International Journal of Innovative Studies in Sociology and Humanities (IJISSH)

ISSN 2456-4931 (Online) **www.ijissh.org** *Volume: 3 Issue: 1 | January 2018*

Identifying the Final Use of Scrap Tires in Reverse Logistics Chains

Cristiane Duarte Ribeiro de Souza* and Márcio de Almeida D'Agosto

Abstract: *Due to the growing generation of scrap tires and the negative impacts they cause on the environment and quality of life, there is increasing concern with their proper reuse or disposal. With the aim of identifying the various ways this scrap material can be reused, we carried out a bibliographic review in which we analyzed 110 articles, with the primary objective of identifying the different final uses of scrap tires and the secondary objective of obtaining information to formulate a reverse logistics chain model for scrap tires. That model provides a better understanding of the problem of suitable disposal of scrap tires and the various possibilities and technologies for their recycling. This analysis enabled identifying six groups of industries involved in recycling unserviceable tire material: fuel industry (49%), construction industry (25%), asphalt industry (8%), rubber articles industry (6%), cement industry (2%) and other industries (10%).*

Keywords: *Scarp tires, Reverse logistics chain; Recycling; Final use, Bibliographic review.*

1. INTRODUCTION

There is growing concern regarding the correct disposal of scrap tires (Siddique and Naik, 2004) due to the continuous growth of their number generated by modern society. According to the U.S. Rubber Manufacturers Association, approximately 290 million new scrap tires were generated in 2003 (EPA, 2010). In Brazil, the most recent estimate is that in 2013 about 32 million scrap tires were generated. This problem is not new. According to Search and Ctvrtnicek (1976), the disposal of scrap tires was already considered a major problem in all countries with large vehicle fleets in the 1970s. This worry occurs because although the tires are key elements for the development of modern society, at the end of their useful lifetime they cause a range of problems for the environment and public health if discarded inadequately.

Not only do the sheer volume and shape of tires not allow their compacting, increasing the cost of their transport and storage/disposal (Nohara et al., 2006), they are made of different rubber formulations and reinforcement materials, such as synthetic fibers and steel, making their recycling difficult (Chung and Hong, 2013).

Finding alternatives to allow reuse of scrap tires in new productive cycles can reduce the environmental impacts by minimizing consumption of non-renewable raw materials (considering that most of the tire rubber is made from petroleum instead of natural latex) and increasing the lifetime of sanitary landfills. Besides this, recycling these waste materials can reduce public health problems and generate jobs and income (Souza and D'Agosto, 2013).

Therefore, to identify the various alternatives for reuse of scrap tires, we carried out a systematic literature review with the main objective of identifying the different final uses of these articles and the secondary goal of formulating a model of the reverse logistics, or supply, chain of unserviceable tires.

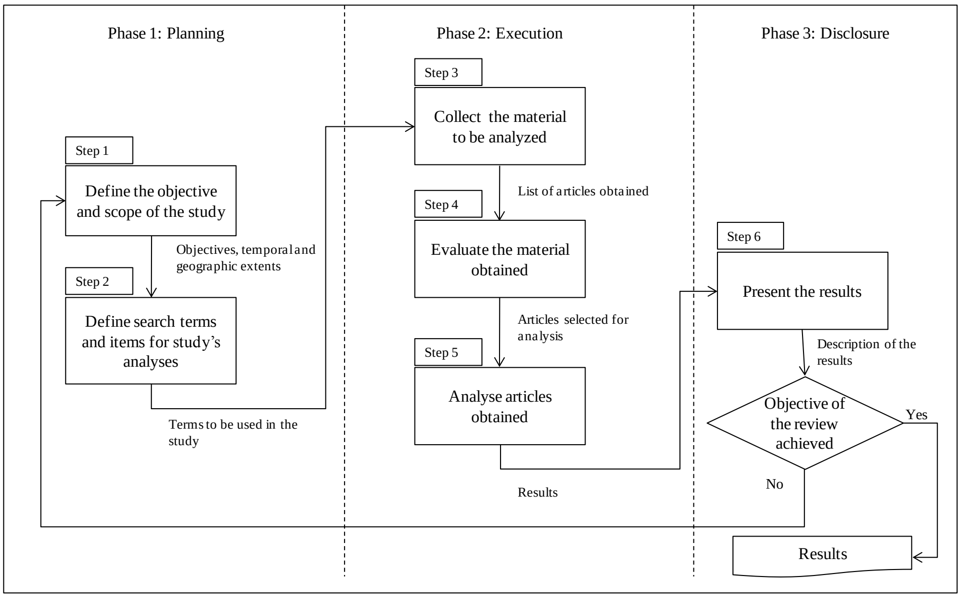
The article is divided into five sections including this introduction. The second section describes the methodology while the third presents the results of the bibliographic review and the fourth describes the proposed reverse logistics chain model for scrap tires formulated, based on the data obtained from the literature review. The fifth section presents our conclusions.

2. MATERIALS AND METHODS

Systematic literature review is a technique used to survey published articles on a determined theme by employing systematic methods to identify, select and critically evaluate relevant studies and to collect and analyze the data found in the sources identified in the review, with the goal of creating a theoretical-scientific foundation on the theme of interest (Biolchini et al., 2007; Clarke and Oxman, 2001 and Levy and Ellis, 2006). Bibliographic review can be used to summarize existing research, identify patterns, themes and questions and/or help identify the content on a determined subject (Seuring and Muller, 2008).

One of the reasons for carrying out a systematic literature review is to provide the necessary foundation for a better understanding of the problem of interest (Kitchenham, 2004; Levy and Ellis, 2006), because the use of systematic procedures increases the reliability of the results obtained and reduces the likelihood of errors, besides enhancing transparency and allowing replication of results (Mulrow, 1994; Cook et al., 1997; Bereton et al., 2005).

For this it is necessary to follow a procedure that guides the researcher in the planning and performance of the bibliographic review and in disclosing the results obtained. The procedure adopted here was developed by us based on Souza (2011), Seuring and Muller (2008) Tranfield et al. (2003), Biolchini et al. (2007) and Levy and Ellis (2006). This procedure consists of three phases: planning, execution and disclosure (Figure 1).



Source: *Own based on Souza (2011), Seuring & Muller (2008) Tranfield et al. (2003), Biolchini et al. (2007) and Levy & Ellis (2006).*

Figure 1: *Study procedure*

In the planning phase, step 1 involves defining the objective, meaning delineating the temporal and geographic scope and the sources that will be consulted. Step 2 entails defining the key search terms that will be used to collect material and the items that will be used in the systematic analysis of the data.

The execution phase is composed of three steps (steps 3, 4 and 5). In step 3, the researcher collects the material from the review by means of searching one or more databases using the key words/expressions defined in the first phase (step 2). The material obtained should be assessed considering the objective and scope defined in step 1, to determine a set of articles that are relevant to the survey, to be analyzed in step 5, based on the items defined in step 2. If it is found that the objectives of the review have not been reached, then the researcher should return to the planning phase and analyze steps 1 and 2 again to make any necessary corrections.

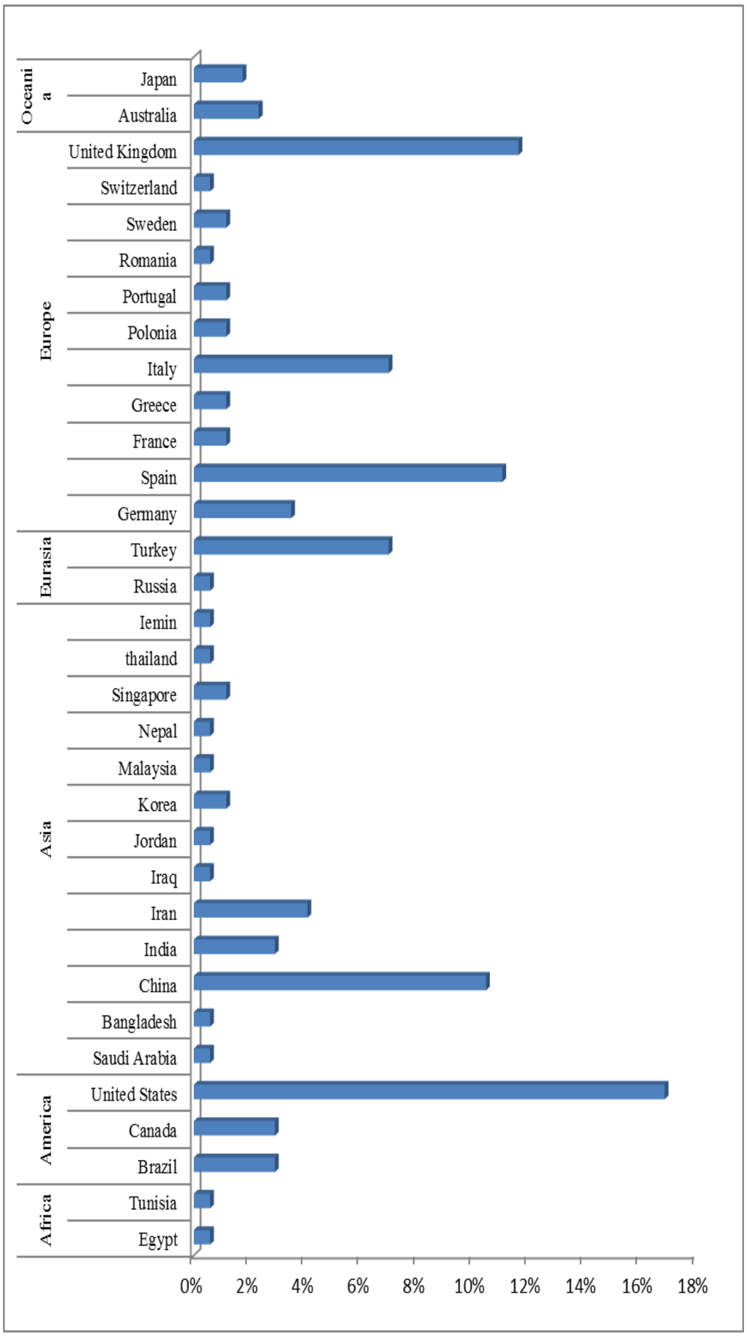
Finally, the disclosure phase consists of a single step (step 6), where the results are described for presentation in a review article.

