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Case study

Lamellae of waste beverage packaging (Tetra Pak) and gamma radiation as tools for improvement of concrete

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ABSTRACT

One of the most important problem when adding recycle or waste materials to cement concrete is the poor adhesion between these materials and the cement matrix. For this reason, in this work, the effects of lamellae from beverage packaging (waste Tetra Pak), as well as of gamma rays on the mechanical properties of cement concrete were evaluated. The concrete specimens were produced with cement, water, gravel and sand; this last was partial substituted by lamellae of waste Tetra Pak (up to 30 wt. %) with sizes ranging 1.5 mm and 3.0 mm. Then, the concrete was irradiated with gamma rays at doses of 200 kGy and 300 kGy. The results show improvements up to 39 % and 30 % for compressive strength and the elasticity modulus, respectively, for concrete produced with 10 % of waste lamellae and irradiated at 300 kGy, respect to the values obtained for control concrete (without lamellae and non-irradiated). Such improvements are produced by both gamma rays and the lamella concentrations. Mechanical features were related with the lamellae before and after irradiation, based on the morphological and thermal changes (analyzed by SEM and TGA-DSC analyses, respectively), as well as with the chemical stability of their components (polyethylene and cellulose), analyzed by FT-IR spectroscopy.

1. Introduction

The development of the industry over the last 50 years, has promoted indiscriminately the use of certain materials; which after a very short shelf life, become trash, contributing to environmental deteriorate. For solving such problems, many clean and innovative technologies have been proposed; within them, those based on the reusing and recycling of waste materials. The construction industry has employed waste materials, which including glass, plastic, tires, ash, slag furnace of steel industry, organic waste (wood, fibers) and agricultural residues [1,2]. In the case of cement concrete, waste generated from construction, as demolished concrete, glass and plastic have been used. The fine aggregates are replaced up to 20 % by ground plastics and glass, and the coarse aggregates up to 20 % by crushed concrete. Such replacement wastes improve the mechanical properties of the concrete [2].

The most important problem when adding recycled plastics to cement concrete is the poor adhesion between the plastics and the cement matrix. To solve this problem foaming agents have been added, but the production and processing costs are

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high. However, not all constructions require high strength concrete, thus, partial addition of recycled plastics is a valuable opportunity for diminishing both costs and the environmental contamination.

One of the most recent waste materials is the post-consumer Tetra Pak packages, which are produced with paper (75 %), polyethylene (20 %), and aluminum (5 %). These materials can be used as a partial substitute of the mineral aggregates in the production of concrete; and create a more resistance and environmentally friendly concrete [3].

The Tetra Pak packages have six layers (Fig. 1), each one as a specific function. The outer layer (number 1), is made with polyethylene for to protect the product from external moisture. Layer 2, made of paperboard (cellulose) gives dimensional stability and strength; layer 3, is need for the lamination of both polyethylene layers; layer 4, made of aluminum foils provides a barrier to oxygen, flavors and light; layer 5, made of polyethylene is necessary for the lamination processes; and the inner layer (number 6), made of polyethylene seals the liquid.

Different processes have been used for recycling of beverage carton packaging. Mainly those that use mechanical and thermal energy without use of additives [4,5]. For example, the pyrolysis process. In a study, waste Tetra Pak was submitted in a batch reactor by using both one- or two-step pyrolysis modes at different temperature (400−600 °C), under inert atmosphere. The results show that the char can be used as solid fuel, due to its high calorific value and low ash content. Moreover, some materials are obtained, as tar, polyethylene wax and recovered aluminum [4]. In other study, different oxygen concentrations (5.37–20.95 %) were employed in the pyrolysis of Tetra Pak. The results show enhanced on the pyrolysis reaction when adding oxygen. The residual masses obtained (10–16 %) are comparable to those for ash concentration. Thus, the Tetra Pak components can be used as fuels or primary chemicals [6].

Most of the waste beverage cartons are recycled for to produce paper and cardboard. The high-quality cellulose fibers obtained of such recycling are used in the production of paper towels, and writing and tissue papers. In a study, waste cardboards containing aluminum were used for preparing low-density boards (density: 0.5 g/cm^3, thickness: 3 cm). Boards with urea-formaldehyde resin exhibit better properties than those with polyvinyl acetate based glue. Both kind of boards could be placed behind radiators or electrical heaters for preventing heat loss or be used in the heat proofing to counter the high thermal conductivity of aluminum [7]. In other study, the physical and mechanical properties of wood-plastic composites modified with waste Tetra Pak (0, 10, 20, and 30 %) and maleic anhydride grafted polyethylene (MAPE) (0 and 3 %) were studied. The results show increment on the flexural strength and modulus of elasticity, reduction of 24-h water absorption as well as thickness swelling, when adding Tetra Pak and MAPE. Moreover, the composite morphologies were analyzed by scanning electron microscopy [8]. Recycled papers, paperboards and Tetra Pak were added to gypsum-based composites for to obtain building materials. The compressive strength and microstructure of the composites were evaluated. The results show compressive strength values of 6.46 N/mm^2 for the gypsum–Tetra Pak composites, which could be suitable for walls in building constructions [9]. Moreover, combinations of shredded Tetra Pak and wool yarn wastes were added to hybrid composites for potential alternative construction and building materials. The results show high rupture modulus values (15.10 ± 1.01 MPa) and internal bonding of 0.60 MPa; moreover thickness swelling and water absorption values are better than commercial particle-boards. Such composites with agro-industrial waste materials could be utilized to manufacture eco-friendly materials as wood panels [10].

