Chapter 9

Waste and Recycled Materials and their Impact on the Mechanical Properties of Construction Composite Materials

Gonzalo Martínez-Barrera, Nelly González-Rivas,
Enrique Vigueras-Santiago, Ángel Martínez-López,
Jorge A. Tello-González and
Carmina Menchaca-Campos

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/65433

Abstract

In a world increasingly fixated on the demands of sustainable development, too much attention has been focused on the widely used building materials, mainly on those tools and strategies for their reuse and those characteristics for considering them as environmental-friendly materials. Among the strategies are the following: (a) increased reliability on waste and recycled materials—such action will have to incorporate the substitution of recycled for virgin materials; (b) improved durability through reduction of materials needed for their replacement; and (c) improved mechanical properties, which reduces the use of raw materials. Extensive research and development activities in recycling composite materials have been conducted, and various technologies have been developed: (a) mechanical recycling, (b) thermal recycling, and (c) chemical recycling. However, gamma radiation is an innovative and clean technology, alternative to conventional recycling procedures. Gamma irradiation has proved to be an adequate tool for modifications of the physicochemical properties of polymers, through different effects: (a) scission, branching as well as cross-linking of polymer chains and (b) oxidative degradation. Moreover, the reuse and recycling of waste materials and the use of gamma radiation are useful tools for improving the mechanical properties of concrete. In this chapter, we show results of the effects of gamma irradiation on the physico-chemical properties of waste and recycled materials and their reuse to enhance the properties of construction composite materials.

Keywords: waste, recycled materials, composite materials, mechanical properties, gamma radiation

1. Introduction

In recent years, due to high demand of construction materials, some actions have been developed such as extraction of large amounts of raw materials, development of new materials, use of recycled and demolition waste; all of them generating higher costs and environmental problems. Special attention on the development of economic and ecological materials through the use of waste materials has generated a novel research area. Moreover, in order to reduce the ecological impact, many efforts have been made for reducing the consumption of nonrenewable resources in the production of construction materials, one of these is the production or addition of waste or recycled materials into the mixture in substitution of the common mineral aggregates, taking care of the final quality that includes parameters such as resistance, modulus of elasticity, and durability, among others.

Although some advantages are obtained when adding waste or recycled materials for improvement of the toughness of construction materials, they present some disadvantages such 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; 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. This chapter attempts to use gamma irradiation as modifier of the physicochemical properties of waste and recycled materials, and use them as reinforcements of construction composites and as a consequence improve their mechanical properties. This chapter promotes the use of waste and recycled materials in the construction industry, as one alternative for reducing environmental pollution.

2. Waste and recycling materials in the research area of construction

Discovered and patented in England in 1941, polyethylene terephthalate (PET) has been used in the packaging industry for a broad range of applications. Annual average consumption per person of 234 l of bottled water is reported. As it has become a widely used material, all disposed bottles are actually a serious environmental issue. Pollution caused by PET bottles includes not only the final disposal of them, but also the by-products obtained during PET fabrication process. Plastic bottles take centuries to decompose and if they are incinerated, toxic by-products, such as chlorine gas and dioxins, are released into the atmosphere. Solid handles of materials have experienced an important impact because of the nonbiodegradability nature of PET. The world consumption of PET is about 15 million tons, of which 3.5 million tons are used in the manufacture of packaging materials, including jars and bottles.

Two methods for recycling of polyethylene terephthalate (PET) bottles are mechanical process and chemical process. (1) Mechanical process includes three well-defined stages such as separation, washing, and grinding. The recycled PET is used for elaborated laminates, metal sheets, and food and nonfood packages. Moreover, recycled PET flakes can be directly employed to elaborate pellets in the creation of products by injection or extrusion. (2) Chemical process consists of separation of the basic components or monomers. The methanolysis, glycolysis, and hydrolysis are the elemental processes to achieve this transformation.

PET can be recycled many times and can be used in a variety of products, such as fibers for clothes, fiberfill for bags, or industrial strapping. One interesting alternative to recycled PET materials consists of using them as a substitute of concrete aggregates; in this, silica sand is partially substituted by waste PET particles. The main goal is improvement of mechanical properties, including compressive strength, deformation, and modulus of elasticity. Demand of technological development in different construction areas makes possible the generation of alternative materials that can be applied with increasing functionality, low costs, and better physical, chemical, and mechanical properties than conventional materials. Fiber-reinforced concrete, in which new materials are applied in order to obtain more efficient crack-resistant concrete, is an important research field these days. PET has been widely used to produce fibers, particles, or flakes to obtain cement-based products with improved properties.

Different kinds of fibers have been used in the concrete, including steel, glass, carbon, nylon, polyester, propylene, among others; however, in order to reduce the environmental impact of industrial or postconsumer waste, recycled fibers have been used. They offer advantages in reducing waste and conserving resources.

Another waste with potential applications in different technological areas is that related with the automotive tires. The typical components of automotive tires are synthetic and natural elastomers, sulfur and its compounds, phenolic resins, oils, and steel wires among others; while zinc oxide, titanium dioxide, and carbon black are used as pigments. Moreover, manufactured tire includes: synthetic elastomers (27%), natural elastomers (14%), carbon black (28%), steel (15%), as well as fabric, infill materials, accelerators, and anti-ionizer (16%) [1, 2].

