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EFFECT OF TETRA PAK WASTE ON MIXED-MODE FRACTURE OF POLYMER MORTARS USING BRAZILIAN DISC TEST

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Abstract. *Mixed-mode fracture, in the form of critical stress intensity factors of polymer mortar reinforced with particles from waste Tetra Pak® aseptic carton packages was investigated. Data from previous work was used for conclusions on this work. Slight increase and subsequent decrease in critical stress intensity factors was observed with the addition of carton particles, a decrease in dry density as carton weight percentage (wt.%) increases.*

Keywords: *polymer concrete, polymer mortar, recycling, carton, fracture*

1. INTRODUCTION

Concrete is the most widely used material in the world after water, it is basically a composite material consisting of an aggregate of particles held together by a binder, the most commonly used binder is Portland cement mixed with water.

Polymer Concrete (PC) came to use as early as 1958 to produce building cladding (Fowler 1999), it consists of aggregate with a polymer binder and contains no Portland cement or water. The binder can be a thermoplastic or thermosetting resin. In addition to its use in precast cladding, nowadays it is used to produce a wide range of precast products, as a repair material in cement concrete, due to its fast curing and excellent bonding properties, in overlays or screeds, and may even replace metals, e.g. cast iron for machine bases. But due to its higher cost, its use in high volume applications is considered impractical except in very unusual cases (Fowler, 1999).

Nowadays, due to stricter legislation regarding the environment and a general trend in society for more environmentally friendly products, manufacturers are becoming more concerned to develop studies regarding the environmental impact of their products, lowering the amount of generated waste and treating those inevitably generated. Other factors taken into account that contribute to reuse of waste materials are high costs associated with raw material extraction, damage to the environment due to this extraction, depletion of raw material sources and conservation of non-renewable sources.

Researches have been performed with the intent of increasing use of recycled materials on PC and Polymer Mortar (PM). (Jo *et al.*, 2008, Reis *et al.*, 2011, Reis, 2006, Reis and Carneiro, 2013, Reis, 2009, Reis and Jurumenha, 2011).

Still, there is a lack of information regarding the use of recycled carton packages in PM. Multi-layer poly coated paperboards, often called tetrapak or *longa vida* in Brazil, are widely used in aseptic packaging for milk, juice or wine. Due to their one-off nature of utilization and wide use they create a significant part of generated municipal solid waste. Typical composition of aseptic Tetra Pak® packaging is: 75% paper by weight (wt.%), low-density polyethylene (21 wt.%), and aluminum (4 wt.%), those three materials are distributed in six layers to form the package, the inner and outer layers are composed of polyethylene, Fig.1 (ACE, 2015a).

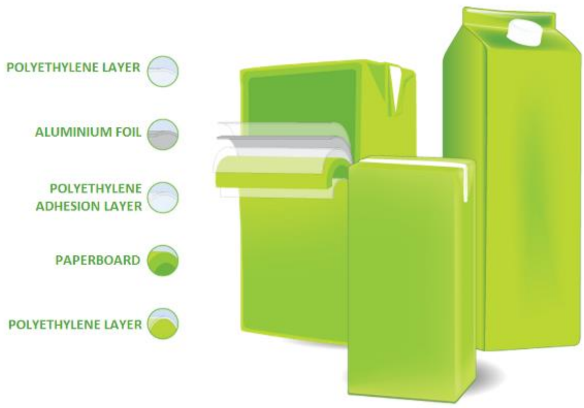

Figure 1. The dominating structure of aseptic beverage cartons. (ACE, 2015a)

Recycling of these packages is predominantly done in paper mills, where fibers from the cardboard are separated from the polyethylene and aluminum (PEAL) by hydro-pulping and used in paper products; the remaining PEAL composite may also be reused in one of three ways: energy can be recovered through incineration of the composite, the aluminum may be recovered through pyrolysis, and the PEAL may be used to create new plastic products (Neves, 1999). As an alternative to repulping for paper applications, Tetra Pak® developed a process that converts shredded cartons into thermally compressed panels to serve as alternatives to traditional wood-based panels, this product is produced in various countries under different brand names (Ayrilmis *et al.*, 2008).

Aseptic carton recycling rate in Brazil was 29% in 2012, totalizing 61000 tons, it is above the world average of 21.6% in 2011 (CEMPRE, 2015), but lower than the European Union average, with a 40% recycling rate in 2012 (ACE, 2015b).