3. SYSTEMATIC BIBLIOGRAPHIC REVIEW

Below we describe the application of the procedure presented in Figure 1.

3.1. Phase 1: Planning

The objective of this systematic bibliographic review was to identify the final uses of scrap tires and then to obtain information for preparation of a reverse supply chain for scrap tires considering these final uses (step 1). For this we used the total time period available in the scientific database surveyed, to identify articles published from 1976 to 2014. Our geographic scope was global, since the generation of scrap tires is a worldwide problem (Search and Ctvrtnicek, 1976). We classified the articles geographically as from the Americas (23%), Europe (40%), Asia (24%), Oceania (4%) and Africa (1%), as depicted in Figure 2. Eight percent of the articles refer to countries located in both Europe and Asia (Eurasia), also shown in Figure 2.



Note: *The geographic range was analyzed considering the country's quote in the article.*

Figure 2: *Geographic distribution of the review*

As can be noted, articles from European countries account for the largest share, with the main countries being the United Kingdom (29%), Spain (28%) and Italy (17%). The Americas and Asia have similar participation. In the Americas, North America (87%) stand out, with the United States leading the way (74%). South America only accounts for 13% of the articles identified, all of them from Brazil. We did not find any articles from Central America. In Asia, the standout countries are China (43%), Iran (17%) and India (12%).

We used the Science Direct database due to its accessibility, daily updating and breadth of coverage of peer-reviewed articles in the main areas of knowledge.

In step 2 we defined the search terms used to gather the material, based on the objective of the survey defined in step 1 and on a preliminary survey of the subject. We chose the following key expressions: "*scrap tire*" and "*supply chain*", "*waste tire*" and "*supply chain*", "*reverse logistics of waste tire*", "*reverse logistics of scrap tire*", "*scrap tire*" and "*recycle*", "*waste tire recycling*", "*scrap tire recycling*", "*scrap tyre*", and "*scrap tyre*" and "*Brazil*".

In line with the objective defined for the review, we established the following items for analysis of the articles collected: whether or not the article presents structuring of a reverse logistics chain for scrap tires, the type of final use covered by the article, the product generated or substituted by recycled waste tires, whether the article considers the existence of co-products, and the type of processing considered for the scrap tires.

From these items, we sought to identify the different destinations of scrap tires and to prepare a conceptual model for their reverse supply chain.

3.2. Phase 2: Execution

As described for step 3, we collected the articles by using the search terms defined in step 2, employing the advanced search option of the Science Direct portal. All told we identified 157 articles, distributed in 50 periodicals, the main ones being *Fuel* (15%), *Journal of Analytical and Applied Pyrolysis* (11%) and *Resources, Conservation and Recycling* (11%). Although the survey covered the period from 1976 to 2014, the articles were concentrated in 2012 and 2013 (25%).

To estimate the relevance of these articles to our research objective, we first analyzed the abstract, and when necessary the content of the article per se (step 4). For this purpose, we analyzed the general objective of each article and whether it presented information on a structured reverse supply chain involving scrap tires and their processing and/or possible final uses.

As a result of step 4 we obtained 110 articles, distributed by periodical, year and geographic region as shown in Figures 3, 4 and 5.

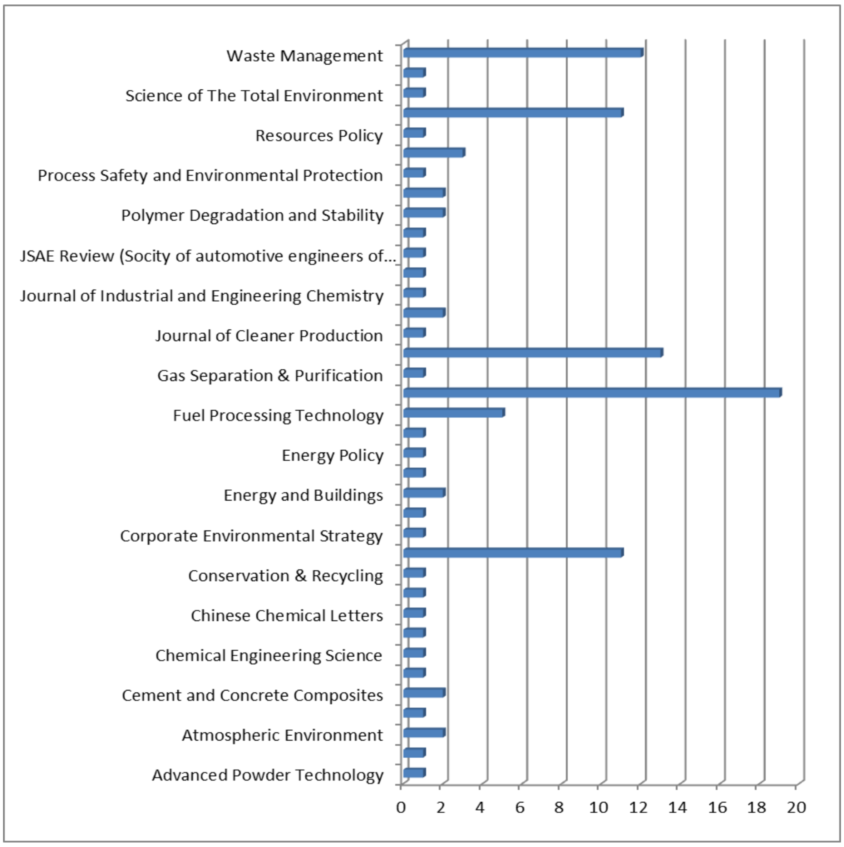


Figure 3: *Distribution of articles analyzed by periodical.*

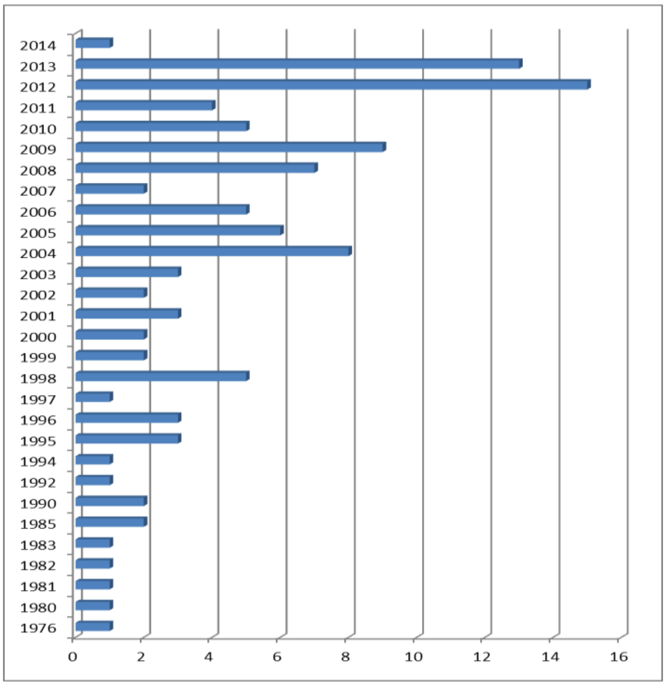
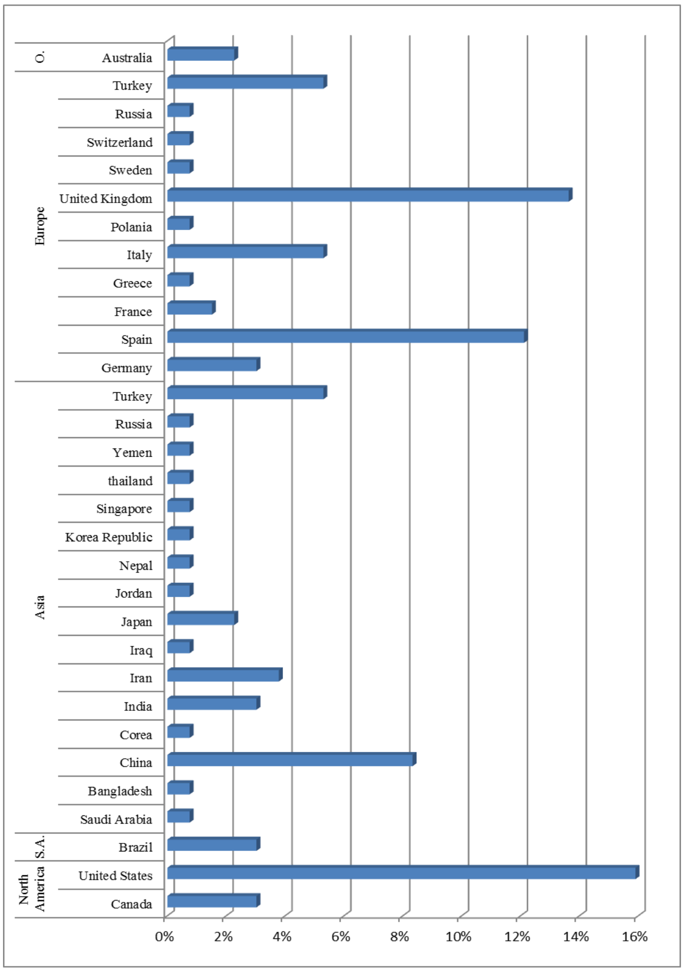


Figure 4: *Distribution of articles analyzed by year.*



Note:: Oceania; S.A .: South America

Figure 5: *Distribution of articles analyzed by region.*

After selecting the articles with possible relevance for our objective, the standout periodicals (Figure 3) were *Fuel* (17%), *Journal of Analytical and Applied Pyrolysis* (12%), *Construction and Building Materials* (10%) e *Resources, Conservation and Recycling* (10%).

