Polymer concrete reinforced with luffa fibers: effect of gamma radiation

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Abstract The interest of many research groups regarding manufacture of composite materials by using natural fibers is increasing world-wide. The main objectives involve the improvement of mechanical properties, mainly those related to resistance and elasticity. In the present study in a first stage, polymer concrete specimens were elaborated by using an unsaturated polyester resin, silica sand and luffa fibers; after, they were gamma irradiated at different doses and their mechanical properties were evaluated. Two different silica particle sizes (0.15 mm and 0.6 mm), and four different luffa fiber concentrations (0.3, 0.6, 0.9 and 1.2 wt%) were used, as well as 50 and 100 kGy of radiation dose. The results show a gradually diminution of compressive strength and modulus of elasticity when adding luffa fiber concentration. Nevertheless, such mechanical features are increasing when polymer concrete is gamma irradiated.

Keywords: Luffa fibers, gamma radiation, polymer concrete, compressive strength, modulus of elasticity.

1. INTRODUCTION

The development of new materials includes the so-called composites, which are a combination of different materials (polymers, metals, ceramics, etc.) with improved properties than those of constituent materials. The properties of composites depend of several parameters, including concentration and distribution of the constituent materials (Kaewtatip, 2012).

The polymer concrete is a composite material consisting of a polymeric material and a ceramic one. The first one, called matrix, is a continuous medium which provides ductility and toughness to the composite. Unsaturated polyester resins and epoxy resins are commonly used for polymer concrete elaboration; nevertheless depending of the final properties different reinforcements as fibers, whiskers or particles have been used. Sometimes such reinforcements are strongly bound to the matrix (Boynard, 2003).

The inclusion of natural fibers as reinforcement of composite materials has been studied extensively in the last decade. Currently about 30 million of tones 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 (Altinisik,2010., Ghali,2011., Demir,2008).

Special attention for natural fibers has been captured by researchers. One of them is luffa fibers due to its physicochemical properties. This is composed primarily of cellulose (55%), hemicellulose (30%) and lignin (15%); luffa comes from the cucurbitacea (subtropical plant), which produces a fruit with a fibrous vascular system, having sizes between 15 cm and 1.5 m, and an average diameter of 8-10 cm (Boynard,2000., Tanobe,2005). It is abundant in China, Japan and other countries in Asia, as well as in Central and South America (Satyanarayana, 2009., Bal,2004., Shen,2012., Siqueira,2010., Oboh,2009).

When fibers are added to polymer concrete several properties are modified, including compressive strength, modulus of elasticity, fatigue and impact resistance, thermal stability and fire resistance (Satyanarayana,2009., Khan,2006., Saw,2013). Besides of improvement in toughness, better control, distribution and width-reduction of cracks (Machnowski,2013).

Cured of polymer concrete can be done by different procedures, including chemical reaction, heat or radiation. In the case of chemical reaction a free radical initiator is necessary, such as organic peroxide, it begins cross-linking reaction between the unsaturated resin and a monomer.

The high-energy ionizing radiation, such as gamma particles (electromagnetic energy) has been used for decades to modify the physical and chemical properties of polymeric materials. This type of radiation promotes ionization and excitation in the irradiated material to produce free radicals that are highly reactive species. These tend to react with neighboring atoms, eventually causing cross-linking or scission of the polymer chains (Martínez-Barrera,2012).

Modifications caused by gamma radiation in the physicochemical properties of polymer depend of several parameters as: amount of absorbed energy per unit mass (dose), irradiation conditions including type of gas (air, N2, etc.), and irradiation temperature. The radiation is the only source of energy which can initiate reactions at any temperature, including room temperature under any pressure, in any phase, whether solid, liquid or gas, without the use of catalysts (Martínez-Barrera,2013).

The degradation or cross-linking of polymer chains modifies the crystallinity, density, coefficient of thermal expansion, permeability and resistance to corrosion, abrasion and solvents, mechanical strength, as well as diminution of the molecular weight (Menchaca-Campos,2012).

In the case of main components of natural fibers, gamma radiation modifies the properties of cellulose and lignin. For the first one, cross-linking of chains occurs at doses greater than 1 Gy, chain scission begins at 31 kGy, and degradation of crystallinity at 1000 kGy. Lignin needs more energy for to show structural changes, greater than 1 MGy. At 1778 kGy only 10% of irradiated lignin shows degradation (Khan,2006., Machnowski,2013., Martínez-Barrera,2012&2013., Menchaca-Campos,2012., Avila-Córdoba,2012).

