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Recycling of Used Car Tyres

Dr.-Ing. Heino Vest

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The increasing number of vehicles on the roads of industrialised and developing nations generate millions of used and worn-out tyres every year. In industrialised countries approx. one old tyre per capita is generated every year. Although the storage or dumping of tyres does not pollute the environment by any emission, their resistance against any kind of decomposition, their enormous consumption of space when stored, the waste of raw material if not further used and the danger of ignition when piled up in heaps, turn them into an environmental problem in many countries.

Particularly in industrialised countries, where a higher car density caused the problem of how to dispose of used car tyres much earlier and to a greater extent, industry and research facilities tried to develop concepts for the recycling of tyres during the last years. Although a fair number of concepts and processes has been introduced, none is able to solve the problem on its own. Depending on existing technological facilities, environmental legislation, availability of money for environmental activities and public awareness, some of these concepts were successful to a certain extent. Nevertheless, a general breakthrough has not yet been achieved.

As pointed out above, the applicability of certain concepts of car tyre recycling depends on the local technical, economical and social environment in the respective country. It is very complicated and almost impossible to decide from outside a country which of the available technologies for car tyre recycling will be appropriate. Therefore a general overview is given in this report about the state of the art of tyre recycling world wide. Judging the described advantages or disadvantages of each technology, it should be possible for someone within the country to select an appropriate solution.

Composition and properties of car tyres

A modern car tyre is a composite product consisting of up to 34 different parts each of which may be a composite body in itself. Apart from differences in design and size, tyres in general are a homogenous product with an average composition given in Tab. 1 /2/.

Carbon	70 %	-	75 %
Hydrogen	6 %	-	7 %
Zinc oxide	1,2 %	-	2,0 %
Sulphur	1,3 %	-	1,7 %
Iron	13 %	-	15 %
Additives	3,5 %	-	5,0 %

Tab. 1: Composition of car tyres /2/

Due to high carbon and hydrogen contents tyres have a calorific value of 28.000 kJ/kg to 31.000 kJ/kg similar to coal. The high ignition temperature of 400 °C normally prevents a spontaneous ignition of stored tyres.

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During vulcanisation of tyres the polymers of natural or synthetic caoutchouc are interlaced by sulphur. The rubber formed by this irreversible reaction combines the different components of tyres giving them the required strength and elasticity over a wide temperature range. The irreversibility of this process, however, creates major problems when recycling tyres at the end of their lifespan.

The number of old tyres generated in a society is dependent on

- the number of operated vehicles,
- the average mileage per vehicle and year,
- the lifetime (max. mileage) of a tyre.

New tyres of passenger cars weigh 8-10 kg, those of LDV (Low Duty Vehicles) 25-30 kg and those of lorries 60-75 kg. Taking into account that tyres loose approx. 15 % of their weight while being used, it is possible to calculate the tonnage of old tyres generated annually in a country.

Places where old tyres are generated:

- at scrap yards,
- at car breakers shops,
- at motor garages,
- with fleet operators,
- by the tyre trade,
- at petrol stations,
- at big warehouses,
- in private households.

Recycling options for used car tyres

Many countries with environmental legislation refer in their waste management practice to the so-called waste management hierarchy. This hierarchy sets priorities when it comes to decide what to do with used articles, once they become waste. In case of tyres, the following order seems to be preferable under environmental aspects:

Recycling of material
- ➢ re-use of tyres:
  - by using retreads
  - in alternative applications
- ➢ rendered into crumbs and straps for various uses
- ➢ depolymerisation:
  - by regeneration
  - with microwaves
  - co-refining with crude oil
  - by pyrolysis
  - by hydrolysis

Energy recovery
- ➢ pyrolysis
  - incineration
  - in energy-from-waste plants
  - in cement kiln

Disposal
- ➢ landfilling

Tab. 2: Waste management hierarchy for used car tyres

In Germany an estimated amount of 44 % of old tyres are recycled (including exports of used tyres), 41 % are converted to energy and 15 % are disposed on landfill sites or disappear unknown /2/.

