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# SWOT ANALYSIS ABOUT THE POSSIBILITIES OF USING CONSTRUCTION WASTE IN POLISH ROAD INFRASTRUCTURE

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ABSTRACT: In recent years, there has been a significant increase in the level of waste generated from construction and renovation (C&D). In the European Union countries, they constitute approximately 40% of all waste generated annually. C&D waste collected in landfills often has a negative impact on the natural environment. The solution to this problem is their reuse in buildings and road works. Currently, the road industry is one of the best-developing construction sectors, which creates great recycling opportunities. The aim of the article is to identify waste and assess the possibility of its reuse in road construction using SWOT analysis. As much as 80% of identified construction waste can be reused. The most useful waste is basalt grit and stone material (100%), and the least useful is recycled tar (11.1%).

KEYWORDS: SWOT analysis, construction waste, demolition waste, recycling, roads

## Introduction

In the EU countries, significant socio-economic development has been consistently observed for many years (Eurostat, 2024). The construction industry deserves particular attention, since many large-scale activities are undertaken related to the construction of new facilities, modernisation of existing ones, as well as demolition of old buildings that have lost their function (Statistics Poland, 2024). These undertakings, implemented both in cubic and linear (road infrastructure) projects, concurrently produce a huge amount of waste, which, according to the EU Commission Decision of December 18, 2014, are listed in group 17 (Commission Decision, 2014). An effective solution to this adverse situation may be the large-scale implementation of recovery processes, including recycling and energy retrieval or else neutralisation (utilisation) of C&D waste (Caro et al., 2023; Iżykowska-Kujawa, 2013). It seems that due to the wide scope of road works performed and the use of large amounts of materials, the road construction industry may play a very important role in the process of reusing waste materials, which will minimise the consumption of natural resources and reduce the negative impact on the environment (Sas & Sobańska, 2010; Wójcik, 2018). Numerous literature reports have shown that recycled materials used, for example, as an addition in the making of a new product, often improve its physical and mechanical properties, thus increasing the durability of the entire engineering facility. Examples include polymeric materials (e.g. polypropylene, polyethylene), plastic post-production waste, processed agricultural waste (Anburuvel et al., 2023; Boom et al., 2023; Czajkowska et al., 2023; Grygo et al., 2022; Guo et al., 2023; Helbrych, 2021; Ołdakowska, 2021; Pietrzak, 2022; Pietrzak & Ulewicz, 2023; Ulewicz & Pietrzak, 2021), fly ash (Jura & Ulewicz, 2021; Kalak et al., 2023; Kalinowska-Wichrowska et al., 2022; Popławski & Lelusz, 2023), recycled aggregates used in the production of concrete (Ahmad, 2011; Gholamhosein et al., 2020; Juveria et al., 2023; Wang et al., 2023; Yuan et al., 2023; Zając & Gołębiowska, 2014). C&D waste was also used to produce asphalt mixes, road bases, parking lots, bicycle paths and roads with low traffic intensity (Akbas et al., 2023; Garzón et al., 2022; Llopis-Castelló et al., 2022; Radević et al., 2020). It is worth noting that not only waste from group 17 is used as recycling material for road construction projects. Many studies also discuss the possibility of reusing post-industrial and post-consumer waste (e.g. waste from metallurgy, glass industry, car tyres, marble waste) in the making of concrete and bitumen surfaces (Duda et al., 2016; Iwański et al., 2022; Wowkonowicz et al., 2018). The latter, however, are most often tested as a possible partial substitute for cement for the production of cement mortars (Pateriya et al., 2022). Mortars based on recycled materials can be successfully used, for example, in renovations of drainage devices (Dębska et al., 2021). Rubber and cork waste are also popular recycling substitutes used in building materials (Dębska et al., 2020; Sybilski, 2009).

