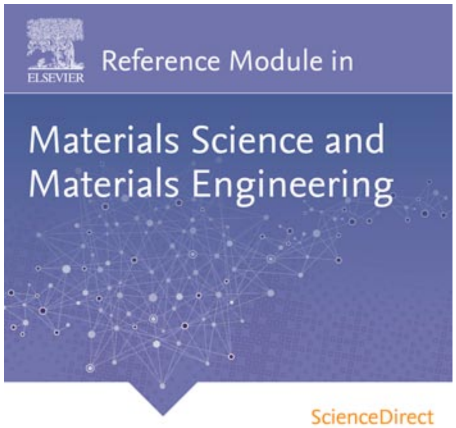

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Rubber Tires ☆

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1 Introduction

Tires are complex engineering structure having evolved from the old age's simple wheel into today's pneumatic tire. It is made from assembling of many components of dissimilar materials to form the structure. For instance the automobile tires contain about 12 components while the truck tires contain about 20 components (Ramarad *et al*., 2015). A typical rubber tire consists of a variety of materials such as natural rubber (NR), synthetic elastomers such as polybutadiene (BR), textiles such as nylon and polyester, and a range of different brass-coated steel wires. Since the 1960s, tires have undergone a major evolution. In the 1960s they were typically of a bias construction and required use of an inner tube for air retention. Bias or diagonal ply tires describe a tire construction where the ply cords extend to the beads, and where the ply cords are laid at an angle substantially less than 90° to the centerline of the tread or the direction of the beads cables (**Figure 1**). Typically in this time period automobile tires reached up to 20 000 miles, after which they were replaced. In the 1970s, the radial tire emerged with significant improvements in mileage, fuel economy, and safety. Radial tires have a structure where the casing ply cords extend to the beads and are laid at a 90° angle to the centerline of the tread. The casing is stabilized by an essentially ridged belt system. This was followed by the introduction of the tubeless tire, which used an airtight membrane inside the tire, and formed an airtight seal between the tire and the rim through compressed fitting of the tire bead on an inclined steel wheel. 'Ultralow-aspect ratio' tires are now emerging where the sidewalls of the tires are considerably shorter, allowing improvements in vehicle stability, rolling resistance, and, in the case of commercial trucks, cargo volume. They are also providing a basis for the development of 'run flat' technology, where tires can operate at near zero inflation pressure.

Tires fall into essentially eight categories, based on the mission profile for the product. These are: racing and sports vehicles; passenger or consumer vehicles; light truck and sports utility vehicles (SUV), where gross vehicle weights do not exceed 7250 kg; commercial trucks; farm applications; earthmoving equipment, where gross vehicle weights can approach 300 t; aircraft; and finally non-pneumatic specialty tires for applications such as fork lift trucks. All tires, whether they are designed for something as simple as a bicycle or as complex as a large commercial aircraft, must meet a fundamental set of performance functions:

(i) provide load carrying capacity;
(ii) provide cushioning, damping, and minimum noise and vibration;
(iii) transmit driving cornering, steering, and braking torque;
(iv) resist abrasion;

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(v) have low rolling resistance; and
(vi) be durable and safe through the expected service life of the product.

2 Basic Tire Design

Figure 2 illustrates the components of a typical commercial truck tire used on vehicles which would have a gross vehicle weight (GVW) up to 40 t. In summary, the components can be described as follows.

2.1 Tread

Tread is the component of the tire that is in contact with the road. It must show wear resistance, good traction characteristics, fuel economy, and resist service-related damage. A base underneath the tread is designed to dissipate heat and ensure good adhesion between the tread and the tire casing. Automobile tires tend to contain blends of styrene butadiene rubber (SBR) and polybutadiene (BR) rubber, oils, carbon black (up to 45% by weight), and silica. Heavy-duty truck tire treads tend to contain high levels of NR and approximately 30% by weight of fine particle size carbon black. Other tires such as for aircraft, farm equipment, or earthmoving equipment can contain blends of NR, BR, and SBR.

