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Environmentally Friendly Recycling of Wooden Railway Sleepers

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Summary
The paper presents directions for ensuring development while protecting the environment and natural resources. Mineral raw materials and natural energy resources should be replaced by secondary raw materials from post-consumer and post-production waste, which is constantly increasing. These demands are the basis of the Community program: Zero Waste for Europe. The circular economy concept should also be implemented in the rail sector to ensure proper waste management as well as energy savings and material recovery. The recycling process should include, among others, depleted wooden railway sleepers impregnated with creosote oil, which cause a great environmental problem.
The principles of application and requirements for wooden railway elements impregnated with creosote oil are discussed. There are also factors that impede a comprehensive approach to recycling of the products concerned. At the same time, methods for the thermal decomposition of organic waste by thermolysis and properties of the obtained products from old wooden railway sleepers are characterized.

Keywords: thermal decomposition, waste, Circular Economy, creosote oil, railway sleepers

1. Introduction

The EU economy is exposed to a shortage of raw materials and sources of energy, as well as the constantly increasing costs of obtaining them. Waste management is one of the elements of the general waste management strategies in the European Union. At present, rapid economic growth, in particular with regard to electronics and transport, entails the creation of relevant technical solutions as well as innovative concepts related to the organization of recycling and recovery. With a view to protecting the environment, while simultaneously developing the economy, it seems necessary to shape economic policy based on the product life cycle (Circular Economy). Such assumptions of recycling and recovery require a suitable pro-ecological attitude of the society towards manufacturers who are obliged to consider such issues as early as at the design stage. It is necessary to use the most effective recovery and neutralization/disposal technologies regarding depleted products. In addition, recycling is a great opportunity for a sustainable economy. The idea behind recycling and recovery in the circular economy serves as a basis for the EU to achieve the goal: no waste in 2050 for Europe - "Zero Waste for Europe".

So far, the growth of the economy has required a regular increase in raw material and energy use. The results of the growth in raw material mining and energy consumption are rising pollution and degradation of the environment. Therefore, to ensure development and protect the environment and natural resources, it is necessary to adopt a policy based on the product life cycle aimed at implementing the closed loop of materials into standards of economy (CE – Circular Economy).

Mineral and natural energy sources should be replaced with secondary raw materials from post-consumer and post-production waste, which is growing in quantity on a continuous basis. The purpose should be to minimize hyper-consumption globally, as well as to undertake actions regarding the system related to the safety of transport and supplies for social needs and under hazardous conditions (war, terrorism, riots and disasters, etc.).

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2. Material circulation economy (Circular Economy)

The circular economy concept should also be implemented in the rail sector in order to ensure suitable waste management and energy savings as well as material recovery. New technologies for managing organic and mixed waste contribute to reducing greenhouse gas emissions and environmental pollution as well as obtaining semi-finished products from waste, thanks to which it is possible to limit the demand for primary raw materials. For this reason, the recycling process should, in the first place, embrace depleted wooden railway sleepers, which are a major environmental problem. The circular economy is supposed to contribute to increased durability of products and their optimization in terms of repair and reuse, as well as limiting the consumption and wastage of natural resources (Notification of EC COM (2015) 614 final; 2.12.2015) [7]. Fig. 1 presents a diagram of the circulation economy. In order to implement CE effectively, it is necessary to add any essential streams of post-consumer waste to the material circulation cycle. One such resource are wooden elements of the railway infrastructure, in particular depleted sleepers, bridge sleepers and switch sleepers. Due to their impregnation, these elements are not suitable for direct use as power fuels because they contain a hazardous (toxic) creosote oil [8]. In addition, the use of worn-out railway sleepers as the fuel in central heating boilers or in power blocks is ineffective, as well as posing a threat to the environment and human health. It would require the use of special filters and high burning temperatures (above 850°C for at least 2 seconds) or the use of costly two-chamber furnaces with exhaust afterburners in order to get rid of cancerogenic dioxins and furans.