In this paper the effect of luffa fiber concentration and gamma radiation on the mechanical properties of polymer concrete elaborated with unsaturated polyester resin and silica sand was studied.

2. EXPERIMENTATION

2.1 Specimen manufacturing

Standard cube specimens (5x5x5 cm) of polymer concrete were elaborated with 20 wt% of ortophthalic polyester resin and 80 wt% of silica sand. The sand with uniform granulometry had an average diameter of 250 μm (sieve 60). Methyl ethyl ketone peroxide (MEKP) was used as initiator.

As reinforcements of polymer concrete Luffa fibers were used covering four different concentrations (0.3, 0.6, 0.9 and 1.2 wt%), which substituting part of the sand amount. Before preparing specimens both aggregates, silica sand and luffa fibers were dried in an oven for 3 hours at 60°C in order to guarantee the absence of water.

2.2 Mechanical tests

The compressive tests of polymer concrete specimens were carried out in a Universal testing machine model 70-S17C2 with a load cell of 30 tons (Controls^{TM}, Cernusco, Italy), at the loading rate of 1.25 mm/min, following the procedure described in ASTM C-109M test standard.

2.3 Morphological characterization

Both irradiated and non-irradiated luffa fiber surfaces were analyzed by scanning electron microscopy (SEM) in the secondary electron mode by using a JEOL model JSM-5200 machine.

2.3 Irradiation procedure

Both the luffa fibers and the polymer concrete with luffa fibers were exposed to gamma radiation dose of 50 and 100 kGy in air at room temperature. A dose rate of 3.5 kGy/h was applied by using a Transelektro irradiator LGI-01 provided with a ^{60}Co source manufactured by IZOTOP Institute of Isotopes Co. Ltd., Budapest, Hungary, and located at the National Institute of Nuclear Research (ININ-Mexico).

3. DATA ANALYSIS AND DISCUSSION

3.1 Compressive strength

Fig. 1 shows the compressive strength of three different types of polymer concrete, elaborated according to the sand particle size: a) Type I, with 0.15 mm particle size, b) Type II, with 0.6 mm particle size, and c) Type III, with combining 0.15 mm and 0.6 mm of sand particle sizes (both sizes show a 1:4 ratio between them).

A general behavior was observed: the compressive strength values gradually decrease when increasing luffa fibers concentration, independently of the sand particle size. Diminution of the values can be related with the weak matrix-fiber interface. When compression strength is applied the fibers create a poor transfer of load with the polymer matrix and in consequence the strength decrease. Moreover, due to luffa porosity each pore acts as a "failure" during mechanical testing, producing cracks and diminishing the resistance.

The values depend on the sand particle size, the highest compressive strength values are for polymer concrete with the lowest particle size. More surface energy is present in small particle size and the particle-particle interaction provides larger effective charge.

In the case of polymer concrete without fibers the compressive strength depends on the sand particle size, for the lowest size (0.15 mm), the value is 78 MPa, and for those with the highest size, 55 MPa, which is 30% lower. For each luffa concentration the behavior is similar, the compressive strength has the highest compressive values when adding lowest particle size.

Special behavior is seen for polymer concrete by combining two particle sizes, because the values are very similar (around 59 MPa) for polymer concrete with 0, 0.3, 0.6 and 0.9 wt%. Moreover, all polymer concretes with 1.2wt% of luffa fibers have similar values, varying from 39 to 42 MPa.