Material recycling of used car tyres

- Retreading of used car tyres

Retreading of used tyres is the most preferable way of making use of old tyres. In this case not only the article "tyre" is re-used in its original function, but also the highest saving in raw material and energy is achieved. On average only 15 % of crude oil is needed to produce a retread instead of a new tyre /2/ /3/. Thus the price of a tyre is reduced up to 45 % /1/ /3/ without any loss in quality. While tyres for passenger cars normally are retreaded once, tyres for lorries are retreaded twice and aeroplane tyres even up to seven times /3/. In Germany 12 % of all passenger cars, 20 % of all LDV and 48 % of all lorries use retreads /1/. 90 % of the world’s airlines use retreaded tyres /4/.

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Before an old tyre is selected for retreading it is examined very carefully. Already in 1974 the American Society for Testing Materials (ASTM) developed a recommended practice for the visual inspection of tyre casings prior to retreading /6/. In Germany tyres which are older than 6 years and which are bald unsymmetrically are not retreaded. The interior structure is investigated by x-ray, holographic methods, shearography and so-called tyre-uniformity-machines /1/ /4/. Only 45 % of all used tyres pass this inspection and are fit for retreading.

In principle there are two methods to retread used tyres - hot and cold retreading. In case of hot retreading an unvulcanised tread strip and side wall strip are placed on the remaining carcass by using an intermediate bond sheet. The tread and side wall are in this case extruded simultaneously onto the carcass by a sophisticated set of machines. The raw tyre is afterwards heated under pressure in appropriate tools, giving the tyre its final shape. At a temperature of 125 °C (inner part of the tyre) to 160 °C (outer part of the tyre) the vulcanising process takes place and combines the new layers with the old carcass irreversibly /1/.

During cold retreading only the tread of the tyre is renewed. In this case an already vulcanised tread strip is added to a prepared carcass using again an intermediate bond sheet. The binding process between the old and new parts takes place in an autoclave at a temperature of 100-120 °C. Opposite to hot retreading minor damages of the tyre cannot be repaired by cold retreading. So only tyres with no injuries and are symmetrically bald can be used for cold retreading.

The above given process descriptions indicate that hot retreading is mainly used for mass production of standardised types of tyres because of higher investment costs and lower flexibility in changing size and model. Cold retreading is used for single piece production or smaller series mainly in retreading lorry tyres.

Because of savings in cost and energy retreading of tyres is interesting for all developing countries. Two aspects might be of negative impact on the production and distribution of retreads:

- the acceptance of retreads by the customers

People tend to think that retreads are of minor quality compared to new tyres. All investigations have shown that tyres which are retreaded with modern technology using old carcasses of high quality have the same quality and properties as newly fabricated tyres. If there was any problem, airlines for example wouldn't use retreads for their planes. German manufacturers of retreads give 2 year guaranty on their products and allow their tyres to be driven up to 190 km/h /1/ /4/ (one manufacturer allows 210 km/h /2/).

- the availability of enough old carcasses of high quality

In countries where tyres are valuable products compared to the average income, people want to drive a tyre as long as possible. If in addition no safety regulations or regular inspections by the police or other authorities ensure that tyres are only operated when at least a minimal contour thickness (in Germany at least 1 mm) exists, tyres are often driven until the threads or other internal layers become visible. These tyres are of no use for retreading. The customers therefore must be convinced to stop using their old tyres before carcass and reinforcement layers are damaged.

The international tyre market is flooded by cheap tyres of poor quality. Since the price difference between new tyres and retreated ones is in this case reduced, people tend to buy new tyres of minor quality instead of retreaded tyres of high

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quality. If too many tyres of minor quality are in use, which cannot be retreaded at the end of their lifespan, the availability of old tyres of high quality decreases.