Over the last few decades, changes have been observed in the methods of reprocessing construction waste (Brycht, 2020), which is used both in the construction of bitumen and concrete road sections, which fits well into the idea of sustainable development (Silvestre et al., 2023). It is important that already, at the building structures design stage, special attention be paid to the selected materials, including waste materials, which should have no negative impact on the environment (Matuszny, 2020; Sagan & Sobotka, 2016). In accordance with the principles of sustainable construction, it is necessary not only to limit the use of natural resources but also to consider the consequences resulting from the waste materials used in building construction (Adamczyk & Dylewski, 2010). The facility's operation should also be taken into consideration, as well as the possibility of using the built-in materials after the end of the facility's life cycle, using appropriate instruments and models in the field of management and organisation. One such tool is the strategic SWOT analysis, which, thanks to its simplicity and practical dimension, can be used in all sectors of the economy, including the construction industry (Helms & Nixon, 2010). It supports the strategic planning of the enterprise, thanks to which it enables the optimisation of its management strategy (Jackson et al., 2003). The subject of the analyses is management activities, including implementation plans for given investments. By pointing out the strengths and weaknesses, opportunities and threats, you can determine the prospects for individual implementations. This is confirmed by publications in which, among others, the use of SWOT analysis in cement producing enterprises was presented in the decision-making context re-garding the introduction of low-energy construction to the domestic market, as well as to assess the quality of structural and material solutions for steel structures (Bizon-Górecka & Matuszczak, 2017; Matuszko et al., 2018; Szczęsna & Klimecka-Tatar, 2017).

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This paper describes exemplary construction waste and assesses the possibility of their reuse in the road construction sector. A SWOT analysis was carried out in relation to the level of suitability of recycling materials in road construction, and the relevant current situation in the Polish road industry was presented. The innovation of the work is the presentation of a detailed analysis of the recycling potential of various types of construction waste and its consequences for environmental sustainability in the road construction industry. The presented SWOT analysis is comprehensive and specially adapted to the use of construction and demolition waste in road infrastructure in Poland. The work focuses on the Polish context, assessing local regulations, market requirements and environmental considerations. This localised approach distinguishes it from the more general research presented to date in the literature in this field, providing tailored insights and solutions relevant to the Polish road construction sector. The detailed analysis of Strengths, Weaknesses, Opportunities, and Threats analysis, offering a multifaceted view of the subject matter is very important for the European Union countries.

## Recycling of construction waste in Poland and in the European Union

In 2020, according to Eurostat data, a total of approximately 1 971 000 Gg of waste was processed in the European Union countries, of which 1 165 000 Gg was recycled or energy or submitted to energy regaining processes (59.1%), and 806 000 Gg was utilised (40.9%) (Eurostat, 2023b). The percentage share of reused waste divided into individual methods is depicted in Figure 1. The data indicates that the highest percentage, almost 40%, relates to recycling processes, while the least frequently used method was waste incineration without energy returns (only 0.5%).

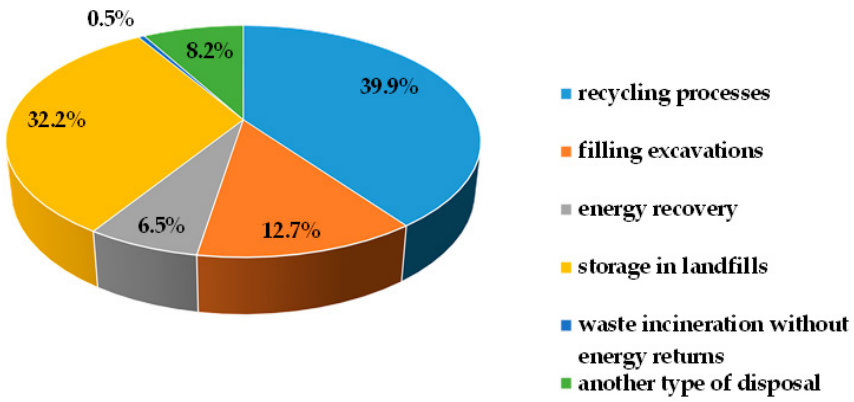


Figure 1. Waste management in European Union countries in 2020
Source: authors' work based on Eurostat (2023b).

