
Volume 32, Issue 10, October 2012 ISSN 0956-053X
ELSEVIER
waste management
International Journal of Integrated Waste Management, Science & Technology
GENERATION
MINIMIZATION
RECYCLING
COLLECTION
TREATMENT
DISPOSAL
ECONOMICS
POLICY
Editor-in-Chief
Raffaello Cossu
iwwg

Waste Management 32 (2012) 1742–1751

Contents lists available at SciVerse ScienceDirect

Waste Management

journal homepage: www.elsevier.com/locate/wasman

Review

Progress in used tyres management in the European Union: A review

Maciej Sienkiewicz *, Justyna Kucinska-Lipka, Helena Janik, Adolf Balas

Polymer Technology Department, Chemical Faculty, Gdansk University of Technology, Gabriela Narutowicza Street 11/12, 80-952 Gdansk, Poland

A R T I C L E I N F O

Article history:
Received 15 January 2012
Accepted 14 May 2012
Available online 9 June 2012

Keywords:
Waste tyres
Recycling tyres
Rubber recyclates
Used tyres management

A B S T R A C T

The dynamic increase in the manufacture of rubber products, particularly those used in the automobile industry, is responsible for a vast amount of wastes, mostly in the form of used tyres, of which more than 17 million tonnes are produced globally each year. The widely differing chemical compositions and the cross-linked structures of rubber in tyres are the prime reason why they are highly resistant to biodegradation, photochemical decomposition, chemical reagents and high temperatures. The increasing numbers of used tyres therefore constitute a serious threat to the natural environment.

The progress made in recent years in the management of polymer wastes has meant that used tyres are starting to be perceived as a potential source of valuable raw materials. The development of studies into their more efficient recovery and recycling, and the European Union's restrictive legal regulations regarding the management of used tyres, have led to solutions enabling this substantial stream of rubber wastes to be converted into energy or new polymer materials.

In this article we present the relevant literature describing innovative organizational approaches in the management of used tyres in the European Union member countries and the possible uses of waste tyres as a source of raw materials or alternative fossil fuels.

1. Introduction

Worldwide, the amounts of used polymer products are increasing by the year: most of them are used automobile tyres. According to reports from the largest associations of tyre and rubber product manufacturers, the annual global production of tyres is some 1.4 billion units, which corresponds to an estimated 17 million tonnes of used tyres each year (RMA, 2009; JATMA, 2010; ETRMA, 2011; WBCSD, 2010). China, the countries of the European Union (EU), the USA, Japan and India produce the largest amounts of tyre wastes – almost 88% of the total number of withdrawn tyres around the world (JATMA, 2010). The dynamic growth in the numbers of used tyres is well exemplified by the EU, where their production increased from 2.1 million tonnes in 1994 to 3.3 million tonnes in 2010, and the annual cost of their disposal in EU countries has been calculated at nearly 600 million euros (ETRMA, 2010a). The scale of the problem is magnified by the environmentally dangerous dumps already in existence, where some 4 billion tyres are being uselessly stockpiled (WBCSD, 2008). These dumps are indeed a serious threat to both the natural environment and human health because of the risk of fire and their being used as a suitable habitat by rodents, snakes and mosquitoes (Naik and Singh, 1991; Li et al., 2006).

Used tyres are a category of waste whose recycling is exceedingly difficult. This is due to their highly complex structure, the diverse composition of the raw material, and the structure of the rubber from which the tyre was made. The technology of manufacturing rubber products is based primarily on the irreversible vulcanization reaction that takes place between natural and synthetic diene rubbers, sulphur and a variety of auxiliary compounds. As a result, transverse bonds connect the elastomer chains to form the cross-linked structure of rubber. That is why rubber articles are elastic, insoluble and infusible solids that cannot be reprocessed, as is the case with thermoplastic materials. Their recycling therefore requires a high time and energy outlay and is based solely on the mechanical, thermal or chemical destruction of the rubber product; recovery of the raw materials used to produce them is impossible (White and De, 2001). A conventional tyre is a product with a complex structure and composition, which can be made using various variants of high-quality synthetic rubbers, mainly butyl rubber (IIR) or styrene-butadiene rubber (SBR), and natural rubber (NR), along with a host of other compounds added to obtain the final utilitarian form or the high mechanical strength of the tyre. A tyre consists not only of rubber, which makes up some 70–80% of the tyre mass, but also of steel belts and textile overlays, which give the tyre its ultimate form and utilitarian properties (Pehlken and Müller, 2009; Ganjian et al., 2009). The presence of these latter two components is a serious problem, however, because they have to be separated from the rubber during tyre recycling. Hence, to obtain a new product derived from automobile

* Corresponding author. Tel.: +48 0583471093; fax: +48 0583472694.
E-mail addresses: maciej@urethan.chem.pg.gda.pl, macsienk@pg.gda.pl (M. Sienkiewicz).

0956-053X/$ - see front matter © 2012 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.wasman.2012.05.010

tyre recycling that would satisfy high quality norms requires the application of technologically highly complex processes. Table 1 shows the basic raw material composition of tyres, together with the percentage content of the various components used in the manufacture of passenger and truck tyres in USA and Europe.

The widely differing chemical compositions and the cross-linked structures of rubber in tyres are the prime reason why they are highly resistant to biodegradation, photochemical decomposition, chemical reagents and high temperatures. It is for this reason that the management of used tyres has become a serious technological, economic and ecological challenge.

The present work is a thorough review of recent EU legislation in this respect as well as organizational approaches to the management of used tyres, and characterizes innovative methods of recovering and recycling this type of waste in member countries. It also describes recent progress in research into the application of ground waste tyres as a source of valuable raw materials used to produce various kinds of polymer composites, obtained largely with the aid of synthetic and natural rubbers, polyethylene, polypropylene and polyvinyl chloride.

1.1. Legislation regarding used tyres management in the European Union

The EU legislation on the procedures to adopt with regard to used automobile tyres, which constitute a threat to the natural environment, is an extensive set of regulations based on provisions and dispositions of EU law. EU policy in this matter is founded on a "hierarchy of wastes": in the first place, waste formation should be prevented, but if this is not possible, wastes should be re-used following recovery and recycling, and eliminating as far as possible stockpiling in landfills (COM, 2005). That is why the EU's strategy for the management of used rubber products, and used tyres in particular, is based on the 1999 Directive on the Landfill of Waste 1000/31/EC. Accordingly, member states were obliged to prohibit the stockpiling of whole tyres in landfills from July 2003, and ground tyres from July 2006, with the exception of bicycle tyres and tyres with an external diameter of more than 1400 mm. Supplementary to this legislation is the End of Life Vehicle Directive 2000/53/EC, passed in 2000, which regulates procedures for dealing with vehicles withdrawn from service. According to this, tyres must be removed from vehicles before these are scrapped, so that they can be recycled. The recommendations in these directives do not stipulate the means by which these aims are to be achieved. Member states are thus presented with fresh challenges, stimulating the development of their own internal legal and organizational regulations enabling state-of-the-art methods of recycling the increasing numbers of used tyres without their being stockpiled in landfills.

On the basis of past experience with waste management, EU countries have developed three models to regulate and improve supervision of used tyre management (ERTMA, 2010a):

1. *Management model based on Extended Produced Responsibility (EPR)*. According to this model, the management of used tyres is the responsibility of the producers and importers who put them on the market. It obliges them to organize collections of used tyres and to ensure the legally required levels of recovery and recycling of these wastes. This can be done directly by the producer or through the mediation of specialized recovery/recycling organizations acting on their behalf. Fig. 1 names the largest recovery/recycling organizations operating in European countries.
2. *A tax system*. Producers or sellers levy a disposal duty, added to the cost of a new tyre and paid into the national budget. The management of used tyres in this model is the responsibility of the recovery/recycling organizations and is financed by the state from the funds obtained from customers purchasing new tyres.
3. *The free market system, which assumes the profitability of recovery and recycling of tyres*. This model assumes that used tyres are a source of valuable raw materials, the management of which is profitable to the firms involved.

