained. After irradiating physical properties are affected.

For example, the vulcanization of chlorine butyl rubbers by using gamma radiation decreases the tensile strength and elongation at break up to 25 kGy, but after this dose stability of such properties is observed, up to 200 kGy. Moreover, thermal stability is reduced through the degradation and scission of molecular chains [22]. In another study, polydimethylsiloxane rubber foams were gamma irradiated and their mechanical properties and chemical structure were evaluated, through compression test, infrared attenuated total reflectance spectroscopy (ATR), and X-ray induced photoelectron spectroscopy (XPS). The results show a higher cross-linking of polymer chains when increasing the irradiation dose; thus foams became harder [23].

The high-energy radiation is not frequent in the preparation of composites; nevertheless it has special advantages in the control polymerization because it can be initiated uniformly within small thicknesses of material. This process, compared to thermal process or chemical attack, presents several advantages; for example, initiating radiation requires no activation energy and does not require catalysts or additives to initiate the reaction; the initiation is homogeneous throughout the system, the process can be carried out at any temperature and can be interrupted at a specific reaction time, the termination reaction is practically controlled, the polymer can be analyzed to a specific reaction step, and during temperature initialization reaction is maintained, unlike the one presented in a conventional exothermic curing without irradiation, and, above all, it is faster spending less time and money [21, 24, 25].

Some studies covered the effects of gamma radiation on composite materials, for example, on the mechanical properties and durability of cement concretes. Some applications include concrete as material for nuclear power reactors; for this purpose the specimens were submitted to dosages from 227 MGy and 470 MGy with a dose rate of 5.0 kGy/h. The results show a diminution of about 10% on the elastic and tensile properties, as well as loss of weight, caused by one or more of the following mechanisms: (a) "natural" drying (including gamma heating); (b) radiolysis-induced accelerated drying (where large gas is released); (c) radiolysis-induced carbonation; and (d) degradation of the calcium-bearing cement hydrates [26, 27].

Another study is related to cement concrete and irradiated nylon fibers; it shows higher compressive strength values, when adding nylon irradiated fibers at 50 kGy. Load transfer mechanism between the concrete and fibers under loading is seen. Moreover, a reinforced concrete is created with high elastic modulus and high deformability. Furthermore, 50 kGy seems to be the dose at which the reaction mechanism changes from cross-linking to chain scission. Ionizing energy generates more contact points on the fiber surfaces and in consequence a larger contact area between the fibers and the concrete phase [28]. Another study is devoted to polymer-ceramic composite material, as gypsum/poly(methyl) acrylate composite where the yield of polymerization increased up to 88% with increasing radiation dose and leveled off at a dose around 4 kGy [29].

Table 1: Components of the concrete for producing 1 m^3.

Mix code	Waste tire (Vol%)	Waste tire (kg)	Portland cement (kg)	Sand (kg)	Gravel (kg)	Water (kg)
M-0	0	0	337.1	758.5	662.6	286.3
M-10-7	10	36.2	337.1	596.4	758.5	278.4
M-20-7	20	72.4	337.1	530.1	758.5	270.6
M-30-7	30	108.7	337.1	463.8	758.5	262.7
M-10-20	10	47.2	337.1	596.4	758.5	278.4
M-20-20	20	94.5	337.1	530.1	758.5	270.6
M-30-20	30	141.7	337.1	463.8	758.5	262.7

Modifications on the cement and different mineral aggregates have been done by using gamma radiation; such materials are mixing into the concrete. In other cases all concrete components are mixed and then concrete specimens are irradiated. Both kinds of concretes are evaluated by mechanical tests. The results are different, and the scanning electron microscopy has been a good tool to evaluate the contribution of each component in nonirradiated and irradiated concretes. After mechanical testing, morphological characterization on some fractured cement concrete pieces is carried out. SEM technique provides good images of distribution of dispersed phases in a matrix [30].

