Review of the use of waste tires in concrete

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Abstract. The volume of tires at the end of their life cycle in the EU as well as worldwide has witnessed an increasing trend since 2013. This is the type of waste that is of great interest to scientists in Europe and in the whole world. This article presents the current methods of processing, recycling and disposal of tires at the end of their life cycle. The main attention is focused on the results of research and development, which dealt with the issue of the use of tires at the end of the life cycle in concrete. The building industry segment offers us great opportunities to use by-products in order to save natural resources of raw materials.

1. Introduction
With the development of the automotive industry, tires have become an integral part of everyday life. We use them almost every day, whether it is when driving a passenger car or when using a public transport bus. They are also widely used in air transport, but they are also an important part of freight traffic. As a result of the development of the society in the world, the demand for tires is rising and the production of waste tires is proportionally related to this fact. Waste tires represent a global problem and an increasing risk to the environment, because they are not biodegradable and are often improperly stored and disposed. These stocks pose a threat of uncontrolled fires and other environmental risks. It is estimated that almost 1,000 million tires end their life cycle every year and more than 50% are scrapped without any further use.

2. Methods and possibilities of using waste tires
Tire recycling makes it possible to obtain rare materials, to save energy in relation to primary production, and to reduce waste. Used tires represent the largest share of the total amount of recycled rubber. A worn tire contains a number of chemicals with energy potential, but it is also a source of secondary raw material. Tires are made of flexible rubber material, the construction of which is reinforced with textile and metal materials. The composition of tire consists of materials containing rubber, carbon black, steel inserts, oils and vulcanizing agents, synthetic rubber and textile. Fig. 1 shows the percentage composition of tires used for passenger and freight transport. When recycling tires, certain measures have to be taken, namely:
• reducing the risk of pollution from the temporary storage of used tires,
• increasing the usability of used tires,
• reducing the consumption of raw materials, especially those originating from non-renewable sources and the use of used tires as secondary raw materials.
The use of tires as a source of raw materials leads to three product categories. They are rubber granules, steel wires, and nylon and textile fibres. With the help of modern technologies, these materials can be separated from the rubber crumb, and the material can be recycled or reused.
Energy recovery is one of the most common ways of using tires at the end of their life cycle. The company Považská cementárňa, a.s. has extensive experience in this area. They have used whole tires at the end of their life cycle as fuel for the rotary kiln when firing clinker since 1983. Another way of processing tires at the end of the life cycle includes pyrolysis. It is decomposition by heat of up to 800 °C without air access. Rubber asphalt is one of the relatively new possibilities for using tires at the end of their life cycle. The main advantages of rubber asphalt include its elasticity, reduced noise and resistance to weathering. Other options for processing of tires at the end of their life cycle include ozonation. It is a technology that uses selective oxidation effect on tires and turns them into rubber granulate. The steel frame remains intact. About 500 kg of rubber granules can be obtained from a ton of tires using this method.

3. Use of waste tires in concrete

According to the study [1], recycled tires as a substitute for the coarse aggregate component in the amount of 10 wt.% and 20 wt.% in combination with recycled aggregate in pressed concrete were used. Research has shown that the use of recycled crumb as a substitute for the coarse aggregate increases the compressive strength and modulus of elasticity of concrete prepared by the pressing process (pressed concrete).

Abbassi and Ahmad [2] tested concrete prepared on the basis of recycled tire crumb using 3D digital image correlation. Natural aggregate was replaced with recycled rubber in the amount of 10% up to 50% of volume. The results show that:

- Increasing share of recycled rubber (10% to 50%) improves the deformation properties of concrete.
- Replacement of natural aggregate with recycled rubber will improve the ductility of the material, but there will be a significant reduction in compressive strength (up to 80% with 50% replacement of natural aggregate with recycled rubber).