With respect to the time frame, it can be seen that very few articles were found in the first three decades under analysis (1970s to 90s), only 0.8 per year on average, and only 22.7% of all the articles dated from these decades. The number of publications increased markedly thereafter, with a yearly average of 4.7 in the 2000s (42.7% of all articles) and 7.6 in the final years (2010 to 2014), accounting for 34.6% of the articles, with further concentration in 2012 and 2013 (25.5%). These findings indicate that although the problem of disposal of waste tires was identified many decades ago, discussions of mechanisms and technologies to solve this problem only has become intense in the past few years.

After the evaluation carried out in step 4, we found there were no articles addressing this issue from African countries, which can indicate that these countries are still in the initial phase of discussion of this question. The main concentration of articles was from Europe (45%), with predominance of the United Kingdom (31%), Spain (27%) and Italy (12%). In Asia (31%), the leading countries by number of articles were China (27%), Iran (12%) and India (10%). We considered Turkey, a Eurasian country, to be both in Europe (12%) and Asia (17%).

For the Americas, we found articles from North America (19%), with the United States accounting for 84% and Canada the other 16%, and South America (3%), represented only by Brazil.

The articles selected in step 4 were analyzed according to step 5 and the results (step 6) are presented in item 3.3.

3.3. Phase 3: Disclosure

We analyzed the selected articles according to the items defined in step 2. Step 6 consists of disclosure of the results of this analysis.

To facilitate comprehension of the results obtained from the literature review, these are organized in three tables (Tables 1 to 3), where they are grouped by type of industry that uses scrap tires (final user of the waste material).

3.3.1 Type of scrap tire processing

According to Amari et al. (1999), tires are generally composed of styrene-butadiene rubber or a combination of this with natural rubber. Besides rubber, tires contain carbon black, used to strengthen the rubber and increase its abrasion resistance; synthetic fibers (rayon, nylon and polyester) and steel, used to strengthen the tire; other petroleum derivatives, used to control viscosity and reduce internal friction during production and improve flexibility during vulcanization at low temperatures; and catalysts, used in the vulcanization process.

According to Souza and D'Agosto (2013) and Search and Ctvrtnicek (1976), scrap tires can be utilized whole or undergo some type of processing, usually shredding to reduce them to small particles. There are three basic types of processing: (1) mechanical, (2) cryogenic, and (3) devulcanization.

Mechanical processing mainly involves shredding or chopping the used tires into small pieces. It is typically carried out at ambient temperature (Dehghanian and Mansour, 2009). A magnetic system to remove steel and a fiber separation system can be incorporated in the shredding process to remove impurities from the rubber material (Sunthonpagasit and Duffey, 2004). Further according to those authors, this combined mechanical process is the most widely used. Mechanical processing can produce rubber particles with sizes between 0.6 and 2 mm, with a tendency to be irregularly shaped (Owen, 1998). According to CIWMB (2004), this process is relatively cheap, but the heat generated during shredding can degrade the rubber.

The main objective of the cryogenic process is to reduce the size of the particles by cooling the material to very low temperatures where it becomes extremely fragile (approximately -200 ^{o}C), generally using liquid nitrogen (Dehghanian and Mansour, 2009; Liang and Hao, 1999; Owen, 1998). Nitrogen is used because of various advantages, among them: inertness; good cooling ability at low pressure; rapid heat transfer; low boiling point at atmospheric pressure; moderately high refrigeration value; and easy flow control (Liang and Hao, 1999). According to Owen (1998), this process is carried out in the absence of oxygen.

The cryogenic technique can be applied both to whole tires and shredded material from mechanical processing. In either case, the material is cooled to the point of extreme brittleness and is placed in a hammer grinder where the material is fractured, followed by separation of rubber, steel and synthetic fibers.

According to Corti and Lombardi (2004), cited in Dehghanian and Mansour (2009), the advantage of this process over others is the large quantity of high-quality rubber that can be recovered. The rubber particles obtained are uniformly shaped without alteration of their composition or thermal degradation (Owen, 1998).

The devulcanization process aims to recover the properties of vulcanized rubber so that the recycled material can be reused in place of virgin rubber. According to CIWMB (2004), this process consists of two steps: (1) pre-processing, to reduce the size of the waste rubber and remove unwanted elements, such as steel and synthetic fibers; and (2) the devulcanization process itself, which breaks the chemical bonds existing in vulcanized rubber.

The size of the material to be devulcanized (step 1) can be reduced by mechanical or cryogenic processing, as described previously. A common feature of all devulcanization methods is the need for very small vulcanized rubber particles. The reason is that the chemical, thermal or biological conversion subsystems only work efficiently with fine particles, because a high relative surface area is necessary for effective devulcanization reactions (CIWMB, 2004).

As reported by CIWMB (2004), the devulcanization process can be carried out by chemical, ultrasound, microwave, biological, mechanical or steam processing, or a combination of biological and microwave action. According to Dubkov et al. (2012), the method using ultrasound is still in the initial development phase, only having been applied on a pilot scale. Besides this, the equipment is expensive and requires high energy inputs.

After processing, the co-products (steel and synthetic fibers) are separated out. Usually the steel is removed by magnets and the synthetic fibers by aspiration. These co-products can be used by other industries, reducing the unusable waste from scrap tires and generating complementary revenue for the processor.

In the case of steel particles, they can be used by steel mills (Souza and D'Agosto, 2013) to make new steel or by the construction industry, mainly to reinforce concrete (Centonze et al., 2012). In turn, the synthetic fibers, composed variously of rayon, nylon and/or polyester, can be used by the pulp and paper industry to reinforce cardboard boxes (Lagarinhos, 2008) and the asphalt industry, where they can be used as stabilizing additives to improve drainage capacity (Putman and Amirkhanian, 2004).

The processing of scrap tires can still leave unusable waste material, which according to PNRS (2010) is all the solid residue that cannot be treated and recovered by the available and economically feasible technologies. This material needs to be sent to landfills or other adequate disposal sites.

3.3.2 Final users of scrap tires

As shown in Tables 1 to 3, the industries that can use scrap tire material in their productive process can be classified into six groups: (1) rubber articles industry, (2) asphalt industry, (3) construction industry, (4) cement industry, (5) fuel industry; and (6) other industries. Souza and D'Agosto (2013) also mention the use of this material in the pulp and paper industry.

In the rubber articles industry (Table 1), there are various possibilities for use of recycled scrap tires, from floor tiles/sheets and playground paving material to recovery of rubber (also called devulcanization). Among other rubber articles, this recovered rubber can be used to make new tires (Fukumori et al., 2002), thus configuring a closed-cycle reverse supply chain. However, in relation to playground pavement, consideration should go to the possible presence of compounds that are harmful to human health, as pointed out by Llompart et al. (2013), so there should be careful controls or even restrictions on use for this purpose.

In the asphalt industry, the addition of scrap tire material is used to modify the asphalt's characteristics, for application to roads or other surfaces. This modified asphalt comes in two types, depending on the recycling process: (1) asphaltic concrete, obtained by dry processing, and (2) asphalt-rubber, obtained from wet processing. According to Celauro et al. (2012), besides the employment of water or not, the two processes also stand apart according to the amount of material added, its granulometry, the number of other components and the type of production equipment used. The dimensional variation of the rubber particles used in the dry process (0.1 to 6.4 mm) is considerably larger than that of the wet process (0.1 to 0.74 mm). This occurs because in the dry process the rubber is added to the bitumen aggregate before being mixed with a binder (Navarro et al., 2004; Celauro et al., 2012). Although this process improves the mixture's resistance at intermediate temperatures, it does not inhibit the occurrence of cracks at low temperatures (Navarro et al., 2004). In turn, in the wet process, the finely ground rubber is added to the binder at high temperatures, causing a reaction that modifies the original properties of the binder (Navarro et al., 2004; Celauro et al., 2012). Unlike what happens in the dry process, the asphalt-rubber produced by the wet process has high resistance to cracking.

Table 1 shows that 14.3% of the articles analyzed cover the dry process, while 71.4% refer to the wet process and 14.3% refer to both processes.

In the construction industry, recycled scrap tire material is mainly used for landfill (28%) and as aggregate for cement (68%). For landfill purposes, the objective is usually to fill in a determined space with lighter material that does not easily decompose (reducing the possibility of subsidence). As aggregate it can replace sand or gravel in different applications, such as cement paste (5.55%), mortar (11.11%), concrete (66.68%), controlled low-strength material - CLSM (11.11%) and bricks (5.55%).

In the case of replacement of sand, usually the tire material is used without steel and fibers. Turgut and Yesilata (2008) focus on the use of recycled tire rubber as an aggregate in cement to make bricks, while Yesilata et al. (2011) discuss its use to improve the thermal protection of bricks. In both cases, there is a need to use material with small grain sizes. Tires of virtually all types can be used (bicycle, car, bus, truck, etc.). In the literature review, we only identified the use of car and truck tires for this purpose, but 71.8% of the articles (79) did not specify the tire type, since the material analyzed had been acquired already processed. The construction industry can also use the steel retrieved from shredded scrap tires (co-product) as cement aggregate (Centonze et al., 2012).

The cement and fuel industries can also use scrap tire material as an energy source through thermal conversion. According to Galvagno et al. (2002), there are three thermal conversion methods: (1) incineration, (2) gasification and (3) pyrolysis. The difference among them refers to the operational conditions, and consequently the products generated.

While in the incineration process, the material is totally consumed, releasing the energy contained in the residue, the main objective of the other two techniques (gasification and pyrolysis) is to recover the byproducts to transform them into oil, gas and carbon residue (Galvagno et al., 2002).