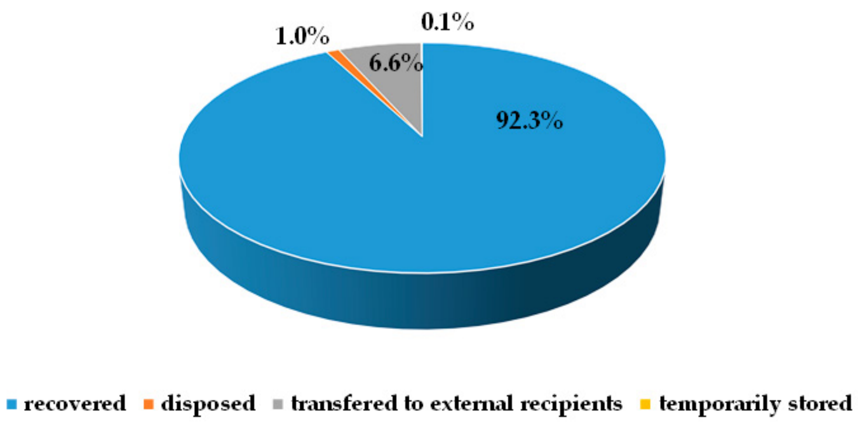


Figure 2. Construction waste management in Poland in 2021
Source: authors' work based on Statistics Poland (2023).

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According to Eurostat data, the largest amount of waste generated was in the construction sector and amounted to 37.5% of the total (Eurostat, 2023b). Building Performance Institute Europe estimates that in the European Union, as a result of renovations, modernisations and reconstructions, approximately 500 million Mg of waste is produced annually, of which as much as 90%. can be reused.

According to data from Statistics Poland (GUS), 3 504 000 Mg of C&D waste were generated in the construction sector, with 5 925 000 Mg stored so far (Statistics Poland, 2023). Figure 2 shows the percentage share of various C&D waste management methods in Poland. The data show that the highest percentage share (92.3%) is the recovery process (including recycling), and the lowest is the transfer to external recipients. However, the level of recycling of C&D waste in EU Member States varies greatly and ranges from less than 10% to over 90% (Eurostat, 2023b).

The EU countries, in various ways, deal with hazardous C&D materials, including used asbestos cement sheets (Ulewicz, 2021). Among all member states, only Poland has taken actions aimed at removing all asbestos cement roof coverings by 2032. According to data from the Polish Asbestos Database, in 2021, this type of waste inventoried in Poland amounted to 8 429 626 Mg. However, it can be assumed that the actual amount is much higher due to many unrecorded sites where this material was and still is illegally disposed of. Currently, the only legally binding method of asbestos waste utilisation in Poland is by placing it in designated landfills. For this purpose, the concerned party should use the services of companies specialised in the dismantling of Eternit corrugated sheets, which are mainly used as a roof covering. Residents can apply for funding from public funds, but it does not include the roof replacing costs (Ulewicz & Liszewski, 2020). Hence, illegal waste management practices are often observed in smaller towns (Pawluk, 2010). Other EU countries, in particular Finland, the Czech Republic, Belgium, Slovakia, Hungary, Cyprus and the Baltic states (Lithuania, Latvia, Estonia), where on average there is over 240 kg of asbestos per apartment, are also struggling with the problem of disposal of asbestos-cement products. In most regions of Central Europe, on average, there is over 120 kg of asbestos per apartment (Maduta et al., 2022). In these countries, as in Poland, this dangerous material, after being dismantled, is deposited in landfills. However, literature reports clearly indicate that there are certain possibilities for its reuse, and the main barriers to their implementation at the same level of advancement in each country are legal, technological and financial limitations (Ligabue et al., 2022). The relevant EU regulations that will soon enter into force in Poland specify the necessary waste reprocessing level of 70%, which, unfortunately, is not currently achievable. Circular Restart! Polish Circularity Gap Report states that currently, the Polish economy is only 10.2% circular. The desired level is to be achieved thanks to changing legal regulations, which place more and more emphasis on appropriate waste segregation. In the works (Mantalovas et al., 2020; Piñones et al., 2023), the topic of circular economy was discussed as an important aspect in directing the road industry towards sustainable development, and attention was also paid to the disproportions occurring between road authorities in individual countries. The practice of collecting waste from construction sites, renovation or demolition works in a common container is to be banned under Article 101a of the Waste Act, in force from 1 January 2025. Selective collection will be based on waste segregation into at least 6 containers, which will include mineral waste, metal, wood, glass, plastics and plaster (Act, 2022). These raw materials constitute an important element in the production of materials needed for the construction of new three-dimensional and linear building projects. The constantly developing road industry offers great opportunities for waste reuse and recycling. According to the General Directorate for National Roads and Motorways (GDDKiA – in Polish: Generalna Dyrekcja Dróg Krajowych i Autostrad), as of 16 May 2022, the length of the public road network in Poland was approximately 420 000 km. At this point, it is worth noting that two main technologies are used in the construction of road surfaces: those for surfaces made of mineral-asphalt mixes (MMA) and those for cement concrete surfaces. The vast majority are bitumen roads, but recently there has been an increase in the construction of roads using new concrete technology. These roads currently include 1 100 km of expressways and motorways and approximately 1 500 km of local self-government roads.

