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RUBBER WASTE MANAGEMENT

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Abstract: The issue of rubber waste management, among others, due to the intensively developing branch of road transport, and hence a large number of manufactured car tyres, is particularly important for the sustainable development paradigm. Tyres are used not only in internal combustion cars, but also in electric cars, which are considered more ecological. Worn car tyres are not the only type of rubber waste; however, due to the scale of production, they occur most often. The article discusses laws related to this group of waste and methods of its recovery and recycling. All discussed methods of disposal of rubber waste have been characterised in terms of their advantages and disadvantages. An innovative, newly designed pyrolytic installation has also been discussed.

Keywords: pyrolysis, thermolysis, material recycling, raw material recycling, product recycling.

1. Introduction

Nowadays, civilization undertakes challenges related to the implementation of sustainable development principles in every sector of the economy. The problem of the sustainable development paradigm is not only focused on minimising the consumption of non-renewable resources from the environment, but also on extending the “life-cycle” of the product, using recycled raw materials, and thus it also sets specific requirements for this waste management phase (Sienkiewicz et al., 2017).

The problem of managing rubber waste is becoming more and more important, e.g. due to the size of world production of these products (Thomas, Gupta, 2016). Globally in 2015, 2.68 million tonnes of rubber products and 4.89 million tonnes of rubber tyres were produced. The production of rubber products in 2017 was by 2% higher and reached 2.70 million tonnes and 4.94 million tonnes of car tyres were produced, which translates into a 1% increase in production. It should be noted that the trend of production growth of rubber products and car tyres is not a constant trend, when analysing the previous years, but due to the scale of production, management of rubber waste is a challenge for the present civilization.

Assuming that the lifetime of car tyres ranges from 4 to 6 years (U.S. Department of Transportation, 2007), it can potentially be considered that after this period of time, they will become waste. It is worth adding here that about 20-25% of tyre weight decreases during operation (Wojciechowski et al., 2012), as well as the fact that only a small part of car tyres will be recycled in the form of re-treading (in Poland about 20% (www.opony.com.pl)) and will be returned to the use phase.

In the European Union, in 2014 and 2016, 3.19 million tonnes and 3.37 million tonnes of rubber waste were generated, respectively. In Poland, in these years (respectively), 0.063 million tonnes and 0.081 tonnes of rubber waste were generated (Eurostat).

Due to the scale of the phenomenon, the search for appropriate, sustainable waste management methods is particularly important for environmental protection. Worn car tyres have been qualified as a nuisance waste because of their quantity and durability, and they are not degraded in the environment even over a 100-year period (Gronowicz, Kubiak, 2007).

The following article introduces selected methods of rubber waste management with particular emphasis on an innovative method of disposal of rubber waste – thermolysis. The innovativeness of the newly designed and constructed thermolytic installation by GMG lies primarily in its mobility.

The purpose of the article is to review rubber waste disposal methods in the context of their advantages and disadvantages, including the newly designed thermolytic installation.

2. Legislative issues in rubber waste management

Legislation in Poland regarding the management of rubber waste evokes three laws. The waste act of 14 December 2012 does not directly refer to the generally understood group of rubber waste (waste code: 07 02 80, 19 12 04), and the only group of waste mentioned in this act are used tyres (waste code: 16 01 03). According to the provisions of art. 122, para. 1, the storage of tyres and their parts, excluding bicycle tyres and tyres with an outside diameter greater than 1,400 mm, at the landfill is prohibited (*Ustawa o odpadach*). The above act introduced a ban on landfilling from as early as 1 July 2003, while since 1 July 2006, it has not been allowed to store tyre components (Wojciechowski et al., 2012).

The issues of managing rubber waste are also applied to in the act of 11 May 2001 on the obligations of entrepreneurs in the management of certain waste and the product fee. This act imposes an obligation on the entrepreneur to ensure an appropriate level of recovery and in recycling of the same type of waste as from the products introduced by them in the territory of the country (article 3, *Ustawa o obowiązkach przedsiębiorców...*). Currently, the levels of recovery and recycling of tyres, regardless of the type, have been set at 75% and 15%, respectively, of the weight of tyres introduced to the Polish market.