The effects of gamma irradiation on the compressive properties of polymer concretes show that the compressive strain and the elasticity modulus depend on the particle sizes used and the applied radiation dose; in particular, more resistance to crack propagation is obtained. Alternative studies were using recycled polymers and gamma radiation, for example, (a) polymer concrete with recycled high density polyethylene (HDPE) and tire rubber particles, irradiated from 25 to 50 kGy. The results show significant increase on the impact strength and in the elongation at break; such improvements were attributed to the good adhesion between tire rubber particles and the polymer matrix [31]; (b) polymer concrete with waste tire rubber and styrene butadiene rubber (SBR) improved its tensile strength, elongation, and heat resistance up to 75 kGy [32].

This study attempts to use gamma irradiation as modifier of the physicochemical properties of waste automotive tire particles and use them as reinforcement of cement concrete and in consequence improve their mechanical properties. This investigation promotes the use of waste materials in the construction industry, as one alternative for reducing environmental pollution.

2. Experimental

2.1. Design and Manufacture of Concrete. All mixes were elaborated with Portland cement CPC-30Rs and gravel and water (according to ASTM C 150 cement type I) [33]. The objective was to obtain a mix with 24.5 MPa in compression strength at 28 days of curing, according to ACI 211.1 standard [34]. Physical properties of the concrete components and the sieve analyses of fine and coarse aggregates are described in [35].

2.2. Mixing, Casting, and Curing Specimens. Plain concrete mixtures were prepared with dry aggregates (fine and coarse), cement, and water. Cement was mixed with addition of 85% of water; after mixing by one minute, 15% of water was added and mixed for a total time of 5 minutes, in order to prevent fresh concrete from segregation.

Concrete with or without irradiated-tire particles was elaborated. For each concrete mixture ten specimens were casted in cylindrical molds of 150 mm diameter and 300 mm height, as well as two beams of 150 × 150 × 600 mm. After 24 hours, they were placed in a controlled temperature room at 23.0 ± 2.0°C and 95% of relative humidity. Cured process was performed in accordance with ASTM C511 standard [36].

The component concentrations of the concrete are shown in Table 1. Regarding the manufactured concrete replacing sand by waste tire particles, two different waste tire particle sizes were used (2.8 mm (mesh 7) and 0.85 mm (mesh 20)), having an approximate waste particle size ratio of 1 : 3. Moreover, three different concentrations of waste tire particles 10, 20, and 30% by volume were used. The mix code was labeled as Mix-Concentration-Mesh; for example, M-10-7 specimens means mix with 10% of waste tire and mesh size 7. The water/cement ratio was kept constant at 0.54.

2.3. Irradiation Procedure. Waste tire particles were irradiated at 200 and 300 kGy with a ratio of 4 kGy/h. Then, they were added to the concrete mix; finally, after mixing, the concrete was casted in molds. For irradiation process an irradiator Gamma Beam 651-PT loaded with ^{60}Co pencils was used; it is located at the Institute of Nuclear Sciences of the National Autonomous University of Mexico.

2.4. Mechanical Tests. Concrete specimens were tested after 28 days of curing time. Testing tolerance allowed was 28 days ±12 hours according to ASTM C/192M-00 standard [37]. Compressive strength evaluation was carried out in a universal testing machine Controls 047H4 (Milano, Italy) with capacity of 2000 kN [38]. The modulus of elasticity was determined from the slope of the stress-strain curve; while the flexural strength by using Elvec 72-4 machine with capacity of 10 kN [39]. The pulse velocity evaluation was carried out with an ultrasonic pulse velocity tester Controls 58E0048 with transmitter and receiver head (54 kHz) and pulse rate of 1/s [40].