The goal of this article is to determine mode-I and mode-II critical stress intensity factors (SIFs) of epoxy PM, with partial substitution of foundry sand aggregate for waste Tetra Pak® aseptic carton particles, the only necessary previous treatment is separation of the cartons and washing of organic residue. The PM specimens used are as similar as possible as previous work by Martínez-López *et al.* (2014), currently journal manuscript in review process, in fact, the only change is the substitution of sand for carton particles, their results for mixed-mode critical stress intensity factors of polymer concrete are used for comparison.

The Brazilian disc test consists of a diametrical compression of a cylinder, it was introduced by Carneiro (1947, 1953) and Akazawa (1953) as a substitute for the direct tension test, it is nowadays a unique tool for easy determination of the critical stress intensity factor, especially for brittle geomaterials. This is achieved by using the centrally cracked Brazilian disc configuration proposed by Awaji and Sato (1978). The main advantage of this configuration (beyond the relatively simple experimental procedure) is that any combination of mode-I and mode-II loading types can be achieved by an appropriate choice of the crack inclination angle θ, (with respect to the loading direction) and the relative crack length, l/a (with respect to the disc radius, a) (Fig. 2)(Dong, 2008). A widely used solution for the stress intensity factors (SIF) in a cracked Brazilian disc loaded under diametrical compression by concentrated forces was presented by Atkinson *et al.* (1982) in the form of infinite series, it will be used in this work. Recently Dong *et al.* (2004) also introduced a solution for a centrally cracked Brazilian disc under uniform radial pressure in the form of infinite series.

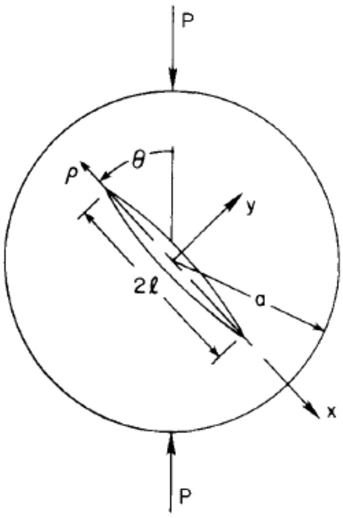

Figure 2. Geometry of the cracked Brazilian disk test. (Atkinson *et al.*, 1982)

Polymer concrete, with reasonable fractions of sand, has a quasi-brittle behavior (Nunes *et al.*, 2011). For low-loading rates and quasi-brittle behavior, some concepts of Linear Fracture Mechanics can be used.

2. MATERIALS AND METHODS

2.1. STRESS INTENSITY FACTORS FOR THE CENTRALLY CRACKED BRAZILIAN DISC

Noting w the disc thickness, 2a the diameter and 2l the crack length and P the compression force, the stress intensity factor are given by the following expressions (Atkinson et al., 1982). For the series approximation with two terms:

$$K_I = \frac{P}{\sqrt{\pi a} w}\sqrt{l} N_I \tag{1}$$

$$K_{II} = \frac{P}{\sqrt{\pi a} w}\sqrt{l} N_{II} \tag{2}$$

$$N_I = T_1\left(1-4(\sin(\theta))^2\right)+T_2\left(\frac{l}{a}\right)^2 8(\sin(\theta))^2\left(1-4(\cos(\theta))^2\right) \tag{3}$$

$$N_{II} = 2\sin(2\theta)\left[S_1+S_2\left(\frac{l}{a}\right)^2\left(-5+8(\cos(\theta))^2\right)\right] \tag{4}$$

In the present case, the value of (l/a) is equal to 0.3125. From Atkinson et al. (1982), the following parameters were selected: $T_1 = 1.135551$; $T_2 = 0.533477$; $S_1 = 1.089702$ and $S_2 = 0.522272$. The critical values of the stress intensity factors, K_{IC} and K_{IIC} were obtained measuring experimentally the rupture force $P_{\max}$ for a given angle θ and using eqs. (1-4).

$$K_{IC} = \frac{P_{\max}}{\sqrt{\pi a} w}\sqrt{l} N_I \tag{5}$$

$$K_{IIC} = \frac{P_{\max}}{\sqrt{\pi a} w}\sqrt{l} N_{II} \tag{6}$$

Since the solution proposed by Atkinson *et al.* (1982) does not take into account unilateral contact and friction, at the point of crack closure, the previous equations are no longer valid (negative values for the stress intensity factors can be obtained). As proposed by Atkinson *et al.* (1982), we may use eq.(3) to obtain the angle for which the crack just begins to close. Figure 3 displays the behavior of this function for l/a=0.3.