In the cement industry, scrap tire material is used to replace other fuels (the main one being petroleum coke) in the process of making clinker from finely powdered material (generally a mixture of lime and clay). For this purpose, the scrap tires are usually subjected to mechanical processing to generate particles with size of approximately 50 mm, without removal of steel and synthetic fibers. The material is then incinerated to produce heat and the ashes left over are added to the clinker material.

In the fuel industry, gasification and pyrolysis of scrap tire material are used to produce oil, gas and carbon residue. According to López et al. (2012), gasification is a thermo-chemical process by which a carbon-based material, such as scrap tire shreds, is converted into a gas, composed mainly of carbon monoxide (CO) and hydrogen (HC), but the gas can also contain carbon dioxide (CO_2) and light hydrocarbons (methane, ethane, propane and butane). The composition depends on the operational conditions of the converter (or reactor), such as temperature and composition of the gasification agent (air, oxygen and/or steam). The resulting mixture of gases, also called synthetic gas or "syngas", can be burned in gas turbines and fuel cells after a scrubbing stage. The possibility of using this fuel depends on the composition of the original material and the final application (López et al., 2012).

In the bibliographic review (Table 2) we found that 6.2% of the articles mentioning the use of scrap tires in the fuel industry focused on gasification, using rubber particles with size between 0.1 and 4.5 mm. Of these, 75% involved generation of gas and 25% generation of gas and carbon residue.

Pyrolysis, as explained by Galvagno et al. (2002) and López et al. (2012), is a thermochemical decomposition process where the input material is indirectly burned in an oxygen-free atmosphere. The entire process consists of a series of parallel and subsequent reactions inside a pyrolytic reactor. According to Galvagno et al. (2002), this process normally generates three types of products: (1) a gas fraction, composed essentially of hydrogen, methane and carbon oxides; (2) a liquid fraction, composed of water, tar and oils (organic compounds); and (3) a solid residue containing carbon and ashes (metals, oxides and inert materials).

The yield from the reaction (or conversion) and the composition of these fractions depend on processing parameter values (temperature, heating rate, pressure, residence time and granulometry of the material) and the condensation temperature of the volatile fraction (Galvagno et al., 2002; López et al. 2012).

Part of the gases resulting from pyrolysis can be used to generate heat for the pyrolysis process itself. They can also be used directly in the form of extracts from the reactor or be converted into products with higher aggregate value, such as commercial fuels and chemical products (Lucchesi et al., 1982; Bridgewater et al., 1999, cited in Galvagno et al., 2002).

Table 2 shows that among the articles citing the use of scrap tire material in the fuel industry, 91.8% consider the pyrolysis process. Of these, 2.2% mention coke (from carbon residue) as the product generated, while 4.5% only mention generation of gas, 11.1% only generation of oil, 48.9% cover oil and gas, and 33.3% generation of oil, gas and carbon residue.

The authors consider the use in pyrolysis of rubber particles in the size range of 0.1 to 400 mm. Williams et al. (1998), Kaminsky (1980) and Kaminsky (1985) also mention the use of whole tires. Only 2% of the articles mention both pyrolysis and gasification to obtain oil, gas and carbon residue, in these cases with rubber particles smaller than 12 mm.

Besides the industries mentioned above, we also found articles discussing the use of scrap tires in other industries, with a variety of uses, such as absorbents for oil spills in water bodies (10%), water filter ballast (10%), electricity generation (10%), fabrication of carbon namomaterials (20%) and manufacture of activated charcoal (50%), usually from the carbon residue from pyrolysis.

In this group (other industries), the articles refer to use of several tire types (bicycle, car, truck) and a wide range of particle sizes (0.5 to 20 mm) due to the diversity of final use.

Based on analysis of the content of the articles found, it was possible to prepare a conceptual model for the reverse logistics chain of scrap tires, described next.

4. REVERSE SUPPLY CHAIN FOR SCRAP TIRES

Souza and D'Agosto (2013) carried out a review of the Brazilian and international literature on management of scrap tires. From the articles analyzed, they found that the existence of particularities and factors such as varied legislation and regulation, regional cultural differences and territorial extension influences this management.

The main sources of scrap tires found were bus companies and scrap dealers, and 75% of the articles covered a single aggregation point (deposit). In 33% of the articles the authors reported the occurrence of sorting at the deposit point. In all the countries analyzed there was processing of scrap tires, with the main users of the material being cement makers (mentioned in 100% of the articles analyzed) and manufacturers of rubber articles (Souza and D'Agosto, 2013).

Based on this information and analysis of Tables 1 to 3, presented in section 3, we prepared a model for the reverse supply chain of scrap tires (Figure 6).

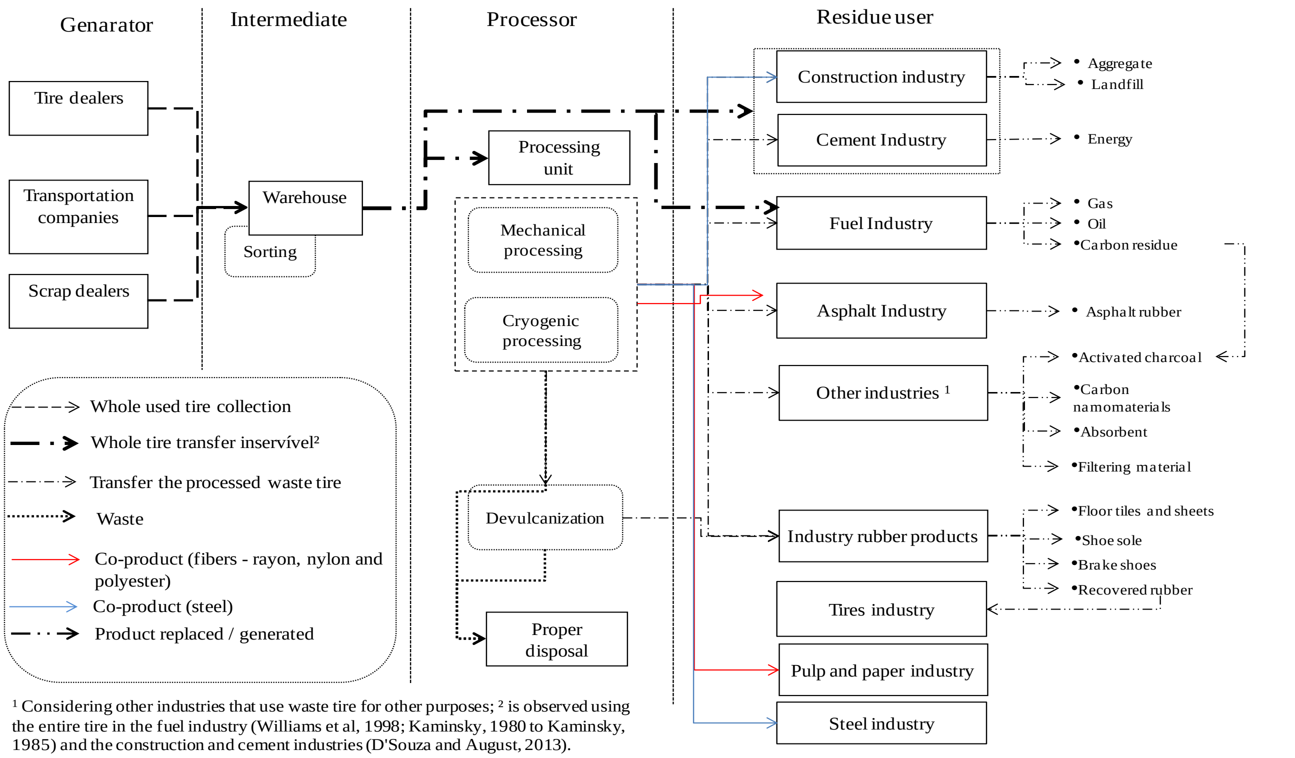


Figure 6: *Model for scrap tire reverse logistics chain.*

After preliminary sorting, the scrap tires are sent by the generating source to a deposit (intermediary), which can be located next to or near the generator, processor or user of the waste, or situated at a strategic site in relation to the other participants in the chain. At this deposit, the main sorting is carried out, to separate the tires that are really unserviceable from those that can be recapped, for delivery to a scrap processor or retreadder. The generator and intermediary are not directly affected by the definition of final use of the scrap material.

According to Souza and D'Agosto (2013), the scrap tires can be used whole by construction companies (as landfill) and cement makers (energy). However, it is most common to submit the tires to processing, depending on the intended final use. This processing can be mechanical, cryogenic or devulcanization. The final use will also determine the particle size and quality (content of steel and fibers), which directly influence the resources (financial, technological and human) necessary for processing.

According to Fleischmann et al. (1997), in the case of reverse supply chains, the impact of logistics costs grows with the degree of uncertainty regarding the quantity and quality of the waste material. In the case of unserviceable tires, this impact can be particularly high because tires cannot be compacted for transport and storage, making these steps more difficult and costly (Nohara et al., 2006; Aylon et al., 2009). The costs must also be considered of delivering the final waste material to the user and storage there before use.

Because of the need to reduce these costs, especially transport of whole tires, processors should be located near the waste source (Sunthonpagasit and Duffey, 2004). The transport costs are influenced by various factors, among them the type of vehicle, type of waste, distance between generator and processor, etc. In this respect, location of the intermediary at a strategic point for aggregating the waste material for later transfer at lower cost (scale gains) can be advantageous. However, there is a tradeoff between transport and storage costs.

The processing cost also obviously has a strong influence on the overall cost of the reverse supply chain. Souza and D'Agosto (2013b) analyzed the use of scrap tires by a cement maker and found that the processing cost accounted for 30% of the cost of the final material obtained.

The choice of the right equipment for the final use and scale gains can help reduce the costs. The sale of co-products obtained from processing, like steel and synthetic fibers, can also help the bottom line, as can reduced generation of unusable material through efficient processing. This unusable material, regardless of the process used, should be sent to a suitable disposal site.