Fig. 1 shows the distribution of the various systems of managing used tyres in the countries of the European Union, Norway, Croatia and Switzerland, and details the non-profit organizations administering the program for recovering and recycling tyres in each country.

In Europe the most popular of these three models is the one based on extended producer responsibility (EPR). The success of this approach can be measured by the high, even 100% recovery of used tyres achieved by the countries that implemented it (Finland, Hungary, Italy, Lithuania, Latvia, the Netherlands, Norway, Poland, Romania, Spain and Sweden) In case of Belgium, France and Portugal tyres recovery rate have achieve over 100%, because recovery/recycling organizations operating in this countries may have collected more waste tyres than their obligation (see Table 2).

Its advantage is the substantial transparency in the control of the organizations fulfilling the imposed norms. In addition, the efficient financing of the recovery organizations by the world's largest tyre manufacturers has enabled the development of research and the implementation of modern technologies that raise the efficiency of tyre recovery and recycling. According to ETRMA, the annual investment in this respect in the EU is currently 5 million euros. It is for these reasons that this model has become the foundation of modern used tyre management in these 17 European countries. On the other hand, the system based on the recovery duty, operating in Bulgaria, Croatia, Ireland, Germany, Switzerland and the UK, and the free market system (Denmark, Slovakia Rep.), despite their simplicity, have turned out to be less attractive, which means they are more difficult to control.

In accordance with the system based on the responsibility of tyre producers and importers, they can fulfill the obligation of managing used tyres themselves or devolve it to a non-profit orga-

Table 1
Typical materials used in tyre manufacturing (in Europe and USA) according to the percentage of the total weight of the finished tyre that each material class represents (wdk, 2003; Pehlken and Müller; 2009).

Materials	In USA		In European Union	
	Passenger tyre	Truck tyre	Passenger tyre	Truck tyre
Natural rubber (%)	14	27	22	30
Synthetic rubber (%)	27	14	23	15
Carbon black (%)	28	28	28	20
Steel (%)	14–15	14–15	13	25
Fabric, fillers, accelerators, antiozonants, etc. (%)	16–17	16–17	14	10
Average weight	New 11 kg, Scrap 9 kg	New 54 kg, Scrap 45 kg	New 8,5 kg, Scrap 7 kg	New 65 kg, Scrap 56 kg

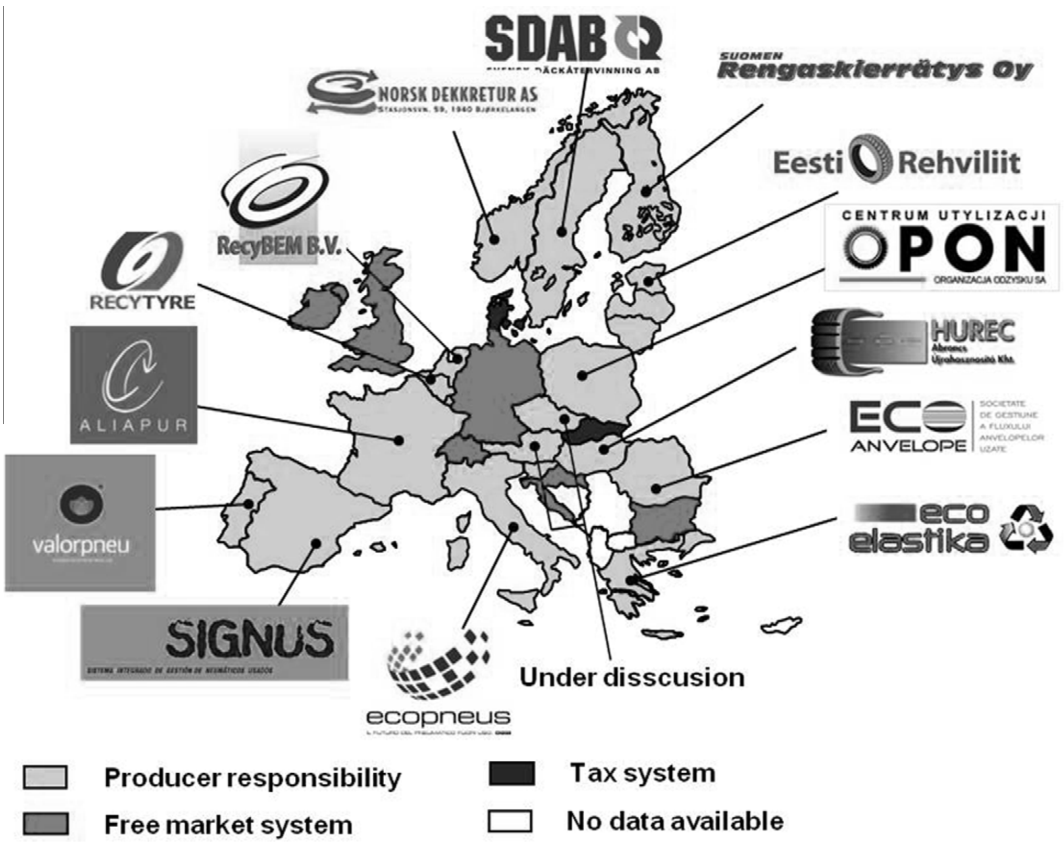

Fig. 1. Models for administering the management of used tyres in the Europe, showing the largest recovery/recycling organizations operating in EU countries (ETRMA, 2010a).

nization expressly appointed to carry out this task on their behalf (ERTMA, 2010a). The principles according to which recovery/recycling organizations operate in the EU market are shown in Fig. 2.

It is the task of the recovery organization to fulfill on behalf of the manufacturer the obligations regarding the achievement of the stipulated levels of recovery and recycling. In the EU their activity mainly involves the organization and coordination of a national system of tyre collection from service and tyre exchange points, automobile workshops and scrap yards and communities. They are also obliged to pass on tyre wastes to the companies dealing with energy recovery from tyres and to send them for retreading or recycling. In accordance with the legislation, recovery organizations are duty bound to file annual reports on the effects of their activities, and should they have been unable to reach the required recovery and recycling targets, they are obliged to pay a product tax, separately for recovery and for recycling. A non-legal requirement of these organizations is their educational activity, i.e. explaining to the general public the problems of used tyre management.

If manufacturers or the organizations acting on their behalf fail to discharge their obligations, they are required to pay a product tax. How much they pay depends on the quotient of the difference between the required and achieved recovery/recycling target and the product tax rate as established by the government department responsible for waste management. The funds obtained in this way are used to finance the recycling and recovery of unmanaged wastes and to support environmental programs concerning the subject of used tyres.

According to figures published by the European Tyre & Rubber Manufacturers' Association in EU Member States, Norway and Switzerland over around 3.2 million tonnes of used tyres were generated in 2010. After sorting, over 2.6 million tonnes of waste tyres were introduced on the EU market for recovery and recycling, beside of this 574 thousand tones were sent to retreading, reuse and export. The estimated recovery rate of waste tyres achieved 96%, as compared with the 72.2% recovery rate of paper and the 58% recovery rate of total plastics, waste recycling and recovery indicates that the EU's policy regarding used tyre management is highly effective (ETRMA, 2010a; PlasticsEurope, 2011; ERPA, 2010). In comparison to Japan (91% of recovery rate) or USA (89% of recovery rate) Europe is one of the most advanced regions on the world in the recovery and recycling of used tyres. Next to Fig. 3, testimony of the highly efficient management of used tyres in the EU27, statistical data also show that, the recovery rate of waste tyres increased in EU27 by 34% over the last 6 years, while the waste tyres arising increased only by 5%.