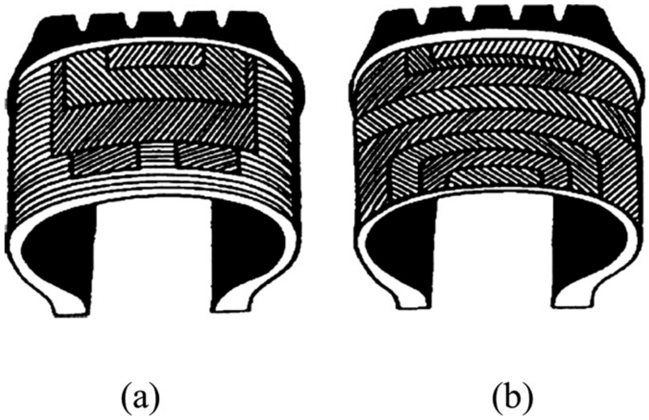

Figure 1 Tire construction, (a) radial and (b) bias types.

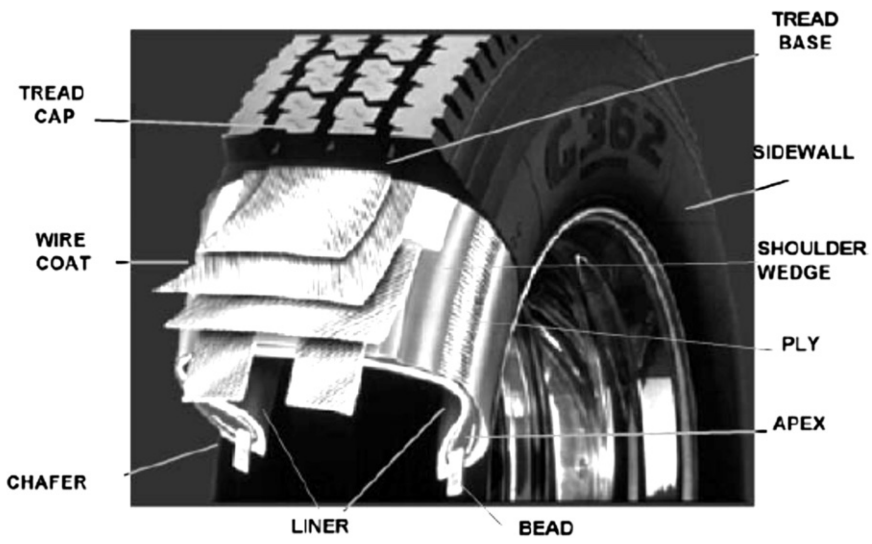

Figure 2 Radial truck tire components.

2.2 Sidewall

The sidewall protects the tire from impact and curb scuffing. It also provides long-term weathering protection and casing durability. It is typically a blend of NR and BR and contains carbon black, high levels of antioxidants, and antiozonants.

2.3 Bead Region

The bead region consists of a number of components, such as the bead cable which locks the tire onto the wheel or rim, apex or bead filler, chipper wire which protects the ply from rim damage, and the chafer, which is the abrasion-resistant rubber component in contact with the rim.

2.4 Plies

Consisting of steel or fabric, plies extend from bead to bead, and serve as the primary reinforcing member on the tire. They provide strength to the tire to enable high-pressure air retention. Fabric plies can be made from either poly(ethylene terephthalate) (PET), nylon-6, or nylon-66.

2.5 Belts

Belts consist of layers of steel wire and fabric forming a hoop under the tread. They restrict deformation of the casing and provide rigidity to the tread region, thereby allowing improved wear and handling performance, better damage resistance and protection of the ply cords. Belts are composed of either steel wire, PET, nylon-66, or nylon-6 coated with a NR based compound.

2.6 Shoulder

This is a wedge, which is a stiff component composed of compounded NR, designed to provide stability of the belts and tread.

2.7 Liner

The liner is a membrane consisting of a compounded bromo-isobutene-isoprene rubber (BIIR), or other derivatives of this polymer or blends of butyl (IIR), halobutyl, and NR polymers, and whose function is to retain compressed air inside the tire.

3 Tire Engineering

Tire section width is the section width of the tire from sidewall to sidewall, illustrated in **Figure 2**. The section height is the distance from the bottom of the bead of the tire to the top of the tread. These two parameters are important in describing the tire size seen on the sidewall. For example, the tire size designation LT235/75R15 denotes:

- 235 approximate section width in millimeters
- LT light truck
- 235 approximate section width in millimeters
- 75 aspect ratio or the ratio of section width to section height
- R radial construction
- 15 nominal rim diameter in inches

Other sidewall markings include construction and manufacturing information, speed rating, and load carrying capability. Reference should be made to the *Tire and Rim Association Inc. Year Book*, or the European Tire and Rim Technical Organization (ETRTO) *Standards Manual*, for a full description of tire nomenclature and rim specifications for a given tire size.