Road construction, while developing, generates large amounts of waste. In the context of bitumen roads, this is the so-called reclaimed asphalt, i.e. material obtained mainly in the process of milling asphalt layers of the road surface as a result of crushing broken slabs. Until recently, this material was considered a useless waste. However, in accordance with the Regulation of the Minister of Climate and Environment of 23 December 2021 on determining the detailed conditions for losing the waste status for decarded asphalt waste, this material can be recycled, provided it meets specific requirements (Regulation, 2021). GDDKiA estimates that 72,000 Mg of this waste was not used in 2018-2019. Figure 3 shows the amount of reclaimed asphalt compared to the amount of asphalt produced in the European Union countries in 2021 (European Asphalt Pavement Association, 2021). Unfortunately, the lack of data reflecting the recycling situation in all 27 member states makes a full statistical summary impossible. Values marked with (*) are estimated on the basis of historical data.

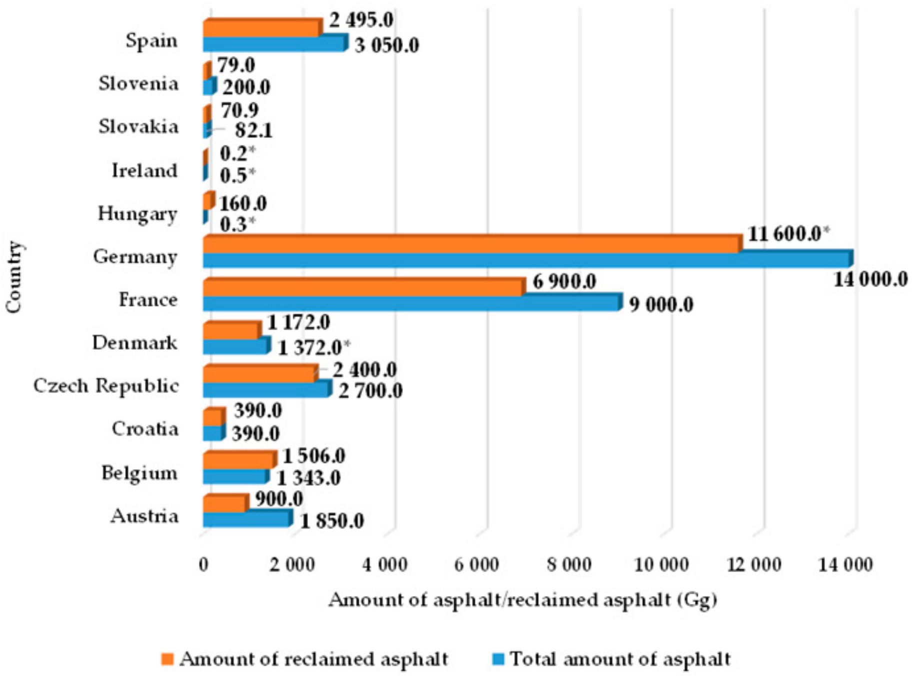


Figure 3. Amount (in Gg) of bitumen from construction sites and reclaimed asphalt for recycling in some EU member states in 2021

Source: authors' work based on European Asphalt Pavement Association (2021).