- **Alternative use of old tyres**

The property of used tyres - elasticity of material, non decomposable, inert - have led to a number of alternative applications:

- in agriculture:
  as weights for silage cover sheets,
- in landscaping:
  as erosion protection for dam walls and slopes,
- in shore protection:
  as breakwaters
- in harbours and docks:
  as dock bumpers and ship fenders
- in the fishing industry:
  as artificial reefs for fish breeding
- in household and communities:
  as bumpers in garages, playground equipment

It is obvious that this useful application for used tyres can only offer a limited outlet for the millions of old tyres generated every year in a country. Nevertheless about 10.000 tons of tyres per year (= 2,5 %) are used in Germany for these types of applications /2/.

- **Recovery of secondary raw material from old tyres**

To recover secondary raw material from old tyres a mechanical or thermal treatment has to be applied. Mechanically, the tyres are cut or ground into pieces or crumbs to use either the composite material as a whole or to separate the different materials from each other. The thermal treatment leads to a depolymerisation or decomposition to recover synthesis gas, liquid hydrocarbons or soot.

a.) Mechanical treatment of tyres to recover secondary raw material

Particularly in developing countries old tyres are a valuable source of raw material to produce a great variety of products /6/. The tyre structure consists of layers of textile(steel)-reinforced rubber sheets, laid on top of each other with the "grain" running in alternate directions and a final layer of solid rubber moulded on top. These sheets can be split one from another and are about 2 mm thick, or even less. Thus the tyre provides:

- split material of even thickness to cut into straps,
- material with solid rubber adhering to it that can be carved, or the tread markings are used to form grips on soles for shoes.

Since the soles, heels and straps of sandals can be made from tyre material, shoemaking and repairing from tyre rubber are huge industries in developing countries. The shoes which result from this technology are extremely strong and hard wearing. Even in industrialised countries there are shoes available (for working purposes) which use soles made from old tyres.

Besides shoemaking tyre rubber can be used in small scale manufacturing of a large variety of products: cords for tethering animals or for fixing goods on lorries; mats for cars; household doormats or protective layers for the back of pick-ups; pads for handling glass in the glass industry; hinges for gates; stools and chair seats. Nylon cords, wires of tyre beads from steel braced tyres are used for all kinds of applications.

On an industrial scale rubber crumbs or flower, steel parts and the fibre are recycled and used for a number of applications. Tab. 3 give applications for rubber from used tyres after communition:

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Used tyres

- **rubber pieces**
  - cast with polyurethane to form basement tiles in riding hall
  - insulating material for cold storage facilities
- **rubber granules**
  - cast with bitumen/asphalt cement in road basement construction
  - sound insulation material
  - mixed with sand as basement structure for sport grounds
- **rubber powder**
  - additive in production of new tyres
  - cast with PVC or PU forming new products:
    - running tracks for sport grounds
    - floor tiles and mats
    - cover sheets and protective layers
    - shoe soles
    - sound insulation material
    - bumpers, signboards, roadside, impact

Tab. 3: Applications for rubber from used tyres after communition /7/

The communition of old tyres takes place at normal temperatures, or due to grinding energy at slightly elevated temperatures or at very low temperatures.

In case of warm communition old tyres are cut into chips after removing the tyre bead. Further communition produces granules of 1-6 mm, from which textile fibres and iron wires are separated. The remaining rubber granule is used to manufacture new articles or is further ground in a grinding extruder to produce rubber powder of 0,1-0,5 mm grain size.

Cold communition or cryogenic grinding utilises the increased cold brittleness of rubber, textile and steel at low temperatures. Due to specific communition mechanisms the surface of the granules is very smooth with little pores. This leads to higher consumption in additives during subsequent moulding processes. The savings in energy during communition are consumed by higher costs for the required nitrogen (nitrogen consumption: 0,6-0,7 tons per ton of tyres).

Ground rubber from secondary sources can be used for many purposes. For the manufacturing of new tyres only minor quantities (1-2 %) can be mixed with primary material. Since the recycled rubber granules co-vulcanise only partly with the fresh material, the properties of tyres are highly affected by adding recycled rubber. Although new developments have improved the situation by modifying the surface of recycled rubber particles by covering them with latex, the manufacture of tyres won't be a significant outlet for recycled rubber in the near future /1/ /7/.