The tread pattern influences the ability of the tire to transmit steering, braking and driving forces while operating in a broad range of highway and off-road surfaces. Reference should be made to Clark (1982) for a description of tread pattern design and influence on wear, traction, vehicle handling, tire damage resistance, and tire rolling resistance.

3.1 Tire Reinforcements

A tire is a textile/steel cord/rubber composite, where the steel and fabric cords reinforce the rubber compounds and are the primary load-bearing structure within the tire.

Polyester (PET) is used as the ply cord in automobile and light truck tires. It is also used for belts of fabric reinforced tires such as farm tires. The selection and strength of a polyester cord are defined by the tire performance requirements. These in turn are determined by the mission profile of the vehicle for which the tire has been designed.

Nylon-6 (polycaprolactam) and *nylon-66 (poly(hexamethylenediamine) adipamide)* are used in the plies of commercial tires (farm, aircraft, bias truck) and also as an overlay in high-performance passenger and light truck tires. The overlay sits over the steel belts and serves to hold the belts in place while the tire is operating at high speeds. Nylon-66 is preferred over nylon-6 due to its higher melting point (265 vs. 225 °C). Nylon has good fatigue resistance, durability, and tenacity. However, it tends to have poor dimension stability.

Steel cords used in tires are brass coated. Steel rod is first drawn down to a diameter of 1.2 mm and the brass plating applied. The filaments are then drawn down to their final diameter, which could range from 0.15 to 0.45 mm depending on the application for which the cord is needed. Steel cord construction terminology such as 3 + 6x.22 describes a cord of three filaments, wrapped with six additional filaments with a diameter of 0.22 mm. Steel cords used for plies have been designed for fatigue resistance. Belt wires have greater rigidity for stiffness. Ford and Charles (1988) have a comprehensive discussion on steel cord design and application.

Cotton and rayon are no longer used in tires to any significant extent. Aramid is used in special applications such as in aircraft tires. New technology cords under development include hybrid cords of nylon, aramid, and polyester, very high tensile strength steel cords, and new polyesters such as PEN (poly (ethylene-2,6-naphthalene dicarboxylate)), POK (polyethylene ketone), and carbon fibers.

Cord construction such as 1400/1/3 defines the linear density of base yarn, in decitex (1400), the number of yarns in the ply (1), and number of plies in the cord (3). The direction of twist on the filaments or yarns in a cord can be described as in the 'S' direction, which is clockwise around the central axes of the tire cord, or 'Z' twist, which is counterclockwise around the central axes (Bhakuni *et al.*, 1997).

3.2 Tire Compounds

Compounding ingredients fall into one of five general categories: (1) polymers, which are typically NR, styrene butadiene rubber (SBR), and polybutadiene (BR); (2) fillers such as carbon black, silica, clays, and calcium carbonate, though the latter two are used more in rubber products for industrial applications; (3) protectant systems consisting of antioxidants, antiozonants, and waxes; (4) a vulcanization system; and (5) special purpose chemicals such as processing aids, oils, and resins. Product performance objectives define the initial selection of materials. These materials must be benign with respect to environmental concerns, must facilitate processing in production plants, and be cost-effective.

NR is classified into three categories: (1) technically specified rubbers (TSR), where contaminant levels such as ash, nitrogen-containing chemicals, and viscosity are defined; (2) visually inspected rubbers such as smoked sheets and crepe, which are shipped in 115 kg bales; and (3) specialty rubbers such as epoxidized NR and powdered rubber. NR use in radial tires has increased over that used in bias tires because of improved green strength, i.e., strength before vulcanization, tear strength, tire component-to-component adhesion, lower heat generation (hysteresis) under dynamically loaded conditions, and lower tire rolling resistance (Roberts, 1988).

Classification of synthetic rubbers is governed by the International Institute of Synthetic Rubber Producers (IISRP). For SBR, polyisoprene, and polybutadiene, a series of numbers have been assigned which define the basic properties of the polymer. For example, the IISRP 1500 series describes the range of commercially available, cold-polymerized emulsion SBR polymers. The series 1200 through to 1249 defines non-oil extended polybutadienes, and 2200 to 2249 is for polyisoprene and copolymers of isoprene.