The most common method to dispose waste tires is to burn them for vapor, heat, or electricity. The usage of waste tires as alternative fuel in cement furnaces is generalized across the U.S. and Europe. However, these practices result in the generation of organic and inorganic compounds such as zinc oxide (ZnO) and zinc sulfide (ZnS), in hydrocarbon gas, aromatic volatile compounds, and liquids formed by heavy and light oils, all these by-products which are highly polluting.

Recycling of automotive tire includes reuse in plastic and rubber products as well as alternative fuel in cement furnace or as material in the carbon black production. Another approach for the application of waste tires includes hot bituminous mixes as pneumatic dust for the agglutinative modification in asphalt pavements. This application has been more or less effective, but not enough for reducing the reserves of waste tires, since these novel technologies are more expensive than conventional methods. Moreover, components of the recycled waste tires have been used in the construction industry, for example: (a) waste steel fibers as mechanical

reinforcement of concrete [3] and (b) recovered rubber as replacement of natural aggregates (fine and coarse), in which the elasticity features are improved and a lower diminution on the compressive strength and brittleness values is found [4–6]. In general, use of them as a substitute of fine or coarse aggregate can improve mechanical properties of concrete such as strength and modulus of elasticity, instead of those achieved by sand or stone.

Addition of particles into concrete produces internal stresses, which promote sooner cracking and subsequent failure, which can be avoided with the control of the particle sizes. Early studies pointed out that those elastomeric particles can reduce propagation of cracks, show increment in tensile strength, and have capacity in energy absorption. One advantage of the rubber particles is concerning energy absorption through ultrasonic waves, in order to benefit the concrete elasticity. However, differences in the values of Young's modulus modulus between rubber particles and concrete matrix, besides concentration of rubber particles into concrete, could promote great deformations when applying loads and thus results in progressive diminution of the mechanical properties. Other properties of concern for concrete workability include diminution of slump and increment of air content when increasing the elastomeric concentration, which promotes a low unit weight.

Tetra Pak is an aseptic packaging material, elaborated of several laminated layers of three raw materials: paper (75%), low-density polyethylene (20%), and aluminum (5%). The barriers consist of six layers of these materials. After recycling Tetra Pak packages through hydropulping process, cellulosic fibers are recuperated, which have superior quality when compared to those found in the waste paper market. Moreover, they are used in the production of tissue and paper towels. Percentage of recovery of the Tetra Pak components in a separate way shows 63 wt% for paper, 30% for polyethylene, and 7% for aluminum.

Recycling of these materials is based on mechanical milling and chemical attack, from which it is possible to obtain size reduction and component separation. In the case of the cellulosic fibers, the surface energy is closely related to the hydrophilicity of the fiber. Another important parameter is concerning reduction of the moisture adsorption of cellulose fibers, which are involved in reduction of the number of cellulose hydroxyl groups and the hydrophilicity of the fiber's surface, as well as restraint of the swelling of the fiber. Moreover, degradation produces water-soluble or insoluble oxygenated compounds.

Cellulose is the most abundant, inexpensive, and readily available carbohydrate polymer in the world, traditionally extracted from plants or their wastes. Currently about 30 million tons of natural fibers are produced by year around the world. The current interest for using such fibers is based on the environmental preservation; there is great interest for replacing synthetic fibers for natural ones [7, 8]. However, due to environmental problems caused by products made using cellulose (boxes, bags, containers, office supplies, etc.), different ways to recycle thosematerials have been developed.

Some natural fibers are composed mainly of cellulose (54%), hemicellulose (20%), and lignin (15%). Natural fibers are a resource that is environmentally clean, renewable, and biodegradable; one of them that has captured attention in applied research is Luffa fiber, due to its physicochemical properties. They are obtained from a subtropical plant of the Cucurbitaceae

family, which produces a fruit with a fibrous vascular system (luffa), with sizes between 1.5 cm and 1.5 m and an average diameter 8–10 cm [9]. Their morphological surfaces show roughness surfaces, containing width channels (4–12 μm), and particles with different lignin shapes (indicated by arrow), and thin layers of lignin and hemicellulose covering the cellulosic fibers (**Figure 1**).

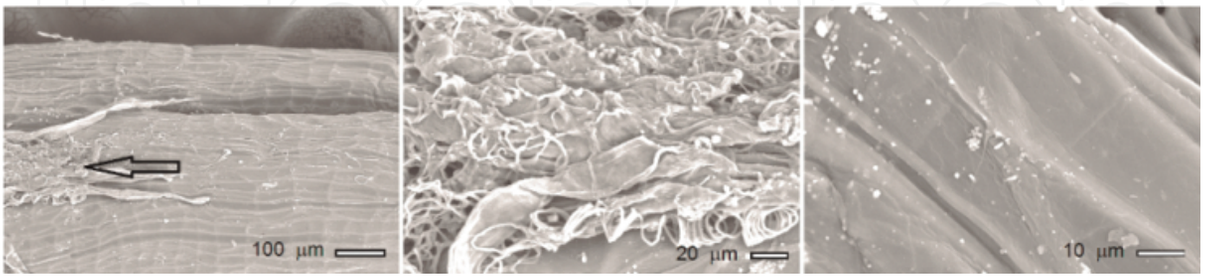

Figure 1. Morphological surfaces of Luffa fibers.