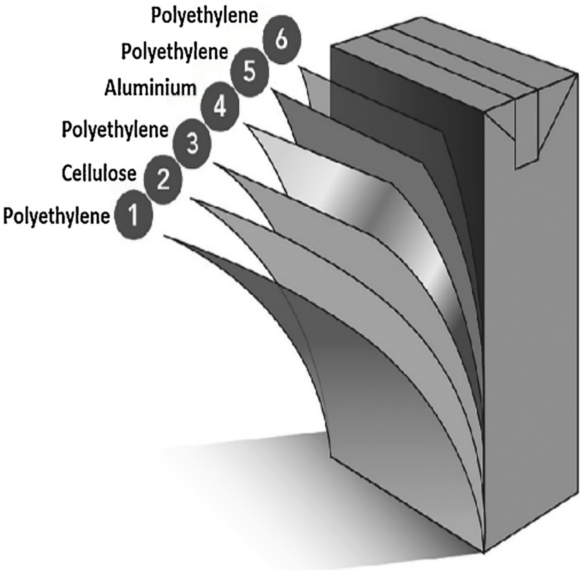

Fig. 1. Layer arrangement in the Tetra Pak packaging.

Modified cellulose fibers are used extensively in building materials. In a study, recycled fibers obtained from waste paper and packaging, were used for to obtain lightweight cement composites. They were added in concentration up to 16 % by mass of cement. The results show improvement on the thermal insulation properties, but reduction on the compressive strength when the fiber content increase [11]. Recycled paper residues (up to 30 wt. %), were used for preparing porous and lightweight bricks. The results show reduction of the fired density down to 1.28 g/cm^3, higher compressive strength, and diminution up to 50 % of the thermal conductivity (0.4 W/mK) [12]. Bond strength and thermal behavior of hollow clay bricks produced with paper waste were studied. The results show decrease on the thermal conductivity (up to 43 %). However, a nonlinear function of its thermal resistance was obtained, which depends on the geometry of the recesses, the material properties and the temperature distribution [13].

In the case of the concrete, the added fibers provide improved on their properties. For example: a) Its hydrophilic characteristic promotes outstanding bonding with the cement paste; it is possible to absorb up to 85 % of its weight in moisture, b) As the concrete cures intensifies, this becomes more fully hydrated, c) Since cellulose fibers are bonded and fully anchored within the concrete paste, it does not require fiber lengths as long to provide excellent mechanical properties, d) The intense bonding with the cement paste reduces microscopic voids within the concrete, e) The fibers are not deteriorate in the highly alkaline environment of the concrete. Moreover, f) The fibers enhance the concrete properties by reducing the plastic shrinkage cracking (micro crack propagation and cracking), caused by the strains within the concrete [2,11].

Cellulose pulp fibers were modified with chemicals and used for preparing cementitious composites. The results show improvement on the adhesion, between cellulose pulp fibers and cementitious matrix, but decrease of the rupture modulus and toughness of the composites, after exposition to accelerated aging cycles. The adhesion was evaluated following the surface energy of the fibers [14]. In other study, the effects of waste plastic bags into the cement concrete were studied. The results show that the compressive strength values decrease up to 20 % when adding 1 % of plastic pieces, for concrete cured at 28 days. Nevertheless, the splitting tensile strength values increased when 0.8 % of plastic pieces were added [15]. Cement concrete was modified with different concentrations of aluminum dross (5, 10, 15 and 30 %), and their mechanical and chemical properties were evaluated. The results show high corrosion strength as well as low setting time. Both characteristics are the most adequate for manufacturing of panels and blocks [5].

An alternative proposal to improve poor adhesion between polymers and the ceramic matrix is to use gamma rays. As it is known, such rays produce different effects on the polymers, as the formation of bonds between chains (cross-linking), breaking chains (scission), damage in crystalline regions, oxidation, radical detachment of monomer units, and molecular weight diminution. These mechanisms contribute to a greater or lesser extent, to modify the mechanical behavior of the polymers [16]. In the case of cellulose, gamma rays produce: a) degradation on its structure (from 6 to 12 %) at 31.6 kGy, b) decrease on the degree of polymerization (DP) at 10 kGy, c) total change on the degree of crystallinity at 300 kGy, and d) complete degradation at 6.55 MGy. Moreover, physicochemical properties of the cellulose can be modified by induced grafting by gamma rays. For example, cellulose with grafted glycidyl methacrylate (GMA), which is monitored by FT-IR spectroscopy and X-ray diffraction, while that the decomposition of grafted cellulose is analyzed by thermogravimetric analysis (TGA) [17,18].

Two ways are followed for production of the cement concrete when gamma rays are employed. In the first one, the polymers are modified by gamma rays, after, they are mixed into concrete. In the second, polymers are mixed with the concrete components; after, the concrete is irradiated. In this last case, chemical reactions occur, and certain polymerization is obtained, thus a heat source is not required and the costs are reduced. For example, gypsum/styrene composites were produced by using gamma rays at 43.2 kGy. The gypsum particles had sizes smaller than 0.42 mm. The results show improvement on the mechanical strength as well as on the impervious to water [19].

There exist a lack of information concerning to use ionizing radiation for improvement of the mechanical properties of cement concrete produced with waste materials, specifically those related with carton packaging. Thus, in this work, cement concrete specimens were produced with lamellae of Tetra Pak (at concentrations of 10, 20 and 30 wt. %), and irradiated with gamma rays at dose of 200 and 300 kGy. After curing, the mechanical properties of the specimens were evaluated.

2. Experimental

2.1. Specimens preparation

Cement concrete cylindrical specimens (2″ diameter and 4″ long), were produced with Portland cement CPC-30R, silica sand, gravel and water. Silica sand had an average diameter of 3.0 mm (mesh 50), free of impurities; while size of the gravel was 9.5 mm (sieve 3/8). These sizes were selected in order to avoid problems concerning homogeneity and workability. The properties of the aggregates are shown in the Table 1. Moreover, the water/cement ratio was kept constant at 0.65. Potable water was used, without any solid residue or organic material suspended, and absent of fats or oils.

Cement concrete without lamellae of waste Tetra Pak was denominated as control concrete. While, for cement concrete with lamellae, silica sand was gradually replacement by lamellae of waste Tetra Pak (1.5–3.0 mm), at concentrations of 10, 20, and 30 % by weight (Fig. 2). The lamellae were obtained from waste beverage Tetra Pak packages.