Copetti et al [3] addressed the issue of surface treatment of rubber grains resulting from the recycling of tires for subsequent use in concrete, as a partial replacement of the fine fraction of aggregates in the amount of 15% and 30%. The purpose of the treatment was to improve the physical, mechanical and microstructural properties. NaOH was used to treat the surface of the rubber grains. Furthermore, microsilicates were used in amounts of 7.5% and 15% as substitute for Portland cement. The research has revealed that:

- Replacement of natural aggregate with rubber crumb will cause a decrease in the density by approx. 10.5%, and an increase in porosity by approx. 18%.
The use of microsilica caused a decrease in the volume of cavities in the concrete structure by about 13% compared to the comparative sample of concrete. Gayathri and Raja [4] examined the mechanical properties of concrete based on rubber crumb and microsilica. Microsilica was used as an admixture (Portland cement substitute) in the amounts of 5%, 10%, and 15%. Rubber crumb was used as a 5% substitute for fine aggregate. The research has shown that:

- The use of recycled rubber causes a 15% decrease in the tensile strength of concrete.
- When using recycled rubber and microsilica in an amount of 10%, it will increase the flexural strength.

Habib et al. [5] studied the mechanical and dynamic properties of high-strength concrete prepared on the basis of fine and coarse rubber crumb from tires. CEM II/B-S 42.5 N was used as a binder. GLENIUM 27 superplasticizer based on polycarboxylate was used as the plasticizer. Microsilica and steel fibres were used as well. The replacement of fine and coarse aggregates was performed with rubber crumb in the amount of 15% and 25%. The rubber crumb was surface treated with 10% NaOH. Based on the results of the research, it is clear that:

- A concrete mixture for the production of high-strength concrete with required consistency and maximum rubber grain size of 12 mm can be prepared.
- Replacement of natural aggregate with rubber in the amount of 25% improves the behaviour of concrete during vibrations.
- Concrete with the amount of 25% of rubber crumb is characterized by a damping ratio of up to 90%, so it can be used in places with strong dynamic loads.

Polydorou et al. [6] dealt with the surface treatment of rubber crumb grains using dust from aggregate treatment in order to modify the contact zone between the rubber grains and the cement paste. The results of the research show that the use of dust from the aggregate treatment can improve the contact zone between the rubber grains and the cementing compound. This hypothesis is based on the strength characteristics, where the compressive strength increased by 282% after 7 days and by 276% after 28 days.

Sambucci et al. [7] dealt with the use of recycled rubber from tires in the form of dust and granules as a substitute for natural aggregate in cement mixtures intended for printing. The research has revealed that:

- New materials based on recycled rubber crumb have a homogeneous structure.
- The water-cement ratio of mixtures containing recycled crumb decreases compared to the comparative recipe, which results in the minimization of pore formation.
- Rubber dust in the mixture ensures compaction of the mixture and rubber crumb prevents the propagation of cracks.
- The presence of rubber crumb and dust reduces the absorption capacity of the material.

Chaikaew et al. [8] dealt with the use of rubber crumb from tire recycling in the production of concrete blocks (interlocking pavement) reinforced with steel fibres 35 and 65 mm long. Rubber crumb replaced the fine aggregate in the amount of 10% and 20%. The results of the research have shown that the addition of rubber crumb reduced the strength characteristics of concrete elements depending on the crumb content.

Jalal et al. [9] studied the design of concrete based on waste rubber from tire and pozzolan recycling. Natural aggregate was replaced by sorted rubber crumb in the amount of 10% and 15%. 10% of cement was replaced by microsilica and zeolite. The research has revealed that:

- The addition of waste rubber and zeolite reduces the workability of fresh concrete mix, while the addition of microsilica increases the workability.
- Replacement of natural aggregate with waste rubber reduces the compressive strength of concrete.
- Replacement of natural aggregate with waste rubber leads to a decrease in the modulus of elasticity of about 14% and 19% after 28 days and 10% and 16% after 42 days.