One of the main characteristics of raw luffa fibers (without surface treatment) is its capacity to absorb moisture easily and its high potential as reinforced material in hybrid composites, mainly on the mechanical properties. In the case of Tetra Pak packaging, an optional recycling way for this is based as a substitute of mineral aggregates in the elaboration of composite materials, which improving its properties, including lower weight and density, higher mechanical strength and toughness [10].

Some investigations are concerning use of natural fibers, such as cellulose, for elaboration of composite materials. Different thermosetting polymers, namely polymeric resins, have been used for such purpose. The main idea is to use inexpensive and abundantly available fibers. Mechanical properties, including tensile strength, flexural strength, compressive strength, and wear resistance, increase their values when increasing the concentration of the cellulosic fibers. Moreover, the impact properties significantly increase. Such behavior is due to an excellent dispersion of the reinforcements. But for higher content of fibers, decrement on the values is observed; this is due to agglomeration of the fibers. Composite elaborated with cellulose fibers has light weight. Surface modification of the cellulose fibers facilitates elaboration of composites. Silane and alkali treatments are used for such proposal, having higher fiber-matrix adhesion strength. Moreover, reduction of water absorption is observed, as a consequence of the strong interface. Another treatment is referred to coupling agents; the presence of double bonds is necessary to obtain the formation of covalent bonds between fiber and matrix. Residue cellulose can act as a natural coupling agent and improve the interfacial bonding by reducing the hydrophilicity of the fiber. The water absorption increases with an increase in fiber content. Moreover, fibers can be further subdivided into microfibrils with high elastic modulus by hydrolysis, followed by mechanical disintegration. Such fibers are produced commercially by the pulp and paper industry.

3. Structural modification by using gamma irradiation

As it is known that environmental problems caused by waste materials are in a constant growth and as a consequence different methods have been developed, some of them are consuming money and time. One novel alternative is to use ionizing radiation, such as gamma rays.

Gamma radiation has many advantages over other conventional methods such as chemical attack or thermal process. For example, initiation process is different; gamma particles only are necessary if that material is in contact with radioactive source, while in a chemical reaction, catalysts or additives are required; another important aspect is referred to the production of free radicals, when using chemicals these are produced through decomposition of the initiator in fragments, while in the case of irradiation process free radicals are produced by the absorption of energy of the polymer; moreover, with irradiation process the reaction can be controlled and be free from contamination. With respect to the temperature, gamma irradiation shows better behavior, because in the case of a chemical reaction often local overheating of the initiator is produced, while for irradiation no activation energy is found [11–13].

Applying gamma radiation for recycling polymers has increased its acceptation as a current technology due to the ecologic and economical features and mainly its capacity to modify physicochemical properties of the wastes without introducing any chemical initiators or the need to dissolve them [14]. In principle the molecular structure of materials can be modified by using gamma irradiation; this creates free radicals which will often chemically react in various ways, sometimes at slow reaction rates. The free radicals can recombine, forming the cross-links.

A competing process, called scissioning, occurs when polymers are irradiated. In this case, the polymer chains are broken and molecular mass decreases. The other process is called cross-linking, which depends on kind of polymer, and the number of cross-links can be controlled by the amount of irradiation dose. Scissioning and cross-linking occur at the same time where one may predominate over the other, depending upon the polymer and the dose. Both phenomena change the physical, chemical, and mechanical properties of polymer materials. In fact, more benefits can be obtained from recovered scrap polymer cross-linking by using gamma radiation [15, 16].

In the case of polyethylene terephthalate (PET), different opinions about radiation stability have been reported. Some authors report fair stability in the mechanical and physicochemical properties at high doses (900 kGy), with changes from cross-linking processes up to 35% from the starting values. Some authors have reported changes due to the chain scission process at low dose (from 0 to 10 kGy) while others have reported such events at a high dose (from 120 kGy to 5 MGy). The degradation mechanism for PET fibers or PET bulk is the same. No chemical degradation for PET fibers is found up to 200 kGy [17–20].

The recycling and reutilization of cross-linked elastomers are difficult due to their 3D formed network; nevertheless, it is necessary to find wise-strategies for reuse and to avoid ground contamination. The natural and synthetic rubbers such as styrene-butadiene-styrene (SBS) and

styrene-butadiene-rubber (SBR) are the raw materials in the production of tires; the natural rubbers provide elastic properties while the synthetics provide thermal stability.

In the case of elastomers (such as tire rubber), gamma radiation causes morphological deterioration and chemical changes, including accelerated oxidation [21]. Physicochemical properties of blends of rubber stocks and virgin or recycled elastomers are improved after irradiating with gamma particles. For example, rubber stocks blended with recycled and irradiated butyl crumb show shortened vulcanization period and antitearing properties. Moreover, improvement on the plasticity of crumb rubber, as well as great moldability of virgin rubber and recycled crumb blends, when they are irradiated at 70 kGy.