The concrete components were mixed according to ASTM C-305 standard. For each concrete mixture, five specimens were casting in cylindrical molds of 50 mm diameter and 100 mm height. After mixing, the concrete specimens were cured in a controlled temperature room at 23.0 ± 2.0 °C and 95 % of relative humidity, in accordance to ASTM C/192 M-00 standard.

Table 1
Properties of aggregates.

Property	Standard	Sand	Gravel
Density (kg/m^3)	EN 1097-6	2650	2650
Water absorption (%)	EN 1097-6	0.60	1.00

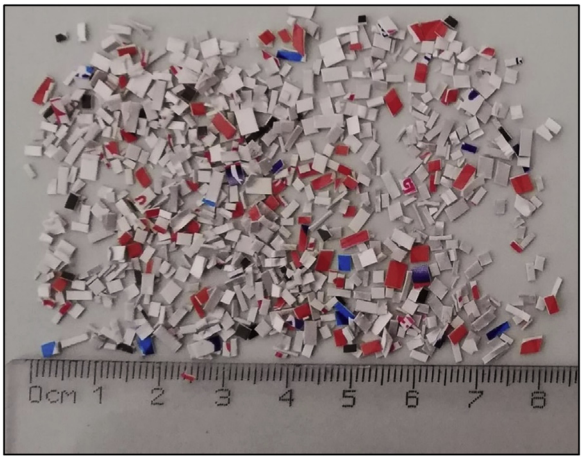

Fig. 2. Lamellae of waste Tetra Pak packaging.

2.2. Mechanical tests

Compressive strength evaluation of concrete specimens with or without lamellae of waste Tetra Pak were carried out in an Universal testing machine model 70-S17C2 (Controls, Cernusco, Italy), with capacity of 3000 kN according to ASTM C-39M-01. From the collected data, the compressive strain was evaluated, while that the compressive elasticity modules were calculated from the linear region on each stress vs. strain graph obtained. Concrete specimens were tested after 7, 14 and 28 curing days. Testing tolerance was 28 days ±20 h according to ASTM C39/C39M-14 standard.

2.3. Irradiation procedure

The concrete specimens were irradiated with gamma rays at 200 and 300 kGy at dose rate of 3.5 kGy/h, by using pencils of ^{60}Co source. The experiments were made in air at room temperature, in an irradiator Transelektro LGI-01 IZOTOP located at the National Institute of Nuclear Research Mexico (ININ).

2.4. Morphological characterization

The surfaces of fractured zones of the concrete as well as of the lamellae of Tetra Pak were analyzed by scanning electron microscopy (SEM) in a JEOL equipment model JSM-6510LV with a maximum resolution of 5.0 nm, and an acceleration voltage 30 kV, in the secondary electron mode.

2.5. Thermal property

The thermal behavior of non-irradiated and irradiated lamellae of Tetra Pak was performed by thermogravimetric analysis (TGA) in a Perkin Elmer TGA 7 equipment, covering the range from 30 °C to 450 °C at heating rate of 10 °C/min under nitrogen atmosphere. While, the phase transitions were analyzed by Differential Scanning Calorimetry (DSC) in a Perkin Elmer DSC 6 equipment, conducted under nitrogen atmosphere, from 30 °C to 450 °C at heating rate of 10 °C/min.

3. Results and discussion

3.1. Compressive strength, strain and elasticity modulus for non-irradiated concrete

Compressive strength values of the concrete specimens are shown in Fig. 3. Control concrete (without lamellae of waste Tetra Pak) had the highest compressive strength values, at 28 curing days, namely 22.7 MPa. In the case of concrete with

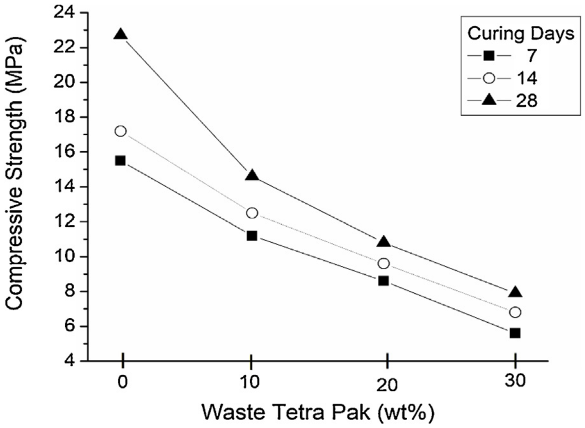

Fig. 3. Compressive strength of non-irradiated concrete.

lamellae of Tetra Pak two well-defined behaviors were obtained: a) the values gradually decrease when increasing the Tetra Pak concentration; having a diminution up to 36 % for concrete cured at 28 days ; b) for each Tetra Pak concentration the values increase when increasing curing time; such values have a minimal difference among them.

Diminution on the compressive strength values depends on the relationship between the waste Tetra Pak concentration and the water-cement ratio (w/c). As it is known, the lamellae of Tetra Pak are hydrophobic materials and substitute the sand in the mixture (up to 30 wt%); at this concentration more amount of water is available to interact into the surface of unhydrated grains of cement particles. Therefore, weak interfacial adhesion between the lamellae of Tetra Pak and hydrated cement particles is obtained; in consequence, the compressive strength values decrease.

Similar behavior was obtained for the compressive strain values of the concrete (Fig. 4). Concrete without lamellae of waste Tetra Pak had the highest compressive strain value at 7 curing days, namely 0.0098 MPa. For concrete with lamellae of Tetra Pak: a) The values gradually diminish when increasing the waste Tetra Pak concentration; having a diminution up to 52 % for concrete cured at 28 days, b) for each Tetra Pak concentration the values decrease when increasing curing time.

