

## THE EFFECT OF POLYMER WASTE ADDITION ON THE QUALITY OF CONCRETE COMPOSITE

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**Abstract:** Concrete is one of the most important construction materials, which, due to its properties, provides complete freedom in using it in construction, and thus in shaping the space. Despite numerous advantages (ease of use, high compressive strength, low production cost, resistance to high temperatures), it also has disadvantages, which include, first of all, low tensile strength and sensitivity to the destructive effects of chemical agents. The continuous increase in expectations regarding the improvement of concrete quality meant that concrete began to be modified, *inter alia*, with polymers to eliminate the above-mentioned disadvantages. This paper presents a review of articles on the possibilities of using polymer waste in concrete technology and their impact on the quality of the produced concrete composites.

**Keywords:** concrete, polymer waste, concrete quality

### 1. INTRODUCTION

In modern construction, concrete, a composite material with a cement matrix, is used on a large scale. The systematic increase in the amount of concrete produced causes the consumption of a large amount of natural aggregates, and the excessive exploitation of mineral resources causes environmental degradation. Therefore, in recent years, many research centers have carried out tests concerning the possibility of using various waste materials, such as domestic and industrial waste (Kishore and Gupta, 2020), bottom ash (Aggarwal and Siddique, 2014, Pietrzak, 2019), sanitary and utilitarian ceramic (Halicka et al., 2013, Ulewicz and Halbiniak, 2016), cathode ray tube glass (CRT) (Walczak et al., 2015), recycled glass sand aggregates (Bostanci et al., 2016, Pietrzak and Ulewicz, 2019) and slag aggregate (Choi et al., 2020). These activities are aimed at effectively reducing the consumption of energy and mineral resources. Natural resources used in the production of construction materials can be successfully replaced with materials derived from the recovery or recycling of construction waste (e.g. ceramics or rubble) or other waste materials from various industries (e.g. slag, fly ash from hard coal or lignite combustion process, glass cullet, or some polymer materials). Among the various materials, waste polymer materials are very popular. The literature reports show that among the most frequently studied waste

in terms of waste management are polyethylene terephthalate (PET), polystyrene and expanded polystyrene, polyethylene (PE), and polypropylene (PP) and rubber.

## 2. POLYETHYLENE TEREPHTHALATE MATERIALS

Polyethylene terephthalate (PET) is a macromolecular compound (polymer) with a linear structure, obtained in a polycondensation reaction. PET is a material belonging to thermoplastic polyesters with high mechanical strength and high dimensional stability. Due to its properties, this material is used, among others, for the production of fibres, dishes, food packaging (e.g. bottles, jars, trays, films), fabrics (e.g. fleece, dacron and tergal), and ropes. The uncontaminated waste polyethylene terephthalate material can be subjected to feedstock or material recycling, and the contaminated material can be subjected to energy recovery processes. One of the methods of material recycling of waste polyethylene terephthalate can be used for the production of cement-matrix composites. Research on the use of polymer recyclates as substrates involved in the production technology of mortars and concrete mixes is particularly important in ecological and economic terms.

The literature reports show that polyethylene terephthalate (PET) is one of the waste materials that is most frequently used in this way. Among the analysed studies, those by Choi et al. and Rahmani et al. should be given particular attention (Nibudey et al., 2013). Choi et al. produced a lightweight waste aggregate (WPLA) by mixing a liquid granular PET waste bottle with granular blast furnace slag (GBFS) (Choi et al., 2005) and river sand (Choi et al., 2009). These two types of aggregates had smooth surfaces and rounded shapes, and were used as fine aggregate in concrete in the amount of 25, 50, and 70%. The tests were carried out at a W/C ratio of: 0.53, 0.49, and 0.45. According to the authors, the surface texture and shape of the granules are important factors affecting the workability of concrete. They noted an increase in the value of concrete slump and a decrease in the air content in the mix with an increase in the content of the used aggregates. They attributed it to the spherical shape and smooth surfaces of the aggregate. After a 28-day maturation period, the prepared samples were tested for compressive strength. The obtained results showed that the compressive strength of the control concrete samples was higher than that of the samples containing recyclants. The results showed that the 28-day compressive strength of lightweight waste aggregate (WPLA) concrete with an exchange rate of 75% was reduced by approximately 33% compared to the control concrete. The lowest decrease in strength was obtained for concrete, where 25% of aggregate made of recyclate was added. The SEM microscopic analysis of the modified concrete showed that the interphase transition zone between the waste aggregate and the cement slurry was wider than that between the cement slurry and natural aggregate. The authors attributed this to the spherical properties of the obtained aggregate and its hydrophobic properties, which inhibit the cement hydration reaction near the aggregate surface, resulting in a poor bond between the aggregate and cement slurry. All this affects the reduction of the compressive strength of concretes modified with PET waste, and thus, the quality of the obtained composite. The physical and mechanical properties of concretes containing WPLA aggregate were higher than those of concretes containing directly recycled PET.