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]. Other study is based on the effects of gamma irradiation in polydimethylsiloxane rubber foams and their relationship with mechanical properties and chemical structure, which are measured by compression strength, infrared attenuated total reflectance (ATR) spectroscopy 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 [22].

By using gamma radiation, ground tire rubber (GTR) and recycled high-density polyethylene (HDPE) blends can be functionalized through higher interaction between elastomer and acrylamide functional groups, allowing improvement of their mechanical properties for doses from 25 to 50 kGy. Elongation-at-break and Charpy impact strength of the blends are significantly increased due to the presence of GTR; moreover, blends' Young's modulus values are only slightly decreased due to the radiation-induced cross-linking of the HDPE matrix [22, 23].

The use of gamma radiation as a mechanism for reaction initiation and accelerator of the polymerization of a monomer in a ceramic matrix can bring considerable advantages. One of the most important objectives is to obtain higher adhesion between fibers and the matrix. In the case of the Tetra Pak components, the first investigations focused on the influence of gamma radiation on lignocellulose materials, in terms of increasing the solubility of insoluble high-polymerized sugars such as cellulose. Application of gamma irradiation on cellulose results in decrease in molecular weight and crystallinity, as well as formation of oxidation products, because cellulose is a predominantly chain-scissioning polymer. After irradiation, changes in the main chain of the cellulose are observed, where radicals provoke random cleavage of glycoside bonds, as well as splitting of carbon-bonded hydrogen and dehydrogenation reactions. Another studied parameters are the degree of polymerization (DP) and specific gravity. Such changes are beneficial for manufacturing products such as medical grade cellulose.

As it is known, the cross-linking reaction is affected by the initial degree of crystallinity, crystal size distribution, and molecular weight. In general terms, crystallinity increases and reaches a maximum at certain irradiation dose, but it decreases on further increase of irradiation dose. Microfibrils are composed of cellulose crystals and amorphous zones, in which more pene-

tration of chemicals is observed. Such zones have different appearances such as cracks and irregular morphological shapes.

Tetra Pak panel boards (TPPBs) show decrease in the mass up to 200°C which is related to the evaporation of physical water. In general, thermal degradation of paper is located between 200°C and 400°C, particularly two decomposition peaks are observed. The first one at 300°C due to hemicellulose and the second at 360°C due to thermal degradation of α-cellulose. For higher temperature from 400°C to 461°C, degradation of remaining paper and LDPE is considered. After thermal process can be found two kinds of residues, char and aluminum foil [24].

In the case of irradiated polyester resin some physicochemical properties are affected, for example, when increasing the dose a better thermal stability is obtained at low temperatures, because its glass transition temperature increases. But at high temperatures, the decomposition temperature is unaffected. After analyzing both thermal and mechanical properties a relationship is observed. Moreover, a typical behavior is observed: improvement of the compressive strength depends on the increment of the irradiation dose [23].

4. Modified waste and recycled materials and their uses in construction materials

In this section different studies concerning the structural modification of waste and recycling materials by using ionizing irradiation and their possibilities as reinforced materials of hydraulic and polymer concrete are shown.

For recycled PET, nonirradiated concrete follows a typical behavior for compressive strain: it increases progressively as PET particle concentration increases, but it does not happen for compressive strength or elasticity modulus. In the case of irradiated concrete, different behaviors are observed regarding nonirradiated ones. When increasing PET concentration, the compressive strength values diminish; it is more notable: the diminution of compressive strain. In general, irradiated concrete containing PET particles had similar modulus of elasticity, higher compressive strength, and lower compressive strain values compared to nonirradiated concrete.

Compressive strength and Young's modulus of concrete specimens containing waste PET particles of beverage bottles were evaluated before and after irradiation. Three different sizes of waste PET particles (0.5, 1.5, and 3.0 mm) were considered, and for each size, three different concentrations of waste PET particles were used (1.0, 2.5, and 5.0% by volume). Concrete specimens after 28 days of moist curing were irradiated at 100 kGy with gamma rays at 3 kGy/h ratio.

In the case of irradiated concrete, different behaviors are observed regarding nonirradiated ones. When increasing PET concentration, the compressive strength values diminish; it is more notable: the diminution of compressive strain. Nevertheless, elasticity modulus has an opposite behavior to that shown for nonirradiated concrete. In terms of the particle sizes,

different behaviors are observed; at the lowest sizes, compressive strength has minimal values; whereas for highest sizes, both compressive strength and modulus of elasticity have the maximal values. Such situations are similar for irradiated specimens because modulus of elasticity, higher compressive strength, and lower strain values are maximal.

Irradiation effects are caused over PET particles, as it is well known that irradiation causes chain scission and generation of free radicals, which can produce a hard material instead of a ductile. In the case of irradiated PET particles (at 150 kGy), a smooth and homogeneous surface is observed (**Figure 2**); when increasing the irradiation dose, morphological changes are produced; small particles and cracks are observed (at 400 kGy). For the highest irradiation dose, more defined cracks and particles of different sizes are observed (at 800 kGy); in general, a roughness surface is obtained (**Figure 2**).