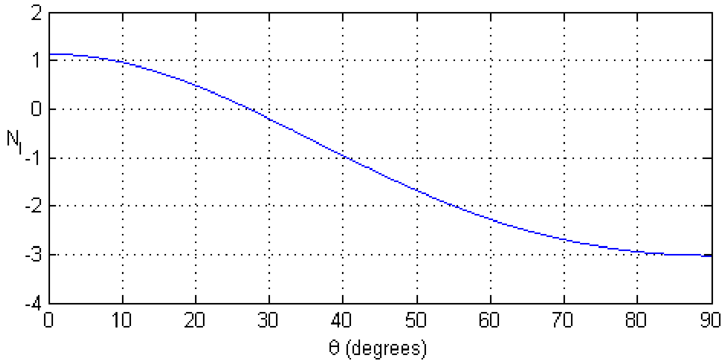

Figure 3. N_I as a function of θ. (l/a)=0.3

For $N_I>0$ the crack tends to open, and for $N_I<0$ the crack tends to close. In this case, the angle θ for which the crack just begins to close is 27.4°.

2.2. MATERIALS

In order to manufacture PM specimens, shredded Tetra Pak® aseptic cartons, foundry sand and polymer resin were mixed in an industrial mixer. The cartons were obtained as post-consumer waste from a cooperative of waste pickers, using a paper shredder, they were cut up to 0.85 mm (25 mesh size).

The foundry sand is used in the foundry industry and is a quartz foundry sand with a rather uniform particle size; the particles have an average diameter of 245 μm. The sand specific gravity is 2.65 $g.cm^{-3}$ (ASTM, 2007) and fineness modulus of 2.5 (ASTM, 2011).

The epoxy resin system was based on a diglycidyl ether of bisphenol A and a aliphatic amine hardener. This system has low viscosity, and is processed with a maximum mix ratio to the hardener of 4:1. Epoxy polymer resin thermal and mechanical properties are provided in Table 1.

The resin content was 12 wt.% with substitution of foundry sand by 1, 2 and 3 wt.% by Tetra Pak® particles, mix formulations of fiber-reinforced polymer concrete and number of samples are presented in Table 2.

Table 1. Properties of the epoxy resin

Property	Epoxy
Viscosity at 250C μ (cP)	12000-13000
Density ρ (g/cm^3)	1.16
Heat Distortion Temperature HDT (ºC)	100
Modulus of Elasticity E (GPa)	5.0
Flexural Strength (MPa)	60
Tensile Strength (MPa)	73
Maximum Elongation (%)	4

Table 2. Mix formulations of fiber reinforced polymer concrete

Resin (wt.%)	Tetra Pak particles (wt.%)	Aggregate (wt.%)	Nº of samples
12	1	87	11
12	2	86	11
12	3	85	11

2.3. METHODS

The Brazilian disc specimen used in this study has the nominal dimension of 40mm in radius and 38 mm in thickness. The crack length was 25 mm.

All specimens were initially cured at room temperature and then post-cured for 4 hours at 80 ºC. After the PM specimens were fully cured, the dry densities were identified using the weight and volume of the resulting specimen. Dry densities are displayed in Table 3, addition of carton particles decreases specimen dry density, a decrease of 4% in density is observed from 1 wt.% to 3 wt.% carton particles.

Table 3. Average dry densities of the different formulations of PM

Tetra Pak particles (wt.%)	Dry density (kg/m³)	
	Average	St.Dev.
1	1768	21
2	1733	28
3	1695	26

The specimens were loaded at a constant crosshead speed of 0.5 mm/min using two parallel steel plates on a universal testing machine, Shimadzu AG-X 100, Fig. 4-a, they were divided into four groups according to the desired angle between crack and applied force, Tab. 4. Markings were made in each specimen for positioning them in the apparatus, Fig.4-b.

Figure 4. a) Experimental setup; b) Sample with positioning markings for 20 degrees

Table 4. Crack inclination angles and number of test samples for each angle

Crack inclination angle θ (degrees)	Tetra Pak particles (wt.%)		
	1	2	3
0	3	3	4
10	3	3	3
20	3	3	3
30	2	2	1

3. RESULTS AND DISCUSSION

Figure 5 displays typical Load versus Displacement curves for the three formulations of particle-reinforced PM studied, for various angles.