Fig. 5 shows the elasticity modulus of the concrete. As it is shown, concrete without lamellae of Tetra Pak had a value of 2.83 GPa, at 28 curing days. In the case of concrete with lamellae of Tetra Pak: a) the values decrease gradually when increasing the waste Tetra Pak concentration. The lowest values were obtained for concrete with 30 wt% of lamellae of Tetra Pak, which meaning 62 % lower than that for control concrete. Such diminution is consequence of the hydrophobic nature of the lamellae of waste Tetra Pak, which do not provide efficient load transfer to cement matrix. Moreover, lamellae of Tetra Pak can produce pores into concrete and contribute to the diminution of its mechanical properties, b) for each lamellae concentration, the values increase when increasing curing time. Nevertheless, for concrete with 30 wt% of lamellae of Tetra Pak there is minimal difference on the values for each curing time.

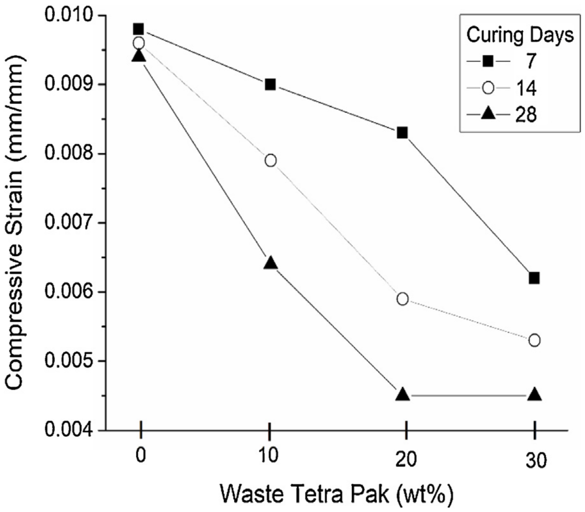

Fig. 4. Compressive strain of non-irradiated concrete.

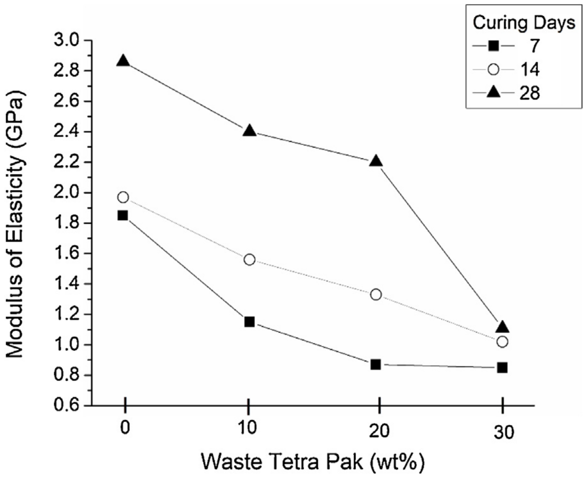

Fig. 5. Elasticity modulus of non-irradiated concrete.

According to the results of compressive strength, compressive strain and elasticity modulus, the concrete specimens with 10 % of lamellae of Tetra Pak had the highest values. Thus, in the second experimental stage, this concentration was selected for the production of concrete, which was irradiated with gamma rays and its mechanical properties were evaluated.

3.2. Mechanical properties of irradiated concrete with 10 % of lamellae of Tetra Pak

The compressive strength values of non-irradiated and irradiated concrete are shown in Fig. 6. For a better understanding of the cement concrete behavior with respect to the control concrete (without lamellae and non-irradiated), a straight horizontal line was put starting from the value for control concrete cured at 28 days. Moreover, mechanical behavior was analyzed according to: I) radiation dose, and II) curing time.

The compressive strength values for control concrete ranging from 15.5 MPa to 22.7 MPa. For non-irradiated concretes with lamellae of Tetra Pak the values are lower than those for control concrete. The values decrease up to 36 % for concrete cured at 28 days. In the case of irradiated concrete three behaviors were obtained: a) at 200 kGy, the values are lower than those for control concrete, b) but at 300 kGy, the values are higher. Improvement up to 39 % was obtained for concrete cured at 28 days, respect to control concrete, c) the compressive strength values gradually increase according to the dose increase. Respect to curing time, the compressive strength values increase when curing time increase.

After irradiation, there is no evidence of chemical interactions between cement matrix and the lamellae of waste Tetra Pak. The increment on the compressive strength values are attributed to the effects of the gamma irradiation, caused in both the concrete and waste Tetra Pak components (cellulose, polyethylene and aluminum). Ionizing energy produces two well-defined effects on both polyethylene and cellulose components: a) modification of the polyethylene-cellulose interface due

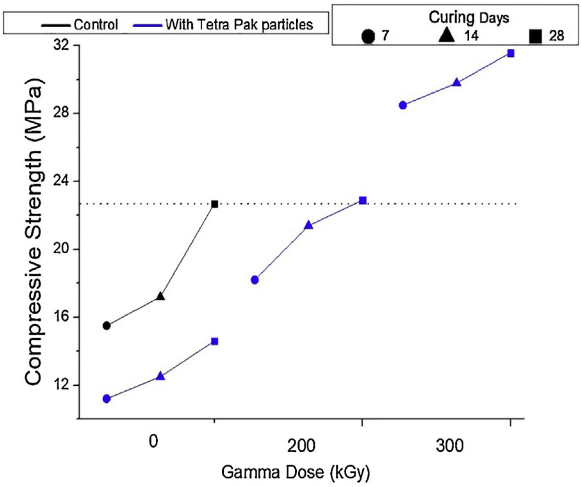

Fig. 6. Compressive strength of concrete with 10 wt% of lamellae of waste Tetra Pak.

to the cross-linking of polymer chains, b) increment of the surface area on the lamellae of Tetra Pak. These changes produce great interfacial interactions and in consequence the mechanical resistance is improved.

Increment on the compressive strength values can be explained in terms of the morphological changes produced on the fracture zones of the concrete, as it is shown in Fig. 7. For non-irradiated concrete a roughness surface is observed. Nevertheless, when gamma rays are applied (at dose of 200 kGy), the SEM images of the fracture zone show small detached particles (which are indicated by an arrow), as well as homogeneous particles (indicate by a circle). For high radiation dose, 300 kGy, the changes on the lamellae of Tetra Pak, produce cracks (indicate by an arrow), small cavities as well as a glossy surface.