The place where used tyres should be taken from individual users is clarified in the law on maintaining cleanliness and order in municipalities. According to art. 3.2. point 6 of this act, municipalities create points for selective collection of municipal waste in a manner ensuring easy access for all residents of the commune, which ensure the acceptance of various municipal waste, including used tyres (*Ustawa o utrzymaniu czystości i porządku w gminach*). This provision is of particular importance due to the dispersed generation of rubber waste in the country. The separate municipal waste collection points (PSZOK) are to collect worn tyres in order to minimise the risk of abandoning them anywhere in the surrounding environment or by throwing them into containers for mixed municipal waste. Unfortunately, the above law does not apply to other types of rubber waste.

3. Selected methods of rubber waste management with particular emphasis on worn tyres

Worn tyres (rubber) can be subjected to disposal and recovery processes, such as:

- regeneration,
- material recycling,
- product recycling,
- raw material recycling,
- energy recovery.

3.1. Re-treading of car tyres

The tyre re-treading process can be regarded as regenerative processes. The purpose of tyre re-treading is to extend its lifetime. Considering the fact that about 80% of the mass of the original product is recycled again for use, this is a method with a high recovery rate (Januszkiewicz et al., 2010).

Two methods of tyre re-treading can be distinguished:

- cold, where the carcass[1] of a tyre is subjected to cleaning processes by roughening, then a thin layer of glue and a new tread in the form of a rubber layer are applied to the carcass. The whole is subjected to pressure and increased temperature, approx. 370 K for 4 to 5 hours;
- hot, where the carcass of a tyre, as in the cold method, undergoes cleaning processes from the old tread, the glue is also applied, and the rubber compound is applied, and the whole is placed in a hot form (about 450 K). This form imparts an appropriate tread, and after the process is completed, the tyre is further vulcanised at the same temperature. The process takes about 1.5 hours (Smejda-Krzewicka et al., 2015).

Advantages:

- high rate of tyre recovery,
- the re-treaded tyre is cheaper than a new one by about 30-40%,
- the tyre can be re-treaded up to three times, provided that the tyre is no more than seven years old,
- the driver can theoretically choose a new tread pattern,
- 20-30% of new raw materials are used for the re-treading process.

Disadvantages:

- uneven tyre structure, which is the result of several vulcanisation processes,
- not every tyre is suitable for this method of recovery; damaged tyres and those above seven years of "life" are not suitable for re-treading,
- the cold re-treading method is dedicated only to truck tyres,
- thermal and mechanical energy consumption for cleaning and pressing the vulcanised tyre,
- re-treaded tyres do not have a label,
- these tyres most often generate elevated noise levels and have a lower level of road grip,
- the hot re-treading method requires the use of separate moulds for each tyre size and tread pattern,
- it is not possible to recover other types of rubber waste.

3.2. Material recycling of tyres

[1] Carcass – the basic part of the tyre, the skeleton responsible for the shape, maintaining the appropriate pressure inside the tyre and for carrying loads.

Material recycling involves processing rubber waste into a product with a utility value, usually for a purpose other than the original purpose. The basic process enabling material recycling of rubber waste is its fragmentation. Grinding is carried out mechanically in five ways (Mroziński, Flizikowski, 2012; Yehia et al., 2012):

- at ambient temperature, it consists in grinding pieces of cut tyres with mills or pulverising them on rolling mills,
- after freezing in liquid nitrogen (cryogenic method), it consists in cooling the pieces of the tyres with liquid nitrogen below the brittleness temperature (about 200 K ≈ -80°C) and subjecting them to fragmentation with the use of flail mills,
- wet, consisting in grinding pre-ground rubber in an aqueous suspension,
- under high water pressure, consisting in separating the rubber from the cord and its fragmentation with water at a pressure of over 200 MPa; the method is mainly used for large size tyres,
- the Berstorff method, consisting in the use of rolling mills equipped with grooved rolls and twin screw extruders, which are arranged in series to crush post-use tyres.