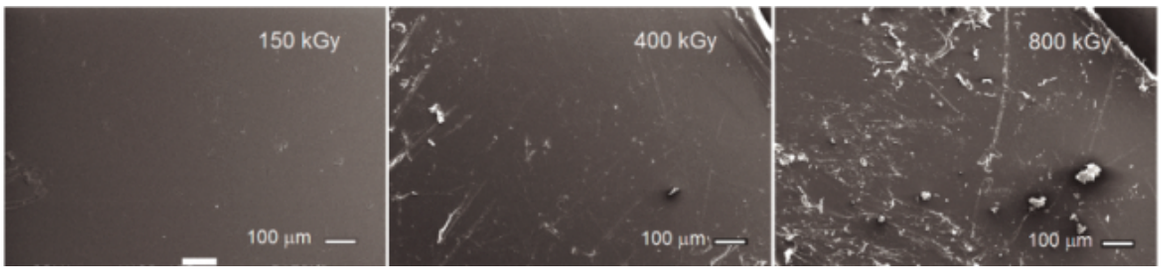

Figure 2. SEM images of irradiated PET at different application doses.

Generally speaking, as waste PET concentration increases in the concrete specimens, a decreasing tendency on the mechanical properties is observed. Moreover, irradiated concrete specimens show higher compressive strength values, similar elasticity modulus values, but lower deformations when compared to nonirradiated specimens.

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 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.

In hydraulic concrete where silica sand is partially replaced by recycled automotive tire fibers. Both tire fibers and modified concrete are irradiated at different gamma doses. Main mechanical properties are studied before and after irradiation process. These include compression and flexural strength. The mechanical properties of concrete depend on the waste tire particle sizes and their concentration. Compressive and tensile strength values decrease due to waste tire particles, because they promote stress concentration zones, as well as, generation of tensile stresses into concrete, resulting in a fast cracking and soon failure. Nevertheless, when applying gamma radiation to waste tire particles, in some cases, improvements on mechanical

properties are found. Concrete with irradiated particles can be support up to 30% of tire particles, making possible to reduce the final cost of the concrete.

In the case of polymer concrete with recycled tire fibers, strength and strain results show improvements of mechanical properties according to the tire fiber concentration as well as gamma irradiation dose. In general terms, addition of recycled tire fibers as well as higher radiation doses generate greater ductility on the polymer concrete; features no common for ordinary polymer concrete.

In **Figure 3**, surface characteristics of the recycled tire particles are shown. Nonirradiated particles have different sizes; some of them show roughness on their surface and others smooth surfaces. Average size of recycled particles varies from 30 to 600 μm. In general, when recycled particles are added to concrete, a poor elastomer-matrix adherence is found, but when increasing the volume fraction of particles, mechanical interactions are augmented, therefore improvements on the mechanical properties are obtained. For irradiated tire particles, at 200 kGy, rough surfaces are created, with some small and disperse particles. According to the literature, sometimes smooth surfaces are generated after irradiation as a 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 for irradiated particles at 250 kGy (**Figure 3**).

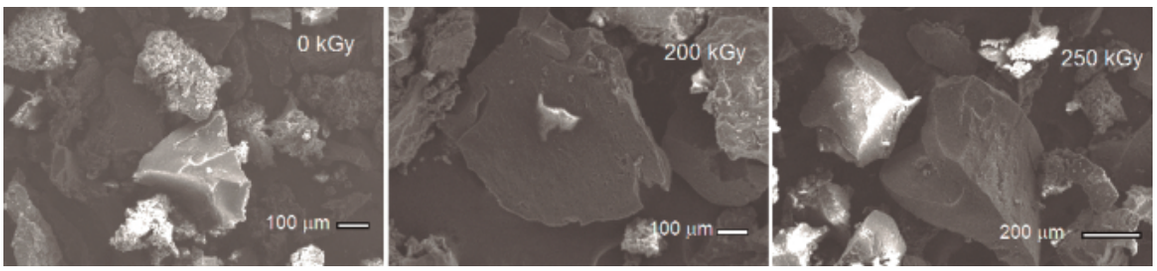

Figure 3. SEM images of nonirradiated and irradiated tire rubber.

In polymer concrete elaborated with polyester resin and silica sand; partial replacement of the silica sand by recycled tire fibers at concentration from 0.3 to 1.2% in volume, was done. Such concrete was submitted to gamma rays at doses from 50 to 100 kGy, and studied its mechanical properties, including compression and flexural strengths, as well as elasticity modulus. The results show noticeable improvements on the mechanical deformation, which are related with morphological and structural changes of the recycled tire fibers.

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. In studies based on two parameters, use of recycled polymers and gamma radiation shows that: (a) polymer concrete with recycled high-density polyethylene (HDPE) and tire rubber particles, irradiated from 25 to 50 kGy, has significant increase on the impact strength as well as in the elongation-at-break; such improvements are attributed to the good adhesion between

tire rubber particles and the polymer matrix [21]; (b) polymer concrete with waste tire rubber and styrene-butadiene-rubber (SBR) improves its tensile strength, elongation, and heat resistance up to 75 kGy [25].