Rahmani et al. also used PET recyclate obtained from bottle grinding to modify concrete (Rahmani et al., 2013). The authors found that, due to the more specific shape of the waste surface than the natural aggregate, there is greater natural friction, which leads

to a lower workability of the mix. They observed that replacing 5% of fine aggregate with PET waste in concrete resulted in an increase in the compressive strength of concrete. The use of 5% of the waste resulted in an increase in compressive strength by 8.9% and 11.9%, respectively, for concrete with the c/w ratio of 0.42 and 0.52. However, increasing the amount of PET granulate added to 10 and 15% resulted in a decrease in the compressive strength of concretes. The tensile strength of concretes containing PET granulate also decreased. The authors explained this by the negative influence of the smooth and increased surface of the PET aggregate on the bond strength compared to sand.

The effect of the size and shape of polyethylene terephthalate (PET) aggregate on fresh and hardened properties of concrete was also assessed by Saikia et al. (Saikia et al., 2012, Saikia et al., 2013). Scientists modified the concrete mix with three types of PET aggregates of different shapes and sizes. The recycle was obtained from post-consumer PET bottles. Coarse flakes and fine fractions were obtained after mechanical grinding of the waste, followed by purification and separation by physico-chemical methods. The recycle was added to the concrete mix in the amount of 5, 10, and 15% of the natural aggregate volume. The tested concrete properties (compressive strength, tensile strength, modulus of elasticity, and flexural strength) deteriorate due to the inclusion of PET aggregate, and the deterioration of these properties increases with an increase in the content of this aggregate. The abrasion resistance of concrete mixes containing various types of PET aggregate is higher than that of the reference concrete. Moreover, the authors noticed that adding coarse-grained, flaking PET aggregates to concrete resulted in a greater increase in water absorption capacity than in the case of fine PET and granular recycles. It was reported that the drying shrinkage of concrete containing waste PET was lower than that of conventional concrete. This was explained by the fact that the amount of water absorbed by the aggregate was lower due to the impermeable nature of the plastic aggregates, which resulted in an increase in the amount of free water to hydrate the cement.

The recycled PET waste was not only used in concrete as a replacement for aggregate, but also as a fibre. Ochi et al. (Ochi et al., 2007) used flakes from recycled PET bottles as a raw material for the production of PET fibres. The PET flakes were melted, extruded from a nozzle, and pulled into the fibres during heating. In this way, the polymer chains were arranged in the longitudinal direction of the fibre so that the tensile strength of the fibres increased and exceeded 450 MPa. The tensile strength of unmodified recycled PET fibre was below 400 MPa. The authors observed that the content of 0.5% of the fibres in the concrete does not significantly reduce the concrete slump in relation to the concrete of the control series. However, when the fibre content increased to 1%, the value of the fresh concrete slump was 25% of the control concrete slump. Moreover, Ochi et al. demonstrated that the compressive strength of concrete increases with an increase in the volume fraction of PET fibre, reaching an increase with 1.0% content in the tested parameter by approx. 10% compared to the control concrete. With a higher volume fraction of fibres (1.5%), the compressive strength decreased. They also observed that the flexural strength of the tested concretes increased (36.1%), with the increase of PET fibre content to 1.5%.