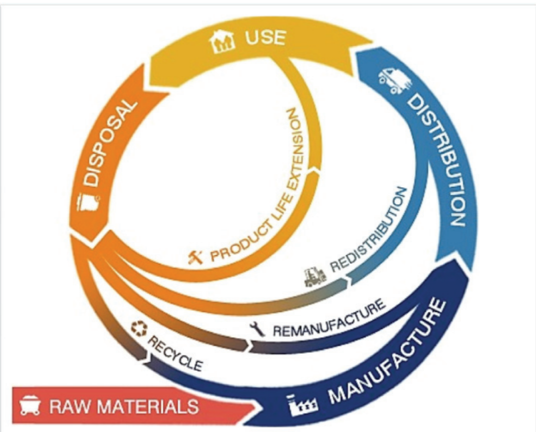

Fig. 1. Circular economy [source: www.kisspng.com/free/circular-economy.htm/png-circular-economy-circular-flow-of-income-sustainab-3385136]

3. Railway infrastructure resources

Facing incredibly serious environmental challenges and the reduction of non-renewable natural resources, waste processing is proving to be an economic necessity and imperative of the modern economy. The dynamics of economic growth determine the need to develop waste recycling technologies and material recovery solutions. The economies of the best-industrialized countries in the world had a considerable impact on waste recycling initiatives, in particular product and material recovery, and set the direction for potential research and development works, as well as industrial studies focused on the efficient waste material management and application.

The railway infrastructure is one of the largest material-consuming markets, and consequently a large source of potential waste (long life span). The Central Statistical Office as well as PKP-PLK railway company data demonstrate that the length of worn-out railway lines (as of 31 December 2015) is as follows:

- single-track lines 10 623 km,
- two- and more-track lines 8 617 km.

In accordance with the data as of 31 December 2014, the elements of the railway infrastructure used for PKP PLK S.A networks are the following:

- 36 100 km of mainline tracks and railway station tracks,
- 40 343 railroad switches,
- 24 858 track kilometers (tkm) of traction network.

This means there are a large number of elements which must be replaced after being worn-out, or neutralized/disposed of, recycled and recovered.

4. Railroad wooden materials [3]

Railway sleepers are made of pine, oak and beech. Wood is a natural composite material, thanks to which it has optimal properties, e.g. in terms of flexibility, durability and resistance to miscellaneous operating conditions (resistance to variable weather and ground conditions). Due to the place of application, wooden elements of the railroad surface take the form of sleepers, switch sleepers and bridge sleepers (Fig. 2).

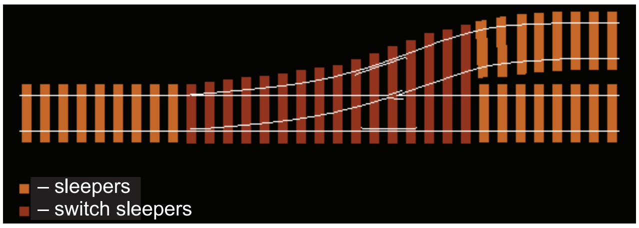

Fig. 2. Exemplary scheme of wooden sleepers and switch sleepers application on a railway line; own elaboration based on [3]

Wooden sleepers are still used for technical reasons (e.g. low resistance on fluctuations of temperature, existence of flexible soil – low-quality ballasts) as well as for economic reasons (less expensive than prestressed ones). Table 1 shows the age structure of railway sleepers used – as of 31 December 2016. In turn, Fig. 3 presents photographs of impregnated and depleted wooden sleepers, removed from railway lines.

5. Impregnating (saturating) railway sleepers with oil

The elements are saturated with creosote oil with the use of the high-pressure Rüping method, also called the vacuum-pressure method or empty-cell method [3, 4, 6] The greatest advantage of this method is the increase in the resistance and durability of wood, which is crucial when using the products impregnated during construction of the railway surface (e.g. an impregnated beech sleeper has a durability of 30 years, while a non-impregnated one has only 3 years). Fig. 4 shows the autoclave for the Rüping method impregnation process as well as a diagram of wooden sleeper saturation. The creosote oil [13] obtained from oil fractions deriving from coal tar distillation, despite such advantages as:

- good anti-rotting and bactericidal properties,
- it does not vanish from wood under the influence of water or humid ground,
- it does not change its properties under the influence of ground elements,
- has drawbacks, namely the content of cancerogenic compounds.