In practice, technological developments of the above methods are used. For example, the WATER-JET method (under high pressure), where the water pressure from the nozzle orifice is from 100 to 300 MPa, or the ROTAREX FAST&EASY method (at ambient temperature), in which a head consisting of a shield with its circumference exchangeable cutting blades.

Advantages (Sienkiewicz, 2010):

- obtaining very good rubber fines and a well-developed specific surface of grains in "wet" and "high pressure water" methods,
- in the cryogenic method, grains with a smooth surface, sharp edges and similar shape and sizes are obtained,
- wide use of recyclate.

Disadvantages (Sienkiewicz, 2010):

- high energy inputs, in particular in the cryogenic method (it is possible to use compressor chillers, which are more economical); the method considered more energy-efficient is the "high pressure water" method,
- the possibility of rubber contamination, except for the "high water pressure" method, defects are especially seen in the ROTAREX FAST&EASY method,
- during the mechanical (dry) grinding of tyres, a significant amount of heat is released, which can cause auto-ignition,
- in "wet", "high pressure water" and cryogenic recycling methods, the recyclate is moist;
- emission of high noise levels with "dry" methods,
- in most cases (described below), the use of recyclate to produce products requires another process called devulcanisation,

– most installations are not mobile due to dimensions (not included in WATER-JET and ROTAREX FAST&EASY).

Recyclate in the form of dust and granules has found wide application as an addition to new rubber mixtures for the production of: insulation of tunnels, roads, asphalt, bridge surfaces, playground lining, sports halls, screens and insulation mats, synthetic peat, cast industrial tyres, roof coverings, railway crossings, materials absorbing petroleum products, wipers, car floor mats, etc. Cemented recycled composites have found application as surface layers of roads, sidewalks and highways (separators of motorways) and as noise barriers (Wojciechowski et al., 2012). Research is also being carried out on the use of recyclate for the production of concrete. The mechanical properties of concrete with the addition of crushed rubber deteriorate; however, some of the physical properties of the concrete improve, e.g. the acoustic properties of the concrete or the reduction of concrete mass with the amount of recycled tyre added (Svoboda et al., 2018).

3.3. Product recycling

Product recycling relies on the re-use of used waste entirely without subjecting it to any treatment processes. This type of recycling is not widely used. In the European Union, product recycling is at a level of 5% of the management of worn tyres. Rubber waste most often finds application in (Januszewicz et al., 2010):

– protection of coasts and riverbanks,
– construction of breakwaters and erosion barriers,
– creating artificial reefs,
– sound absorbing barriers,
– bumpers on port quays,
– insulation of construction foundations,
– road surfaces,
– in irrigation systems as reservoirs and water channels,
– construction of membranes and drainage layers,
– strengthening the sides of mountain roads.

Currently, a new material recycling method is also used, the so-called packages of pressed down car tyres (SZOS). Compressed in the press and stapled with tapes, worn cubic tyres replace natural aggregates in construction. This method is widely used in Great Britain (Duda, Sobala, 2017).

Advantages:

- small energy expenditure related only to transport from the place of origin (temporary collection) to the place of reuse,
- due to the high availability of rubber waste in each region, transport is carried out over small distances,
- rubber waste/tyres replace the use of a large amount of building materials,
- SZOS packages are cheap and have unique properties, such as: low weight, high water permeability, ability to suppress vibrations and noise.

Disadvantages:

- due to the scale of rubber waste generated/tyres, this method is potentially unable to develop them in 100%,
- this method uses only car tyres,
- applying this method in practice affects the appearance of the landscape.

3.4. Product recycling

3.4.1. Thermal rubber recycling – regeneration (devulcanisation)

This involves the use of mechanical, thermal or chemical energy to break network-forming bonds, such as: C-S and/or S-S, as well as partial degradation of elastomer chains. Depending on the method used and the degree of degradation of the obtained regenerate, it is possible to further process it and vulcanise it to obtain a new product (Wojciechowski et al., 2012; Yehia, 2004).