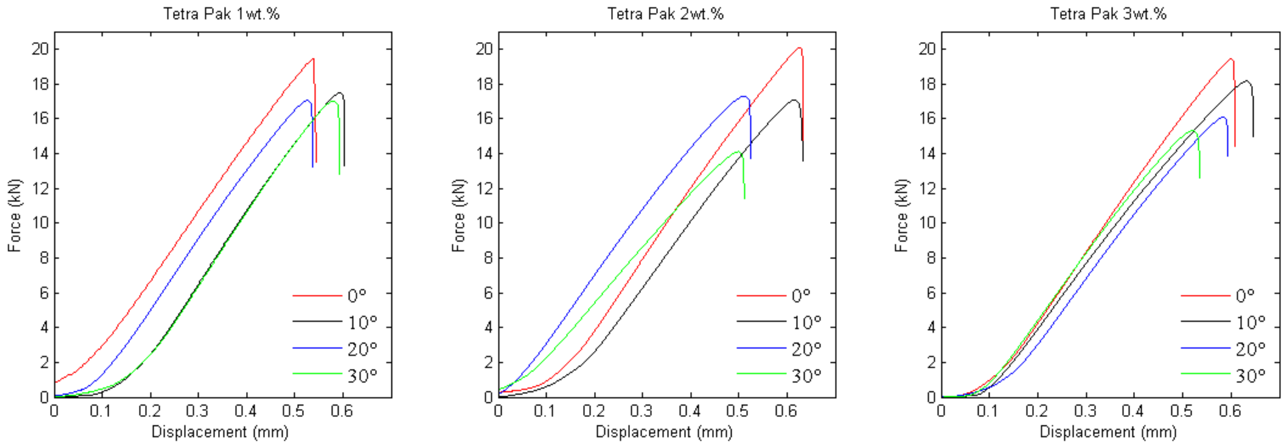

Figure 5. Applied load vs vertical displacement

According to Fig. 5 it can be seen very similar curves. There is a high decrease in applied force after peak load. This suggests the addition of carton particles does not change brittle failure behavior of PM.

Figure 6 displays rupture load versus crack inclination angle of particle-reinforced PM specimens.

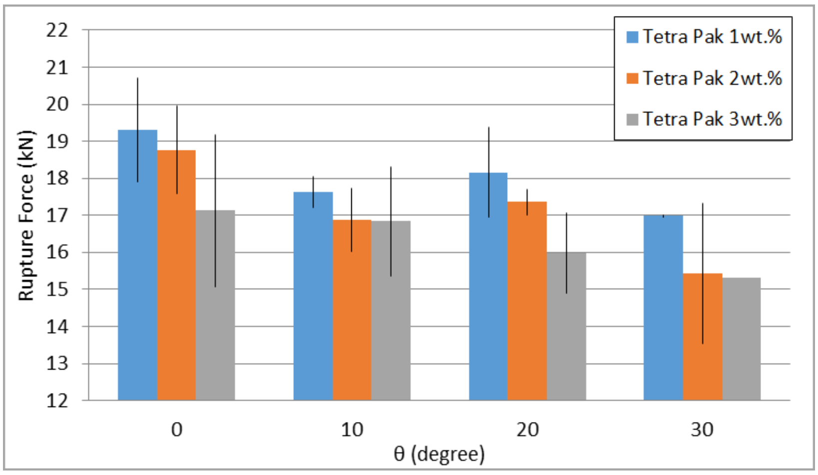

Figure 6. Rupture load vs crack inclination angle for different Tetra Pak particles weight fractions.

Analyzing figure 6, higher breaking load was observed for 0 degrees in all formulations. While it is not possible to assert in-between behavior due to high dispersion of data, there is a clear decrease in breaking load from 1 wt.% to 3 wt.% Tetra Pak® particles for all crack inclination angles studied.

Figure 7 and Table 5 show the K_{IC} and K_{IIC} for different compositions of PM. Critical SIFs for plain PM were obtained from Martínez-López *et al*. (2014), manuscript submitted to journal currently in reviewing process, it should be stressed that aside difference in aggregate composition, the parameters are the same, so data may be used in comparison.