Table 1

Age structure of depleted railway sleepers – as of 31.12.2016

Type of sleepers	Total quantity [mln pcs]	Lifetime period [years]	Sleepers used after lifetime period	
			Quantity [mln pcs]	Share of given type [%]
Coniferous	17.8	18	13.7	77.0
Hardwood	2.3	25	0.7	30.4
Prestressed	37.0	35	5.8	15.7
Other	1.2	30	0.5	41.7
Total	**58.3**	–	**20.7**	**35.5**

[Source: Railway Office PKP PLK, 2017].

a) b) c) d) e)

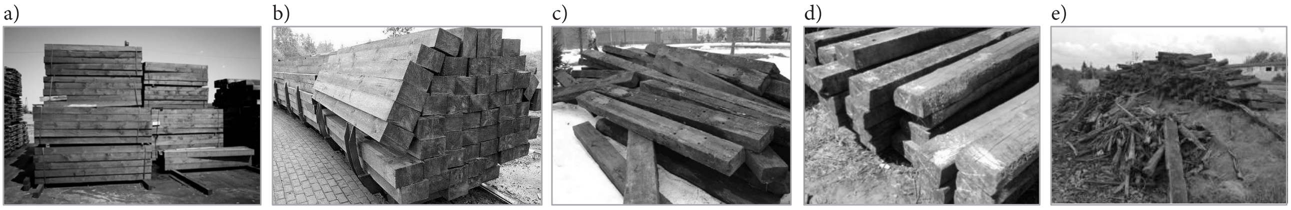

Fig. 3. View of impregnated (a, b) and depleted (c, d, e) wooden sleepers (switch sleepers) removed from railway lines [3]

a) b)

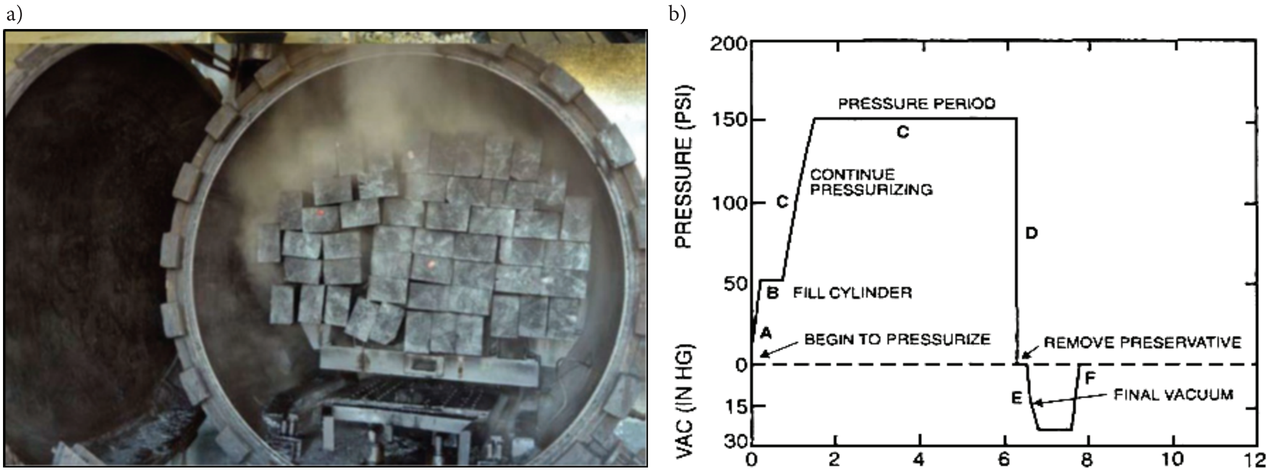

Fig. 4. View of autoclave for impregnation with the Rüping method and wooden sleeper saturation (a) and schem of the Rüpinga process (b); own elaboration based on [3]

Thus, although the entire sleeper volume is not subject to saturation in the impregnation process (Tables 2–4) in accordance with [11, 12] as mentioned above in Section 2, the recycling requires the use of special methods.