Methods of rubber regeneration (Żmuda et al., 2006; Wojciechowski et al., 2012; Shah et al., 2013):

- **oil-steam -** consisting of the mixing of rubber granulate (grinding of rubber is carried out using the methods described earlier) with tallol/oils, then it is subjected to a mixture with water vapour in an autoclave and mixed until a homogeneous mass is obtained. The process takes place at a pressure of 1-2 MPa at 175-205°C within 5-12 hours (Wojciechowski et al., 2012);
- **thermo-mechanical -** consisting in the action of steam with a pressure of up to 4.0 MPa for the ground rubber in rotary spherical boilers at 200-220°C;
- **biotechnology -** consisting in subjecting the ground rubber to the action of bacteria assimilating sulphur. The process, carried out at 65°C, takes a few days, and after the process, the bacteria die.

Advantages (Żmuda et al., 2006; Wojciechowski et al., 2012):

- recyclate is used as a component in the production of rubber products, among others car tyres, in the amount of 5÷30% of the raw material charge,
- it is possible to receive a range of products with excellent functional properties from the recyclate.

Disadvantages (Żmuda et al., 2006; Wojciechowski et al., 2012):

- high energy expenditure in the oil-steam method; thermal-mechanical method ensures higher efficiency, lower labour consumption, energy consumption and production costs,
- technological and usable properties of the recyclate are slightly lower than those of rubber,
- the introduction of many types of synthetic rubbers and their mixtures, cross-linking agents and protective agents to the production of tyres reduces the quality of recyclate,
- in chemical processes, it is necessary to clean the recyclate from sludge,
- installations are not mobile.

Recyclate is used in production similar to the one described earlier in section 3.2, i.e. for the production of: bridge surface, playground lining, sports halls, screens and insulation mats, roof coverings, railway crossings, wipers, car mats. As a component in the production of rubber products, among others car tyres, in the amount of 5÷30% of the raw material charge.

3.4.2. Pyrolysis of rubber tyres

Pyrolysis of rubber waste consists in the decomposition of organic chemicals with higher molecular weights into smaller molecules under the influence of temperature (300÷800°C) and in the absence or shortage of oxygen. As a result of the pyrolysis process of rubber waste, the following products are created:

- carbon derivative (coke breeze), substitute for technical carbon black,
- post-process oil, gas (synthesis gas),
- steel (reinforcement of tyres or some group of rubber hoses).

The newly designed thermolysis plant at GMG Sp. z o.o. is based on starting the process in the first furnace with an exchangeable rotary reactor through its initiation with the use of additional propane-butane gas. When the temperature in the first reactor after the initiation of the process rises to 180°C, the batch drying process takes place, and all remaining water contained in the waste evaporates. The exchangeable rotary reactor is then gradually heated to 290ºC without any interruption, where the process of vapour production begins. The vapour under low pressure 0.2÷0.45 bar is directed to the rectification column are divided into three basic fractions.

In the lower part of the column, there is a process of division of the heavy fraction (mazut), through intermediate and light to gaseous fractions (this applies to every exchangeable rotary reactor exchanged in the process, max. every 8 hours). Regardless of the number of interconnected (gas mains) stations to which three replaceable horizontal rotary reactors are prescribed, the firing process takes place only after the previous initiation every 3 hours, whereas each reactor must be replaced in the system every 8 hours.

Acquisition of high-quality liquid fractions from gas-steam fractions enables newly designed and patented gas-steam bumpers to be installed at individual column levels. The liquid fractions remain in the rectification column until the pressure drain valve automatically opens, which collects all the fractions created in the column in the specially designed two-jacket storage tank, while the process gas generated during the thermolysis process passes through the upper gas line to the low pressure gas tanks and is then cooled through a set of pre-cleaning and final gas cleaning filters to the furnaces located under the reactors in the next plant module, thus maintaining the entire process without the need to fire the furnaces from an external power source until the furnaces are intentionally extinguished. This operation, after the first initiation during the technological start-up of the first reactor, is repeated every 3 hours for each subsequent furnace with an installed rotary reactor, regardless of the number of stations, thus causing an unlimited supply with the necessary thermal energy, in this case process gas (synthetic gas). This process may take place without the need to later supply any station with an external source of thermal energy (except for initiation of the process at the time of its first commissioning).

The installation has a modular construction, which allows it to be expanded with additional furnaces, as it is not permanently connected to the ground and can be moved to any place designated by the investor at any time.