3. Results

3.1. Unit Weight. The unit weights of concretes are shown in Figure 1. These results are discussed in terms of three

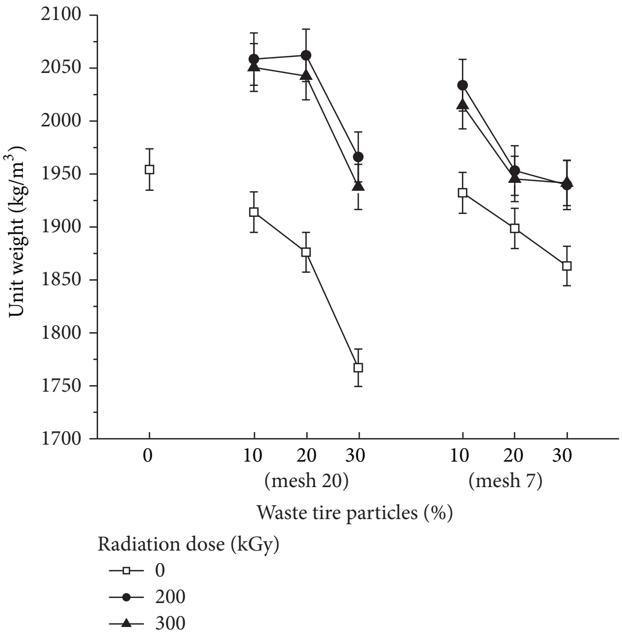

FIGURE 1: Unit weight of concrete with waste tire particles at different irradiated doses.

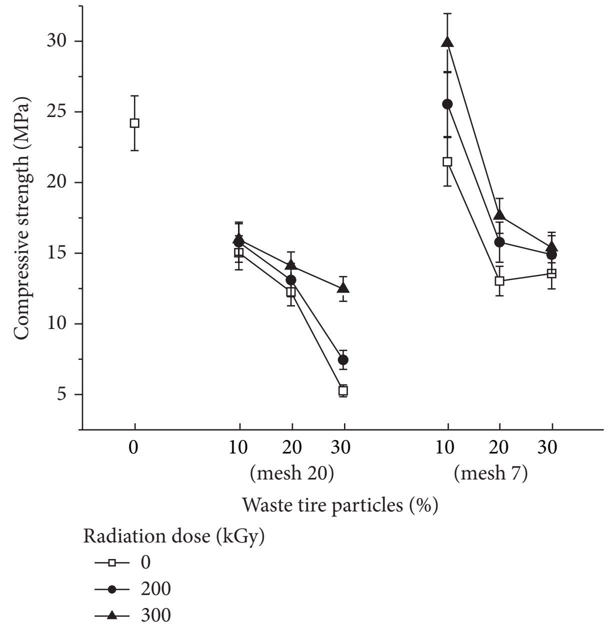

FIGURE 2: Compressive strength of concrete with waste tire particles 0.85 mm (mesh 20) and 2.8 mm (mesh 7).

parameters: concentration and size of the tire particles, as well as irradiation dose. With respect to particle concentration, the unit weight diminishes progressively when it is increasing; reaching the lowest value for concrete with 30% of particles, the reduction on the values means 10% lower than those for control concrete (1954 kg/cm^3). Taking into account the particle size, lower values are observed for concrete with small size particles (0.85 mm). Moreover, all nonirradiated concretes have lower values with respect to the control concrete. Thus, a combination of small particle size and more particle concentration creates lower unit weight of concrete. In fact the values decrease because waste tire particles are porous and then air content is increased in concrete mixtures generating low unit weight. This fact is in accordance with a related research in which the air content in concrete increases when using bigger rubber particles [41].

In the case of concrete with irradiated waste tire particles, highest values are observed for 200 kGy, followed by those with irradiated particles at 300 kGy. Nevertheless, all irradiated concrete specimens show higher values than nonirradiated ones. The maximum value obtained was 5% higher than those for control concrete. It is important to mention that during mixing process with irradiated particles some small lumps were formed, different from the control concrete which showed a homogeneous surface. Then modifications on the tire particle surfaces after irradiating cause lumps when mixing to concrete and in consequence higher unit weight is seen.

3.2. Compressive Strength. Compressive strength values of concretes are shown in Figure 2. The compressive strength values vary as a function of size and concentration of waste tire particles. For concrete with nonirradiated waste tire particles, the following behaviors are observed: (a) the values decrease progressively according to the particle concentrations increase. Moreover, all these kinds of concretes have lower values than those for control concrete, namely, 24.1 MPa; (b) with respect to the particle size, the compressive strength values are higher for concretes with particles of 2.8 mm than those with 0.85 mm. Thus, when increasing the waste particle concentration and adding large particles more air content is obtained which may cause microcracking and in consequence lower compressive values.