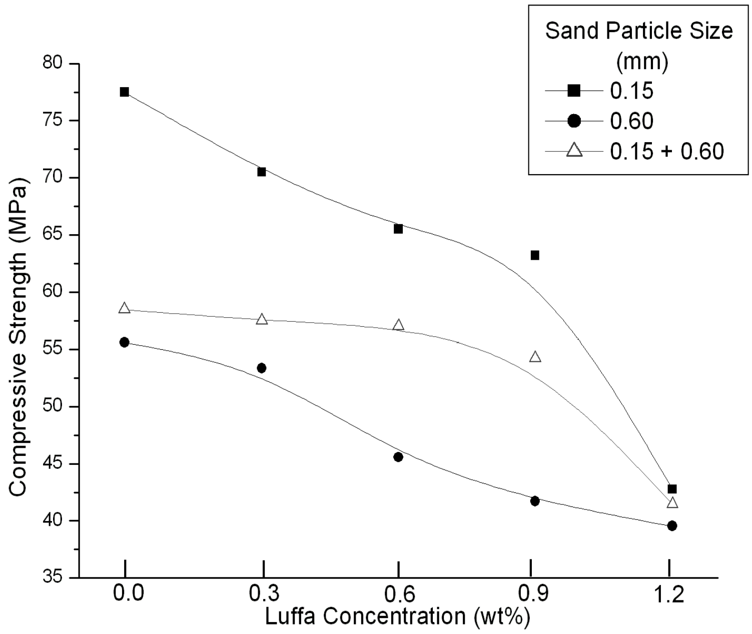

Fig. 1. Compressive strength of polymer concrete with luffa fibers.

As we seen in Fig. 1 the highest value for polymer concrete with luffa fibers is obtained for those with sand particle size of 0.15 mm and 0.3% of luffa fiber concentration. We decided to study the effect of gamma radiation on this kind of polymer concrete; the results of compressive strength show a slightly diminution when irradiating at 50 kGy (Fig. 2) but increment of 18% for those irradiated at 100 kGy, whose value, 84 MPa, is higher than those obtained for polymer concrete without luffa fibers (78 MPa). Such increments are consequence of gamma radiation which promoting ionization and excitation in the polymeric resin, generating free radicals which reacting with neighboring atoms, causing cross-linking of polymer chains and thus improvement of mechanical properties.

3.2 Compressive Strain

Different behaviors with respect to the compressive strain behavior of polymer concrete were observed in this study as seen in Fig. 3. These results are; a) the values increase slightly (5% on average) for concentrations up to 0.6% of luffa fibers; after this concentration the deformation decreases considerably compared to concrete without fibers; b) the highest deformation values are for polymer concrete with highest sand particle size while the lowest deformation is for those with lower particle size. Both behaviors can be attributable to particle size because more interaction between the sand particles is present for a major contact area resulting in a better load transfer. Conversely, with larger particle sizes, the polymer matrix absorbs the greater part of energy and, as a polymeric material; the deformation of the composite is increased. Furthermore, more compact and rigid concretes are obtained with smaller particle sizes, and so this causes the smaller deformation.

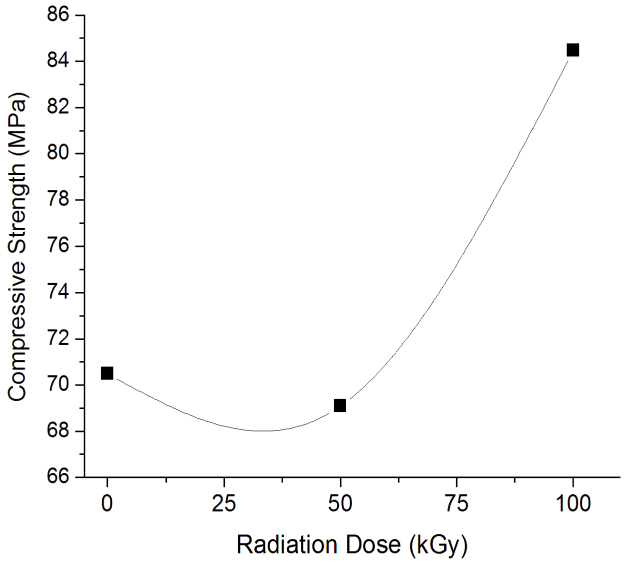

Fig. 2. Compressive strength of polymer concrete with 0.3% of luffa fibers, irradiated at 50 y 100 kGy.