In Europe over the past 16 years we can observe a dramatic decrease of landfilling used tyres from 62% in 1994 to 4% in 2010, while in this year reuse, retreading, recycling and energy recovery in total has reached the level of 96% used tyres recovery (Fig. 4). The major methods of recovery waste tyres in 2010 were energy recovery 38% and material recycling 40%.

2. Methods of used tyre management

Tyres withdrawn from use because of their composition and properties are now a source of valuable raw materials, and the development of recovery methods has led to their effective conversion to energy or materials, which can be used to produce new goods of practical or utilitarian significance. The legal prohibition of tyre stockpiling in landfills was the spur forcing levels of recovery and recycling to rise. In view of this, the policies of most countries regarding used tyre disposal is based on their selective collection and management by means of (RMA, 2009; ETRMA, 2010a; JATMA, 2010):

Table 2
Used tyres (in kilo tones) recovery in Europe Union (EU27), Norway (NO) and Switzerland (CH) in 2010, (italic indicates of countries which have introduced models based on extended producer responsibility), (ERTMA, 2010b).

Country	Used Tyres Arising (*A*)	Reuse of part-worn tyres			Waste tyres Arising $(E) = A - B + C + D$	Waste tyres recovery			Landfil/ unknown (*J*)	Total recovery $(K) = B + C + D + F + G + I$	Used tyres treated $(L) = K/A$ (%)
		Reuse (*B*)	Export (*C*)	Retreading (*D*)		Civil engineering (*F*)	Recycling (*G*)	Energy (*I*)			
Austria	60	0	7	3	50	0	20	30	0	60	100
Belgium	*82*	*1*	*2*	*10*	*69*	*1*	*56*	*17*	*0*	*87*	*106*
Bulgaria	20	0	0	0	20	0	0	0	20	0	0
Cyprus	8	0	0	0	8	0	0	0	8	0	0
Czech Rep.	57	0	0	2	55	0	9	29	17	40	70
Denmark	38	0	0	1	37	0	37	0	0	38	100
Estonia	*10*	*0*	*0*	*0*	*10*	*0*	*5*	*4*	*1*	*9*	*90*
Finland	*41*	*0*	*0*	*1*	*40*	*40*	*0*	*0*	*0*	*41*	*100*
France	*381*	*36*	*0*	*43*	*302*	*38*	*128*	*147*	*0*	*392*	*103*
Germany	614	10	84	45	475	0	215	260	0	614	100
Greece	*49*	*0*	*0*	*2*	*47*	*0*	*27*	*15*	*5*	*44*	*90*
Hungary	*30*	*0*	*0*	*1*	*29*	*5*	*10*	*14*	*0*	*30*	*100*
Ireland	35	3	2	2	28	8	17	0	3	32	91
Italy	426	0	12	43	371	20	80	180	91	335	79
Latvia	10	0	0	0	10	0	5	4	1	9	90
Lithuania	11	0	0	0	11	0	5	4	2	9	82
Malta	1	0	1	0	0	0	0	0	0	1	100
Netherlands	*65*	*0*	*13*	*2*	*50*	*1*	*39*	*10*	*0*	*65*	*100*
Poland	*239*	*0*	*0*	*20*	*219*	*0*	*51*	*168*	*0*	*239*	*100*
Portugal	*92*	*1*	*2*	*18*	*71*	*0*	*50*	*26*	*0*	*97*	*105*
Romania	*33*	*0*	*0*	*0*	*33*	*0*	*1*	*32*	*0*	*33*	*100*
Slovak Rep.	23	0	0	1	22	0	21	1	0	23	100
Slovenia	11	0	0	0	11	0	6	5	0	11	100
Spain	*292*	*31*	*0*	*27*	*234*	*8*	*114*	*112*	*0*	*292*	*100*
Sweden	*79*	*0*	*1*	*0*	*78*	*12*	*19*	*47*	*0*	*79*	*100*
UK	465	44	54	32	335	75	149	102	9	456	98
Norway	*51*	*1*	*1*	*0*	*49*	*34*	*4*	*11*	*0*	*51*	*100*
Switzerland	50	3	7	5	35	0	5	30	0	50	100
EU27 + NO + CH	3273	130	186	258	2699	242	1073	1248	157	3137	96

- Retreading.
- Energy recovery.
- Pyrolysis.
- Product recycling.
- Material recycling (grinding and devulcanization).

2.1. Retreading

Retreading is a process for extending the lifetime of tyres. It is based on the preliminary preparation of a tyre for regeneration, by stripping it of its tread and then applying a new one. Only tyres that have passed a wear and tear inspection, and have been certified to have no damage to the tyre carcass, may be retreaded. Retreading can be done using either a cold or hot process. (Glijer and Lipinska, 2002; Lebreton and Tuma, 2006; Zebala et al., 2007). In the low-temperature method the suitably prepared carcass is coated with a layer of a rubber mixture, acting as binder, and an initially vulcanized tread of suitable pattern and size. This is all pressed onto the carcass using special rubber envelopes and vulcanized in an autoclave at around 100 °C for 4–5 h. In the high-temperature method, the fresh rubber mixture of the requisite composition and volume is laid on the carcass, after which the whole is vulcanized in molds producing the tread pattern. The process takes place at a temperature of 150–180 °C and elevated pressure. Retreading is economically very profitable: it requires only 30% of the energy and 25% of the raw materials needed to produced new tyres (Ferrer, 1997; Gieréa et al., 2006). Moreover, it is a practically waste-free process, the only by-product of retreading being pulp rubber, which can be used for manufacturing polymer composites and in the construction industry. In practice, automobile tyres are not retreaded, because of their uncompetitive cost vis-à-vis new tyres, poorer quality and safety at high speeds (Pipilikaki et al., 2005; Zebala et al., 2007). Truck and aircraft tyres are regularly retreaded, however, for reasons of economy: the quality-to-price ratio for large-size retreaded tyres is much higher than in the case of new tyres. The largest tyre manufacturers estimate that every other truck tyre worldwide is regenerated by retreading. This allows considerable savings to be made when it comes to the purchase of new tyres and significantly reduces the amounts of rubber wastes (ChemRisk LLC, 2009).