More promising are applications where recycled rubber is mixed with a plastic matrix (PVC, PU) and moulded under pressure and heat in order to produce elastic and flexible articles for different purposes. Mats, sheets, bumpers and noise insulating material, floor tiles and shoe soles have been mentioned earlier. Other applications are cable insulation, garden hose pipes, sewage pipes, carpet underlays, roof tiles, solid wheels and many more /2/ /9/.

One of the most promising application is the development of road construction material which incorporate tyre crumb. In this case crumb rubber is mixed with asphalt cement forming asphalt-rubber. Extended pavement life has been achieved by the use of asphalt-rubber in chip seal applications. These applications act as stress absorbing membranes, which reduce the rate of crack propagation from the old pavement surface to the new surfacing material. Besides the asphalt-rubber chip seals, asphalt-rubber interlayers are in use /10/.

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Test work with asphalt-rubber has shown that the lifetime of road surface layers could be doubled while using layers of only half of the usual thickness. Asphalt-rubber has a high flexibility with a low danger to form cracks. Good friction properties reduce the danger of gliding and the noise emitted while driving on this type of road is low. Unfortunately the cost of asphalt-rubber is 20 to 100 % higher than ordinary construction material /11/. A long lifetime with low life cycle costs may compensate the disadvantage of higher initial costs. In the United States government financed roads have to use a certain portion of asphalt-rubber (5% since 1994, 20% from 1997 onwards) /11/.

b.) Thermal treatment of tyres to recover secondary raw material

During thermal/chemical treatment of rubber products in the absence of oxygen, the polymer chains of the rubber are cracked, forming shorter chains or monomers. Depending on the type and intensity of the process the rubber is only partly devulcanised (regeneration), depolymerised (microwave treatment, co-refining with crude oil, hydrolysis) or split into synthesis gas, pyrolysis oil and soot (pyrolysis). Ideally, the C-H-bonds should not be destroyed by these processes.

Regeneration of waste rubber

The regeneration of vulcanised rubber is the oldest known process for the recycling of waste rubber. This process is nowadays a costly exercise due to the required extensive off-gas cleaning systems. Last, but not least, the quality of tyres with major additions of regenerated rubber does no longer fit today's high standards. So the consumption of this material went down dramatically in the last years (from 20% of the total amount of consumed caouchouc (1959) to 1% (1992) /1/ /7/).

By thermo-chemical treatment of rubber granules (1mm) the interlacing structure of vulcanised rubber is partly cracked. Mixed with fresh caouchouc regenerated rubber will be incorporated into the newly formed interlaced structure during subsequent vulcanisation.

Depolymerisation by microwaves

At temperatures below 350 °C the molecules of trubber are forced by microwave energy to change their polarity and to start vibrating in resonance frequency. This generates heat in the molecular structure and finally leads to the breaking of the molecular bonds. Depending on the material composition and intensity of treatment soot, steel, sulphur and oil can be recovered after several separation steps /1/.

Co-refining with crude oil

Waste rubber is added to the hot residue (300-350 °C) of the distillation column for crude oil and is depolymerised. The products resulting from the thermal cracking combined with the dense and less volatile fractions of crude oil follow the normal refining route. Since crude oil is substituted by the rubber input, no major supplement process lines are needed and the necessary process heat is supplied by the waste heat of the refinery. The process should thus be economically viable.

Depolymerisation by hydrolysis

In theory hydrolysis leads to direct recovery of the original raw material by a targeted reaction of water molecules at the linkage points for polymerisation, thus reversing the polymerisation process. In the majority of cases this is only possible at high temperatures and pressures /13/ and therefore requires some financial and technical inputs. In case of rubber recycling it is possible to produce synthetic crude oil by this process. A promising pilot operation was established in Dec. 1992 by VEBA ÖL AG and Ruhrkohle Öl und Gas GmbH, Germany, when 50 tons of shredded tyres were used to produce a

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high quality synthetic crude oil by hydrolysis /14/.