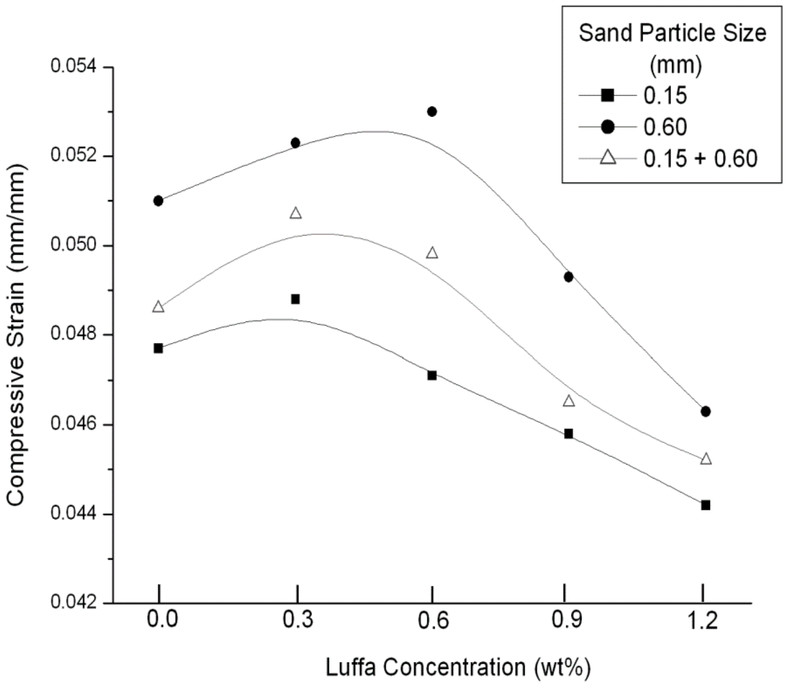

Fig. 3. Compressive strain of polymer concrete with luffa fibers.

Diminution of compressive strain as well as compressive strength values of polymer concrete is related to physical and chemical properties of the fibers. Luffa is a natural fiber with high water absorbency (13.6 g / g). Due to the absorption and desorption phenomena, is possible to observe "swelling" of the fiber in wet environments or "contraction" in dry environments; thus when luffa fiber is added to polyester resin a liquid layer between them is created, thus a weak fiber-matrix interface is generated, which involves a transfer of inefficient loads and consequently diminution of the mechanical properties.

Fig. 4 shows the deformation of concrete with 0.3% of luffa fiber irradiated at 50 and 100 kGy. The deformation increases when the radiation dose increases. Increments of 40% and 60% for irradiated concrete at 50 and 100 kGy, respectively, are seen with respect to non-irradiated concrete control. Such improvements are related to the gamma radiation effects on the polymer matrix; because certain cross-linking degree of the polymer chain is generated, thus more deformation is observed and as a consequence a more ductile material is obtained.

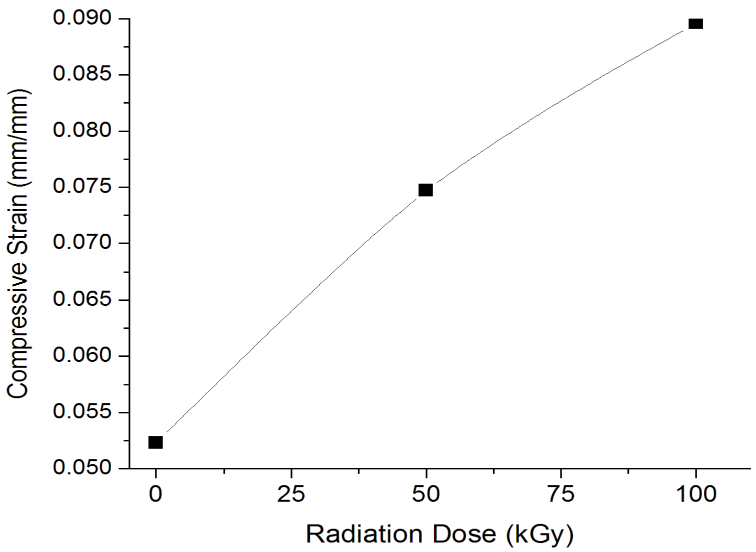

Fig. 4. Compressive strain of polymer concrete with 0.3% of luffa fibers, irradiated at 50 y 100 kGy.

3.3 Modulus of Elasticity

Fig. 5 shows the modulus of elasticity of polymer concrete. The modulus of elasticity increases slightly when adding luffa fibers up to 0.6 wt%, independently of the particle size used for elaborating polymer concrete. For higher fiber concentrations (above 0.6 wt%) the modulus of elasticity decreases until 15% lower than those for concrete without fibers. As compressive strength and compressive strain values reported in previous sections, the elasticity modulus values for concrete with combining two different particle size are located between values for concrete with highest or lowest particle sizes.

The modulus of elasticity is also affected by the sand particle size. The highest values are obtained with smaller particle sizes, which is attributed to the greater contact area of them and their great interactions between them, resulting in a more compact and rigid material.