However, some researchers reported (Nibudey et al., 2013, Pelisser et al., 2012, Fraternali et al., 2014) a decrease in the compressive strength of concrete after adding PET fibres to concrete. Pelisser et al. reported that, with the volume fraction of PET fibres in concrete equal to 0.3%, the compressive strength dropped by 10%. Fraternali

et al. also note that the compressive strength of concrete containing 13.4 kg/m<sup>3</sup> PET fibres is reduced by 8.2% compared to the strength of the control concrete. Nibudey et al., observed that the tensile strength of concrete containing PET fibre increased by 18.6% after adding 1% fibre, and decreased by 19% after adding 3% fibre. Additionally, the flexural strength of concrete containing 1% PET fibre increases by 20% compared to the flexural strength of the control concrete. However, with a PET fibre content of 3%, the flexural strength is reduced by 16.4%.

Based on the analyzed papers on the use of polyethylene terephthalate (PET) waste from bottles in the technology of concrete production, it can be concluded that the method of preparing PET recycle has a significant effect on the concrete parameters. The recycle used by the authors was obtained for research in the process of mechanical processing or in the melting process. The method of mechanical processing of PET bottles is a more efficient and economical way of obtaining artificial aggregate and fibres from them. It leads to obtaining the PET artificial aggregate with a relatively low specific weight and bulk density in relation to the natural aggregate. However, the melting process produces a material with uniform dimensions and properties and a higher bulk density than in case of mechanical recycling. Essentially, by using aggregates and fibres obtained from direct mechanical processing in the production of concrete, a material (concrete) with worse properties is obtained compared to concretes made of aggregate and PET fibres obtained in the melting process.

The presented papers show that waste polyethylene terephthalate was used in concrete mainly in two forms, namely as aggregate (coarse-grained and fine-grained) replacing natural aggregate and as a polymer fibre. The shape of the aggregate has a significant effect on the workability of concrete. Aggregates with a smooth, spherical surface have a lesser effect on workability than those with non-uniform shapes. The density of the concrete containing PET aggregates is lower than that of the control concrete. However, PET fibres do not affect the density of concrete. All these studies show that an increase in volumetric interchangeability of PET aggregates in concrete as aggregate reduces the quality of concrete. A decrease in compressive strength, modulus of elasticity, tensile strength, and flexural strength of concrete, regardless of the consistency and water-cement ratio.

### **3. MATERIALS MADE OF POLYSTYRENE AND EXPANDED POLYSTYRENE**

Expanded polystyrene (EPS), commonly known as polystyrene, is obtained by foaming polystyrene granules obtained in the process of styrene polymerisation. This material contains 98% air and up to 2% polymer.

Post-production waste generated during the production of EPS is recycled back into the process, while waste from prefabrication plants that is contaminated with glue or mortar is sent to waste landfills. Post-use and post-production polystyrene waste is a major ecological problem, and requires finding an appropriate method for its management. An example is the use of this waste for the production of concrete (prestressed concrete). Expanded polystyrene (EPS) beads are a kind of artificial, ultra-light, water-resistant aggregate. It can be used to produce low density concretes which are essential in some construction applications, namely facade panels for curtain walls, composite floor systems, and load-bearing concrete blocks.

Among the analysed literature, the paper of Sabaa et al. (Sabaa and Ravindraraiah, 1997), deserves attention. They used chemically coated, crushed polystyrene granules in concrete as a replacement for coarse-grained aggregate in the amount of 30, 50, and