6. Thermal decomposition of organic waste

An effective method for managing post-consumer waste harmful to the environment and dominated by organic materials is low-temperature thermal decomposition (thermolysis). This is connected with the anaerobic thermal decomposition of waste in the steel reactor at a temperature of up to 490°C. Fig. 5 depicts the types of waste thermal decomposition processes that are currently used [2].

So far, thermal decomposition methods have been based on waste thermolysis with the use of car tires and other elastomers (gaskets, conveyor belts, etc.) as well as polymers and multi-material waste (among others, TetraPak packaging, diagnostic medical equipment and instrumentation, etc.) in which the products acquired are gas fraction, liquid fraction (oil) and solid fraction (biochar, steel cord, aluminum film, etc.) [2].

Table 2

Requirements in accordance with PN-D-95014 – oil absorption (supersaturation)

Type of wood	Wood sections	Supersaturation depth
Pine	Lack of sapwood sapstain	Entire thickness of sapwood layer
	Sapwood sapstain	80% of thickness of sapwood layer
	Uncovered heartwood	minimum 7 mm from the surface
Oak	Sapwood up to 20 mm thick	Entire thickness of sapwood layer
	Sapwood >20 mm thick	80% of thickness of sapwood layer
	Uncovered heartwood	minimum 4 mm from the surface
Beech	Sapwood covering the entire cross section	80% of thickness of sapwood layer
	Sapwood up to 60 mm thick	Entire thickness of sapwood layer
	Uncovered false heartwood	minimum 5 mm from the surface

Table 3

Requirements in accordance with PN-D-95014 – amount of absorbed oil (retention)

Type of wood	Type of product	Amount of absorbed impregnation oil [kg/m³ of wood]	Allowance range [%]
Pine	sleepers	100	–10 to + 20
	switch sleepers	100	
	bridge sleepers	80	
Oak	sleepers	50	–10 to + 20
	switch sleepers	50	
	bridge sleepers	45	
Beech	sleepers	150	–10 to + 20
	switch sleepers	150	
	bridge sleepers	150	

Table 4

Comparison of standard requirements – depth of wood supersaturation (clear sapwood and heartwood)

Type of wood	Wood supersaturation depth in accordance with:	
	PN-EN 13145	**PN-D-95014**
Pine	full supersaturation of sapwood in accordance with PN-EN 351-1	minimum 7 mm from the surface (uncovered heartwood)
Oak	as above	minimum 4 mm from the surface (uncovered heartwood)
Beech	as above	minimum 5 mm from the surface (uncovered false heartwood)

WGW Green Energy Poland Sp. z o.o. [15] has developed these methods and modernized the structure of the processing devices and the installation as well as optimizing the engineering process. It enables valuable and quality products to be obtained from the organic and composite waste, dedicated for the market in an economically justified way. In cooperation with the Institute of Precision Mechanics and as part of performing R&D works, WGW has also developed technology for processing multi-material and hazardous post-consumer waste, and in particular TetraPak packaging and medical diagnostic waste (Figs. 6-8) [2, 16].