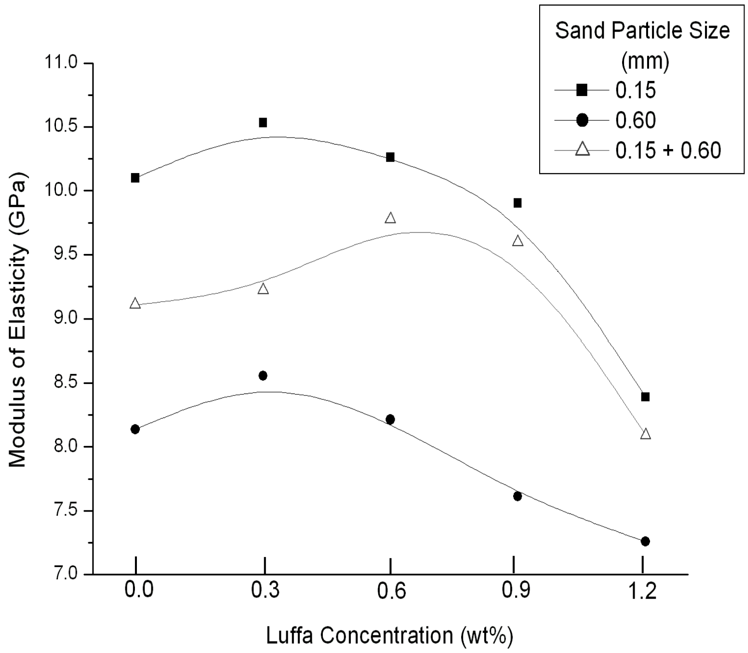

Fig. 5. Modulus of elasticity of polymer concrete with Luffa fibers.

The effect of gamma radiation on the elasticity modulus of polymer concrete with 0.3% of luffa fibers is shown in Fig. 6. The values are increasing 70% or 40% when applying 50 kGy or 100 kGy of radiation dose, respectively, with respect to non-irradiated concrete. This increment is due to the higher degree of polymerization of the polyester resin and to the cross-linking between it and the luffa fiber components, mainly cellulose. Such reticulation generates lower deformation.

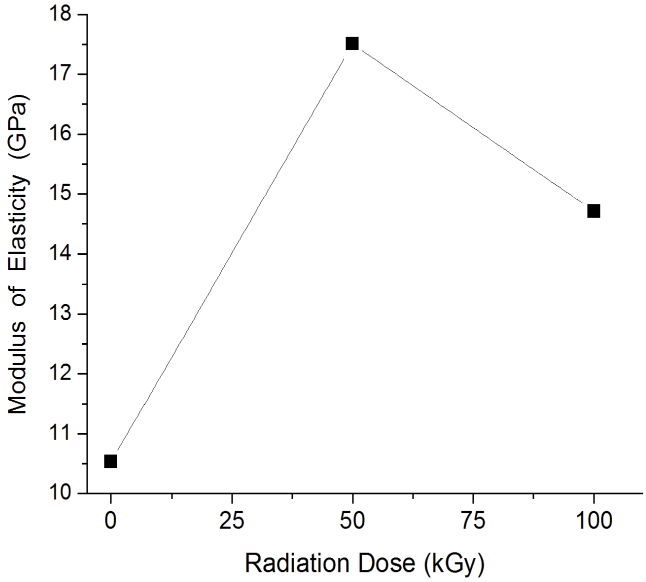

Fig. 6. Modulus of elasticity of polymer concrete with 0.3% of Luffa fibers, irradiated at 50 kGy and 100 kGy.

As previously mentioned, compressive strength and strain as well as modulus of elasticity are increasing when they are irradiated. Such improvements can be related with the effects produced by gamma radiation in the luffa fibers. Fig. 7 shows non-irradiated and irradiated luffa fiber SEM images. For non-irradiated luffa fibers a homogeneous surface is seen (Fig. 7a). When increasing the radiation dose, at 50 kGy, rough surface with presence of some cracks and particles (identified as lignin particles) are covering by a thin layer (Fig. 7b). For higher dose, at 100 kGy, "channels" and cracks are seen on the surface (Fig. 7c) (hemicellulose and lignin layers remain).