The information in Tables 1 to 3 shows that the material produced by mechanical or cryogenic processing can be sent to the construction, cement, fuel, asphalt and rubber articles industries, as well as companies in other industries for various uses.

Table 1: *Possible final uses of scrap tires.*

Final use	Product generated/substituted	Process used[1]	Type of tire	Specification of processed material	Process used in recycling[2]	Reference	Observation
Rubber articles industry	Recovered rubber	Mechanical / cryogenic	Car and/or Truck	1 to 5 mm	Chemical	Dubkov et al. (2012); Fukumori et al. (2002);	
	Brake shoes	NI	NI	0.595 to 0.841 mm	Chemical	Chung and Hong (2013);	
	Different uses	NI	NI	NI	NI	Smith et al. (1995);	
	Floor tiles and sheets					Krüger et al. (2013); Llompart et al. (2013)	
	Playground pavement material					Llompart et al. (2013)	
Asphalt industry	Asphalt-rubber	NI	NI	0.1 to 6.4 mm	Dry	Huang et al. (2007); Moreno et al. (2012)	
		Cryogenic / mechanical	NI	0.1 to 0.74 mm	Wet	Huang et al. (2007); Almeida Junior et al. (2012); Navarro et al. (2004); Celauro et al. (2012); Wang et al. (2012); Xiao et al. (2009)	
	Asphaltic concrete modified with addition of rubber	Cryogenic	NI	3 to 13 mm	Dry	Putman and Amirkhanian (2004)	Use of co-product (nylon)
Construction industry	Landfill	NI	NI	0.6 to 300 mm	Mixture / filling	Youwai and Bergado (2004); Aderinlewo and Okine (2009); Tafreshi and Norouzi (2012); Shalaby and Khan (2005); Lisi et al. (2004); Yoon et al. (2006); Edinçliler et al. (2010)	
	Aggregate	Mechanical / Cryogenic	Car, Truck	0.075 to 450 mm	Mixture	Eldin and Senouci (1994); Meyer (2009); Fattuhi and Clark (1996); Ganjian et al. (2009); Uygunoglu and Topçu (2010); Najim and Hall (2012); Turgut and Yesilata (2008); Bantsis et al. (2012); Yesilata et al. (2011); Chulin et al. (2011); Thomas et al. (2012); Siddique (2009); Pierce and Blackwell (2003); Siddique and Naik (2004); Batayneh et al. (2008); Wu and Tsai (2009); Aiello and Leuzzi (2010)	
	Aggregate	NI	NI	0.24 mm	Mixture	Centonze et al. (2012)	Use of co-product (steel)
Cement industry	Co-processing	Mechanical	Bus	50 mm	Incineration	Souza and D'Agosto (2013); Dong et al. (2013)	

Table 2: Possible final uses for scrap tires – continued.

Final use	Product generated/substituted	Process used[1]	Type of tire	Specification of processed material	Process used in recycling[2]	Reference	Final use
Fuel industry	Coke	NI	NI	NI	Pyrolysis	Chaala and Roy (1996)	
	Generation of gas	NI	NI	0.1 to 4.5 mm	Gasification	Karatas et al. (2012); Piatkowski and Steinfeld (2010);	
		Mechanical / cryogenic	NI	0.1 to 12.7 mm	Pyrolysis	López et al. (2010); Roy et al. (1992)	
	Generation of oil	NI	Car	0 to 1.5	Pyrolysis	Kebritchi et al. (2013); Williams and Brindle (2003)	
		NI	Car, Truck	1 to 3 mm	Pyrolysis	Hariharan et al. (2013); Sharma and Murugan (2013); Frigo et al. (2014)	Test in diesel engine
	Generation of oil and gas	Mechanical / Cryogenic	Bicycle, Car and Truck	0.1 to 400 mm	Pyrolysis	Chen et al. (2007); Islam et al. (2004); Stelmachowski (2009); Uçar et al. (2005); Murillo et al. (2006); Rushdi et al. (2013); Williams et al. (1990); Williams and Bottrill (1995); Kershaw (1998); Money and Harrison (1999); Uçar et al. (2005); López et al. (2013); Cunliffe and Williams (1998); Leung and Wang (1998); Aguado et al. (2005); Berrueco et al. (2005); Olazar et al. (2008); González et al. (2001); Fernández et al. (2012); Qu et al. (2006); Williams et al. (1998); Quek and Balasubramanian (2013)	
		NI	NI	Entire	Pyrolysis	Williams et al. (1998)	
	Generation of oil, gas and carbon residue	Mechanical / Cryogenic	Car, Truck	< 8 to 150 mm	Pyrolysis	Flecher and Wilson (1981); Acevedo et al. (2013); López et al. (2011); Niksiar el at (2013); Appleton et al. (2005); Lucchesi and Maschio (1983); Rodriguez et al. (2001); Avenell et al. (1996); Napoli et al. (1997); Kaminsky and Mennerich (2001); Kaminsky (1980); Saraf et al. (1995); Roy et al. (1990); Galvagno et al. (2002); Kaminsky (1985)	
		NI	NI	< 12 mm	Pyrolysis and Gasification	López et al. (2012)	
		NI	Car	Entire	Pyrolysis	Kaminsky (1980); Kaminsky (1985)	
	Generation of gas and carbon residue	NI	NI	2 mm	Gasification	Galvagno et al. (2009);	

Table 3: Possible final uses for scrap tires – continued.

Final use	Product generated/substituted	Process used[1]	Type of tire	Specification of processed material	Process used in recycling[2]	Reference	Observation
Other industries	Absorbent	NI	NI	0.4 to 4 mm	Absorption	Lin et al. (2008)	
	Activated charcoal	NI	Car, Truck	2 to 20 mm	Pyrolysis and activation	Min and Harris (2006); Giavarini (1985); Sainz-Diaz and Griffiths (2000); Barbooti et al. (2004); Hajizadeh et al. (2011)	
	Filtering material	NI	NI	0.5 to 4 mm	Filtering	Tang et al. (2006)	
	Electricity generation	NI	NI	NI	Incineration	Nimmo et al. (2008)	
	Carbon namomaterials	NI	Bicycle	NI	Chemical vapor deposition	Yang et al. (2012)	
		NI	NI	76 to 13 mm	Pyrolysis, catalytic synthesis	Alves et al. (2012)	

Inadequate disposal	None	None	NI	NI	NI	Shakya et al. (2008)	Outdoor burning
Processing	-	NI	NI	NI	NI	Liang and Hao (2000); Chien et al. (2003); Biddulph and Burford (1982); Figueiredo and Mayerle (2008); Sunthonpagasit and Duffey (2004)	Refers to the theory of scrap tire processing
Different uses	NI	NI	NI	NI	NI	Dehghanian and Mansour (2009); Amari et al. (1999); Search and Ctvrtnicek (1976); Owen (1998)	Has no application, only conceptual

For devulcanization, the tires first need to undergo mechanical or cryogenic pre-processing. Besides this, the rubber particles need to be free of steel and fiber residues. After devulcanization, the material can be reused to make new tires or other rubber articles. The co-products generated in the processing (steel and fibers) can also be incorporated in a new productive process.

According to Souza and D'Agosto (2013), the processing technology and final use of scrap tires depends on the legal and regulatory rules of the country or sub-national jurisdiction, the available technology and the economic feasibility.

In general, there is strong concern over proper use of recycled scrap tire material and disposal of the unusable waste throughout the world. Countries like the United States, United Kingdom, Canada, Australia, Germany, France and Italy, among others, have laws and regulations mandating proper disposal of scrap tires. In most of these countries, the disposal of scrap tires in landfills is prohibited, encouraging the reuse of the processed material (Souza, 2011).

Brazil has a National Solid Waste Management Policy, known by the initials PNRS, supported by a series of regulations issued in the form of normative resolutions that set targets for municipal and state governments regarding disposal of waste tires. The overall policy vision is that solid wastes must be managed based on systematic considerations and sustainable development (PNRS, 2010).

5. CONCLUSION

The aim of this work was to gather information for formulation of a reverse supply chain model for scrap tires considering different final uses for the various types of waste material produced from them. That model permits better understanding of the various technologies for recycling and uses of the material obtained, as well as adequate disposal of the unusable portion. The model enables perceiving the relations among the various elements of the reverse supply chain and which elements and processes are influenced by the choice of final use.

This model is innovative because it allows observing not only the elements in the chain, but also their relations and the flow of scrap tires and the material produced from them along the chain. The model considers the existence of co-products and the possibilities of using these in new productive cycles, thus reducing the consumption of virgin raw materials and minimizing the environmental impacts. Besides this, it also considers the generation of unusable waste from processing scrap tires and suitable treatment and disposal of this portion of the material.

To prepare the model we carried out a systematic bibliographic review, based on a procedure prepared by us (Figure 1). By applying this procedure, we obtained 157 articles, of which 110 presented a contribution regarding the reverse supply chain of scrap tires.

From analyzing these articles, we verified that 49% consider the use of the recycled material in the fuel industry, to generate gas and oil that can partially replace petroleum derivatives. That concentration of articles on this particular aspect can be associated with the search for new energy alternatives and the fact that because it is still an unconsolidated application, there is room for a wider range of tests and evaluations.

Of the articles found, 25% discuss the use of scrap tires in the construction industry, not only to reduce costs but also improve the products generated. In this sense, there appears to be a trend in this sector to search for new materials, recycled when possible, that can reduce the problems of shortage of material resources, to reduce operating costs and improve the sector's image.

A further 8% of the articles are associated with the use of scrap tires in the asphalt industry, 6% in the rubber articles industry and 2% in the cement industry, mainly presenting more consolidated technologies. The remaining 10% of the articles involve other industries, where the use of this material is still incipient.

Mechanical processing of scrap tires is the method most widely utilized according to the literature consulted, even though cryogenic processing produces a more homogeneous and higher quality product.