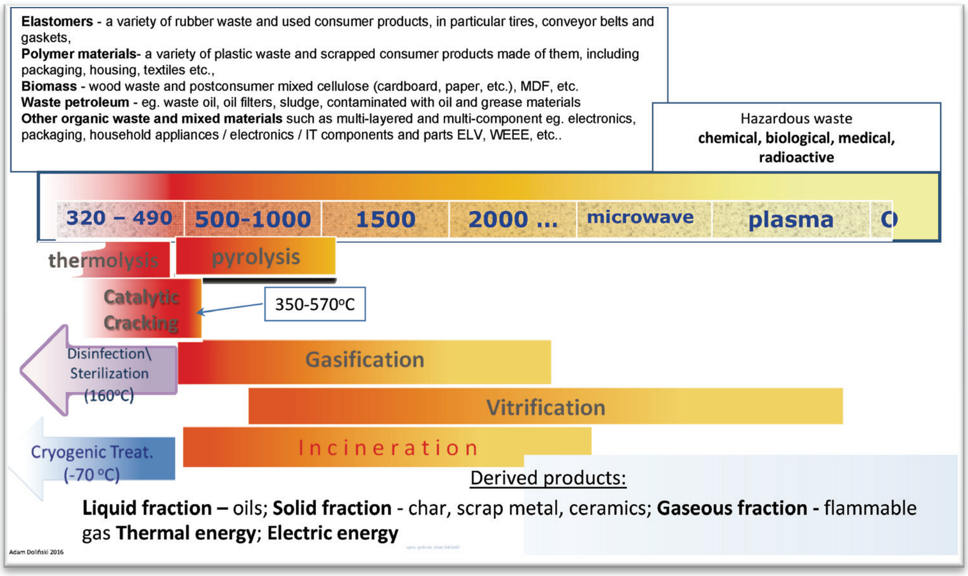

Fig. 5. Waste thermal decomposition processes [2]

a) b) c)

Fig. 6. Examples of thermal decomposition systems based on thermolysis by WGW Green Energy Poland Sp. z o.o. [2]

Fig. 7. Examples of waste subject to thermal decomposition and transformation into materials [11]

Fig. 8. Examples of products obtained in the thermal decomposition process of various waste flammable oils, carbon char, steel/metal scrap, aluminium foil [2]

Thermolysis / pyrolysis is similar to dry wood distillation, known since the XIX century, which is concerned with wood thermal decomposition without access to air (or with minimized access) in filled reactors heated to reach temperatures of about 500°C. The products of wood thermal decomposition are charcoal, wood gas, wood vinegar (acetic acid, methanol) and tar [5, 9] The wood gas which is generated during this process, the so-called "holzgas", is primarily composed of hydrogen (about 20% of volume), carbon monoxide (about 20%) and minor amounts of methane and non-flammable nitrogen (about 50-60%), carbon dioxide and water steam. Previously, wood gas was used as fuel to power internal-combustion engines in cars and, for example, heating stoves.

The modern thermal decomposition technology developed by WGW guarantees the safe processing of diverse organic and mixed waste as well as the management of all products.

At present, under its engineering activities, WGW in cooperation with the Railway Research Institute has decided to develop an environmental-friendly and optimal thermal decomposition technology, based on thermolysis, for depleted wooden railway sleepers along with comprehensive technology for managing decomposition products for market purposes.

7. Thermal decomposition of organic waste – railway sleepers

Previous experiments have demonstrated that there are no obstacles to implementing initial waste recycling process technology for wooden railway sleepers along with other wooden waste (e.g. chips). The method in question seems to be prospective with regard to managing existing post-consumer railway waste. This will be an important supplementation for the railway infrastructure in the system, allowing the introduction of the circular economy in railways. The products of wood thermal decomposition (pyrolysis) are charcoal, water, carbon monoxide and dioxide, methane and other carbohydrates, methanol, acetic acid and wood tar containing valuable organic compounds (its composition is dependent on the way of processing and kind of wood). Wood chips are small pieces of wood from a few millimeters to 10 cm large, generated as a result of grinding in machines, called wood chipping machines, or wood processing in the lumber mill (among others, for railway sleepers).

8. Trial processes of thermal decomposition of depleted wooden railway sleepers based on thermolysis

The first attempts at thermal decomposition based on wooden waste thermolysis (chips and ground depleted railway sleepers) showed a high likelihood of implementing the neutralization/disposal process on an industrial scale. Table 5 presents a composition of charcoal created at thermolysis of 20 kilograms of railway sleeper chips, while Fig. 9 lists solids s obtained by the thermal decomposition of railway sleepers. The charcoal samples derived from thermolysis were subjected to the toxicity test of gases produced during thermal irradiation. The measurement was carried out in the Railway Research Institute applying a single-chamber test in accordance with PN-EN ISO 5659-2 [9] (radiation intensity of 25 kW/m^2) in combination with a FTIR analyzer. This analyzer adopts the Fourier-transformation spectroscopy method in the range of infrared and the so-called far infrared ($25\text{-}1000 \cdot 10^{-6}$ m) radiation. The results are presented in Table 6.