A series of empirical guidelines can be used in designing a tread compound polymer for a set of tire performance criteria (Nordsiek, 1985):

(i) there is a nearly linear drop in abrasion resistance, or tread wear, as polymer glass transition temperature (T_g) increases;
(ii) as T_g increases, wet grip or traction improves;
(iii) inclusion of styrene, and an increase in the styrene level, increases tire wet traction and decreases tire tread wear performance.

Carbon black grades fall into one of typically seven classes: SAF (super abrasion furnace), ISAF (intermediate super abrasion furnace), HAF (high abrasion furnace), FEF (fast extrusion furnace), GPF (general purpose furnace), SRF (semi-reinforcing furnace), and MT (medium thermal). Selection of the appropriate grade of carbon black, further described in ASTM D1765, can, however, lead to significant improvements in performance. For example, the larger surface area carbon blacks (SAF) are required for tread wear. However, as particle surface area increases with a corresponding improvement in tread wear, rolling resistance of the tire can increase with adverse effects on fuel economy. Reduction in carbon black loading will lower tire rolling resistance.

Addition of silica to a compound will improve tear strength, reduce heat build up, and improve compound adhesion in multicomponent products such as tires. Two fundamental properties of silica influence their use in rubber compounds: ultimate particle size and the extent of surface hydration.

Unsaturated elastomers are susceptible to oxidation. Atmospheric ozone will also readily degrade elastomers. For example, tire sidewalls which are subject to a high degree of flexing will show crazing and cracking; such damage is clearly visible in most tires after about four years of operation. To protect an elastomer from oxidation or ozonolysis, three categories of materials are added to the elastomeric formulation, i.e., waxes, antioxidants, and antiozonants.

Antioxidants are mainly amine or phenolic derivatives such as 1,2-dihydro-2,2,4-trimethylquinoline (TMQ), and they function by reacting with oxides or broken polymer chain ends caused by reaction with oxygen. They therefore prevent the propagation of oxidative degradation, enabling the retention of the physical properties of the elastomer.

Ozone protection is obtained through the use of two materials, waxes and, typically, paraphenylene diamines. A number of empirical guidelines can be used to develop an antidegradant system for a compound in a tire. Short-term static protection is achieved by use of paraffinic waxes. Microcrystalline waxes provide long-term ozone protection while the finished product is in storage. A critical level of wax bloom is required to form a protective film for static ozone protection. Optimized blends of waxes, paraphenylene diamines such as N-(1,3-dimethylbutyl)-N-phenyl-paraphenylenediamine (6PPD) and antioxidants, such as TMQ, provide long-term tire protection under both static and dynamic applications, and over an extended temperature range.

The vulcanization system in a tire compound consists of three components: the activation system, typically zinc oxide and stearic acid; the vulcanizing agent, which is typically sulfur; and accelerators, such as cyclohexylbenzothiazole sulfenamide (CBS). In an idealized tire compound, zinc oxide and stearic acid react to form zinc stearate at tire vulcanization temperatures. The zinc stearate then reacts with the accelerators in the compound to form a 'sulfurating complex,' which with sulfur creates the required cross-link network. Accelerators can be classified into different categories, depending on the reaction rate and nature of the cross-links they create. Thiurams such as tetramethylthiuram disulfide (TMTD) give predominantly monosulfidic sulfur cross-links. Sulfenamides, when used with high sulfur concentrations, build predominantly polysulfidic cross-links. The structure of the cross-link network can therefore be designed to meet a specific set of service requirements.

A broad range of other materials are used in a compound. For example, titanium dioxide is used for tire white sidewalls; processing oils are used to assist in mixing, extrusion and calendaring of compounds through the factory. Plasticizers such as dioctylphthalate are also used as processing aids. Chemical peptizers such as pentachlorothiophenol are added to the compound during the initial mixing to reduce energy consumption in mixing and provide a more uniformly mixed compound. Resins include extending or processing resins, tackifying resins, which help in handling of components during the tire assembly operation, and curing resins, which are used to improve properties such as tensile strength. A comprehensive review of materials used in rubber compounding has been compiled by Mark *et al.* (1994), further reference to which is recommended.