Compared to the already mentioned processes the decomposition of waste rubber and used tyres by pyrolysis takes place at much higher temperatures (e.g. 600 to 1000 °C). Mainly in rotary kilns or fluidised bed reactors the rubber feed decomposes into the products soot (with impurities of zinc and potassium sulphide), oil and volatile hydrocarbons like benzene, toluene, xylene and a synthesis gas with high amounts of methane (Tab. 4). Depending on temperature and retention time the distribution of the different products (gas, oil, solids) changes (Tab. 5). While soot, liquid hydrocarbons and the synthesis gas are recovered in the off-gas cleaning system, steel components and some coarse carbon particles stay in the furnace. In some applications the pyrolysis gas is directly utilised to heat the furnace and to keep the process running.

pyrolysis temperature			**720 °C**
pyrolysis gas			**21,8 %**
	with:	hydrogen	3,3 %
		methane	40,3 %
		ethane	8,6 %
		ethylene	11,5 %
		propene	1,9 %
		carbon dioxide	7,2 %
		carbon monoxide	7,2 %
pyrolysis oil			**21,0 %**
	with:	benzene	12,1 %
		toluene	11,9 %
		naphtalene	2,3 %
		heavy oils	48,9 %
		aliphatic comp.	4,1 %
water			**4,6 %**
solid residue			**49,2 %**
	with:	soot	
		(iron)	

Tab. 4: Composition of pyrolysis oil of pilot operation with fluidised bed reactor /23/

A pilot scale operation was able to pyrolyze 120 kg of tyre/h. The fluidised bed consisting of sand and tyre fractions is heated indirectly by steel heating rods to a temperature of 600-900 °C. The gas stream which is responsible for the formation of the fluidised bed and the transport of the generated pyrolysis products is formed by the re-circulated pyrolysis gas.

pyrolysis product	amount (%)	calorific value (kJ/kg)
carbon (soot)	30-52	28.270
gas (methane)	6-30	50.241
liquid hydrocarbons	40-50	~ 38.000

Tab. 5: Products of the pyrolysis of used tyres /16/

Energy recovery from used tyres

Since tyres consist to 80 % of carbon and hydrogen, they can be used as fuel for industrial processes or to produce energy. Tab. 6 shows the calorific value of tyres in comparison to other types of fuel.

Fuel	calorific value (kJ/kg)
Garbage	5,800
Mixed biomass	15,100
Paper/cardboard	17,400
Textiles	18,600
Coal (bituminous)	26,200
Coal (anthracite)	28,000
Tyres	31,400
Oil (crude)	39,500

Tab. 6: Calorific values of various types of fuel

In practice old tyres are used as fuel in energy-from-waste plants or as alternative fuel in cement kiln.

- **Incineration of used tyres for energy production**

To recover the energy of old tyres they are either directly incinerated in appropriate

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energy-from-waste plants or the tyres are transformed into combustible products (gas, liquid hydrocarbons and soot) via pyrolysis. In the last case the sooty off-gas from pyrolysis is subsequently burned in appropriate combustion chambers recovering the heat by waste heat boilers.

In case of direct incineration of tyres in energy-from-waste plants the tyres are either burned together with ordinary household waste or fed into special waste tyre incinerators. Since old tyres are a very homogenous feed without any fluctuation in composition, waste tyre incinerators have the advantage of easy handling. The residues of this type of operation are very homogenous and marketable. While the incinerator slag could be used in the steel industry, for road construction or at least be landfilled without any problems (Tab. 7), the ash and flue dust recovered in the off-gas cleaning system is a valuable raw material for the zinc producing industry due to its high zinc content (Tab. 8). The generated SO_2 requires a desulfurisation step in the off-gas cleaning system.