70% of the solid volume of coarse-grained aggregate. The results of the experimental tests showed that the drying shrinkage and the creep of concrete with polystyrene aggregate increased, while the compressive strength and modulus of elasticity decreased compared to the control concrete, along with the decrease in concrete density. Another method of EPS granules' modification was proposed by Kan et al. (Kan and Demirboa, 2009) Scientists modified the waste EPS granules by heat treatment, heating them in a furnace at 130 °C for 15 minutes. EPS granules obtained during processing were used to replace mineral aggregate by dosing them in amounts of 25, 50, 75, and 100% of the conventional aggregate volume. The increase in EPS content in concrete mixes resulted in deterioration of their workability and difficulties with their compaction. A deterioration of the degree of fluidity of concrete mixes was also observed along with an increase in the EPS content. Despite the negative assessment of resistance to low temperatures, concretes made with the use of thermally modified EPS granulate waste can be successfully used as a construction and insulation material. Moreover, such a use of recycled waste brings measurable benefits in the form of reduced costs of waste disposal. Babu et al. (Babu and Babu, 2003, Babu et al., 2005, Babu et al., 2006) attempted to increase the strength of concretes made with the addition of EPS aggregate using silica fume in the amount of 3, 5, and 9% of the cement mass. The authors demonstrated that the size of the plastic balls affects the mechanical parameters of concrete. The strength of concrete increased as the diameter of EPS balls decreased. The addition of silica fume has a positive effect on the speed of development of the compressive strength of concrete. The effect of EPS granules on concrete properties was also investigated by Chen et al. (Chen and Liu, 2004). They proposed to reduce the shrinkage of concrete containing EPS granules by adding a 25 mm long steel fibre. They demonstrated that concrete containing EPS with a density of 0.8 to 1.8 t/m<sup>3</sup>, with the addition of silica fumes, may increase the compressive strength up to 25 MPa, while steel fibre limits the shrinkage of the concrete. On the other hand, Madandoust et al. (Madandoust et al., 2011) used EPS granulate for self-compacting concretes (SCC). The EPS aggregate was used in amounts of 10, 15, 22.5%, and 30% by volume to replace conventional mineral aggregate. It was demonstrated that mixes with the EPS content up to 22.5% met the criteria for self-compacting concretes. On the other hand, Xu et al. produced a lightweight brick with a lower thermal conductivity using EPS beads with a rounded shape and a diameter of 3.0 mm (Xu et al., 2012). EPS granulate as a substitute for mineral aggregate was used in the amount of 15% and 25% of the volume. The densities of the tested concretes ranged from 1720 kg/m<sup>3</sup> to 2060 kg/m<sup>3</sup>. The compressive strength of concrete after 28 days for the above density range varied from 7.85 MPa to 20.77 MPa. On the other hand, the authors of the paper (Royer et al., 2005) used waste from polystyrene cups for the synthesis of sodium polystyrene sulfonate (NaPSS), which they then used as a cement concrete modifier. The modifier enabled the reduction of the water to cement ratio. The modified concrete demonstrated an increase in compressive strength by 24% after 28 days of maturation. The analysis of the test results showed that the workability and homogeneity of the concretes obtained in this way increased. On the other hand, (Kołtuńczyk and Nowicka, 2007) proved that the compound of sodium polystyrene sulfonate (NaPSS), obtained by modifying polystyrene waste, can serve as a superplasticiser, i.e. a substance reducing the amount of water in concrete mixes and cement mortars. The paper by Choi et al. (Choi and Ohama, 2004), who investigated the effect of using a binder made of EPS waste dissolved in styrene in the amount of 40% on the properties of cement

mortars, is also worth mentioning. The authors showed that, with the increase of the modifier content, the service life of fresh mortars is shorter, and flexural strength also decreases, but, at the same time, compressive strength and resistance to hot water increase.

The analysed papers show that it is possible to produce concrete with EPS granulate or reglanulate. These concretes are called polystyrene concretes and are used mainly as: sloping thermal insulation layers on roofs, balconies, and terraces; filling and insulation layers for use during reconstruction and renovation; evening out thermal insulation layers under floor underlays or floor coverings; filling and insulating layers for filling trenches around heating pipes, hot water supply, etc.; insulation filling around foundation walls or swimming pools.

#### **4. MATERIALS MADE OF POLYETHYLENE (PE) AND POLYPROPYLENE (PP)**

Polyethylene (PE) belongs to the group of polyolefins, i.e. polymers that chemically consist only of carbon and hydrogen. Polyethylene is produced from the monomer ethylene, obtained from petroleum refining products in the pyrolysis process carried out at a temperature of approx. 800°C in tube furnaces. The basic auxiliary raw materials are, among others: particle mass regulators, antioxidants, light and heat stabilisers, lubricants, enhancers and fillers, pigments and dyes, and antistatic agents. The properties of polyethylenes are mainly a function of their chemical structure and physical structure, as well as their modification with various auxiliary agents.

For over fifty years, modifiers in the form of polymers have been used to improve the quality of concrete. The plastic fibres added to the fresh concrete mix act as micro-reinforcement, reducing plastic shrinkage and limiting the formation of shrinkage cracks in the hardened concrete. These fibres, however, cease to function after the concrete has achieved the designed strength and the appropriate modulus of elasticity. Then, the stresses are transferred by the concrete itself or the main reinforcement. The group of polymer concretes includes: resin concretes (PC), polymer-cement concretes (PCC), and polymer-impregnated concretes (PIC). Concrete with the addition of polypropylene fibres is used for industrial floors, road and airport surfaces, and prefabricated thin-walled elements. Polypropylene fibres are produced in two types: as monofilaments (cut from yarn) and fibrillated fibres (cut from foil). The monofilaments are obtained by pulling the yarn, while the fibrillated fibres are obtained from sheets of polypropylene film, which are cut into tapes.