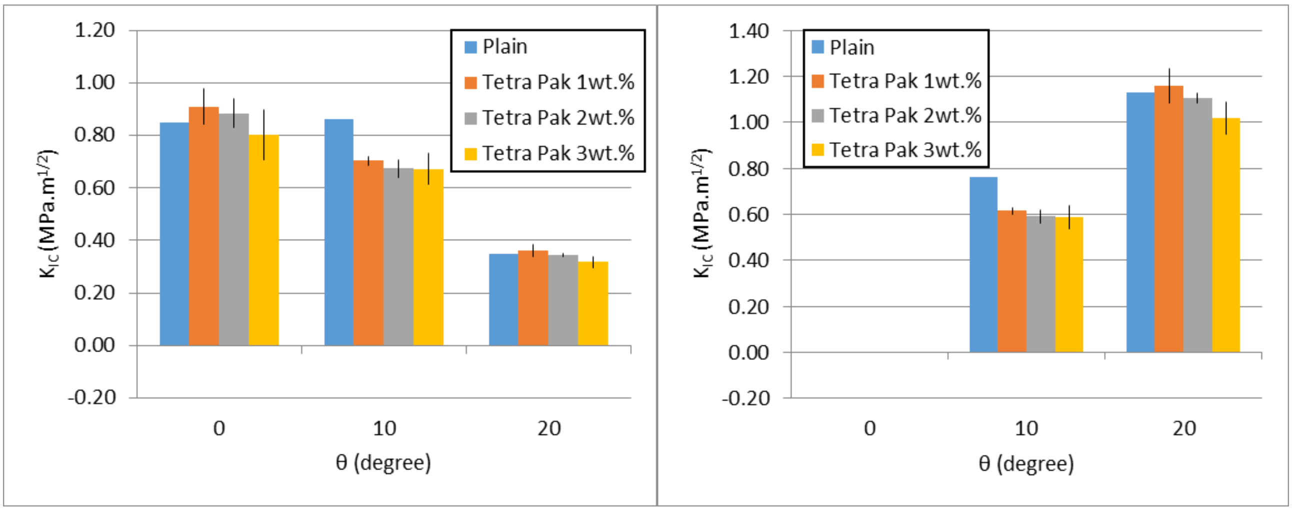

Figure 7. a)K_{IC} vs crack inclination angle for different Tetra Pak particles weight fractions. b) K_{IIC} vs crack inclination angle for different Tetra Pak particles weight fractions.

Table 5. Critical stress intensity factors for each combination of PM and crack inclination angle

Crack inclination angle θ (degree)	Tetra Pak particles (wt.%)							
	0*		1		2		3	
	K_{IC} and K_{IIC} Critical Stress Intensity Factors (MPa.m$^{1/2}$)							
	K_{IC}	K_{IIC}	K_{IC}	K_{IIC}	K_{IC}	K_{IIC}	K_{IC}	K_{IIC}
0	0.85	0.00	0.91±0.07	0.00±0.00	0.88±0.06	0.00±0.00	0.80±0.09	0.00±0.00
10	0.86	0.76	0.70±0.02	0.62±0.01	0.67±0.03	0.59±0.03	0.67±0.06	0.59±0.05
20	0.35	1.13	0.36±0.02	1.16±0.08	0.35±0.01	1.11±0.02	0.32±0.02	1.02±0.07

* Data obtained from Martínez-López *et al.* (2014)

Figure 7 shows that pure mode-I fracture happens when crack inclination angle, θ, equals zero. With addition of 1 wt.% carton particle there is an increase of 7% in the critical SIF, while with 3 wt.% it decreases and is approximately 6% lower than pure PM. Using 2 wt.% test data it is not possible to assert critical SIF behavior in-between due to high dispersion of data, testing with more samples is necessary.

When mixed-mode fracture is analyzed the same trend is seen, an increase of 3% for 1 wt.% and a decrease of 9% for 3 wt.% compared to plain PM, for 20 degrees. Though data obtained from Martínez-López *et al.* (2014) for crack inclination angle of 10 degrees shows a very high critical SIF, it is considered an anomaly is this work. We did not try to determine pure mode-II critical SIF due to the inherently low accuracy in the method used for specimen crack angle positioning.

4. CONCLUSIONS

Waste Tetra Pak® aseptic carton particles, when mixed with thermosetting epoxy resin and foundry sand for substitution of up to three percent of weight fraction might be used as substitutes of aggregate in PM.

Addition of carton waste particles yields decreases in dry density, the particles yield changes in critical SIFs, in the order of 10%, they might not be used for reinforcement in plain PM, but in small additions, 1 wt.% generates a material with similar or slightly better critical SIFs, with the added benefit of recycling post-consumer waste. In order to better define limits for maximum addition of carton waste particles in critical SIFs tests with more samples need to be performed for the particle-reinforced specimens and for the plain PM.

Addition of carton changes critical SIFs of PM, but more studies of other fracture and mechanical properties are necessary to validate use of this recycled aggregate as partial substitute of foundry sand.

Highest breaking load, for any of the PM formulations investigated, occurs for crack inclination angles of 0 degrees.

5. ACKNOWLEDGEMENTS

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