2.2. Energy recovery

One of the basic ways of recovering used tyres or other used rubber products is to use them as an energy raw material. Fuel consisting of shredded tyres is denoted as TDF (tyre derived fuel) in the international classification. Used tyres have a calorific value of 32 MJ/kg, which makes them competitive with other types of fuel, especially with coal, which has a far lower calorific value (Gieréa et al., 2006). The cement industry is one of the greatest consumers of shredded tyres, which uses them as an alternative fuel co-combusted with coal; their management is thus waste-free. Cement plants are now able to use as a fuel only whole tyres. This is possible because of the high temperatures in cement kilns (>1200 °C), which ensure the complete combustion of all the tyre components. The ash and steel cord are permanently bound to the clinker, but this does not seriously impair its physicochemical properties apart from a slightly longer cement binding time and a greater water demand (Pipilikaki et al., 2005). Moreover, the combustion of tyres in cement kilns is environmentally safe because of the much lower emission, compared to coal combustion, of dusts, carbon dioxide, nitrogen oxides and heavy metals (except zinc)

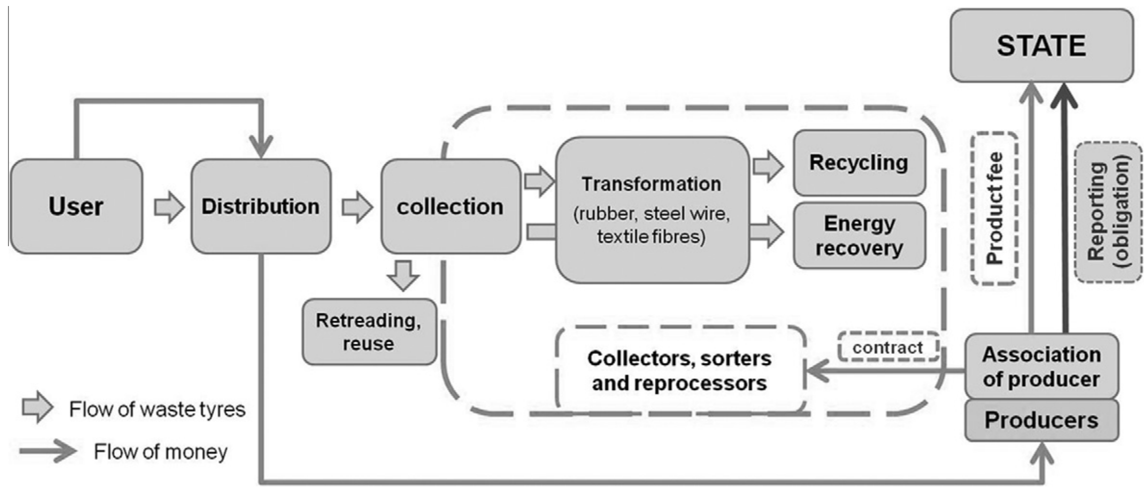

Fig. 2. Diagram describing the activity of organizations recovery/recycling tyres within the system based on extended producer responsibility (ETRMA, 2010a).

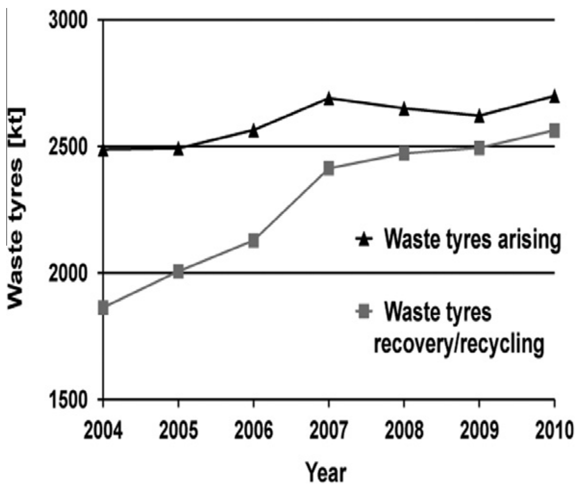

Fig. 3. Evolution of used tyres recovery between 2004 and 2010 (ETRMA, 2010a).

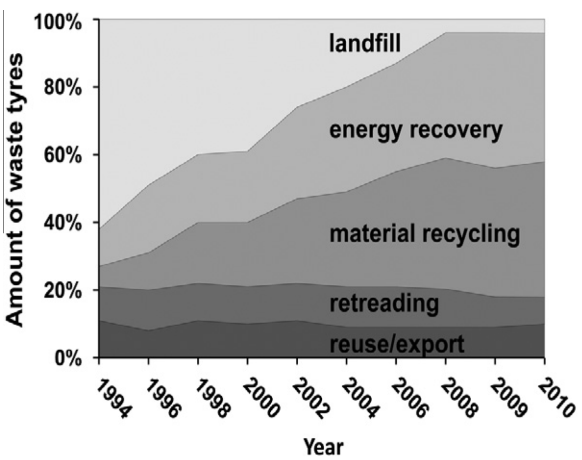

Fig. 4. Progress in recovery routes of waste tyres between 1994 and 2010 (ETRMA, 2010a).

(Conesa et al., 2008; Aliapur, 2009). Apart from the cement industry, used tyres are also used as a fuel for the production of steam, electrical energy, paper, lime and steel. This is because the co-combustion of coal with ground rubber wastes improves the thermal efficiency of steam boilers and furnaces, and the amounts of exhaust gases and dusts do not exceed any permissible limits (Levendis et al., 1996; Courtemanche and Levendis, 1998; Singh et al., 2009).

2.3. Pyrolysis of rubber wastes

The management of used tyres by means of pyrolysis is based on the decomposition of the elastomers contained in the rubber as a result of heating them to temperatures of 400–700 °C, in the absence of oxygen. Tyres are pyrolyzed in special pyrolytic furnaces which, depending on the technology employed, can operate at normal or reduced pressure, in an atmosphere of a neutral gas (mainly nitrogen) (Berrueco et al., 2005). There also exist pyrolysis technologies performed in the presence of substances in a supercritical state (e.g. CO_2) or plasma- or microwave-assisted (Appleton et al., 2005; Olędzka et al., 2006; Huang and Tang, 2009). The pyrolysis of tyres yields a series of valuable chemical compounds in solid, liquid or gaseous form, which after suitable processing can be used in the petrochemical, energy or iron and steel industries (Yu-Min, 1996). The solid products of tyre pyrolysis include fly ash, soot, the charred remains of the oxides and sulphides of zinc, silica and steel. The gas phase is rich in hydrogen, carbon monoxide and dioxide, aliphatic hydrocarbons and hydrogen sulphide. The liquid phase contains aromatic hydrocarbons and oils with a high calorific value, which on removal of contaminating sulphur compounds, are usually mixed with diesel oils and other petrochemical products. Unfortunately, because of the high cost of installations and of servicing the process, and also because of the uncompetitive prices of its products, the pyrolysis of used tyres is very rarely used on an industrial scale. Nevertheless, in view of the ongoing research into the improvement of existing pyrolysis technologies and the mounting costs of energy and petrochemical raw materials, this method of managing waste tyres has considerable potential.

2.4. Product recycling

Product recycling is a separate form of material recycling that is based on the recycling of entire used tyres, in their original form, without any physical or chemical treatment. Because of their shape and sizes, high elasticity, good damping properties of vibrations, noise and shocks, tyres are used as a cheap material in construction engineering. They can be used to form protective barriers along roads and highways and to protect sloping waterfront banks and roadsides. They can also be used as fenders for boats, artificial reefs offering protection to marine organisms, as a material for road substrates and as insulation for the foundations of buildings (Murugan et al., 2008; Bosscher et al., 1997; Collins et al., 2002; Lee and Roh, 2007). A very interesting solution in this respect was developed by the Solerebels company of Ethiopia, which produces footwear with soles made from suitably shaped pieces of tyre treads. Likewise, the Alchemy Goods Company (USA) manufactures handbags, wallets and belts entirely from spent inner tubes. Nonetheless, the product recycling of tyres is of marginal importance, so contributes little to solving the problem of their management.

2.5. Material recycling

Material recycling, besides energy recovery, is the most common means of managing used tyres. It is realized as mechanical grinding of tyres, which yields rubber materials of different degrees of comminution, or as devulcanization, which produces rubber regenerates (De et al., 2005).