In some experiments, waste Tetra Pak particles obtained from trash beverage bottles are used as reinforcements in polymer concrete; they partially substitute the mineral aggregates. The effects of the concentration and size of them on the compressive and flexural strength of polymer concrete are evaluated. The results show that the compressive and flexural strength as well as modulus of elasticity values decreases gradually when increasing the addition of waste particle concentration. A slight increment on the flexural strength values is observed for polymer concrete with smallest particle size. It is convenient to mention that to improve the mechanical properties of polymer concrete, gamma irradiation has been an adequate tool, because this improves the interfacial interaction between polymer concrete and Tetra Pak particles. However, improvements in compressive and flexural strength, as well as modulus of elasticity, when irradiating the concrete specimens, are observed.

Through SEM images the influence of gamma radiation on waste cellulose obtained from Tetra Pak packaging and its effect on the mechanical properties of concrete can be observed. As it is appreciated, a smooth and homogeneous surface, as well as agglomerations of particles is appreciated for polymer concrete. There are no chemical interactions between polyester resin and waste cellulose particles, and as a consequence, decrements of mechanical properties can be observed (**Figure 4**). For irradiated polymer concrete, deformation decreases which can be attributed to the stress transfer between polymer matrix and waste cellulose particles. The greater contact area between the particles and the concrete matrix, thus the greater stress transfer; moreover, rough surface and irregular distribution of the particles are observed (**Figure 4**).

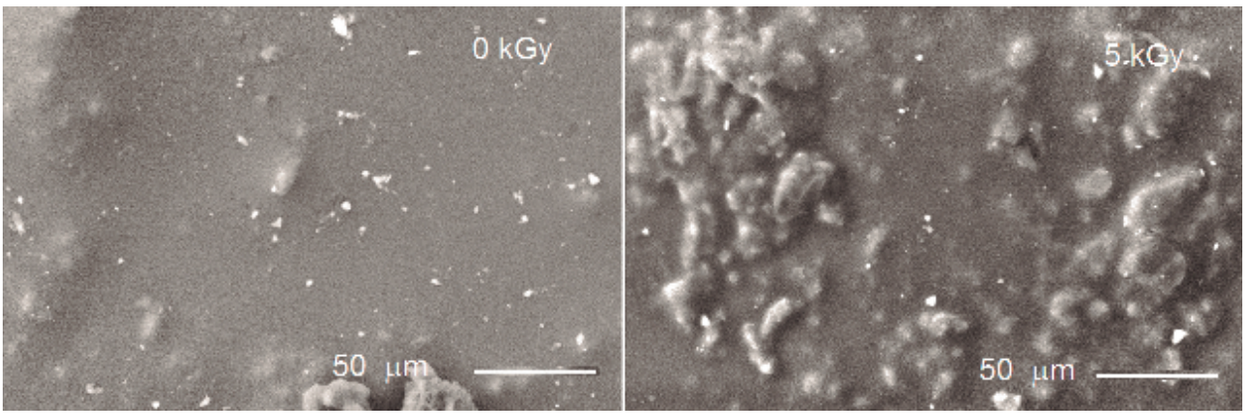

Figure 4. SEM images of nonirradiated and irradiated polymer concrete.

The effects of the concentration of Tetra Pak` particles as mechanical reinforcements and gamma irradiation as a tool for improvement of interfacial coupling in polyester-based composite are evaluated. The main proposal is to finda material with improved ductility, that is, with more elasticity instead of a rigid property. After irradiation, the deformation increased

substantially, having a maximum value at 400 kGy when compressive evaluation is done; while for flexural test, maximal deformation is obtained at 500 kGy. Such improvements are due to the cross-linking and degradation processes in both cellulose and polyester resin.

In the case of polymer concrete for improvement of the interfacial surface, gamma irradiation is a novel proposal. As it is known that in a composite material only physical interactions are present between matrix and aggregates, nevertheless, by using gamma irradiation, chemical bonds can be obtained [26]. In **Figure 5**, the irradiation process in the polyester resin causes chain scission and it also produces some cross-linking, chain relaxation, and cage breaking. As a consequence, the formation of bonds into polymer chains increases the degree of polymerization of the resin matrix. Homogenous surface is affected by gamma radiation because a higher number of chemical bonds are established and a rougher surface is observed (**Figure 5**), and for higher radiation dose, voids and small particles created from the cross-linking of the resin are observed. One can achieve good control of the dimensions and the elimination of internal stress, which cause reduction in mechanical strength [27, 28].