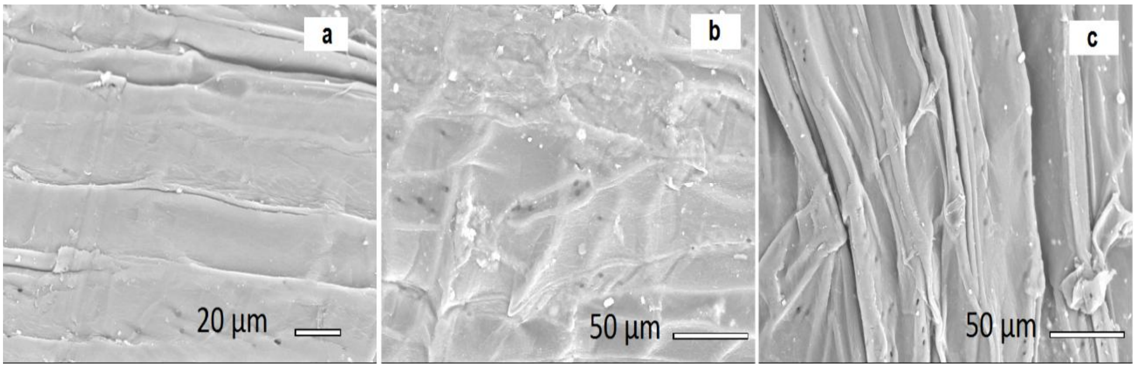

Fig. 7. SEM images of luffa fibers: non-irradiated (a); irradiated at 50 kGy (b), and at 100 kGy (c).

In the case of silica sand when irradiating some modifications on surface are observed (Fig. 8). For non-irradiated silica sand a homogeneous surface is seen, with sporadic cracks (Fig. 8a); When increasing the radiation dose at 50 kGy, cavities of different sizes and shapes are observed (Fig. 8b); and finally at 100 kGy larger cracks and more surface changes are observed. Deterioration of silica sand surfaces are increasing when irradiation dose is increasing, too. The mechanical performance of the polymer concrete can be related to morphological changes on the surfaces. When the composite is irradiated, the cavities are produced on the surface of silica sand and then this increases the surface area of silica sand in contact with the resin and improves the transfer of loads. Furthermore, during the irradiation process free radicals are generated and it is possible that during the new polymerization "anchoring" of the resin with sand cracks occurs, which may result in an increase in the mechanical strength of composite.

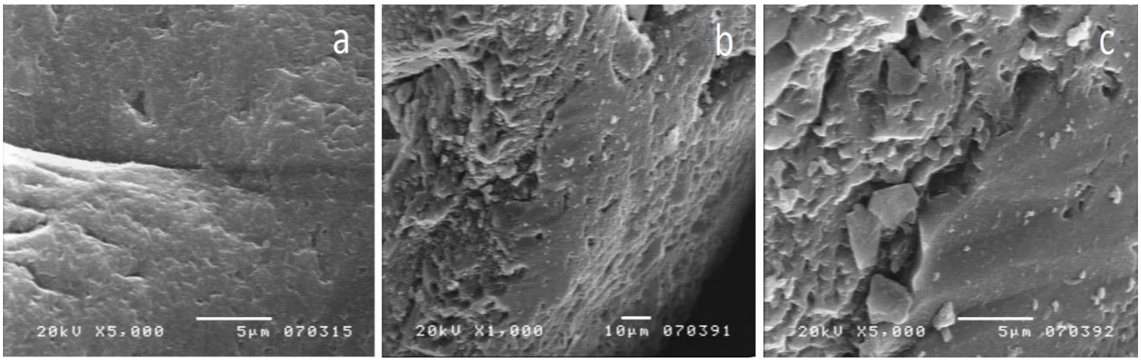

Fig. 8. SEM images of (a) not-irradiated sand, and irradiated (b) at 50 kGy, and (c) 100 kGy.

4. CONCLUSION

Both luffa fibers and gamma radiation are already adequate tools for improvements of the mechanical properties of polymer concrete. These mechanical properties gradually decrease as the concentration of luffa fiber increases. For highest fiber concentration and smallest particle size, the compressive strength decreases by 43%, deformation decreases by 9% and the modulus of elasticity decreases by 15%. This can be attributed to the luffa fiber properties as porosity and moisture on the surface. Nevertheless, when irradiated, the properties of the concrete improve greatly: modulus of elasticity by 40% and compressive strength by 20%. These changes are attributed to cross-linking of polymer chains produced by gamma radiation. To obtain an improved polymer concrete, it is recommendable to use 0.3% of concentration of luffa fibers and an irradiation dose of 100 kGy.

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