Devulcanization is based on decomposing the cross-linked structure of vulcanized natural rubber, as a result of the partial or complete breaking of the poly-, di- and monosulphur cross-linking bonds formed during the original vulcanization process. Unfortunately, devulcanization also degrades the chains in the main rubber polymer, as a result of which the rubber product obtained no longer possesses the properties of the starting material (natural rubber); the process is thus termed 'regeneration'. The known methods of producing rubber regenerates include thermomechanical, thermochemical, physical (microwave, ultrasound methods) and biological ones – processes that involve complex transformations leading to depolymerization, oxidation, and in many cases the degradation of the main chains of the natural rubber polymer, which in turns reduced the viscosity of the material. Detailed descriptions of these methods will be found in numerous papers and patent applications, reviewed in papers (Holst et al., 1998; Adhikari et al., 2000; Myhre and MacKillop, 2002; Rajan et al., 2006). At present, rubber regenerates play an important role in the rubber industry, which uses them as additives to fresh rubber mixtures. They are employed in the manufacture of washers, cable housings, rubber mats and slabs, as well as footwear.

The grinding of used rubber goods enables rubber granulates to be used in the production of new materials, from which multifarious objects of practical use can be made. This is not easy, since the steel belts and textile overlays used in the production of the tyres have to be separated from the granulate during grinding. Once separated, however, these materials can be put to use again. The scrap steel is sent for smelting, whereas the textile cord, after cleaning up, is either combusted (then energy is recovered) or used to produce thermal insulation materials for the construction industry. The main aspect of tyre recycling is the obtained of the crumb rubber. Its usefulness for particular applications is determined primarily by the grain sizes of the various fractions and its degree of purity. In EU the European Committee for Standardization (CEN) has classified products of grinding waste tyres according to their size (CEN/TS14243:2010). The objective here was to standardize the market for products of the material recycling of used tyres; as a result, five different types of rubber products (see Table 3).

Table 3
Classification of rubber recyclates obtained during the grinding of tyres (CEN TS14243).

Type of recyclate	Size fraction
Cut tyres	>300 mm
Shreds	20–400 mm
Chips	10–50 mm
Rubber granulate	0.8–20 mm
Rubber dust	<0.8 mm

The grinding of end-of-life tyres is a complex process requiring special machines and equipment capable of shredding and granulating materials of a high mechanical strength. In addition, this operation requires a high energy costs, essential to ground tyres into suitable fractions, which to a great extent determines the profitability of the whole process. Nevertheless, the development of studies aiming to improve the yield of this recycling method and of new approaches to the utilization of crumb rubber for the manufacture of practicable materials means that grinding is at present a major form of used tyre management.

There are many methods for the efficient grinding of tyres, the most important ones being grinding at ambient temperature, cryogenic grinding, wet grinding, Berstorff's method and high-pressure grinding with a water jet.

Obtaining a crumb rubber as a result of the mechanical grinding of rubber wastes at ambient temperature involves the mechanical grinding and granulation of the tyres using shredders, mills, knife granulators and rolling mills with ribbed rollers (Sunthonpagasit and Duffey, 2004; Myhre and MacKillop, 2002). They are usually set up in a process line that enables the repeated grinding of wastes until a crumb rubber of the required grain size is obtained. The lower size limit of crumb rubber in this technology is rubber dust with grains no bigger than 0.3 mm in size and a very rough surface. In this process line there are also pneumatic separators to remove fibres from the textile cordage, and electromagnets to remove the steel parts of tyres. The mechanical grinding of tyres produces considerable quantities of heat, which oxidizes the rubber grains produced; the process line must therefore be equipped with an arrangement for cooling the crumb rubber in order to prevent its spontaneous combustion (De et al., 2005).

In cryogenic grinding liquid nitrogen is used to cool the previously cut up tyres to a temperature below that of the glass transition of the natural rubbers in the tyres. The frozen, brittle rubber at −80 °C is then sent to hammer mills, which crush the tyres into suitable fractions. The process line for the cryogenic grinding of tyres is also equipped with systems for removing the textile cordage and electromagnets for removing the steel parts.

The cryogenic grinding of tyres yields rubber granulates of very small grain size, even as small as 75 μm. Crumb rubber obtained in this method consists of grains with smooth surfaces and sharp edges, beside this most of them have the same shapes and sizes (Myhre and MacKillop, 2002). Fig. 5 shows micrographs of rubber granulates obtained from ambient temperature mechanical grinding and from cryogenic grinding using liquid nitrogen.

Moreover, it is purer than that obtained by mechanical grinding at ambient temperature. But it also has a higher humidity content, about 12–15% of the mass. The main disadvantage of this method is the high cost of the liquid nitrogen for cooling the rubber wastes. Economically, cryogenic grinding is uncompetitive in comparison with conventional grinding at ambient temperature. However, there are methods for reducing the consumption or completely eliminating the use of liquid nitrogen from this process. For example, liquid nitrogen can be replaced by a system of compressors capable of cooling used tyres to −100 °C with the aid of expanding air (Reznik, 2002). Another possibility is to replace the electric hammer mills with eddy mills, in which the material to be crushed is made to rotate by expanding air (Liang and Hao, 2000).

The wet grinding of rubber wastes is an improved version of ambient temperature grinding (Brubaker et al., 1984; Rouse, 2001; Rouse and White, 1996). This process involves grinding a water suspension of an initially comminuted rubber granulate obtained by other methods. Special mills with stationary and moving grindstones are used here, which crush the stream of rubber granulate entering the space between them. The water of the rubber granulate suspension continuously cools the product formed, not to mention the grindstones, which heat up as a result of friction.

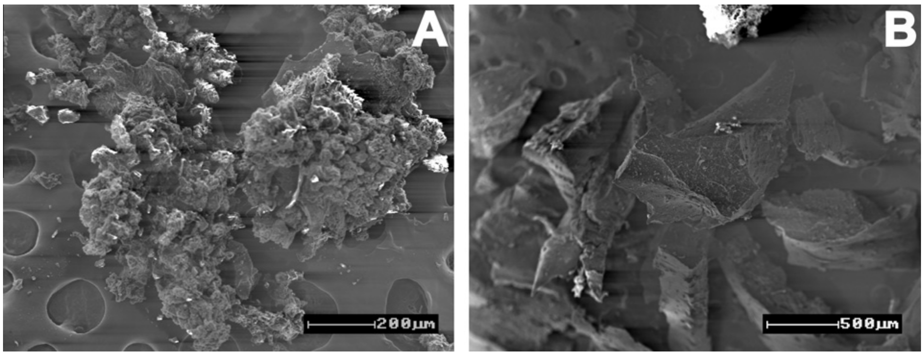

Fig. 5. Micrographs of rubber granulate grains obtained at ambient temperature (A) and cryogenically (B), (Sienkiewicz and Janik, 2009).

The advantage of this method is that we can obtain a very fine rubber dust with the grain size as small as 10–20 µm and with a large specific surface area. This dust is added as a filler to rubber mixtures from which products with high quality requirements, for example, solid tyres.

Grinding with a water jet was developed for the recycling of highly resistant, large-size tyres from trucks, construction vehicles and farm tractors. Conventional methods of grinding large-size tyres require very massive grinding machines, which consume enormous amounts of energy. The grinding factor is solely the water jet, which at a pressure of more than 2000 bars and high velocity strips the rubber from the tyres (Rutherford, 1992; Gyorgy, 2009). An important merit of this technique is that it selectively strips away from the steel cord the crumb rubber formed from the butyl rubber membrane on the inside of the tyre and the rubber material from which the tread and walls were made. The crumb rubber obtained in this way is of a high degree of purity since only the rubber is ground, the steel banding remains intact. The crumb rubber is also very finely ground, and the grains have a large specific surface area. The inventors of this method consider it to be environmentally friendly, as it is energy-saving, produces only a low level of noise, and does not generate pollutants.