For concrete with irradiated waste tire particles the compressive strength values follow a similar behavior: they increase gradually according to irradiation dose increases. Due to gamma irradiation, the tire particles are progressively harder and no cracks are seen on its surfaces; such behavior generates a composite material with harder particles, which contribute to improving the resistance of the concrete. Additionally, bigger size tire particles create more mechanical resistance compared to smaller ones; such behavior is a consequence of its bigger surface area. It is important to mention that only concretes with 10% of tire particles of 2.8 mm and those irradiated at 200 or 300 kGy showed higher values than those for control concrete, up to 23% of improvement.

3.3. Splitting Tensile Strength. Splitting tensile strength values of concretes are shown in Figure 3. For concrete with nonirradiated waste tire particles, the following behaviors are observed: (a) with respect to particle concentration, the values decrease when increasing the particle concentration; when considering the particle size, higher values are found for concrete with particles of 2.8 mm. However, all values are lower than those for control concrete.

The splitting tensile strength for concrete with irradiated waste tire particles shows a peculiar behavior: at 200 kGy

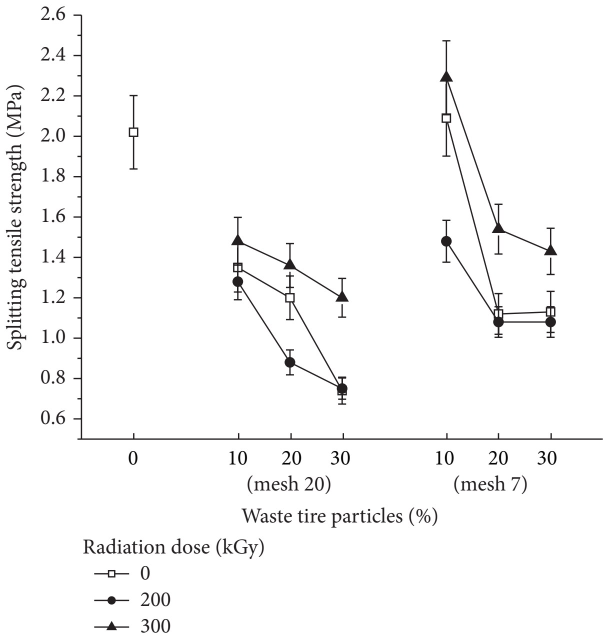

Figure 3: Splitting tensile strength of concrete with waste tire particles of 0.85 mm (mesh 20) and 2.8 mm (mesh 7).

the values decrease below the control concrete value; nevertheless at 300 kGy the values increase, now above the control concrete value. Such results are dependent on two parameters, the dispersion of particles into the concrete and the morphology changes on the particle surfaces. More structural damage on the particles is caused when applying higher doses. Such behavior of below-above for the values with respect to control concrete depends on the arrangement of the irradiated particles into the concrete; dose of 300 kGy allows a better arrangement and in consequence an increment of the tensile strength up to 13%. Only concretes with 10% of particles of 2.8 mm and irradiated at 300 kGy have higher values than those for control concrete.

Figure 4 shows nonirradiated and irradiated particles (at 200 kGy and 300 kGy). For nonirradiated tire particles a rough surface is observed, containing small particles of different sizes (left image); when irradiating at 200 kGy smooth surfaces are created, with some small and disperse particles. According to the literature, sometimes smooth surfaces are generated after irradiating as consequence of the cross-linking of polymer chains, while for higher dose scissions of the polymer chains are done, which is manifested by appearances of cracks on the surfaces; as it is shown in Figure 4, for 300 kGy.

3.4. Flexural Strength. The flexural strength values are shown in Figure 5. The results for concrete without irradiated particles indicate (a) progressive diminution of the values when increasing the concentration of particles; (b) variations in terms of the particle size; higher values are for concretes with particles of 2.8 mm. Inclusively, only concrete with 10% of waste particles has a higher value than those for control concrete; such improvement is of 10%.