At difference of the compressive strength behavior of the concrete, in the case of the compressive strain an opposite behavior was obtained (Fig. 8). The values for control concrete ranging from 0.0094 mm/mm to 0.0098 mm/mm. For non-irradiated concrete with lamellae of Tetra Pak the values are lower than those for control concrete. The values decrease up to 32 % for concrete cured at 28 days. In the case of irradiated concrete two behaviors were obtained: a) concrete irradiated at 200 kGy had lower values than those for control concrete. The values decreased up to 24 %, b) Nevertheless, at 300 kGy, higher values were obtained for concrete cured at 7 and 14 days, with an improvement up to 7 %. Respect to curing time of the concrete specimens an opposite behavior was obtained: the compressive strain values decrease when curing time increase.

The compressive behavior can be related with the changes produced on the lamellae surfaces by gamma rays. In the case of non-irradiated lamellae, SEM images were taken on the outer layer, as it is shown in Fig. 9, is to say, in this direction the layers follow the sequence: PE-CE-PE-Al-PE-PE, which means that the first layer has 5 % of polyethylene (PE), followed by 75 % of cellulose (CE), then 5 % of polyethylene (PE), 5 % of aluminum and two more polyethylene layers (10 %). As it is shown in Fig. 9, the outer surface without irradiation shows a rough surface.

When irradiation is applied, the gamma rays interact firstly with PE layer, then with CE layer (the majority component), and so with the innermost layers. For an irradiation dose of 200 kGy, a rougher surface with detached particles and some sunken regions, (which are indicate by arrows in Fig. 9), are obtained. Moreover, at higher dose (300 kGy), a more deteriorated surface is observed, with major concentration of detached particles, as well as preferential direction of deterioration (indicate by an arrow).

The elasticity modulus values are shown in Fig. 10. The values for control concrete ranging from 1.85 GPa to 2.86 GPa. For non-irradiated concrete with lamellae of Tetra Pak the values are lower than those for control concrete. In the case of irradiated concrete three behaviors were obtained: a) at 200 kGy, the values are lower than those for control concrete, b) but at 300 kGy, the values are higher. Improvement up to 30 % was obtained for concrete cured at 28 days, respect to control concrete, c) the elasticity modulus values gradually increase according to the dose increase. Respect to curing time of the concrete specimens, the elasticity modulus values increase when curing time increase.

As it is mentioned the elasticity modulus values increase when irradiation dose increase. Such increment is related to the cross-linking of polymer chains in both polyethylene and cellulose, caused by ionizing energy, Whereby, changes on the morphologies of each polymer are produced. The presence of detached particles and a rougher surface on each lamella generate higher stress transfer to the cement matrix, thus the elasticity modulus increases.

In addition, the lamellae of Tetra Pak were irradiated with gamma rays. SEM images of the lamellae taken on the inner layer are shown in Fig. 11, is to say, now the sequence of the layers' arrangement is: PE-PE-Al-PE-CE-PE. In this case, the gamma rays, firstly interact with two polyethylene (PE) layers, then with aluminum layer, and so. SEM images of non-irradiated lamellae show a smooth and homogeneous surface. For high irradiation dose (200 kGy), minimal detached particles are obtained, and finally at 300 kGy a little rough surface is obtained.

Modifications on the surface of the inner layer are different compared than those produced on the outer layer. In the inner layer, gamma rays interact with two layers of polyethylene (10 %), then with aluminum layer (5 %); but aluminum does not

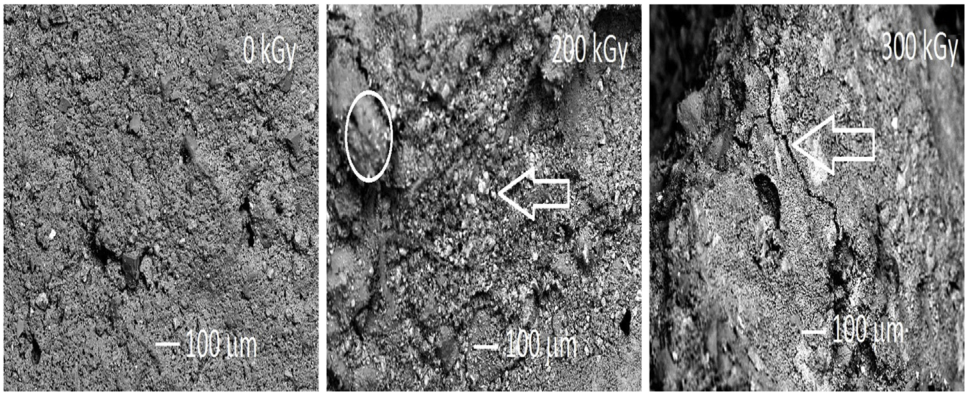

Fig. 7. SEM images of the fracture zone of concrete with 10 % of lamellae of waste Tetra Pak.

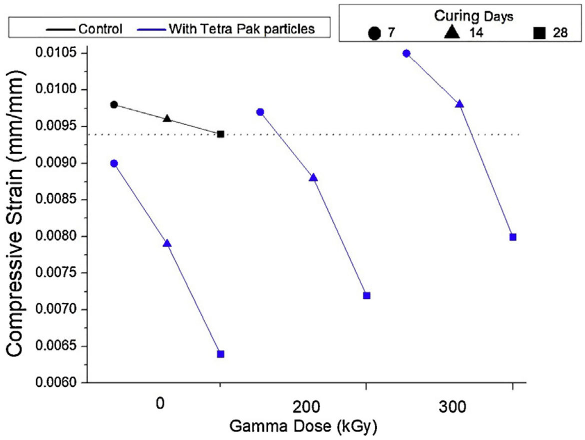

Fig. 8. Compressive strain of concrete with 10 wt% of lamellae of waste Tetra Pak.