Berstorff's method is an improved version of obtaining crumb rubber from the mechanical grinding of rubber waste at ambient temperature (Capelle, 1997; Khait, 2005; Khait et al., 2001;). It uses a rolling mill equipped with ribbed rollers and a twin-screw extruder, which when set up in series in the process line grind used automobile tyres. This process can be divided into three stages. In the first, the steel parts of the tyre are removed and cut up in a knife mill into ca 85 × 50 mm pieces. The tyre pieces from stage I are then broken up in ribbed rolling mills into fragments about 6 mm in size. The steel and textile cord reinforcements of the tyre are also removed during this stage. In the last stage, the rubber fragments from stage II are further ground in twin-screw extruders; these have specially constructed screws in which the rubber wastes are ground using large shearing forces and high pressures. The end product is a crumb rubber of small grain size (dust), a large specific surface area and low humidity content.

Ground tyre and other rubber wastes containing high-quality of natural and synthetic rubbers have become the raw material basis for a series of approaches for obtaining composite products with utilitarian properties. The magnitude of used tyre recycling is of the order of 2 million tonnes/year just in the EU and USA, which indicates that this method of managing rubber wastes has become a separate branch of industry (RMA, 2009; ETRMA, 2010b). Literature reports and an analysis of the tyre recycling market indicate that tyre rubber granulates are used principally as fillers and modifiers in various different types of polymer compositions and composites.

The specific properties of crumb rubber and their low cost mean that approaches using rubber recycling products in polymer compositions and composites have been extended to their application in various branches of the construction industry and different kinds of engineering applications.

Examples include shreds, chips and cut-up tyres, which are used as light fillers in buildings (Hazarika et al., 2010; Siddique and Naik, 2004). They have good thermo-insulating properties, a low specific gravity, and are waterproof and resistant to environmental factors. They are thus the ideal material for filling tunnel structures, underground passages, road and highway embankments, and retaining walls. They can also be used as materials for forming the drainage layers of embankments and drainage ditches. Crumb rubber, in the form of rubber granulates and dust, can be used as a full-value raw material to obtain various kinds of compositions and mixtures with asphalt used in highway engineering (Navarro et al., 2004; Cao, 2007; Huang et al., 2007; Xiao and Amirkhanian, 2010). Rubber-asphalt compositions improve the quality of road surfaces, making them thermally more stable and resistant to ageing. The addition of ground rubber to asphalt also improves the elasticity of the asphalt binder and reduces the susceptibility of the surface to rutting. Modification of the properties of mineral-asphalt mixtures using rubber granulate improves its resistance to skidding and abrasion, reduces tyre-surface noise, reduces light reflection from the surface and improves tyre grip during wet and frosty weather.

Ground tyres are also used in the building industry as a filler for cement mortar, which enables concrete compositions to be obtained that are more resistant to bending, with better thermal insulation and acoustic properties, and improved resistance to dynamic loading and cracking. The presence of a rubber material in concrete structures also reduces moisture absorption and permeability to chloride ions, thus offering steel structures better protection from corrosion (Piercea and Blackwell, 2003; Benazzouk et al., 2007; Oikonomou and Mavridou, 2009).

2.6. Comparison of the key methods of recovery waste tyres used in European Union

Data from the used tyres recovery/recycling market indicate that their combustion plays a big role in the management of these wastes (ETRMA, 2010a; ChemRisk LLC, 2009). It is mainly economic aspects that are responsible for the popularity of the recovery of energy from tyres over other methods of utilizing them. From an investigation of the total energy and raw material balance of tyre combustion and an assessment of its effect on the environment, Corti and Lombardi (2004) showed that this method has more advantages than the other means of managing rubber wastes. Their results demonstrate that preparing tyres as an alternative fuel requires a smaller financial and energy outlay than their recycling by grinding, which is an energy-consuming process. They point to the considerable advantages accruing from the co-combustion of tyres with coal in cement works, mainly because this

Table 4
Energy balances for the production and recovery of rubber products (Brown et al., 1996; Synder, 1998; Amari et al., 1999).

Amount of energy required to produce a tyre	87–115 MJ/kg
Amount of energy required to produce rubber goods (SBR)	80–90 MJ/kg
Amount of energy obtained from the combustion of tyres	32 MJ/kg
Amount of energy needed to comminute tyres to a rubber recyclate of grain size < 1.5 mm	1.8–4.3 MJ/kg

process produces practically no wastes. This is due to the fact that the ash produced by the combustion is bound to the clinker, and the emission of exhaust gases, like carbon dioxide and nitrogen oxides, is much less than from the combustion of coal alone (Silvestraviciute and Karaliunaite, 2006). Moreover, technologies are now available enabling the combustion of whole tyres, without preliminary processing, and this substantially reduces the cost of the raw materials. Thus, it is the policy of most countries to burn a high proportion of used tyres in cement works. One example is Poland, where 70% of used tyres covered by the legal requirement for their recovery are disposed of in this way (see Table 2).

An analysis of the life cycle of tyres, seen from the moment of their production to their recovery/recycling, indicates, however, that despite the large economic gains to be made, the combustion of tyres to recover the energy they contain is not a desirable method of managing them. An assessment of the energy balance of a tyre's life cycle (see Table 4) shows that some 87–115 MJ/kg of energy are required to produce a tyre, but only 32 MJ/kg are recovered when it is combusted (Brown et al., 1996; Synder, 1998; Amari et al., 1999). This means, then, that only 30–38% of the energy initially invested in the production of the tyre is recoverable. In contrast, the amount of energy needed to recycle tyres by grinding is barely 2–4% of the energy outlay required to produce them. Furthermore, unlike tyre combustion, tyre grinding does not emit harmful compounds into the air, and yields a crumb rubber, textile cord and steel, which are valuable raw materials for other processes (Fiksel et al., 2011).

From the energy balance point of view, then, it is much more beneficial to lower the level of production of rubber goods obtained from classical raw materials and to replace them with composite materials with similar specifications containing products obtained from tyre recycling. This approach is in line with the EU's waste hierarchy policy, which gives preference to the recycling and recovery of tyres by retreading over their management by combustion (EP-PE, 2008). It is also necessary to introduce into used tyre management an approach taking account of the whole life cycle of the product and not just its phase as waste, and to focus on reducing the environmental hazards involved in its production and management.

Figures published by ETRMA show that in most EU countries very great emphasis, as regards used tyre management, is being placed on the development of new technologies and the improvement of existing ones for recycling tyres and their retreading. Evidence for this is provided by the high levels of recycling (42%) and the considerable proportion of retreading processes in tyre recovery, enabling 9% of the total mass of wastes to be managed (ETRMA, 2010b). Countries where used tyre management is based mainly on recycling and retreading, without their combustion, include Denmark, Finland, Ireland, Slovakia and Slovenia.

3. Conclusions

Nowadays, there are many different approaches to develop appropriate strategies to enhance the efficiency of waste polymer management, in accordance with the applicable requirements of the environment protection.

This is a challenge mainly due to a lack of suitable regulations for recovery these wastes and ever growing amount of waste polymer materials. However, as it is shown in this paper, in case of car tyres, achieving a full success in the management of polymer wastes is possible.

We showed that recently there has been great progress in the development of innovative technologies improving management of used tyres in European Union. Nowadays, in many countries of EU, the level of recovery and recycling of used tyres is near 100%. This is possible due to the European Union's restrictive legal regulations (Directive on the Landfill of Waste 1999/31/EC and End of life Vehicle 2000/53/EC), which prohibit stockpiling of tyres in landfills.