Table 5

Results of laboratory tests with regard to charcoal arising from thermolysis

Sample no.	Type of sample	Humidity [%]	Ash [%]	Volatile particles [%]	C_{fix} [%]
1	Carbonized oak chip	4.791	**1.40**	22.46	**76.17**
2	Carbonized alder chip	3.842	**1.30**	24.48	**74.23**
3	Carbonized alder chip	2.686	**1.70**	22.58	**75.73**
4	Carbonized oak chip	2.647	**1.20**	20.76	**78.04**
5	Carbonized oak chip	1.991	**0.90**	20.76	**78.34**
6	Carbonized railway sleepers	36.868	**2.10**	28.73	**69.17**

Fig. 9. Solid products remaining after the thermal decomposition of railway sleepers [2]

Table 6

Results of toxicity tests for burnt charcoal applying a single-chamber test method in accordance with PN-EN ISO 5659-2 with irradiance of 25 kW/m² in combination with FTIR analyzer

Chemical compound	Toxicity in 4th minute Average values [mg/m³]	Toxicity in 8th minute Average values [mg/m³]
CO2	1629.62	4019.91
CO	127.46	333.63
SO_2	3.26	4.96

[Own elaboration].

9. Thermal decomposition of depleted wooden railway sleepers

Taking into account data related to the amount of depleted wooden (hardwood and coniferous) railway sleepers (Tab. 1), we can assume that the number of elements intended for disposal/neutralization exceeds 20 million. Supposing the average weight of a single sleeper is about 80 kg, the weight of waste in the form of railway sleepers amounting to 1,600,000 Mg (tonn).

This creates a need to develop an optimal waste processing technology based on railway sleepers on an industrial scale, assuming the implementation of such a method in cooperation with the Railway Research Institute, of relevant logistics, as well as adapting the WGW's thermolysis installation construction to the nature and required process volume as well as dimensions of the batch.

It is also essential that we develop an engineering process for the thermal decomposition of these materials in order to eliminate hazardous emissions due to the primary composition of substances which impregnate wood. In particular, it is necessary to design and test a post-thermolytic gas treatment system and monitor gas composition [13].

10. Conclusions

The circular economy, including recycling and recovery, is imperative for a modern economy.

Post-consumer waste, which is hazardous and harmful to the environment and primarily consists of organic materials, should be managed in accordance with the environmental protection regulations, and most preferably processed into various forms of fuel (oil, gas, carbon, hydrogen, alcohol, etc.) in order to diversify sources of energy and minimize environmental degradation. The EU has imposed strict requirements related to waste; for this reason and to avoid high penalties, every state must obtain high rates with regard to the following:

- communal waste recycling at the level of 70% until 2030
- reduction of storing waste to a max. of 10% until 2030
- a total ban on storing segregated waste.

The European Parliament and European Commission are still working on a common stance concerning waste management. One of the radical ideas is to stop burning waste by 2020 at the latest [1]. At present, there are difficulties in obtaining approval from member states to the suggestions made by the Commission and European Parliament.

Due to the need to develop the importance of railway transport in the economy, as emphasized in the Strategy 2020 and Sustainable Development Policy, previous traditional solutions must be adapted to the requirements of an innovative economy, and particularly to the currently implemented circular economy.

In the near future, the most serious problems concerning the recycling of worn-out railway infrastructure (especially sleepers) should be solved:

- the railway infrastructure life cycle, being a few dozen years, hinders the approach to recycling as it is difficult to anticipate which recycling technologies will be available in 50 or 100 years' time,
- the relatively limited interest of government and local authorities in recycling of railway infrastructure due to lack of nuisance of that waste usually stored in railway enterprise premises (owner of large lands).
- The use of certain materials currently adopted in production may be banned in 20 years, which will prevent them from being subject to processing (recycling) compliant with environmental protection regulations,
- it is necessary to provide innovative and environmental-friendly technologies related to processing hazardous waste with a long-term return on investment, which is hard to achieve without governmental assistance because of the range and cycle of implementation.

The final purpose of the power and climatic policy and the EU economy is to ensure zero waste in 2050.

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