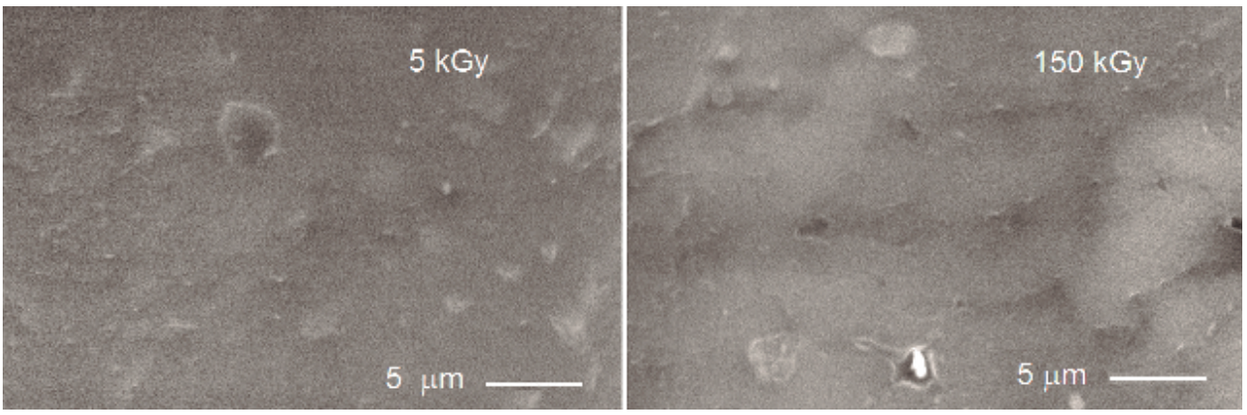

Figure 5. SEM images of irradiated polyester resin.

Other studies show different behaviors, for example: (a) molecular defects on mineral aggregates such as calcium bentonite have been observed [29]; (b) compressive strength values increased while total porosity and water absorption values decreased with increasing irradiation dose, in polymer-modified cement mortar specimens, with styrene-acrylic ester as adding polymer [30]; and (c) improvement on mechanical properties such as compressive strength and Young's modulus was observed for concrete reinforced with polypropylene fibers [31].

5. Conclusions

The main aim of this chapter is to show how both waste and recycled materials as well as gamma irradiation are adequate tools for improvement of mechanical properties of construction composites. Such materials are reused to replace partially those component concrete

materials, such as mineral aggregates. Gamma irradiation is an adequate tool for modification of the physicochemical properties of waste and recycling materials. Moreover, such modified materials act as reinforcements of concrete and as a consequence improve their mechanical properties, through the improvement of interfacial interaction between the matrix and waste or recycled materials. Mechanical properties include compressive and flexural strength, and Young's modulus among others. In general, the results are depending on the particle sizes and concentrations of waste or recycled materials, as well as on irradiation and ratio doses. We believe that this kind of work opens several possibilities in research area of construction with great benefits, in order to ensure economic earnings in the context of sustainable development, by solving environmental pollution problems. Moreover, a simple and inexpensive process based on gamma irradiation is expected.

Acknowledgements

Financial support of the Autonomous University of the State of Mexico (UAEM), located at Toluca City, is acknowledged.

Author details

Gonzalo Martínez-Barrera[1*], Nelly González-Rivas[2], Enrique Vigueras-Santiago[1], Ángel Martínez-López[1], Jorge A. Tello-González[1] and Carmina Menchaca-Campos[3]

*Address all correspondence to: gonzomartinez02@yahoo.com.mx

1 Laboratory of Research and Development of Advanced Materials (LIDMA), College of Chemistry, Autonomous University of the State of Mexico, Toluca-Atlacomulco, San Cayetano, Mexico

2 Joint Center of Research in Sustainable Chemistry (CCIQS) UAEM-UNAM, Toluca-Atlacomulco, San Cayetano, Mexico

3 Center of Research in Engineering and Applied Sciences (CIICAp), Autonomous University of the State of Morelos, Cuernavaca Morelos, México

References

[1] Siddique R, Naik TR, Properties of concrete containing scrap-tire rubber – an overview. Waste Management. 2004; 24: 563-569.

[2] Fattuhi NI, Clark LA, Cement-based materials containing shredded scrap truck tyre rubber. Construction and Building Materials. 1996; 10: 229-236.

[3] Aiello MA, Leuzzi F, Centonze G, Maffezzoli A. Use of steel fibres recovered from waste tyres as reinforcement in concrete: pull-out behaviour, compressive and flexural strength. Waste Management. 2009; 29: 1960-1970.

[4] Mohammed BS, Anwar Hossain KM, EngSwee JT, Wong G, Abdullahi M. Properties of crumb rubber hollow concrete block. Journal of Cleaner Production. 2012; 23: 57-67.

[5] Pelisser F, Zavarise N, Longo TA, Bernardin AM. Concrete made with recycled tire rubber: effect of alkaline activation and silica fume addition. Journal of Cleaner Production. 2011; 19 (6): 757-763.

[6] Bravo M, de Brito J. Concrete made with used tyre aggregate: durability related performance. Journal of Cleaner Production. 2012; 25: 42-50.

[7] Altinisik A, Gur E, Seki Y. A natural sorbent, Luffa cylindrica for the removal of a model basic dye. Journal of Hazardous Materials. 2010; 179: 658-664.

[8] Ghali L, Aloui M, Zidi M, Bendaly H, Msahli S, Sakli F. Effect of chemical modification of luffa cylindrica fibers on the mechanical and hygrothermal behaviours of polyester/luffa composites. BioResources. 2011; 6: 3836-3849.

[9] Zaske OC. Unsaturated polyester and vinylester resins. In: Goodman SH, editor. Handbook of Thermoset Plastics. USA: Noyes Publications; 1986. p. 59-111.