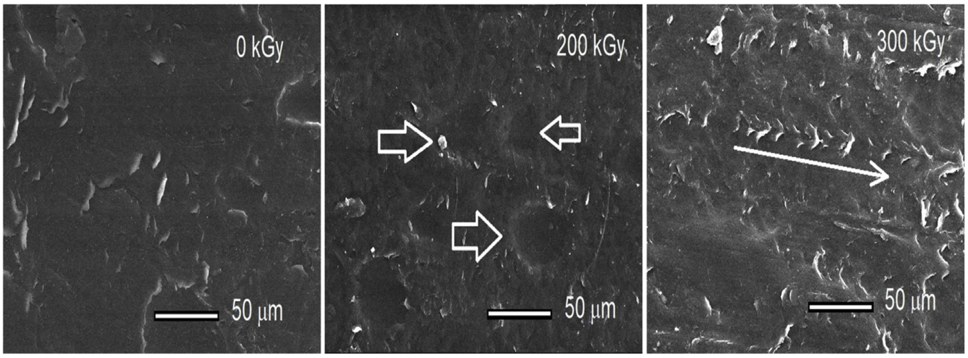

Fig. 9. SEM images taken on the outer Tetra Pak layer.

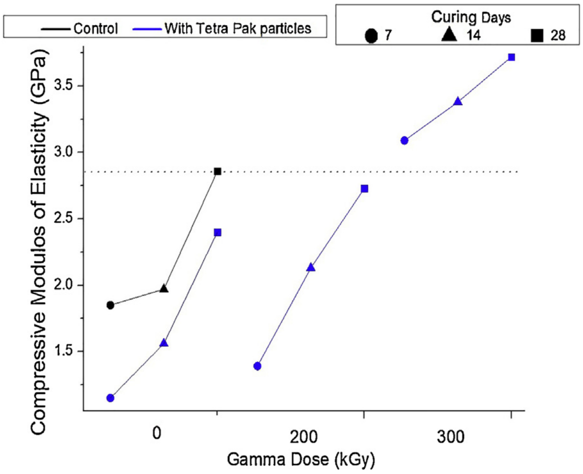

Fig. 10. Elasticity modulus of the concrete with 10 wt% of lamellae of waste Tetra Pak.

allow great structural modifications, due to its metallic nature. Nevertheless, both surface modifications (on the inner or outer layer), generate higher stress transfer to the cement matrix and in consequence the elasticity modulus increase.

The structural stability on the inner layer was corroborated by FT-IR spectroscopy, as it is shown in Fig. 12, for non-irradiated and irradiated lamellae of Tetra Pak. The spectrum of the inner layer shows intense bands at 2916 cm-^{1} (CH2 asymmetric) and 2846 cm^{-1} (CH2 symmetric), due to the stretching vibration of alkane C—H bonds, which are assigned to methylene groups present in the polyethylene structure, as well as two additional bands, at 1462 cm-^{1} corresponding to CH2

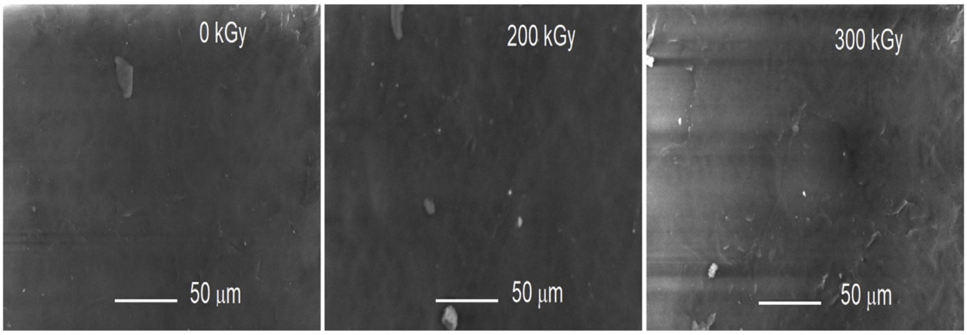

Fig. 11. SEM images taken on the inner Tetra Pak layer.

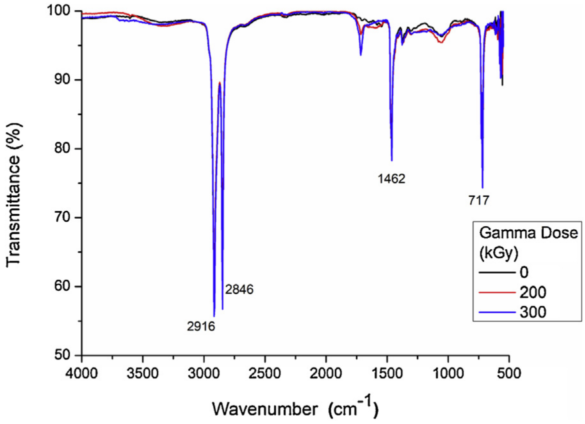

Fig. 12. FT-IR spectra of non-irradiated and irradiated inner layer of the lamellae Tetra Pak.

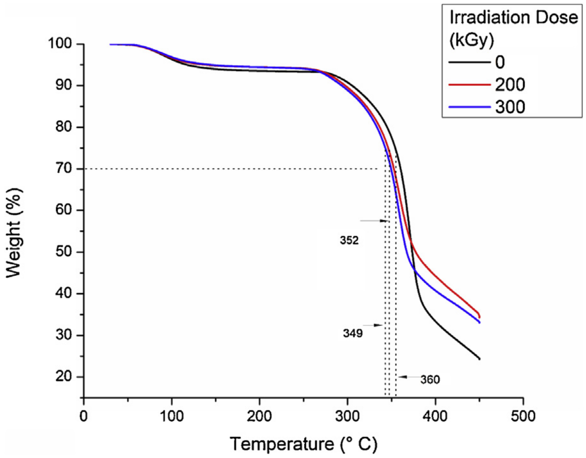

Fig. 13. TGA thermograms of non-irradiated and irradiated lamellae of waste Tetra Pak.

scissor vibration, and at 717 cm-^{1} corresponding [CH2]n rock vibration. Moreover, bands of non-irradiated and irradiated lamellae have the same transmittance percentage.