For concrete with irradiated particles the flexural strength values are lower than those for control concrete. Conversely to compressive strength values where the values for concrete with irradiated particles are higher than those for control concrete, in the case of flexural strength, are lower. Thus a combination of particle arrangement (random distribution) and the type of mechanical test may result in higher or lower values. In the case of flexural test the induced stresses generated in the specimens are in the direction of the two load application axes. The diminution on the values is of 46% with respect to control concrete.

3.5. Modulus of Elasticity. The modulus of elasticity values is shown in Figure 6. As other mechanical features discussed in previous sections, the modulus of elasticity values follows similar behaviors: (a) the values decrease when increasing the concentration of particles; (b) the values are higher for concrete with particles of 2.8 mm. Nevertheless, the values are lower with respect to control concrete. This is due to the fact that the concrete without tire particles is more rigid and does not allow large deformations; nevertheless when adding particles the slope of its stress-strain curve in the elastic deformation region is changing; thus elastic modulus is lower; a stiffer material will have a higher elastic modulus.

For concrete with irradiated particles, modulus of elasticity values has different behaviors: (a) when adding irradiated particles of 0.85 mm, the values increase according to increasing the irradiation dose; (b) when adding large irradiated particles (2.8 mm), the values for concrete with irradiated particles at 200 kGy are lower with respect to control concrete values but higher for those that are using irradiated particles at 300 kGy. Such behaviors can be related to the morphological changes of the irradiated particles as well as their distribution into the concrete. The irradiated particles contribute to incrementing the deformations into the concrete and to diminution of crack formation which results in lower modulus of elasticity. Despite this, improvement of 20% is obtained for concrete with 10% of irradiated particles with respect to those for control concrete.

3.6. Pulse Velocity. In Figure 7 the ultrasonic pulse velocities applied to concrete are shown. Results show similar behavior to compressive strength values; as for concrete with nonirradiated particles the values decrease when increasing the concentration of waste tire particles, and they are bigger when using larger particles of 2.8 mm. Nevertheless, the highest value corresponds to control concrete.

In the case of concrete with irradiated waste particles, a similar behavior is observed: the values diminish when increasing the irradiation dose. Detrimental values are 56% lower with respect to control concrete value. Moreover, the morphological changes on the particles and the increment of their hardness after irradiating contribute to nonpropagation of sound waves.

4. Conclusions

The results show that gamma irradiation as well as concentration and size of waste tire particles are adequate tools

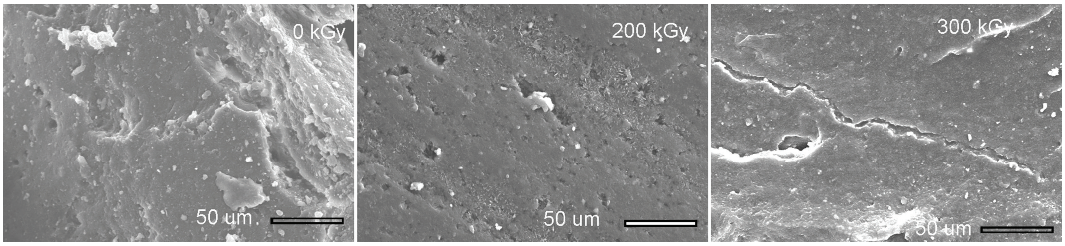

Figure 4: SEM image of waste tire particles at different irradiation dose.

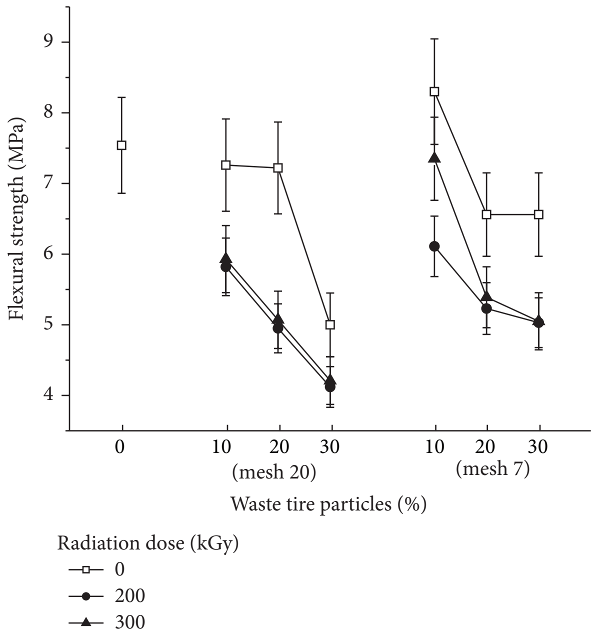

Figure 5: Flexural strength of concrete with waste tire particles of 0.85 mm and 2.8 mm.