Among the analysed authors, the paper by Naik et al. deserves attention, as they used HDPE post-consumer waste as a substitute for aggregate for the production of concrete mix (Naik et al., 1996). The high-density polyethylene was comminuted into small particles, which were subjected to three chemical treatments (with water, bleach, bleach + NaOH solution) to improve their bond with the cement matrix. The recycle was added to concrete in the amount of 0-5% of the total mass of the mix. The test results showed that the chemical treatment had a significant effect on the action of HDPE aggregate in concrete. Among the used recycles, the best effects were observed for the recycle subjected to alkaline treatment with the bleach + NaOH solution, for which the highest compressive strength of concretes was observed in relation to the compressive strength of the control concrete and other modified concretes. In turn, Chaudhary et al. focused their tests on the use of used plastic bags made of low-density polyethylene (LDPE) in the production of concrete (Chaudhary et al., 2014). The waste was used in the concrete mix as a lightweight aggregate with grain size up to 2.63 mm

in the amount of 0.4, 0.6, 0.8, and 1% (by weight). The tests of the compressive strength and tensile strength of concretes showed an average increase in the compressive strength of modified concretes by about 1% compared to the control concrete. Wang et al. (Wang et al., 1994, Wang et al., 2000) however, used waste fibres obtained from carpets as reinforcement in concrete. They used 12 - 25 mm long fibres in the amount of 1 and 2%. The control concrete was made with 19 mm long virgin polypropylene FibreMesh (FM) in the amount of 0.5 and 1% by volume. The authors showed that modifying the concrete mix with waste fibre from carpets can effectively improve the crack resistance, strength, and ductility of concrete.

Numerous researchers of many papers (Khadakbhavi et al., 2010, Martínez-Barrera et al., 2005, Han et al., 2005, Song et al., 2005, Hsie et al., 2008, Martínez-Barrera et al., 2011, Kosior-Kazberuk and Berkowski, 2016) pay attention to the large influence of the shape factor and geometry of polymer fibres on the compressive strength of concretes produced with polymers. Martínez-Barrera et al. (Martínez-Barrera et al., 2005, 2006, 2011) observed that the addition of 0.6% of the volume of concrete fibre with a shape factor of 20, 40, 60, and 80 (defined as the ratio of fibre length to diameter) increased the compressive strength of concretes by 5, 8, 14, and 3%, respectively. However, in the case of the shape factor of 100, the compression strength of concrete decreased by 6%. Furthermore, modifying the properties of PP fibres and nylon fibres by gamma irradiation, according to Fraternali et al., may improve the stress transfer between the fibres and the cement matrix, which significantly increases the compressive strength of concrete (Fraternali et al., 2010). On the other hand, Han et al. reported that, for the volume fractions of PP fibres of 0.05 and 0.10%, the concrete compressive strength ratio slightly increased by 1-3% (Han et al., 2005). Song et al. investigated the strength potential of concrete reinforced with nylon fibre in comparison with concrete reinforced with polypropylene fibre. They found that, with the fibre content of 0.6 kg/m<sup>3</sup>, the compressive strength with the use of nylon fibres increased by 12.4%, and with the use of PP fibres, by 5.8% (Song et al., 2005). The potential for reducing shrinkage cracks also improved. Hsie et al. reported that, with the addition of PP fibres in the amount of 3, 6, and 9 kg/m<sup>3</sup>, the compressive strength of concrete improved by 4.65, 9.0, and 12.0%, respectively, compared to the control concrete (Hsie et al., 2008). According to Khadakbhavi et al., the shape factor of HDPE fibre affects the tensile strength of concrete when splitting. The authors observed that, for fibres with shape factors of 20, 40, 60, 80, and 100, the tensile strength increased by 10, 23, 37, 22, and 5%, respectively, compared to the reference concrete (Khadakbhavi et al., 2010). According to Kosior-Kazberuk et al., adding polypropylene fibres to concrete increases its plastic properties and energy absorption capacity. The authors also showed that, as the fibre content in concrete increases, the compressive and flexural strength increases compared to the control concrete. With the content of smooth PP fibres with a diameter of 0.05 mm and a length of 25 mm in the amount of 0.9% of the volume, the compressive strength and flexural strength increased by 10% (Kosior-Kazberuk et al., 2016).