Devulcanization appears not to be a consolidated process yet. Besides this, it is expensive, with the capital cost ranging from $ 92,000.00 to $ 166,000.00 (CIWMB, 2004).

In principle, any type of tire (bicycle, motorcycle, car, bus, truck, offroad vehicle, airplane etc.) can be submitted to mechanical, cryogenic or devulcanization processing to produce recycled materials for any of the industries in the reverse supply chain model developed here. However we did not find any specific articles dealing with motorcycle, airplane or offroad vehicle tires.

Among the final uses found in the literature review, asphalt-rubber requires the smallest particles (without steel and synthetic fibers), making the processing more expensive.

Of the recycling processes noted in the articles analyzed, thermal processes predominated – incineration, gasification and pyrolysis, together accounting for 51%, with 88.2% of these articles referring to pyrolysis.

More than just the rubber from scrap tires can be reintroduced in a productive cycle. The steel and fibers, used to reinforce tires, also have a market and can generate additional revenue. Moreover, this practice reduces the waste generated along the chain, minimizing potential environmental impacts.In the works analyzed, we did not find any clear indications of the amount of unusable material left over after tire processing. However, this possibility certainly exists, and the material needs to be disposed of properly.

As a limitation of this study, we point out that the reverse supply chain model presented here does not exhaust all the possibilities for using scrap tires. Our aim is to present the trends observed in the literature. For future works, we can suggest analysis considering the environmental and social costs and impacts generated by each of the final uses identified.

REFERENCES

Acevedo, B.; Barriocanal, C.; Alvarez, R. (2013) Pyrolysis of blends of coal and tyre wastes in a fixed bed reactor and a rotary oven. Fuel, Volume 113, pp. 817-825.

Aderinlewo, Olufikayo; Okine, Nii-Attoh (2009) Sensitivity analysis of a scrap tire embankment using Bayesian influence diagrams. Construction and Building Materials, Volume 23, Issue 3, pp. 1446-1455.

Aiello, M.A. e Leuzzi, F. (2010) Waste tyre rubberized concrete: Properties at fresh and hardened state. Waste Management, Volume 30, Issues 8–9, pp. 1696-1704.

Almeida Júnior, Adão Francisco de; Battistelle, Rosane Aparecida; Bezerra, Barbara Stolte; Castro, Rosani de (2012) Use of scrap tire rubber in place of SBS in modified asphalt as an environmentally correct alternative for Brazil. Journal of Cleaner Production, Volume 33, pp. 236-238.

Alves, Joner Oliveira; Tenório, Jorge Alberto Soares; Zhuo, Chuanwei; Levendis, Yiannis Angelo (2012) Use of Stainless Steel AISI 304 for Catalytic Synthesis of Carbon Nanomaterials from Solid Wastes. Journal of Materials Research and Technology, Volume 1, Issue 3, pp. 128-133.

Amari, Takeshi; Themelis, Nickolas J.; Wernick, Iddo K. (1999) Resource recovery from used rubber tires . Resources Policy, Volume 25, Issue 3, pp. 179-188.

Appleton, T.J.; Colder, R.I.; Kingman, S.W.; Lowndes, I.S.; Read, A.G. (2005) Microwave technology for energy-efficient processing of waste. Applied Energy, Volume 81, Issue 1, pp. 85-113.

Avenell, Christopher S.; Sainz-Diaz, C. Ignacio; Griffiths; Anthony J. (1996) Solid waste pyrolysis in a pilot-scale batch pyrolyser. Fuel, Volume 75, Issue 10, pp. 1167-1174.

Bantsis, G.; Mavridou, S.; Sikalidis, C.; Betsiou, M. ; Oikonomou, N.; Yioultsis,T. (2012) Comparison of low cost shielding-absorbing cement paste building materials in X-band frequency range using a variety of wastes. Ceramics International, Volume 38, Issue 5, pp. 3683-3692.

Barbooti, Mahmood M.; Mohamed, Thamer J.; Hussain, Alaa A.; Abas, Falak O. (2004) Optimization of pyrolysis conditions of scrap tires under inert gas atmosphere. Journal of Analytical and Applied Pyrolysis, Volume 72, Issue 1, pp. 165-170.

Batayneh, Malek K.; Marie, Iqbal; Asi, Ibrahim (2008) Promoting the use of crumb rubber concrete in developing countries. Waste Management, Volume 28, Issue 11, pp. 2171-2176.

Berrueco, C.; Esperanza, E.; Mastral, F.J.; Ceamanos, J.; García-Bacaicoa, P. (2005) Pyrolysis of waste tyres in an atmospheric static-bed batch reactor: Analysis of the gases obtained. Journal of Analytical and Applied Pyrolysis, Volume 74, Issues 1–2, pp. 245-253.

Biddulph, M.W. e Burford, R.P. (1982) Thermal properties and heat transfer coefficients in cryogenic cooling. Cryogenics, Volume 22, Issue 6, pp. 283-286.

Celauro, Bernardo; Celauro, Clara; Presti, Davide Lo; Bevilacqua, Antonio (2012) Definition of a laboratory optimization protocol for road bitumen improved with recycled tire rubber. Construction and Building Materials, Volume 37, pp. 562-572.

Centonze, G., Leone, M.; Aiello, M.A. (2012) Steel fibers from waste tires as reinforcement in concrete: A mechanical characterization. Construction and Building Materials, Volume 36, pp. 46-57.

Chaala, A. e Roy,C. (1996) Production of coke from scrap tire vacuum pyrolysis oil. Fuel Processing Technology, Volume 46, Issue 3, pp. 227-239.

Chien, Yeh-Chung; Ton, Shanshin; Lee, Ming-Huang; Chia, Taipau; Shu, Hung-Yee; Wu, Yuh-Shen (2003) Assessment of occupational health hazards in scrap-tire shredding facilities. Science of The Total Environment, Volume 309, Issues 1–3, pp. 35-46.

Chung, Kyungho and Hong, Youngkeun (2013) Friction and wear properties of scrap tire/potassium hexatitanate whisker composites. Journal of Industrial and Engineering Chemistry, Volume 19, Issue 4, pp. 1234-1240.

Chunlin, Liu; Kunpeng, Zha; Depeng, Chen (2011) Possibility of Concrete Prepared with Steel Slag as Fine and Coarse Aggregates: A Preliminary Study. Procedia Engineering, Volume 24, pp. 412-416.

California Integrated Waste Management Board – CIWMB (2004) Evaluation of Waste Tire Devulcanization Technologies.

Cunliffe, Adrian M. and Williams, Paul T. (1998) Composition of oils derived from the batch pyrolysis of tyres. Journal of Analytical and Applied Pyrolysis, Volume 44, Issue 2, pp. 131-152.

Dehghanian, Farzad; Mansour, Saeed. 2009. Designing sustainable recovery network of end-of-life products using genetic algorithm. Resources, Conservation and Recycling, Volume 53, Issue 10, p. 559-570.

Dubkov, K.A.; Semikolenov, S.V.; Ivanov, D.P.; Babushkin, D.E.; Panov, G.I.; Parmon, V.N. (2012) Reclamation of waste tyre rubber with nitrous oxide. Polymer Degradation and Stability, Volume 97, Issue 7, pp. 1123-1130

Edinçliler, Ayse; Baykal, Gökhan; Saygili, Altug (2010) Influence of different processing techniques on the mechanical properties of used tires in embankment construction. Waste Management, Volume 30, Issue 6, pp. 1073-1080.

Eldin, Neil N. e Senouci, Ahmed B. (1994) Measurement and prediction of the strength of rubberized concrete. Cement and Concrete Composites, Volume 16, Issue 4, pp. 287-298.

United States Environmental Protection Agency – EPA (2010) Scrap Tires: Handbook on Recycling Applications and Management for the U.S and Mexico.

Smith, F.G; Daniels, E.J. and Teotia, A.P.S. (1995)Testing and evaluating commercial applications of new surface-treated rubber technology utilizing waste tires. Resources, Conservation and Recycling, Volume 15, Issue 2, pp. 133-144.

Fattuhi, N.I. and Clark, L.A. (1996) Cement-based materials containing shredded scrap truck tyre rubber. Construction and Building Materials, Volume 10, Issue 4, pp. 229-236.

Fernández, A.M.; Barriocanal, C.; Alvarez, R. (2012) Pyrolysis of a waste from the grinding of scrap tyres. Journal of Hazardous Materials, Volumes 203–204, pp. 236-243.

Figueiredo, João Neiva de and Mayerle, Sérgio Fernando (2008) Designing minimum-cost recycling collection networks with required throughput. Transportation Research Part E: Logistics and Transportation Review, Volume 44, Issue 5, pp. 731-752.

Fleischmann, Moritz; Beullens, Patrick; Bloemhof-Ruwaard, Jacqueline M; Van Wassenhove, Luk N. (2000) The Impact of Product Recovery on Logistics Network Design. INSEAD R&D.

Fleischmann, Moritz; Bloemhof-Ruwaard, Jacqueline M.; Dekker, Rommert; Van der Laan, Erwin; Van Nunen, Jo A.E.E.; Van Wassenhove, Luk N.(1997) Quantitative models for reverse logistics: A review. European Journal of Operational Research 103, 1-17.

Fletcher, R.A. and Wilson, H.T. (1981) The role of pyrolysis in the disposal of waste tyres. Resource Recovery and Conservation, Volume 5, Issue 4, pp. 333-342.

Frigo, Stefano; Seggiani, Maurizia; Puccini, Monica; Vitolo, Sandra (2014) Liquid fuel production from waste tyre pyrolysis and its utilisation in a Diesel engine. Fuel, Volume 116, pp. 399-408.