Li et al. [10] dealt with the design of self-compacting concrete based on rubber crumb from tire recycling. Small natural aggregate (sand) and coarse mined crushed aggregate were used in the design of the recipes. Rubber crumb served as a substitute for sand in the amount of 10%, 20% and 30%.
Cement fly ash and slag in the total amount of 530 kg per m$^3$ were used as the binder. Based on the results presented in the study, it is clear that:

- Increasing share of rubber crumb leads to increasing air content in the mixture and the density of the concrete decreases.
- Compressive strength decreases linearly with increasing share of rubber crumb.
- The ductility index increases with the share of rubber crumb.
- The dynamic modulus of elasticity decreases linearly with increasing share of rubber crumb.
- The damping factor increases linearly depending on the increasing share of rubber crumb, which allows better energy dissipation under dynamic loading.
- Water absorption decreases with increasing share of rubber crumb.

Rahal et al. [11] conducted a research on the use of rubber crumb from tire recycling as a substitute for 10%, 15% and 20% of coarse aggregate in combination with 10% and 20% of microsilica. The coarse crumb from tires was also treated in a NaOH solution in order to improve the contact zone between the rubber grains and the cement sealant. The concrete recipe was designed for strength class C35. The results of the research have shown that:

- The increasing content of coarse recycled rubber in concrete leads to decreasing strength.
- The surface treatment of coarse rubber grains with sodium hydroxide caused a slight increase in the strength of the concrete compared to the comparative concrete.
- The optimal amount of replacement of natural coarse aggregate with rubber crumb (10%) and microsilica (20%) in concrete based on recycled tires was determined. The strength of concrete reached the value of about 37 MPa.

Zaleska et al. [12] dealt with the use of rubber crumb fr. 0/4 mm and 4/8 mm in combination with natural aggregates fr. 0/4 mm and fr. 4/8 mm. The cement was used in an amount of 450 kg per m$^3$. The 0/4 mm fraction of natural aggregate was replaced by 10%, 20% and 30% of rubber crumb of the same fraction. The 4/8 mm natural aggregate fraction was replaced with 10%, 20% and 30% of rubber crumb of the same fraction. The tests of the concrete prepared according to the experimental recipes based on rubber crumb were focused on obtaining the mechanical properties, thermal properties, water transport and thermal loading. The results of the research have shown that:

- When replacing natural aggregate with recycled rubber, the density of the prepared concrete is reduced.
- The porosity of the concrete increased depending on the replacement of natural aggregate. The highest porosity (i.e. 25.9%) was found in case of 30% replacement of fine share (fr. 0/4 mm) of natural aggregate with rubber crumb.
- As the rubber content in the concrete increases, the compressive and tensile strength decreases. The highest decrease was found in case of 30% replacement.
- As the share of rubber crumb in the concrete increases, the thermal conductivity decreases.
- The water absorption in concrete based on rubber granulate was similar to that in the comparative concrete.
- Using rubber crumb in the concrete composite accelerated water vapour transfer.
- Concrete based on rubber crumb is stable up to 300 °C.

Kashani et al. [13] studied the surface treatment of rubber crumb grains from tire recycling to be used as filler in the production of foam concrete. Cement coating, silica, sodium hydroxide, potassium permanganate and sulphuric acid were used to treat the surface of the rubber crumb grains. These methods of surface treatment of rubber gran improved the strength of concrete in the range of 27% to 56%. The best improvement was found when using sulphuric acid and silica.

Medina et al. [14] dealt with the mechanical and thermal properties of concrete based on rubber crumb from tires. Portland cement CEM I 42.5R, with water coefficient w/c of 0.5 was used for the design of recipes. Furthermore, two samples of recycled rubber fr. 4/8 mm were used as well. The first sample (FCR) contained rubber crumb, textile fibres, steel fibres, rubber bonded with steel fibres, and rubber bonded with textile fibres. Pure rubber was used as the second sample (CR). Silica sand fr. 0/4 mm and river mined aggregate fr. 4/8 mm were used as natural aggregate. During the recipe design, the natural
aggregate fr. 4/8 mm was replaced with recycled rubber of the same fraction in the amounts of 20%, 40%, 60%, 80% and 100%. Based on the results of the research, it is clear that:

- The use of rubber crumb from tires including fibres (FCR) increases the toughness index of concrete compared to rubber crumb (CR).
- The use of recycled rubber tires increases the absorption of impact energy.
- Concrete based on recycled rubber is characterized by higher abrasion resistance and higher wear resistance.
- As the share of natural aggregate replaced by rubber crumb in concrete increases, the thermal conductivity of the concrete decreases.
- With 100% replacement of natural aggregate with rubber crumb, the coefficient of thermal conductivity $\lambda$ of concrete reached the value of 0.27 - 0.34 W/m·K.
- Concrete with crushed rubber with fibres (FCR) has better physical and mechanical properties compared to pure rubber crumb (CR).

Nitin [15] used waste tires (various types) in the form of fibres (various lengths) and "chips" in the production of concrete. The research is focused on how to find the optimal length of fibres from rubber tires to improve the toughness of concrete (tensile strength). Research has shown that the use of rubber fibres:

- Increases the toughness of concrete.
- Enables the regulation of cracks (width).
- Causes a decrease in compressive and tensile strength.
- Causes holding of individual broken pieces of concrete together.

Abdullah et al. [16] used recycled rubber crumb from tires as a partial replacement for cement in concrete in the amounts of 3% to 12%. The result of the research was the finding that the replacement caused a decrease in the strength of concrete by 6 to 21%.

Thomas et al. [17] used rubber crumb from tires in their study when designing the concrete recipes. The rubber crumb replaced the fine share of aggregate in the amount of 0% to 20% (in multiples of 2.5). The concrete based on rubber crumb was subjected to a chloride ion penetration test. It was revealed that the amount of rubber crumb of 2.5% to 7.5% reduces the depth of chloride penetration. Furthermore, it was proven that the concrete based on rubber crumb is resistant to aggressive environments.

Moustafa and El Gawady [18] examined the mechanical and dynamic properties of high-strength concrete based on rubber crumb from tire recycling. Rubber crumb was used as a substitute for natural aggregate (sand) in the amounts of 5%, 10%, 15%, 20% and 30%. The results of the research show that:

- With increasing content of rubber crumb, the density of concrete decreases.
- The dynamic properties of concrete were tested using vibration tests with an impact machine. The damping effect increases with increasing amount of rubber.

In the study [19], the attention was paid to the use rubber crumb from tires when designing high-strength concrete recipes. Rubber crumb replaced fine aggregate in an amount of 0% to 20% (in multiples of 2.5) in combination with microsilica. The research has shown that the replacement of natural aggregate with rubber crumb in the above-stated percentages contributes to the reduction of compressive strength and flexural strength of high-strength concrete. The results of sulphate resistance are presented as well.

Thomas and Gupta [20] use rubber crumb from tires to design concrete recipes. Rubber crumb replaced fine aggregate in the amounts of 0% to 20% (in multiples of 2.5). Experimental recipes with water coefficient $w = 0.4; 0.45$ and 0.50 were designed. The strength characteristics (compressive and flexural strength) were tested after 7, 28 and 90 days. The results of the research show that:

- With fine rubber grain contents up to 12.5%, it is possible to prepare concrete with a min. strength of 30 MPa.
- Concrete with a fine rubber content of up to 12.5% shows better absorption and carbonation values.

Jedidi et al. [21] examined the effect of rubber crumb fr. 0/4 and 4/8 mm on the acoustic properties of self-compacting concrete. Rubber crumb was represented in 0%, 10%, 20% and 30% of the volume of natural aggregate fr. 4/8 and 8/16 mm. The research results show that:

- A 30% replacement of rubber crumb will reduce water absorption by 19%.
• The coefficient of sound absorption and noise reduction increased depending on the increasing share of rubber crumb in self-compacting concrete.