As results from the analysis of the articles, the majority of the research papers concern the determination of the effect of the addition of polypropylene fibres made of pure polypropylene material to concrete, and only a few concern the use of waste polypropylene material, which is deposited in landfills. The properties of PP fibres made from virgin plastics differ from those of recycled fibres.

Unprocessed PP fibres have a specific weight of 0.9 g/cm<sup>3</sup> and a tensile strength in the range of 550-760 MPa, while PP fibres obtained from recycled PP waste have a tensile

strength of approx. 450 MPa. Concretes containing polypropylene fibres in an amount up to 1% show higher compressive, splitting, or flexural strength compared to ordinary concrete. Increasing the fibre content above this level deteriorates the mechanical properties of the modified concrete.

## 5. RUBBER MATERIALS

Rubber (vulcanized rubber) is an elastomer made of aliphatic polymer chains that have been cross-linked to some extent by vulcanisation. Depending on the used raw materials, a distinction is made between natural rubber and synthetic rubber. The remaining ingredients, such as softeners, fillers, antioxidants, dyes, pigments, cross-linkers, vulcanization accelerators and activators, flame retardants, or increasing adhesion of rubber to other materials, are dispersed in the rubber. By selecting the appropriate components, rubbers with various properties can be obtained, e.g. rubber for the production of tires, tubes, low or high temperature resistant, oil resistant, non-flammable rubber with properties required for materials used in the food industry, or in medicine. Rubber is a very flexible material (it can withstand large deformations) which is also resistant to chemicals. Due to its properties, it is a material commonly used in various industries, including the automotive, aviation, and machine industries.

The management of vulcanised rubber waste is a serious environmental problem. This material is mainly subjected to the combustion process for energy recovery or deposited in waste landfills. However, in order to reduce its nuisance, it should be reused to a greater extent. Among the waste of this group, a large amount is used car tires. In 2016, the level of recovery of car tires was 96.3%, and recycling was 94.3%.

The following can be obtained from car tires: cut tires, tire halves, shreds, chips, granulate of various fractions, fines, dust, textile cord, and steel cord. All these fractions can constitute a valuable secondary material. The literature review shows that many studies concern the determination of the possibility of using recyclates in the technology of concrete, resulting from the recycling of used car tires. Balaha et al. determined the possibility of using both pure ground waste rubber from used tires and treated ground waste rubber (PVA, SF and NaOH) in civil construction, using it as a partial replacement for fine aggregate (sand) in concrete. The waste was added to the concrete mix in the amount of 5, 10, 15, and 20%. The authors concluded that the physical and mechanical properties of rubber-added concrete are comparable to those of ordinary concrete. The results of the tests show that the mass density (bulk density) of hardened rubber-modified concrete decreases with an increase in the rubber content, which is an advantage for this application of concrete. Moreover, concrete samples containing rubber particles are much harder than samples without rubber particles. The damping coefficient of concrete containing 20% rubber is about 63.2% higher than that of normal concrete. Concrete containing treated rubber particles obtained higher physical and mechanical parameters than concrete containing ordinary rubber (. Balaha et al.2007). Rubber granules obtained from recycling rubber from tire treads as a substitute for fine aggregate in concrete were also used by Albano et al. ( Albano et al., 2005). The recyclate was added to the concrete mix in the amount of 5% and 10%. The authors showed that adding this type of waste to the mix reduces the mechanical parameters of concrete. The reduction of the compressive strength of concrete by adding 5 and 10% of rubber sand with a particle size of 0.59 mm was, respectively, 61.54% and 88.5%, while with the addition of waste with a particle size of 0.29 mm, the compressive strength was 70.97 and 97.43%, respectively. The authors found that the reduction in



strength may be related to a bonding defect between the rubber sand and the cement matrix, and the increased porosity of the matrix. The decrease in the compressive strength of concretes is considered to be the reason that limits the wide use of such concrete by engineers. Batayneh et al. also report in their paper that adding rubber powder, obtained from waste car tires, to the concrete mix reduces the mechanical parameters of concrete. The test results showed that, although the compressive strength of waste-modified concretes is lower compared to the control concrete, the concrete still meets the strength requirements for lightweight concrete. Furthermore, the test results and observations indicate that the addition of rubber recycle to the concrete mix has little effect on reducing its workability (Batayneh et al., 2008).