[10] Ávila Córdoba L, Martínez-Barrera G, Barrera Díaz C, Ureña Nuñez F, LozaYañez A. Effects on mechanical properties of recycled-PET in cement-based composites, International Journal of Polymer Science. 2013; 2013: p.6, Article ID 763276, DOI: 10.1155/2013/763276

[11] Cruz-Zaragoza E, Martínez-Barrera G. Ionizing radiation effects on the matter and its applications in research and industry. In: Barrera-Díaz C., Martínez-Barrera G., editors. Gamma radiation effects on polymeric materials and its applications. Kerala, India: Research Signpost; 2009. p. 1-14

[12] Dobo J. Some features of radiation processing in the plastics industry. Radiation Physics and Chemistry. 1985; 26: 555-558.

[13] Clough RL. High-energy radiation and polymers: a review of commercial processes and emerging applications. Nuclear Instruments and Methods in Physics Research Section B. 2001; 185: 8-33.

[14] Martínez-Barrera G, Menchaca-Campos C, Barrera-Díaz CE, Avila-Cordoba LI. Recent developments in polymer recycling. In: Istvan Bikit, editor. Gamma Rays: Technology, Applications and Health Implications. Hauppauge NY, USA: Nova Science Publishers Inc.; 2013, p. 237-255.

[15] Burillo G, Clough RL, Czvikovszky T, Guven O, Le Moel A, Liu W, Singh A, Yang J, Zaharescu T. Polymer recycling: potential application of radiation technology. Radiation Physics & Chemistry. 2012; 6: 41-51.

[16] Dispenza C, Alessi S, Spadaro G. Carbon fiber composites cured by γ-radiation-induced polymerization of an epoxy resin matrix. Advances in Polymer Technology. 2008; 27: 163-171.

[17] Burillo G, Tenorio L, Bucio E, Adem E, Lopez GP.Electron beam irradiation effects on poly(ethylene terephthalate). Radiation Physics & Chemistry. 2007; 76: 1728-1731.

[18] Mariani M, Ravasio U, Consolati G, Buttafava A, Giola M, Faucitano A. Gamma irradiation of polyethylene terephthalate and polyethylene naphthalate. Nuclear Instruments and Methods in Physics Research Section B. 2007; 265: 245-250.

[19] Razek TMA, Said HM, Khafaga MR, El-Naggar MAW. Effect of gamma irradiation on the thermal and dyeing properties of blends based on waste poly(ethylene terephthalate) blends. Journal of Applied Polymer Science. 2010; 117: 3482-3490.

[20] Shiv-Govind P. Abhijit D, Udayan D. Structural and optical investigations of radiation damage in transparent PET polymer films. International Journal of Spectroscopy. 2011; 201: 1-7.

[21] Sonnier R, Leroy E, Clerc L, Bergeret A, Lopez-Cuesta JM. Compatibilisation of polyethylene/ground tyre rubber blends by γ irradiation. Polymer Degradation and Stability. 2006; 91: 2375-2379.

[22] Sui HL, Liu XY, Zhong FC, Li XY, Wang L, Ju X. Gamma radiation effects on polydimethylsiloxane rubber foams under different radiation conditions. Nuclear Instruments and Methods in Physics Research B. 2013; 307: 570-574.

[23] Fainleib A, Grigoryeva O, Martínez-Barrera G. Radiation induced functionalization of polyethylene and ground rubber for their reactive compatibilization in thermoplastic elastomers. In: Barrera-Díaz CE, Martínez-Barrera G, editors. Gamma Radiation Effects on Polymer Materials and its Applications. Kerala, India: Research Signpost; 2009, p. 63-85.

[24] AyselK F, Evren T, Nural Y, Saip NK, Sabriye PK. Thermal degradation characteristic of Tetra Pak panel boards under inert atmosphere. Korean Journal of Chemical Engineering. 2013; 30: 878-890.

[25] Yasin T, Khan S, Shafiq M, Gill R. Radiation crosslinking of styrene–butadiene rubber containing waste tire rubber and polyfunctional monomers. Radiation Physics and Chemistry. 2015; 106: 343-347.

[26] Martínez-Barrera G, Giraldo LF, López BL, Brostow W. Effects of gamma radiation on fiber-reinforced polymer concrete. Polymer Composites. 2008; 29: 1244-1251.

[27] Bobadilla-Sánchez EA, Martínez-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 Polymer Letters. 2009; 3: 615-620.

[28] Menchaca C, Alvarez-Castillo A, Martínez-Barrera G, López-Valdivia H, Carrasco H, Castaño VM. Mechanisms for the modification of nylon 6,12 by gamma irradiation. International Journal of Materials and Product Technology. 2003; 19: 521-529.

[29] Dies J, de las Cuevas C, Tarrasa F, Miralles L, Pueyo JJ, Santiago JL. Thermoluminescence response of heavily irradiated calcic bentonite. Radiation Protection Dosimetry. 1999; 85: 481-486.

[30] Khattab MM. Effect of gamma irradiation on polymer modified white sand cement mortar composites. Journal of Industrial and Engineering Chemistry. 2014; 20: 1-8.

[31] Martínez-Barrera G, Menchaca-Campos C, Ureña-Núñez F. Gamma Radiation as a Novel Technology for Development of New Generation Concrete. InTech: Rijeka Croatia; 2012, p. 91-114.