3.3 Tire Testing

Tire testing occurs in three stages: initial laboratory testing; general proving ground testing, where tires are mounted on vehicles which are then tested on specially prepared roads; and commercial fleet tests. Materials tests include studies of vulcanization kinetics, measurements of compound physical properties such as tensile strength and tear strength, and dynamic properties in both shear and tension. Tire laboratory testing includes tire uniformity tests, speed rating determination, rolling resistance, durability assessment, and basic handling characteristics such as cornering coefficient.

Proving grounds consist of high-speed test tracks, gravel roads, wet and dry skid pads, and tethered tracks for testing of farm tractor tires. Testing is conducted under defined conditions such as loads, inflations, speeds, and specific vehicle types. The vehicles have been specified to meet a set of defined conditions such as wheel alignment, vehicle horsepower, wheel base, and axle configuration.

Finally, commercial testing enables the tire materials engineer to obtain an assessment of how compounds and reinforcements will perform under a broad range of service conditions that the end consumer will experience. The result of the testing protocol which tires undergo is a broad range of products to meet the vehicle manufacturers', as well as the end users', needs for optimum performance under a broad variety of service conditions.

4 Materials Composition of a Tire

Excluding the weight of the tire reinforcements, a tire's material composition typically is presented in **Table 1**.

Tread compound composition is dependent on the mission of the vehicle for which the tire has been designed. Treads for tires on high-performance cars will use high T_g synthetic polymers, silica, and high levels of oil for traction and vehicle handling. For commercial truck tires, where parameters such as tread wear and fuel economy are more important, high levels of NR and high surface area carbon blacks are used. Wire coat compounds are always composed of NR with a HAF or ISAF grade of carbon black and in some instances silica. Sidewalls are composed of blends of NR and polybutadiene, present in a 1:1 ratio. Carbon black levels are typically 25% of weight of the compound. Other internal components such as shoulder wedges, apex or bead fillers, and base compounds are made primarily of NR, for adhesion, hysteretic properties, and tear strength. Innerliners of radial tires contain chloro- or bromo-isobutene-isoprene rubber (CIIR, BIIR) compounded with HAF, FEF, GPF, or SRF carbon black. Carbon black levels can range from 25% to 50% of the compounded formulation weight, depending on the tire design.

5 Life Cycle and Waste Tire Management

The life cycle of a tire include extraction, production, consumption, collection of used Tires and waste management as depicted in Figure 3. The concern for the waste management of tire as the dramatic growth in the number of used tires around the globe was recorded due to increasing number of vehicles on the road. Approximately about 800 million tires are discarded around the globe annually. This statistics is estimated to increase by 2% every year (van Beukering and Janssen, 2001). Similarly, annual global production of tires is about 1.4 billion unit and a corresponding estimated of more than 17 million tonnes of used Tires each year (Sienkiewicz *et al.*, 2012).

According to (Ramarad *et al.*, 2015) land filling and tire mono filling were among the earliest ways of tire disposal around the world, though causes many environmental challenges. It is discovered that legislations were one of the driving forces behind the development of sustainable waste tire management (Ramarad *et al.*, 2015; Sienkiewicz *et al.*, 2012). In addition, a report by European Tire & Rubber Manufacturers' Association (ETRMA) in 2012 depicted that utilization of waste tires in Europe are part worn tires (reusable and retreading), recycling, energy recovery, and pyrolysis. Figure 4 illustrates trend of waste tire utilization in Europe (EU) from year 1994 to 2012 and same trend is expected for rest of the world (ETRMA, 2013).

Management of waste tire may continue to pause problem, though there are many existing techniques and newly developed strategies for efficient management of waste polymer in accordance with environment protection.

Table 1 Typical proportion of a tire material composite

Material	*Percentage (%)*
Natural rubber	36
Synthetic polymers	20
Carbon black and silica	33
Chemicals	6
Protectants	2
Zinc oxide	2
Sulfur	1
Total	100