The efficiency of the installation, regardless of its size (number of stations – modules), brings about the possibility of complete processing of multi-particle waste, where in the technology of thermal decomposition of 1 tonne of tyres and rubber waste, it is possible to produce within 24 hours:

- up to 450 litres of the post-process fluid suitable for driving current generators (derived fuel oil) – calorific value 42,000 KJ/kg – which can be further modified into such fractions as: 30% petrol and solvents, 50% fuel oil, 20% mazut,
- up to 350 kg hard coal carbonate residue (derivative i.e. coke breeze); in this form, without modification, it may be an addition to low calorie alternative fuels or a soot substitute – calorific value 31,500 KJ/kg,
- up to 50 kg of scrap (this value applies only to the charge in which there is, for example, a metal cord or other rubber reinforcement element),
- up to 250 m^3 of process gas (synthetic gas), used in full for the installation process – calorific value of 48,000 KJ/kg.

Advantages:

- the installation newly designed by GMG Sp. z o.o. is a mobile installation, in a modular development together with the infrastructure designed for it,
- additional fuel, i.e. propane-butane gas, is necessary only for the first start-up of the installation (process initiation),
- this method does not pose a threat to the environment by the emission of gaseous pollutants,
- the installation is fully automated,
- low gas pressure (0.2÷0.45 bar) in the installation ensures safety of use,
- construction of a complete plant at the destination takes one day,

- building infrastructure for this installation allows for work in a 24-hour system,
- the plant is fully self-sufficient, both in the media (electricity) and thermal energy generated from the resources obtained for own needs.

Disadvantages:

- noise during operation of the reactor drive unit,
- in order to ensure economic efficiency, continuity of operation of the reactors 24 h/day is recommended,
- there may be an added nuisance related to the need to clean the reactor.

3.4.3. Microwave tyre carbonation process

The neutralisation of rubber waste in microwave reactors consists in using electric energy, converting it into kinetic energy and through photons to thermal energy transferred to the molecules of chemical compounds from which the tyres were built. The molecular particles of the charge, receiving large amounts of kinetic energy from the magnetrons, make them vibrate, causing the kinetic energy to be converted into massive amounts of thermal energy and the breakdown of particles into smaller particles (Linert, 2011).

Advantages (Linert, 2011; Wojciechowski et al., 2012):

- high process efficiency,
- the products obtained are of high purity,
- high degree of utilisation of rubber waste.

Disadvantages (Linert, 2011; Wojciechowski et al., 2012):

- rubber must have a polar character,
- purification discharges gases before being discharged into the atmosphere,
- high energy consumption for running the process,
- high equipment cost.

3.5. Energy recovery

This is the method of managing rubber waste most often used in Poland. Tyres are an alternative fuel in cement plants, where they are burned in smokeless furnaces. Corti and Lombardi (2004) have shown that the process of burning tyres is more environmentally friendly than other methods of managing rubber waste. They based their research on a balance sheet in which they showed that the use of tyres as an alternative fuel requires much less financial and energy inputs than their recycling through shredding, which is an energy-consuming process. Tyre life-cycle analyses from the moment of their production to product decommissioning indicate that despite high economic profits, burning tyres with energy recovery is not the best solution (Shu, Huang, 2014). Assessment of the energy balance of the entire tyre life-cycle proves that the amount of energy needed to produce them is about 87-115 MJ/kg, while from burning tyres, it is possible to obtain only 32 MJ/kg of energy (Sienkiewicz, 2010).

Advantages:
- reducing the demand for non-renewable energy resources,
- higher calorific value of rubber waste than most fuels,
- lower nitrogen, sulphur and ash content in comparison to coal,
- steel content in tyre reinforcement, eliminating the need to add iron oxides to the clinker burning process,
- the process does not produce ash or slag, as the steel cord of the tyres is permanently bonded to the clinker produced, favourably affecting its strength properties,
- it is also possible to recycle other rubber waste and not only tyres.

Disadvantages:
- the raw material in the form of rubber is irretrievably lost,
- high cost of transporting waste to the cement plant,
- installations are not mobile,
- an unfavourable balance of the entire tyre life-cycle.