Fukumori, Kenzo; Matsushita, Mitsumasa; Okamoto, Hirotaka; Sato, Norio; Suzuki, Yasuyuki; Takeuchi, Katsumasa (1995) Testing and evaluating commercial applications of new surface-treated rubber technology utilizing waste tires. Resources, Conservation and Recycling, Volume 15, Issue 2, pp. 133-144.

Galvagno, S.; Casciaro, G.; Casu, S.; Martino, M.; Mingazzini, C.; Russo, A.; Portofino, S. (2009) Steam gasification of tyre waste, poplar, and refuse-derived fuel: A comparative analysis. Waste Management, Volume 29, Issue 2, pp. 678-689.

Galvagno, S.; Casu, S.; Casabianca, T.; Calabrese, A.; Cornacchia, G. (2002) Pyrolysis process for the treatment of scrap tyres: preliminary experimental results. Waste Management, Volume 22, Issue 8, pp. 917-923.

Ganjian, Eshmaiel; Khorami, Morteza; Maghsoudi, Ali Akbar (2009) Scrap-tyre-rubber replacement for aggregate and filler in concrete. Construction and Building Materials, Volume 23, Issue 5, pp. 1828-1836.

Giavarini, Carlo (1985) Active carbon from scrap tyres. Fuel, Volume 64, Issue 9, pp. 1331-1332.

González, Juan F; Encinar, José M; Canito, José L; Rodríguez, Juan J (2001) Pyrolysis of automobile tyre waste. Influence of operating variables and kinetics study. Journal of Analytical and Applied Pyrolysis, Volumes 58–59, 1 pp. 667-683.

Grunow, M.; Gobbi, C. (2009) Designing the reverse network for WEEE in Denmark. CIRP Annals - Manufacturing Technology 58, 391–394.

Hajizadeh, Yaghoub; Onwudili, Jude A.; Williams, Paul T. (2011) Removal potential of toxic 2378-substituted PCDD/F from incinerator flue gases by waste-derived activated carbons. Waste Management, Volume 31, Issue 6, pp. 1194-1201.

Hariharan, S.; Murugan, S.; Nagarajan, G. (2013) Effect of diethyl ether on Tyre pyrolysis oil fueled diesel engine. Fuel, Volume 104, pp. 109-115.

Huang, Yue; Bird, Roger N.; Heidrich, Oliver (2007) A review of the use of recycled solid waste materials in asphalt pavements. Resources, Conservation and Recycling, Volume 52, Issue 1, pp. 58-73.

Islam, M.N; Islam, M.N; Beg, M.R.A (2004) The fuel properties of pyrolysis liquid derived from urban solid wastes in

Bangladesh. Bioresource Technology, Volume 92, Issue 2, pp. 181-186.

Kaminsky, W. (1985)Thermal recycling of polymers. Journal of Analytical and Applied Pyrolysis, Volume 8, pp. 439-448.

Kaminsky, Walter (1980) Pyrolysis of plastic waste and scrap tyres in a fluid bed reactor. Resource Recovery and Conservation, Volume 5, Issue 3, pp. 205-216.

Kaminsky, Walter and Mennerich, Carsten (2001) Pyrolysis of synthetic tire rubber in a fluidised-bed reactor to yield 1,3-butadiene, styrene and carbon black. Journal of Analytical and Applied Pyrolysis, Volumes 58–59, pp. 803-811.

Karatas, Hakan; Olgun, Hayati; Akgun, Fehmi (2012) Experimental results of gasification of waste tire with air&CO2, air&steam and steam in a bubbling fluidized bed gasifier. Fuel Processing Technology, Volume 102, pp. 166-174.

Kebritchi, Abbas; Firoozifar, Hasan; Shams, Kayghobad; Jalali-Arani, Azam (2013) Effect of pre-devulcanization and temperature on physical and chemical properties of waste tire pyrolytic oil residue. Fuel, Volume 112, pp. 319-325.

Kershaw, John R. (1998) Supercritical fluid extraction of scrap tyres. Fuel, Volume 77, Issues 9–10, pp. 1113-1115.

Krüger, O.; Kalbe, U.; Richter, E.; Egeler, P.; Römbke, J.; Berger,W. (2013) New approach to the ecotoxicological risk assessment of artificial outdoor sporting grounds. Environmental Pollution, Volume 175, pp. 69-74.

Lagarinhos, C.A.F., Tenório, J.A.S. (2008). Reutilização, reciclagem e valorização energética de pneus no Brasil. Revista Polímeros: Ciência e Tecnologia, vol.18, nº2, p.106-118.

Leung, D.Y.C. and Wang, C.L (1998) Kinetic study of scrap tyre pyrolysis and combustion. Journal of Analytical and Applied Pyrolysis, Volume 45, Issue 2, pp. 153-169.

Liang S. B. and Hao, Y. C. (2000) A novel cryogenic grinding system for recycling scrap tire peels. Advanced Powder Technology, Volume 11, Issue 2, pp. 187-197.

Lin, Chitsan; Huang, Chun-Lan; Shern, Chien-Chuan (2008) Recycling waste tire powder for the recovery of oil spills. Resources, Conservation and Recycling, Volume 52, Issue 10, pp. 1162-1166.

Llompart, Maria; Sanchez-Prado, Lucia; Lamas, J. Pablo; Garcia-Jares, Carmen; Roca, Enrique; Dagnac, Thierry (2013) Hazardous organic chemicals in rubber recycled tire playgrounds and pavers. Chemosphere, Volume 90, Issue 2, pp. 423-431.

López, Félix A.; Centeno, Teresa A.; Alguacil, Francisco J.; Lobato, Belén; Urien, Andrea (2013) The GRAUTHERMIC-Tyres process for the recycling of granulated scrap tyres. Journal of Analytical and Applied Pyrolysis, Volume 103, pp. 207-215.

López, Félix A.; Centeno, Teresa A.; Alguacil, Francisco José; Lobato, Belén (2011) Distillation of granulated scrap tires in a pilot plant. Journal of Hazardous Materials, Volume 190, Issues 1–3, pp. 285-292.

López, Félix A.; Centeno, Teresa A.; Alguacil, Francisco José; Lobato, Belén; López-Delgado, Aurora; Fermoso, Javier (2012) Gasification of the char derived from distillation of granulated scrap tyres. Waste Management, Volume 32, Issue 4, pp. 743-752.

López, Gartzen; Olazar, Martin; Aguado, Roberto; Bilbao, Javier (2010) Continuous pyrolysis of waste tyres in a conical spouted bed reactor. Fuel, Volume 89, Issue 8, pp. 1946-1952.

Lucchesi, A. and Maschio, G. (1983) Semi-active carbon and aromatics produced by pyrolysis of scrap tires. Conservation & Recycling, Volume 6, Issue 3, pp. 85-90.

Meyer, C. (2009) The greening of the concrete industry. Cement and Concrete Composites, Volume 31, Issue 8, pp. 601-605.

Min, A. and Harris, A.T. (2006) Influence of carbon dioxide partial pressure and fluidization velocity on activated carbons prepared from scrap car tyre in a fluidized bed. Chemical Engineering Science, Volume 61, Issue 24, pp. 8050-8059.

Money, D.M and Harrison, G (1999) Liquefaction of scrap automobile tyres in different solvents and solvent mixes. Fuel, Volume 78, Issue 14, pp. 1729-1736.

Moreno, F.; Rubio, M.C.; Martinez-Echevarria, M.J. (2012) The mechanical performance of dry-process crumb rubber modified hot bituminous mixes: The influence of digestion time and crumb rubber percentage. Construction and Building Materials, Volume 26, Issue 1, pp. 466-474.

Murillo, R.; Aylón, E.; Navarro, M.V.; Callén, M.S.; Aranda, A.; Mastral, A.M. (2006) The application of thermal processes to valorise waste tyre. Fuel Processing Technology, Volume 87, Issue 2, pp. 143-147.

Najim, Khalid B. and Hall, Matthew R. (2012) Mechanical and dynamic properties of self-compacting crumb rubber modified concrete. Construction and Building Materials, Volume 27, Issue 1, pp. 521-530.

Napoli, A.; Soudais, Y.; Lecomte, D.; Castillo, S. (1997) Scrap tyre pyrolysis: Are the effluents valuable products? Journal of Analytical and Applied Pyrolysis, Volumes 40–41, pp. 373-382.

Navarro, F.J.; Partal, P.; Marti´nez-Boza, F.; Gallegos, C. (2004)Thermo-rheological behaviour and storage stability of ground tire rubber-modified bitumens. Fuel, Volume 83, Issues 14–15, pp. 2041-2049.

Niksiar, Arezou; Sohrabi, Morteza; Rahimi, Amir (2013) A correction on a published kinetic model for tyre pyrolysis in a conical spouted bed reactor. Journal of Analytical and Applied Pyrolysis, Volume 104, pp. 707-709. http://dx.doi.org/10.1016/j.jaap.2013.06.013.

Nimmo, W.; Singh, S.; Gibbs, B.M.; Williams, P.T. (2008) The evaluation of waste tyre pulverised fuel for NOx reduction by reburning. Fuel, Volume 87, Issues 13–14, pp. 2893-2900.

Olazar, Martin; Lopez, Gartzen; Arabiourrutia, Miriam; Elordi, Gorka; Aguado, Roberto; Bilbao, Javier (2008) Kinetic modelling of tyre pyrolysis in a conical spouted bed reactor. Journal of Analytical and Applied Pyrolysis, Volume 81, Issue 1, pp. 127-132.

Owen, Kenneth C. (1998) Scrap tires: A pricing strategy for a recycling industry. Corporate Environmental Strategy, Volume 5, Issue 2, pp. 42-50.

Piatkowski, Nicolas and Steinfeld, Aldo (2010) Reaction kinetics of the combined pyrolysis and steam-gasification of carbonaceous waste materials. Fuel, Volume 89, Issue 5, pp. 1133-1140.

Pierce, C.E. e Blackwell, M.C. (2003) Potential of scrap tire rubber as lightweight aggregate in flowable fill. Waste Management, Volume 23, Issue 3, pp. 197-208.