On the other hand, researchers noted an increase in the flexural strength of the modified concrete. Onuaguluchi and Panesar also partially replaced natural fine aggregate in concrete with rubber granulate with a particle size of 2.3 mm in the amount of 5, 10, and 15% by volume. The results showed a reduction in concrete compressive strength, tensile strength, and modulus of elasticity in modified concretes. When using 5, 10, and 15% of rubber sand, the compressive strength of concrete decreased by 6.93, 13.86, and 39.85%, respectively, and the breaking strength by 5.71, 11.43, and 34.28%, respectively. The addition of 5, 10, and 15% of rubber sand also decreased the elastic modulus by 14.51, 20.21, and 29.27%, respectively (Onuaguluchi and Panesar, 2014). On the other hand, Blessen et al. investigated the high-strength properties of concrete containing rubber recycle obtained from post-consumer tires. Rubber crumbs were used to replace the natural fine aggregate in the amount of 0% to 20% in multiples of 2.5%. The authors observed a significant improvement in concrete wear resistance and water absorption, while the mechanical properties of rubber-modified concrete were lower than that of the control concrete (Blessen et al., 2016). According to the authors of the paper (Bravo and de Brito, 2012) shrinkage in concrete also increases with an increase in the rubber waste content. With the use of 15% waste, concrete shrinkage increased by approximately 43% compared to the control concrete.

The authors of paper (Pietrzak and Ulewicz, 2021) presented the physical and mechanical properties of concrete composites containing waste post-consumer thermoplastic elastomer (TPE) from the production of car mats. The designed control concrete mix was modified by adding waste thermoplastic elastomer granulate to the 2-8 mm fraction. Waste elastomer was used as a replacement for fine aggregate in the amount of 2.5, 5.0, 7.5, and 10.0% of the cement weight. It has been shown that the use of post-production waste from the production of car mats in the amount of 2.5% added as a replacement for gravel aggregate to concrete does not change the microstructure of concrete and does not reduce the value of mechanical parameters modified with concrete waste. All the concretes modified by the addition of waste meet the standard requirements, after 150 freeze-thaw cycles, and the average decrease in compressive strength did not exceed 20%. The use of 2.5% waste in concrete allows for reducing the consumption of natural aggregate by about 5%, thus reducing the costs of concrete production. Improving the impact energy and impact load of concrete by including rubber sand is one of the advantages of using this material in the concrete technology. The addition of rubber waste also improved concrete abrasion and increased its frost resistance. The resistance to freezing/thawing increased with an increase in the content of rubber sand in concrete.

## 6. CONCLUSION

Recently, more and more attention has been paid to the need to protect the natural environment, which is being egregiously exploited by reckless human activity. One of the elements of environmental activism is the tightening of legal regulations in the fields of climate protection, waste management, and the use of natural resources. Limiting the consumption of mineral resources is particularly important in the construction sector, which consumes large amounts of mineral resources, especially sand and aggregate. The consumption of these raw materials can be reduced by replacing them with, for example, recycled materials. Such activities are consistent with the idea of sustainable development, which is defined as development meeting the needs of the present generation without reducing the ability of future generations to meet their needs. However, replacing mineral materials with recyclates from various types of waste in the production of new construction materials has a number of technical and technological limitations, and must be preceded by a series of laboratory tests.

Numerous researchers have attempted to determine the feasibility of using various types of waste, including biomass combustion dust, ceramics, glass cullet, and some synthetic materials, for the production of concrete. In the case of plastics, due to their different physicochemical properties (diverse composition of modifying additives and a diverse chemical structure of the main polymer), their use is particularly difficult, and requires separate tests each time for a selected group of plastics. The cited literature review presents both tests with the use of polymer recyclates produced for the needs of the tests, and those with the use of materials derived from the recycling process. Most studies using recycled plastics concern polyethylene terephthalate and polypropylene, while there are few reports on the use of other plastics in the production of concrete (e.g. PC, PUR) or mixtures of various synthetic materials.

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