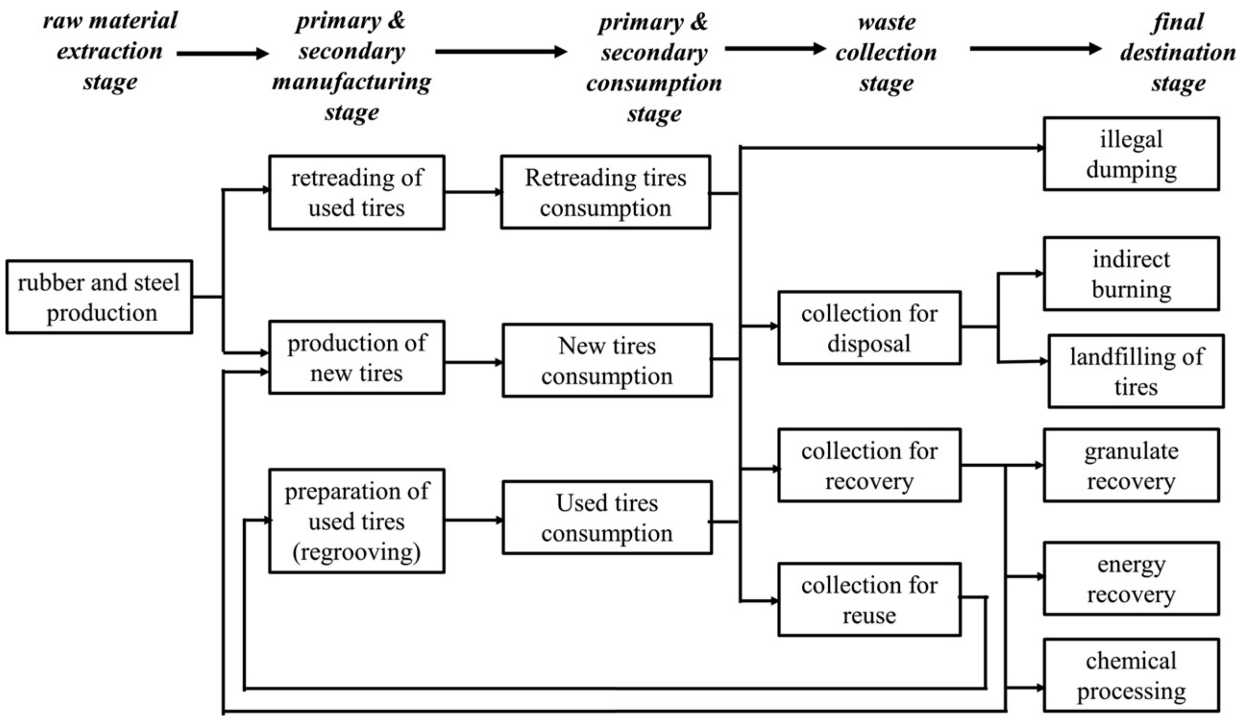

Figure 3 Life cycle of a tire. Reproduced from van Beukering, P.J.H., Janssen, M.A., 2001. Trade and recycling of used tyres in Western and Eastern Europe. Resources, Conservation and Recycling 33 (4), 235–265.

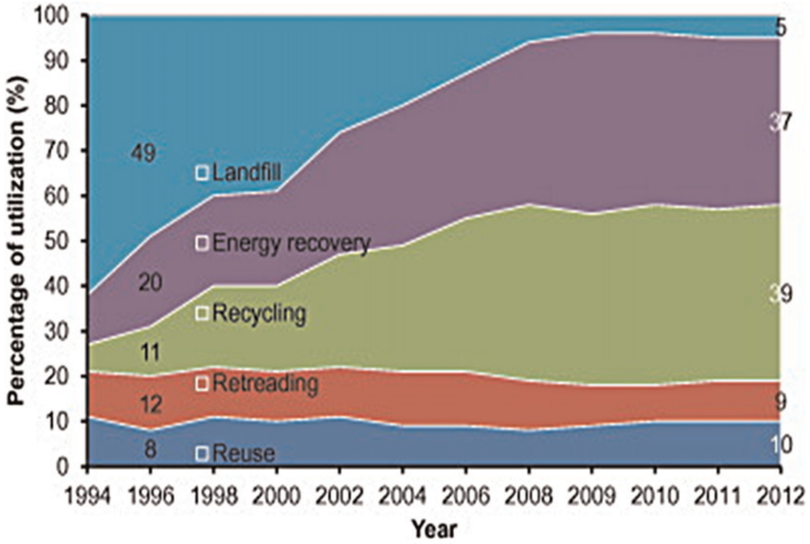

Figure 4 Waste tire utilization in EU from 1994 to 2012. Reproduced from Ramarad, S., Khalid, M., Ratnam, C.T., Chuah, A.L., Rashmi, W., 2015. Waste tire rubber in polymer blends: A review on the evolution, properties and future. Progress in Materials Science 72, 100–140.

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