Política Nacional de Resíduos Sólidos - PNRS 2010. *Lei Nº 12.305, de 2 de Agosto de 2010*. Institui a Política Nacional de Resíduos Sólidos; altera a Lei nº 9.605, de 12 de fevereiro de 1998; e dá outras providências.

Putman, Bradley J.; Amirkhanian, Serji N. (2004) Utilization of waste fibers in stone matrix asphalt mixtures. Resources, Conservation and Recycling, Volume 42, Issue 3, pp. 265-274.

Qu, Wei; Zhou, Qian; Wang, Yu-Zhong; Zhang, Jing; Lan, Wen-Wen; Wu, Yan-Hui; Yang, Jia-Wei; Wang, De-Zhi (2006) Pyrolysis of waste tire on ZSM-5 zeolite with enhanced catalytic activities. Polymer Degradation and Stability, Volume 91, Issue 10, pp. 2389-2395.

Quek, Augustine and Balasubramanian, Rajasekhar (2013) Liquefaction of waste tires by pyrolysis for oil and chemicals—A review. Journal of Analytical and Applied Pyrolysis, Volume 101, pp. 1-16.

Rahman, S., (2003) Reverse logistics: an overview and a causal model. In: Hensher, D.A., Button, K.J. (Eds.), Transport and the Environment Pergamon, Oxford.

Rahman, Shams and Subramanian, Nachiappan (2012) Factors for implementing end-of-life computer recycling operations in reverse supply chains. International Journal of Production Economics, Volume 140, Issue 1, pp. 239-248.

Rodriguez, Isabel de Marco; Laresgoiti, M.F; Cabrero, M.A; Torres, A; Chomón, M.J; Caballero, B (2001) Pyrolysis of scrap tyres. Fuel Processing Technology, Volume 72, Issue 1, pp. 9-22.

Roy, Christian; Labrecque, Blaise; Caumia, Bruno de (1990) Recycling of scrap tires to oil and carbon black by vacuum pyrolysis. Resources, Conservation and Recycling, Volume 4, Issue 3, pp. 203-213.

Roy, V.; Caumia, B. de; Roy, C. (1992) Development of a gas-cleaning system for a scrap-tire vacuum-pyrolysis plant. Gas Separation & Purification, Volume 6, Issue 2, pp. 83-87.

Rushdi, Ahmed I.; BaZeyad, Abdulqader Y.; Al-Awadi, Abdurrahman S.; Al-Mutlaq, Khalid F.; Simoneit, Bernd R.T. (2013) Chemical characteristics of oil-like products from hydrous pyrolysis of scrap tires at temperatures from 150 to 400 °C. Fuel, Volume 107, pp. 578-584.

Sainz-Diaz, C.I. and Griffiths, A.J (2000) Activated carbon from solid wastes using a pilot-scale batch flaming pyrolyser. Fuel, Volume 79, Issue 15, pp. 1863-1871.

Saraf, Sanjay; Marsh, John A.; Cha, C.Y.; Guffey, F.D. (1995) Reactive coprocessing of scrap tires and heavy oil. Resources, Conservation and Recycling, Volume 13, Issue 1, pp. 1-13.

Search, W.J.; Ctvrtnicek, T.E. (1976) Resource recovery systems for non-recappable rubber tires. Resource Recovery and Conservation, Volume 2, Issue 2, pp. 159-170.

Shakya, Pawan R.; Shrestha, Pratima; Tamrakar, Chirika S.; Bhattarai, Pradeep K. (2008) Studies on potential emission of hazardous gases due to uncontrolled open-air burning of waste vehicle tyres and their possible impacts on the environment. Atmospheric Environment, Volume 42, Issue 26, pp. 6555-6559.

Shalaby, Ahmed and Khan, Riaz Ahmed (2005) Design of unsurfaced roads constructed with large-size shredded rubber tires: a case study. Resources, Conservation and Recycling, Volume 44, Issue 4, pp. 318-332.

Sharma, Abhishek e Murugan, S. (2013) Investigation on the behavior of a DI diesel engine fueled with Jatropha Methyl Ester (JME) and Tyre Pyrolysis Oil (TPO) blends. Fuel, Volume 108, pp. 699-708.

Siddique, Rafat and Naik, Tarun R. (2004) Properties of concrete containing scrap-tire rubber – an overview. Waste Management, Volume 24, Issue 6, pp. 563-569.

Siddique, Rafat (2009) Utilization of waste materials and by-products in producing controlled low-strength materials. Resources, Conservation and Recycling, Volume 54, Issue 1, pp. 1-8.

Souza, C.D.R. 2011. Análise da Cadeia de Valor Aplicada a Cadeias Logísticas Reversas. Uma Contribuição ao Reaproveitamento de Pneus Inservíveis. Dissertação (mestrado) – UFRJ/ COPPE/ Programa de Engenharia de Transportes.

Souza, Cristiane Duarte Ribeiro de and D'Agosto, Márcio de Almeida (2013) Value chain analysis applied to the scrap tire reverse logistics chain: An applied study of co-processing in the cement industry. Resources, Conservation and Recycling, Volume 78, pp. 15-25.

Stelmachowski, Marek (2009) Conversion of waste rubber to the mixture of hydrocarbons in the reactor with molten metal. Energy Conversion and Management, Volume 50, Issue 7, pp. 1739-1745.

Sunthonpagasit, Nongnard and Duffey, Michael R. (2004) Scrap tires to crumb rubber: feasibility analysis for processing facilities. Resources, Conservation and Recycling, Volume 40, Issue 4, pp. 281-299.

Tafreshi, S.N. Moghaddas e Norouzi, A.H. (2012) Bearing capacity of a square model footing on sand reinforced with shredded tire – An experimental investigation. Construction and Building Materials, Volume 35, pp. 547-556.

Tang, Zhijian; Butkus, Michael A.; Xie, Yuefeng F. (2006) Crumb rubber filtration: A potential technology for ballast water treatment. Marine Environmental Research, Volume 61, Issue 4, pp. 410-423.

Thomas, Blessen Skariah; Anoop, S.; Kumar, V. Sathish (2012) Utilization of Solid Waste Particles as Aggregates in Concrete. Procedia Engineering, Volume 38, pp. 3789-3796.

Turgut, Paki and Yesilata, Bulent (2008) Physico-mechanical and thermal performances of newly developed rubber-added bricks. Energy and Buildings, Volume 40, Issue 5, pp. 679-688.

Ucar, Suat; Karagoz, Selhan; Ozkan, Ahmet R.; Yanik, Jale (2005) Evaluation of two different scrap tires as hydrocarbon source by pyrolysis. Fuel, Volume 84, Issues 14–15, pp. 1884-1892.

Uçar, Suat; Karagöz, Selhan; Yanik, Jale; Saglam, Mehmet; Yuksel, Mithat (2005) Copyrolysis of scrap tires with waste lubricant oil. Fuel Processing Technology, Volume 87, Issue 1, pp. 53-58.

Uygunoglu, Tayfun and Topçu, Ilker Bekir (2010) The role of scrap rubber particles on the drying shrinkage and mechanical properties of self-consolidating mortars. Construction and Building Materials, Volume 24, Issue 7, pp. 1141-1150.

Wang, Hainian; You, Zhanping; Mills-Beale, Julian; Hao, Peiwen (2012) Laboratory evaluation on high temperature viscosity and low temperature stiffness of asphalt binder with high percent scrap tire rubber. Construction and Building Materials, Volume 26, Issue 1, pp. 583-590.

Williams, P.T.; Bottrill, R.P.; Cunliffe, A.M. (1998) Combustion of Tyre Pyrolysis Oil. Process Safety and Environmental Protection, Volume 76, Issue 4, pp. 291-301.

Williams, Paul T and Brindle, Alexander J (2003) Temperature selective condensation of tyre pyrolysis oils to maximise the recovery of single ring aromatic compounds? Fuel, Volume 82, Issue 9, pp. 1023-1031.

Williams, Paul T. and Bottrill, Richard P. (1995) Sulfur-polycyclic aromatic hydrocarbons in tyre pyrolysis oil. Fuel, Volume 74, Issue 5, pp. 736-742.

Williams, Paul T.; Besler, Serpil; Taylor, David T. (1990) The pyrolysis of scrap automotive tyres: The influence of temperature and heating rate on product composition. Fuel, Volume 69, Issue 12, pp. 1474-1482.

Wu, Jason Y. and Tsai, Mufan (2009) Feasibility study of a soil-based rubberized CLSM. Waste Management, Volume 29, Issue 2, pp. 636-642.

Xiao, Feipeng; Zhao, P.E. Wenbin; Amirkhanian, Serji N. (2009) Fatigue behavior of rubberized asphalt concrete mixtures containing warm asphalt additives. Construction and Building Materials, Volume 23, Issue 10, pp. 3144-3151.

Yang, Wen; Sun, Wen Jing; Chu, Wei; Jiang, Cheng Fa; Wen, Jie (2012) Synthesis of carbon nanotubes using scrap tyre rubber as carbon source. Chinese Chemical Letters, Volume 23, Issue 3, pp. 363-366.

Yesilata, Bulent; Bulut, Husamettin; Turgut, Paki (2011) Experimental study on thermal behavior of a building structure using rubberized exterior-walls. Energy and Buildings, Volume 43, Issues 2–3, pp. 393-399.

Yoon, Sungmin; Prezzi, Monica; Siddiki, Nayyar Zia; Kim, Bumjoo (2006) Construction of a test embankment using a sand–tire shred mixture as fill material. Waste Management, Volume 26, Issue 9, pp. 1033-1044.

Youwai, Sompote e Bergado, Dennes T. (2004) Numerical analysis of reinforced wall using rubber tire chips–sand mixtures as backfill material. Computers and Geotechnics, Volume 31, Issue 2, pp. 103-114.