4. Conclusions

Each of the described methods of managing rubber waste has advantages and disadvantages of use in practice. Due to the scale of the problem of large amounts of rubber waste, the management of this waste becomes a civilization challenge. The choice of a particular method of managing this waste should be based on the balance of economic and ecological profits and losses. It seems that the co-incineration of rubber waste in cement plants and the processing of rubber waste in small mobile installations is the future direction of development.

By in-depth analysis of the above two methods of neutralising rubber waste, co-incineration of rubber waste in cement plants generates very high economic and ecological costs associated with the transport of this waste to the small number of cement plants operating in Poland (currently only thirteen cement plants operate in Poland). The environmental burden and reduction of costs of transporting waste to disposal sites can be minimised by using mobile disposal installations. Another aspect in favour of using mobile installations is the fact that the tyres, due to their shape, do not fill the entire cargo space of the means of transport. A more favourable solution is to transport the installation from the place of their disposal (e.g. PSZOK) to the next place of waste disposal instead of transporting rubber waste to these installations.

Mobile installations can change the approach to reverse logistics of rubber waste. Most installations require the transport of rubber waste over long distances from the place of their formation (temporary collection) to the place of disposal in which they are recycled. The newly designed rubber waste recycling installation is a mobile installation, which can be moved from one waste collection point to another, depending on the needs. This is important for reducing the environmental impact by decreasing the emissions to the atmosphere associated with transport and will reduce the traffic of lorries on roads that transport used tyres to stationary installations.

It also has an impact on economic efficiency, as reducing the costs of transporting waste to a waste neutralisation installation contributes to improving the financial results of recycling companies. In the Polish rubber waste management system, legislation has indicated where to collect worn tyres. However, in practice, it often happens that vehicle owners discard worn-out tyres at unacceptable locations or throw them into mixed waste containers. This is the result of car workshops that provide tyre replacement services imposing small fees in case the tyres are left in the workshop.

Mobility of waste disposal installations is a valuable advantage in the context of the possibility of their use by communal associations[2]. Communal associations cooperating with each other in the field of waste management can jointly finance the purchase of installations and use these installations interchangeably in each of the municipalities of this union, moving them periodically.

The tyre re-treading method is a very desirable method, because it affects its longer use, but due to restrictions on the "age" of the tyre (no tyres older than seven years can be re-treaded) and very stringent provisions on the technical condition of the tyre, only a small amount of these tyres can be subjected to this process.

Taking into account the energy conditions, the most advantageous method of waste disposal is product recycling. Energy expenditure in this method is only related to transport from the place of its selective collection to the place of use. However, due to the low rate of used tyres in this method (about 5%÷10% (Nuzaimah et al., 2018)), this is not significant in the management of rubber waste.

The tyre re-treading method also has low energy expenditure, but due to the numerous restrictions and requirements for re-treaded tyres, it also does not have a high utilisation rate.

Waste treatment methods characterised by low energy expenditure include the newly designed thermolytic installation, where additional energy is used only to initiate the process in the first reactor. For the production of thermal energy in the next reactor, the syn-gas produced in the first reactor is used without the need to supplement the installation with additional fuel. Small amounts of electricity are required for process control (automation), reactor rotation and compressor operation. An important advantage of this method is also the fact that all selectively collected rubber waste, including tyres, can be disposed of.

[2] Communal associations – specific public law corporations established by commune self-governments based on the provisions of the Act of 8 March 1990 on communal self-government (Journal of Laws of 2019, item 506) by means of agreements subsequently approved by resolutions of the commune councils in order to jointly perform public tasks.

The largest energy expenditure is required by methods in which rubber waste is subjected to: low temperatures (cryogenic method), mechanical forces (Berstorff method, ROTAREX FAST&EASY, etc.) or thermal energy (thermolysis, microwave method), respectively.

The choice of the method of neutralising rubber waste may also depend on obtaining a specific type of product (raw material) and its purity, for which there is a demand on the market. In this aspect, one method of disposing of rubber waste which is universal in this respect cannot be clearly indicated.

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