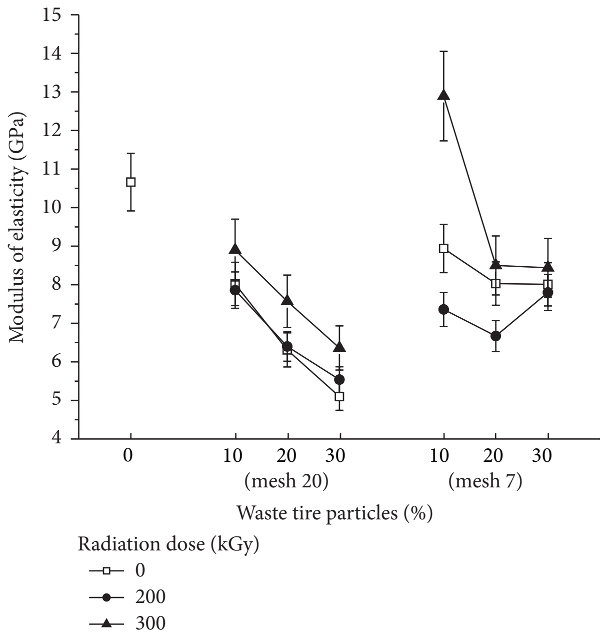

Figure 6: Modulus of elasticity of concrete with waste tire particles of 0.85 mm and 2.8 mm.

for improvement of the mechanical properties of cement concrete. It can be seen that concrete with concentrations no greater than 10% of particles of 2.8 mm and irradiated at 300 kGy show the highest values compared to those for the control concrete for compressive strength, tensile strength, and elastic modulus. Different behaviors were observed in terms of the particle sizes and the irradiation doses. In general terms, higher values are obtained with addition of large particles and high irradiation dose. The gamma irradiation generates more homogeneous and smooth surfaces as well as some cracks on the tire particles. Smooth surfaces are related to a hard particle, and the cracks to a better bond between cement matrix and the tire particles; both characteristics can prevent earliest cracks and in consequence soon failures. The morphological characteristics along with the geometrical arrangement of the tire particles into the concrete allow improvements on the mechanical properties.

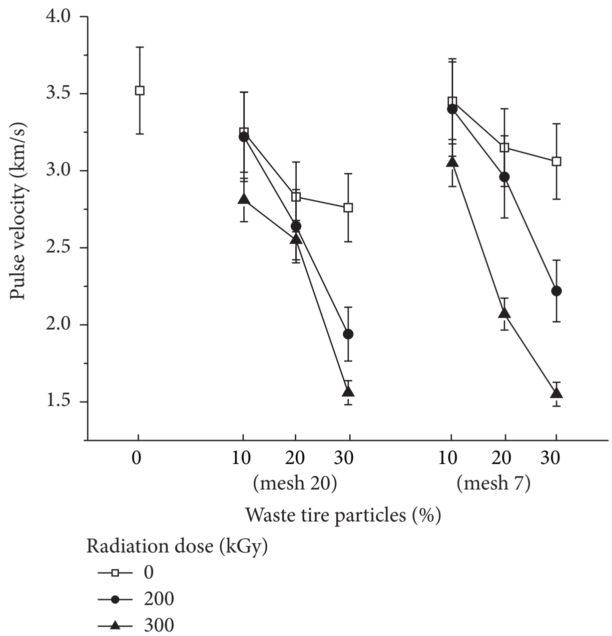

Figure 7: Pulse velocity of concrete with waste tire particles of 0.85 mm and 2.8 mm.