In summary, after irradiation each lamella of Tetra Pak has a rough surface on the outer layer and a smooth surface on the inner layer. Both kind of surfaces provides more interactions with the cement matrix, and in consequence, the compressive strength and the elasticity modulus are improved.

3.3. Thermal analysis of the lamellae of waste Tetra Pak

As it is known, the morphological changes produced by gamma radiation on the lamellae of Tetra Pak are depending of their components: cellulose, polyethylene and aluminum. Each one of them, shows different behavior against to ionizing radiation. Thus, in Fig. 13 the thermogravimetric curves (TGA) of non-irradiated and irradiated lamellae of Tetra Pak are shown.

As can be seen from Fig. 13, the first mass loss is around 4–5 % for non-irradiated and irradiated lamellae of waste Tetra Pak. For non-irradiated lamellae, such mass loss corresponds to polyethylene, which is degraded at 104.0 °C. In the case of irradiated lamellae, higher temperatures are obtained for the first mass loss: 110.3 °C (at 200 kGy) and 114.2 °C (at 300 kGy), which means a maximal difference of 10.2 °C, as it is shown in the Table 2. Increment on the temperature is related with the cross-linking of polymer chains in the polyethylene, because cross-linked structures need higher heat for their disintegration.

The second mass loss coincide with the onset of degradation T0.1 (10 % of mass loss), of non-irradiated cellulose, which is located at 305.2 °C. As it is known, cellulose is a highly hydrophilic polymer; hence water is present on its surface most of the time. As it is known, degradation of hemicellulose occurs at 300 °C. In this study, decomposition of non-irradiated cellulose begins at 305.2 °C. But, for waste lamellae irradiated at 200 kGy and 300 kGy, the decomposition of cellulose happens a lower temperature (up to 11.7 °C minor) (Table 1). Thus, gamma rays generate degradation by scission of polymer chains in the cellulose, and less heat is necessary for begin the degradation.

The maximum degradation of cellulose is at 345 °C, which coincide with the onset of degradation T0.2 (20 % of mass loss). Nevertheless, lower temperatures were obtained for maximal degradation of cellulose (up to 11.7 °C minor) (Table 1). According to the literature, thermal degradation of α-cellulose is located at 360 °C, which coincide with the onset of degradation T0.3 (30 % of mass loss), of non-irradiated cellulose. For irradiated waste lamellae, similar behavior is obtained, is to say, the temperature of degradation decreases when the irradiation dose increase.

Thermal DSC curves of non-irradiated and irradiated lamellae of Tetra Pak are shown in Fig. 14. For non-irradiated lamellae a main endothermic peak, corresponding to the temperature of degradation (Tm) of low-density Polyethylene (LDPE), is located at 104.9 °C. In the case of irradiated lamellae, higher temperatures (Tm) were obtained: 106.1 °C (at 200 kGy) and 105.9 °C (at 300 kGy), which are 1.2 °C higher than that for non-irradiated one. This increment is related with the cross-linking of the polymer chains in the polyethylene, produced by gamma irradiation.

The heat flow is similar from 25 °C to 280 °C, for non-irradiated lamellae and those irradiated at 200 kGy, but for higher temperature (280 °C–450 °C), heat flow is lower for irradiated lamellae. In the case of lamellae irradiated at 300 kGy, the DSC curve data are lower than that for non-irradiated one.

Table 2
Mass loss and temperature of non-irradiated and irradiated waste lamellae.

Mass Loss (%)	Temperature (°C)		
	0 kGy	200 kGy	300 kGy
4	104.0	110.3	114.2
10	305.2	297.3	293.5
20	345.0	336.5	333.3
30	360.3	352.5	349.3

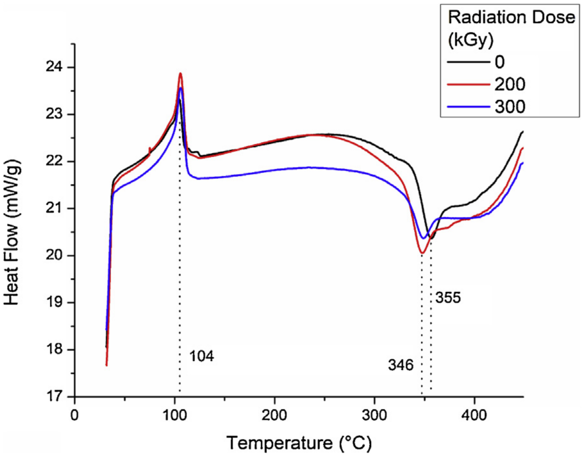

Fig. 14. DSC thermograms of non-irradiated and irradiated lamellae of waste Tetra Pak.

Following the thermal behavior, the major degradation of the lamellae of Tetra Pak occurs in the 265 °C–360 °C range. For non-irradiated lamellae, an exothermic peak, corresponding to the melt temperature of cellulose, is located at 355.9 °C (heat flow: 20.3 mW). According to the literature, thermal degradation of α-cellulose is obtained at 360 °C. In the case of irradiated lamellae, the exothermic peaks are located at 346.9 °C (20.0 mW) and 348.2 °C (20.3 mW), for 200 kGy and 300 kGy, respectively.

4. Conclusions

In this work, the effects of the gamma rays and lamellae of Tetra Pak (obtained from beverage packaging), on the compressive strength of the concrete were evaluated. The results show that for non-irradiated concrete both compressive strength and elasticity modulus values decrease gradually when increasing the lamellae concentration. However, for concrete with 10 % of lamellae of Tetra Pak and irradiated at 300 kGy, compressive strength had an improvement of 39 % and the elasticity modulus of 30 %. Such improvements depend of the changes produced in the lamellae of Tetra Pak after irradiation. These show morphological changes on their surface, either on the outer or inner layer. Such modified surfaces allow more interfacial interactions (more contact points) with the cement matrix. Thus, high stress transfer between the lamellae of Tetra Pak and the cement matrix is obtained. In consequence, improvements on the compressive strength and the elasticity modulus are obtained.