There are three following models helping in improvement of used tyres management in EU's countries: development of organizational solutions based on the concept of extended producer responsibility for products (Extended Produced Responsibility), tax system and free market system. In Europe, the most popular model is the one based on extended producer responsibility (EPR), which legally obligates producers and importers of tyres to collect and then ensure recovery and recycling of the entire quantity of tyres placed on the market in a given year.

The producers of tyres probably would not be interested in recovering and recycling tyres if a new law requiring them to do so did not exist. The new regulations caused increased investments in modern tyre sorting and collection systems and spawned innovative methods to enhance recovery efficiency.

Material recycling and combustion of used tyres are currently the most technologically developed methods of handling with these wastes in the EU. It is worth pointing out that (from an economic point of view) tyre combustion and energy recovery is more attractive than material recycling. However, we get less energy from combustion process of waste tyres, than we needed for production of tires. Therefore, material recycling of waste tyres and using them as a source of raw materials seems to be a better method than combustion.

Moreover, as it is shown in this paper, through grinding processes of waste tyres they can become a source of valuable raw materials. In this way tyres can be reused to produce different kinds of very valuable polymer composites, obtained mainly with the aid of natural and synthetic rubbers, polyethylene, polypropylene and polyvinyl chloride. The advantages of using ground waste tyres for production of polymer composites include cost reduction of such composites and also the ability to classify them as a pro-ecological material.

When using ground rubber as a raw material, it is possible to obtain completely new types of commercial polymer materials. In today's environment, used tyres should no longer be considered a pollutant, but rather a valuable raw material.

References

Adhikari, B., De, D., Maiti, S., 2000. Reclamation and recycling of waste rubber. Progress in Polymer Science 25, 909–948.

Aliapur (France), 2009. Using used Tyres as an Alternative Source of Fuel, Reference Values and Characterization Protocols. Reference Document Downloaded from <http://www.aliapur.fr/modules/movie/scenes/home/index.php?fuseAction=search> (May 2011).

Amari, T., Themelis, N.J., Wernick, I.K., 1999. Resource recovery from used rubber tires. Resources Policy 25, 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 81, 85–113.

Benazzouk, A., Douzane, O., Langlet, T., Mezreb, K., Roucoult, J.M., Quéneudec, M., 2007. Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes. Cement and Concrete Composites 29, 732–740.

Berrueco, C., Esperanza, E., Mastral, F.J., Ceamanos, J., Garcia-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 74, 245–253.

Bosscher, P.J., Tuncer, B.E., Kuraoka, S., 1997. Design of Highway Embankments Using Tire Chips. Journal of Geotehnical and Geoenvironmental Engineering 4, 295–304.

Brown, H.L., Hamel, B.B., Hedman, B.A., 1996. Energy Analysis of 108 Industrial Processes. The Fairmont Press, Inc., Lilburn, USA.

Brubaker, R.L., Tloczynski, J.J., Budzol, M., Ahola, C.J., Boyle, F.P., Parkinson, T.D., Rine, J.C., 1984. Comminuting Apparatus with Improved Rotor and Stator Recess Construction. Patent US 4469284.

Cao, W., 2007. Study on properties of recycled tire rubber modified asphalt mixtures using dry process. Construction and Building Materials 21, 1011–1015.

Capelle, G., 1997. Stoffliche Verwertung von Altreifen und Gummiabfällen. Gummi Asbest. Kunststoffe 4, 297–303.

CEN/TS14243:2010 – Materials produced from end of life tyres. Specification of categories based on their dimension(s) and impurities and methods for determining their dimension(s) and impurities. European Technical Specification. European Committee for Standardization, Brussels April 2010.

ChemRisk LLC (USA), 2009. Tyre Generic Exposure Scenario End of Life Tyre Guidance. Report Prepared for ETRMA. <http://www.etrma.org/public/activitieschemreach.asp> (May 2011).

Collins, K.J., Jensen, A.C., Mallinson, J.J., Roenelle, V., Smith, I.P., 2002. Environmental impact assessment of a scrap tyre artificial reef. Journal of Marine Science 59, 243–249.

COM, 2005 – COMMISSION OF THE EUROPEAN COMMUNITIES – Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions. Taking Sustainable use of Resources Forward: A Thematic Strategy on the Prevention and Recycling of Waste, Brussels 21.12.2005, COM (2005) 666.

Conesa, J.A., Galvez, A., Mateos, F., Ignacio Martín-Gullón, I., Font, R., 2008. Organic and inorganic pollutants from cement kiln stack feeding alternative fuels. Journal of Hazardous Materials 158, 585–592.

Corti, A., Lombardi, L., 2004. End life tyres: alternative final disposal processes compared by LCA. Energy 29, 2089–2108.

Courtemanche, B., Levendis, Y.A., 1998. A laboratory study on the NO, NO_2, SO_2, CO and CO_2 emissions from the combustion of pulverized coal, municipal waste plastics and tires. Fuel 77 (3), 183–196.

De, S.K., Isayev, A., Khait, K., 2005. Rubber Recycling. CRC Press Taylor & Francis Group.

EP-PE, 2008 – II Position of the European Parliament Adopted at Second Reading on 17 June 2008 with a View to the Adoption of Directive 2008/.../EC of the European Parliament and of the Council on Waste and Repealing Certain Directives (EP-PE_TC2-COD(2005) 0281).

ERPA – European Recovered Paper Association (Belgium), 2010. European Declaration on Paper Recycling 2006–2010, Monitoring Report 2009. Report downloaded from <http://www.erpa.info/european0.html> (May 2011).

ETRMA - European Tyre & Rubber Manufacturers' Association (Belgium), 2010a. A Valuable Resource with Growing Potential 2010 edition. Report downloaded from <http://www.etrma.org/default.asp> (May 2011).

ETRMA – European Tyre & Rubber Manufacturers' Association (Belgium), 2010b. Used Tyres Recovery 2010 (table) – UT/Part Worn Tyres/ELT's Europe – Volumes Situation 2010, Data downloaded from <http://www.etrma.org/default.asp> (May 2011).

ETRMA – European Tyre & Rubber Manufacturers' Association (Belgium), 2011. The Annual Report 2010/2011, Report downloaded from <http://www.etrma.org/default.asp> (May 2011).

Ferrer, G., 1997. The economics of tire remanufacturing. Resources, Conservation and Recycling 19, 221–255.

Fiksel, J., Bakshi, B.R., Baral, A., Guerra, E., DeQuervain, B., 2011. Comparative life cycle assessment of beneficial applications for scrap tires. Clean Technologies and Environmental Policy 13, 19–35.

Ganjian, E., Khorami, M., Maghsoudi, A.A., 2009. Scrap-tyre-rubber replacement for aggregate and filler in concrete. Construction and Building Materials 23, 1828–1836.

Gieréa, R., Smith, K., Blackford, M., 2006. Chemical composition of fuels and emissions from a coal + tire combustion experiment in a power station. Fuel 85, 2278–2285.

Glijer, T., Lipinska, M., 2002. Technical and economical aspects of the tyre retreading. Elastomery 6, 16–22.

Gyorgy, M., 2009. Apparatus for Regular Grinding Rubber Vehicle Tires and Otherelastic Materials by Ultra Hich-Pressur Fluid. Patent HU 0800444.

Hazarika, H., Yasuhara, K., Kikuchi, Y., Karmokar, A.K., Mitarai, Y., 2010. Multifaceted potentials of tire-derived three dimensional geosynthetics in geotechnical applications and their evaluation. Geotextiles and Geomembranes 28, 303–315.

Holst, O., Stenberg, B., Christiansson, M., 1998. Biotechnological possibilities for waste tyre-rubber treatment. Biodegradation, 9, 3–4, 301–310.