Conflict of Interests

The authors do not have a direct financial relation or conflict of interests with the commercial identities mentioned in this paper, and the commercial trademarks, such as Controls and Elvec, only were reported to guarantee the reproducibility, in the same conditions, of the different tests.

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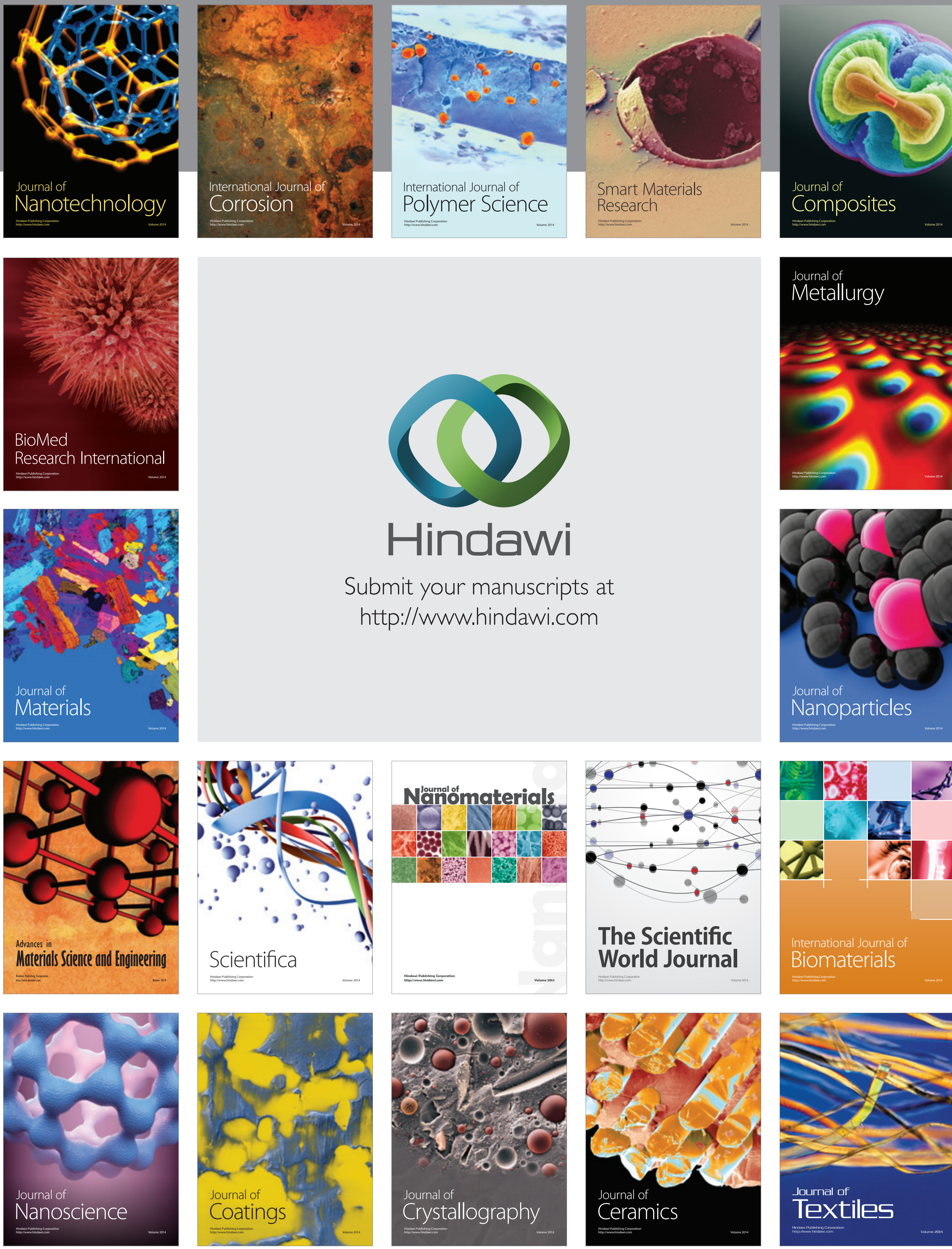
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