Li et al. [22] focused on the mechanical properties of concrete based on rubber crumb from tires in grain sizes of 4mm, 2mm, 0.864mm, 0.535mm, 0.381mm, 0.221mm and 0.173mm. The content of recycled rubber ranged from 2% to 12%. The research has shown that:
• The values of axial compressive strength and modulus of elasticity decrease with increasing rubber crumb content.
• Rubber crumb can improve the deformation properties of concrete.
• Rubber crumb allows cracks to be evenly distributed in the concrete depending on the load.
• Rubber crumb up to 8% can be used for concrete design for seismically active areas.

Malek et al. [23] use rubber crumb obtained from tire recycling (fr. 0/4 mm and fr. 4/8 mm) as a 0%, 10%, 20% and 30% substitute for aggregate fr. 0/4 mm and fr. 4/8 mm in the production of self-compacting concrete slabs. The results of the research have shown that the replacement of natural aggregate with rubber crumb:
• Reduces the consistency of SCC concrete.
• Decreases the thermal conductivity value of SCC concrete.
• Reduces the rate of heat transfer in the material.

Samuel and Seckley [24] studied the mechanical strength of concrete based on recycled rubber from tires. The replacement of natural aggregate with recycled rubber was performed in the amounts of 2.5%, 5%, 7.5%, 10%, 12.5%, 15%, 17.5% and 20%. The test results show that:
• The amount of rubber crumb of 2.5% caused an increase in compressive strength of about 8.5%.
• From 5% replacement of natural aggregate with rubber crumb, a decrease in the strength of concrete has been recorded.

Yung et al. [25] used recycled fine crumb (powder) from tires as a partial replacement for natural sand in the production of self-compacting concrete. The replacement of sand with rubber powder was performed in the amount of 0%, 5%, 10%, 15% and 20%. Cement in the amount of 300 kg per m$^3$, slag in the amount of 150 kg per m$^3$ and fly ash in the amount of 150 kg per m$^3$ were used as the binding component. The research has shown that:
• As the share of rubber powder in the cement composite increases, the rate of passage of the ultrasonic pulse decreases.
• When using rubber powder, a low shrinkage value can be expected (but higher than with conventional concrete). The shrinkage value increases with the increasing amount of rubber powder.
• When using rubber powder in cement composite, it ensures an increase in electrical resistance.
• The use of rubber powder increases the resistance to sulphate corrosion.

4. Conclusion
Based on the current results of research dealing with the use of waste tires in concrete production, we can draw the following conclusions:
• Research into the use of rubber crumb, fibres and dust from recycling of tires at the end of their life cycle is a hot topic of research both at European and global level.
• The use of recycled rubber in concrete has been tested for plain concrete, high-strength concrete and self-compacting concrete.
• In high-strength concretes based on recycled rubber, admixtures (microsilica) were used to improve the strength characteristics.
• In most cases, natural aggregates (fine and coarse fractions) are replaced with recycled rubber in a maximum amount of 40%.
• When replacing natural aggregate with recycled rubber, the strength characteristics (compressive and flexural strength) and the modulus of elasticity are reduced. The decrease depends on the content of recycled rubber in the concrete.
• Replacement of natural aggregate with recycled rubber:
  o increases the toughness of concrete and its resistance to vibration;
o reduces the value of concrete absorption capacity;
o when replacing natural aggregate up to 1%, no significant decreases in the strength characteristics of concrete are observed;
o increases the abrasion resistance of concrete;

- The use of fibres from tire recycling indicates an improvement in the flexural strength of concrete.
- The fine and small share of recycled rubber in concrete contributes positively to the reduction of cracks in concrete.
- The use of rubber crumb in rolled concrete (in the amounts of 10% and 25%) increases fracture toughness.
- Grain surface treatment to improve the contact zone between the recycled rubber grains and the cementing compound is possible using 20% of NaOH, KMnO4 and NaHSO3.
- Recycled rubber was used as partial filler in alkali-activated materials.
- The properties of recycled rubber have been tested and compared in cement and asphalt matrix. It has been established that the asphalt matrix shows better properties of the contact zone compared to the cement matrix.

Acknowledgments
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