Huang, Y., Bird, R.N., Heidrich, O., 2007. A review of the use of recycled solid waste materials in asphalt pavements. Resources, Conservation and Recycling 52, 58–73.

Huang, H., Tang, L., 2009. Pyrolysis treatment of waste tire powder in a capacitively coupled RF plasma reactor. Energy Conversion and Management 50, 611–617.

JATMA – The Japan Automobile Tyre Manufacturers Association NC (Japan), 2010. Tyre Industry of Japan 2010, Report downloaded from <http://www.jatma.or.jp/english/media/> (May 2011).

Khait, K., Carr, S.H., Mack, M.H., 2001. Solid-State Shear Pulverization: A New Polymer Processing and Powder Technology. Technomic Publishing, Lancaster.

Khait, K., 2005. Tire rubber recycling by mechanochemical processing. In: Sadhan, K. De, Avraam Isayev, Klementina Khait (Eds.), Rubber Recycling. CRC Press Taylor & Francis Group (Chapter 4.4).

Lebreton, B., Tuma, A., 2006. A quantitative approach to assessing the profitability of car and truck tire remanufacturing. International Journal of Production Economics 104, 639–652.

Lee, H.J., Roh, H.S., 2007. The use of recycled tire chips to minimize dynamic earth pressure during compaction of backfill. Construction and Building Materials 21, 1016–1026.

Levendis, Y.A., Atal, A., Carlson, J., Dunayevskiy, J., Vouros, P., 1996. Comparative study on the combustion and emissions of waste tire crumb and pulverized coal. Environmental Science & Technology 30 (9), 2742–2754.

Liang, B., Hao, Y.C., 2000. A novel cryogenic grinding system for recycling scrap tire peels. Advanced Powder Technology 11 (2), 187–197.

Murugan, S., Ramaswamy, M.C., Nagarajan, G., 2008. The use of tyre pyrolysis oil in diesel engines. Waste Management 28, 2743–2749.

Myhre, M., MacKillop, D.A., 2002. Rubber recycling. Rubber Chemistry and Technology 75 (3), 429–473.

Naik, T.R., Singh, S.S., 1991. Utilization of Discarded Tires as Construction Materials for Transportation Facilities. Report No. CBU-1991-02, UWM Center for By-Products Utilization. University of Wisconsin-Milwaukee, Milwaukee, 16 pp.

Navarro, F.J., Partal, P., Martínez-Boza, F., Gallegos, C., 2004. Thermo-rheological behaviour and storage stability of ground tire rubber-modified bitumens. Fuel 83, 2041–2049.

Oikonomou, N., Mavridou, S., 2009. Improvement of chloride ion penetration resistance in cement mortars modified with rubber from worn automobile tires. Cement & Concrete Composites 31, 403–407.

Olędzka, E., Pyskło, L., Sobczak, M., Łuksa, A., 2006. Technological and economical aspects of the pyrolysis of end-of-life tyres and the refining of the products obtained. Polimery 6, 405–482.

Pehlken, A., Müller, D.H., 2009. Using information of the separation process of recycling scrap tires for process modeling. Resources, Conservation and Recycling 54, 140–148.

Piercea, C.E., Blackwell, M.C., 2003. Potential of scrap tire rubber as lightweight aggregate in flowable fill. Waste Management 23, 197–208.

Pipilikaki, P., Katsioti, M., Papageorgiou, D., Fragoulis, D., Chaniotakis, E., 2005. Use of tire derived fuel in clinker burning. Cement & Concrete Composites 27, 843–847.

PlasticsEurope (Belgium), 2011. "Plastics – The facts 2011" – An Analysis of European Plastics Production, Demand and Recovery for 2010, Report downloaded from <http://www.plasticseurope.co.uk/Document/plastics—the-facts-2011.aspx?FolID=2> (October 2011).

Rajan, V.V., Dierkes, W.K., Joseph, R., Noordermeer, J.W.M., 2006. Science and technology of rubber reclamation with special attention to NR-based waste latex products. Progress in Polymer Science 31, 811–834.

Reznik, I., 2002. Method and Apparatus for Cooling Air to Cryogenic Temperatures for Recycling. Patent USA 6360547.

RMA – Rubber Manufacturers Association (USA), 2009. Scrap Tire Markets in the United States 9th Biennial Report, Report downloaded from <http://www.rma.org/scrap_tires/> (May 2011).

Rouse, M.W., White, M., 1996. Rubber Comminuting Apparatus. Patent US 5564634.

Rouse, M.W., 2001. Grinding Devices for Rubber Comminuting Machines. Patent US 6238267.

Rutherford, D. Sr., 1992. Process for Recycling Vehicle Tires. Patent US 5115983.

Siddique, R., Naik, T.R., 2004. Properties of concrete containing scrap-tire rubber – an overview. Waste Management 24, 563–569.

Sienkiewicz, M., Kucińska-Lipka, J., Janik, H., Balas, A., 2009. Electron microscopic studies of polyurethane-rubber recyclates composites. In: Proc. V Scientific-Technical Conference Advance in Petroleum and Gas Industry and Petrochemistry, June 9–12, 2009 Lviv, Ukraine, pp. 266–267.

Silvestraviciute, I., Karaliunaite, I., 2006. Comparison of end-of-life tyre treatment technologies: life cycle inventory analysis. Environmental Research, Engineering and Management 35, 52–60.

Singh, S., Nimmo, W., Gibbs, B.M., Williams, P.T., 2009. Waste tyre rubber as a secondary fuel for power plants. Fuel 88, 2473–2480.

Sunthonpagasit, N., Duffey, M.R., 2004. Scrap tires to crumb rubber: feasibility analysis for processing facilities. Resources, Conservation and Recycling 40, 281–299.

Synder, R.H., 1998. Scrap Tires: Disposal and Reuse. Society of Automotive Engineers, Warrendale, PA, USA.

WBCSD – World Business Council for Sustainable Development (Switzerland), 2008. The Report Managing End-of-Life Tyres. Report downloaded from <http://www.wbcsd.org/templates/TemplateWBCSD5/layout.asp?type=p&MenuId=MTYwNg&doOpen=1&ClickMenu=LeftMenu> (May 2011).

WBCSD – World Business Council for Sustainable Development, (Switzerland), 2010. End-of-Life Tyres: A Framework for Effective Management Systems. Report downloaded from <http://www.wbcsd.org/templates/TemplateWBCSD5/layout.asp?MenuID=1> (May 2011).

White, R., De, S., 2001. Rubber Technologist's Handbook, vol. 1. iSmithers Rapra Publishing, UK.

wdk: Wirtschaftsverband der deutschen Kautschukindustrie, 2003. Frankfurt a.M, Germany. Information downloaded from <www.wdk.de/de/index.html> (May 2011).

Li, Xiang-guo, Ma, Bao-guo, Xu, Li, Hu, Zhen-wu, Wang, Xin-gang, 2006. Thermogravimetric analysis of the co-combustion of the blends with high ash coal and waste tyres. Thermochimica Acta 441, 79–83.

Xiao, F., Amirkhanian, S.N., 2010. Laboratory investigation of utilizing high percentage of RAP in rubberized asphalt mixture. Materials and Structures 43, 223–233.

Yu-Min, C., 1996. On pyrolysis of waste tire: degradation rate and product yields. Resources, Conservation and Recycling 17 (2), 125–139.

Zebala, J., Ciepka, P., Reza, A., Janczur, R., 2007. Influence of rubber compound and tread pattern of retreaded tyres on vehicle active safety. Forensic Science International 167, 173–180.