Declaration of Competing Interest

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

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References

[1] C. Meyer, Recycled materials in concrete, in: S. Mindess (Ed.), Developments in the Formulation and Reinforcement of Concrete, Woodhead Publishing Limited, Cambridge, England, 2009, pp. 208–230 ISBN 978-1-84569-263-6.
[2] M. Batayneh, I. Marie, I. Asi, Use of selected waste materials in concrete mixes, J. Waste Manage 27 (2007) 1870–1876, doi:http://dx.doi.org/10.1016/j.wasman.2006.07.026.
[3] G. Martínez-Barrera, C.E. Barrera-Díaz, E. Cuevas-Yañez, V. Varela-Guerrero, E. Vigueras-Santiago, L. Ávila-Córdoba, M. Martínez-López, Waste cellulose from Tetra Pak packages as reinforcement of cement concrete, Adv. Mater. Sci. Eng. (2015)682926, doi:http://dx.doi.org/10.1155/2015/682926 6 pages, 2015.
[4] A. Korkmaz, J. Yanik, M. Brebu, C. Vasile, Pyrolysis of the tetra pak, Waste Manag. 29 (2009) 2836–2841, doi:http://dx.doi.org/10.1016/j.wasman.2009.07.008.
[5] N. Gozde Ozerkan, O. Liqaa Maki, M. Wael Anayeh, S. Tangen, A.M. Abdullah, The effect of aluminium dross on mechanical and corrosion properties of concrete, Int. J. Innov. Res. Sci. Eng. Technol. 3 (3) (2014) 9912–9922.
[6] Ch.-H. Wu, Ch.-Y. Chang, Y.-F. Liu, Y.-L. Yan, Effects of oxygen on pyrolysis kinetics of tetra pack, J. Environ. Eng. 129 (4) (2003) 382–386, doi:http://dx.doi.org/10.1061/(ASCE) 0733-9372(2003)129:4(382).
[7] A. Murathan, A.S. Murathan, M. Guru, M. Balbas, Manufacturing low density boards from waste cardboards containing aluminium, Mater. Des. 28 (2007) 2215–2217, doi:http://dx.doi.org/10.1016/j.matdes.2006.06.014.
[8] M. Ebadi, M. Farsi, P. Narchin, Some of the physical and mechanical properties of composites made from Tetra Pak^{TM}/LDPE, J. Thermoplast. Compos. Mater. 31 (8) (2018) 1054–1065, doi:http://dx.doi.org/10.1177/0892705717734597.
[9] D. Foti, S. Adamopoulos, E. Voulgaridou, E. Voulgaridis, C. Passialis, S.O. Amiandamhen, G. Daniel, Microstructure and compressive strength of gypsum-bonded composites with papers, paperboards and Tetra Pak recycled materials, J. Wood Sci. 65 (2019) 42–49, doi:http://dx.doi.org/10.1186/s10086-019-1821-5.
[10] T. Hamouda, A.H. Hassanin, N. Saba, M. Demirelli, A. Kilic, Z. Candan, M. Jawaid, Evaluation of mechanical and physical properties of hybrid composites from food packaging and textiles wastes, J. Polym. Environ. 27 (2019) 489, doi:http://dx.doi.org/10.1007/s10924-019-01369-3.
[11] M. Bentchikou, A. Guidoum, K. Scrivener, K. Silhadi, S. Hanini, Effect of recycled cellulose fibres on the properties of lightweight cement composite matrix, Constr. Build. Mater. 34 (2012) 451–456, doi:http://dx.doi.org/10.1016/j.conbuildmat.2012.02.097.
[12] M. Sutcu, S. Akkurt, The use of recycled paper processing residues in making porous brick with reduced thermal conductivity, Ceram. Int. 35 (2009) 2625–2631, doi:http://dx.doi.org/10.1016/j.ceramint.2009.02.027.
[13] M. Sutcu, J.J. del Coz-Díaz, F.P. Álvarez-Rabanal, O. Gencel, S. Akkurt, Thermal performance optimization of hollow clay bricks made up of paper waste, Energy Build. 75 (2014) 96–108, doi:http://dx.doi.org/10.1016/j.enbuild.2014.02.006.
[14] G.H.D. Tonoli, U.P. Rodrigues-Filho, H. Savastano-Jr, J. Bras, M.N. Belgacem, F.A. Rocco-Lahr, Cellulose modified fibres in cement based composites, Compos. Pt. A Appl. Sci. Manuf. 40 (2009) 2046–2053, doi:http://dx.doi.org/10.1016/j.compositesa.2009.09.016.
[15] M. Raghatate Atul, Use of plastic in a concrete to improve its properties, Int. J. Adv. Eng. Res. Stud. 1 (3) (2012) 109–111.
[16] G. Martínez-Barrera, C. Menchaca-Campos, C.E. Barrera-Díaz, L.I. Avila-Cordoba, Recent developments in polymer recycling, in “Gamma rays: technology, in: Istvan Bikit (Ed.), Applications and Health Implications, Nova Science Publishers Inc., Hauppauge NY, USA, 2013, pp. 237–255 ISBN: 978-1-62257-697-5.
[17] F. Khan, S.R. Ahmad, E. Kronfli, γ-Radiation induced changes in the physical and chemical properties of Lignocellulose, Biomacromolecules 7 (2006) 2303–2309, doi:http://dx.doi.org/10.1021/bm060168y.
[18] J.F. Madrid, L.V. Abad, Modification of microcrystalline cellulose by gamma radiation-induced grafting, Radiat. Phys. Chem. 115 (2015) 143–147, doi:http://dx.doi.org/10.1016/j.radphyschem.2015.06.025.
[19] M.H.P. Gazineu, V.A. dos Santos, C.A. Hazin, W.E. de Vasconcelos, C.C. Dantas, Production of polymer-plaster composite by gamma irradiation, Prog. Nucl. Energ. 53 (2011)1140e1144, doi:http://dx.doi.org/10.1016/j.pnucene.2011.06.014.