C	0,05	0,21
Al	0,09	0,23
As	0,0016	0,0002
Cd	<0,001	< 0,001
Cr	0,69	0,055
Cu	0,18	0,26
Fe	67,50	78,70
Pb	<0,001	< 0,001
Mg	0,041	0,048
Mn	0,37	0,25
Ni	0,17	0,076
K	0,007	0,012
Si	0,24	0,20
Na	0,60	0,57
Zn	0,037	0,13
Sn	<0,005	<0,005

Tab. 7: Composition (in %) of two samples of incinerator slag of the waste tyre incinerator

The technical experiences of the company Gummi-Mayer which operates two waste tyre incinerators at Landau, Germany (10.000 tons of tyres/a = 1,5 million tyres are transferred to 80.000 tons of steam and 4.4. million kWh) in order to meet their own energy and heat requirements (for retreating tyres) have resulted in two bigger plants being installed or projected in the United States /2/.

ZnO	51,48
PbO	0,22
Fe_2O_3	6,33
Cr_2O_3	0,03
CuO	0,55
NiO	0,03
As_2O_3	0,02
Al_2O_3	0,76
MgO	0,50
Na_2O	< 0,01
K_2O	0,01
MnO_2	0,36
SnO	0,03
SiO_2	6,85
CdO	0,05
C	32,20

Tab. 8: Composition (in %) of flue dust of a waste tyre incinerator

At a 14 MW power plant in Modesto, California, for example, over 5 million of tyres are incinerated every year producing 60 tons of steam of 65 bar and 500 °C, providing enough energy for 15.000 homes. The investment costs in 1987 were 55 million DM /7/ /9/. In Sterling, Connecticut, a 30 MW power plant incinerates 10 million of whole tyres per year (diameter up to 1,20 m /20/), producing 200 million kWh /9/. The 25 MW plant of Elm Energy in Wolverhampton, U.K., is able to burn 90.000 tons of tyres per year and will be the model for a second plant at East Kilbride, Scotland /18/. In Duisburg-Homberg, Germany, the first waste tyre incinerator is in projection. 7 million old tyres will be burned annually producing electrical and heat energy. Due to the practised co-generation of heat and electricity a high energy efficiency will be achieved. The investment costs are projected to be 50 million DM /19/.

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- **Incineration of used tyres in cement kilns**

In large rotary kilns cement clinker is produced from lime stone, silica and clay. The net energy consumption of the process is approx. 1.750 kJ/kg of cement. Besides fossil fuel like oil or coal, organic residues like household waste, shredder waste, used oil, old tyres etc. can be used to generate the necessary process temperatures /21/. To utilise this alternative fuel the cement kiln has to be modified by adding a second combustion zone at the feed side of the furnace.

Tyres are fed to the furnace as a whole or as shredded parts at the feed side of the furnace. Rubber granules and powder can be added similar to the ordinary fuel at the discharge side of the furnace. The long retention time of the tyres in the furnace, the high combustion temperature of up to 2.000 °C and the high oxygen potential in the combustion air guarantee a total combustion of the tyres with only very little generation of dioxines and furanes. The off-gas cleaning system of the cement plant is not affected by using tyres as additional fuel.

Ash and sulphur resulting from the combustion of tyres are incorporated into the cement clinker as normal components. Depending on the amount of tyres to be burned as fuel, there might be an increased intake of iron oxide to the process which has to be compensated.

As mentioned before it is possible to feed upgraded fine rubber granules or powder instead of whole tyres. This has the following advantages /1/:

- since the iron fraction of the tyres has been removed before feeding to the kiln, there is no danger of changing the composition of the cement clinker,
- fine rubber can be mixed with primary fuel and charged in the ordinary way; no change of furnace design is necessary.

In Germany, used tyres make up to 15% of the total fuel for cement production.

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Internet addresses:

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- www.epa.gov (US Environmental Protection Agency)
- www.itra.com (ITRA Tire and Rubber Recycling Advisory Council, USA)
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