The highest recycling rate was recorded in Germany, where the amount of reclaimed asphalt intended for reuse was 11 600 Gg. The lowest was in Ireland, where only 0.2 Gg of reclaimed asphalt was recycled. In the 9 analysed countries, the difference between the amounts of produced and reclaimed asphalt was small, with only 3 countries where a higher or equal indicator of waste recycling was achieved.

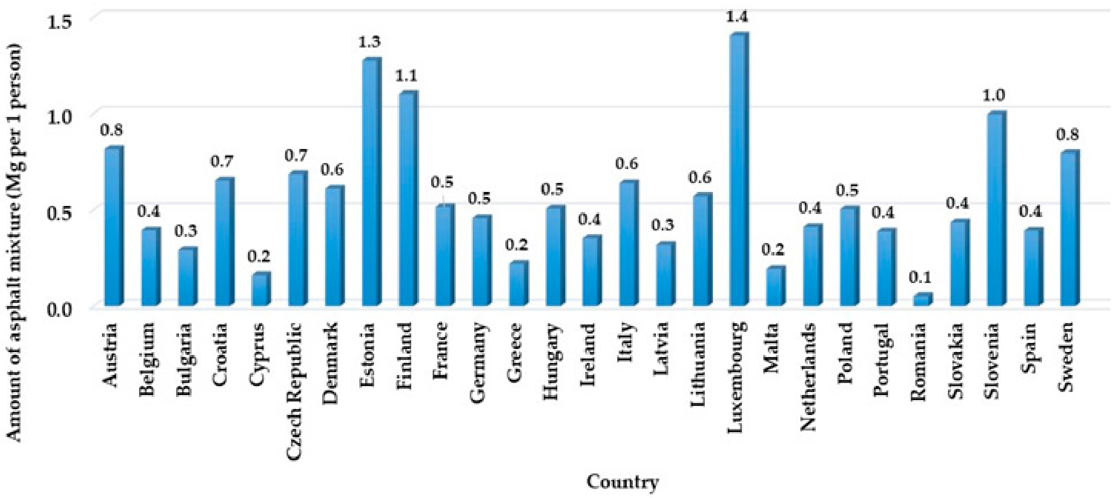


Figure 4. Total production of asphalt mix per capita in the EU member states in 2021

Source: authors' work based on European Asphalt Pavement Association (2021).

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In the report by the European Asphalt Pavement Association (2021), no data for Poland was provided. However, according to a study by Król (2021), as of the end of 2019 in Poland, the level of reuse of reclaimed asphalt for incorporation into the pavements and roadsides was 21%, while 43% of the reclaimed asphalt was still unutilised.

According to data published by the European Asphalt Pavement Association, in 2021, the total production of asphalt mixes in the European Union countries reached 290 600 Gg (European Asphalt Pavement Association, 2021). Figure 4 and Figure 5 shows the production of mix per 1 inhabitant of a given European Union country and per 1 km$^2$ of its area, respectively.

It can be easily observed that only 4 countries achieved a level equal to or above 1 Mg/person, that is 14.8%. The highest rate is in Luxembourg (1.4 Mg/person), and the lowest is in Romania (0.1 Mg/person). In as many as 44.4% of the countries, less than 0.5 Mg of mineral-asphalt mix was produced per capita. The obtained data allowed us to conclude that in as many as 74.1% of EU countries, the mix production level was below 100 Mg/1 km$^2$ of their area.

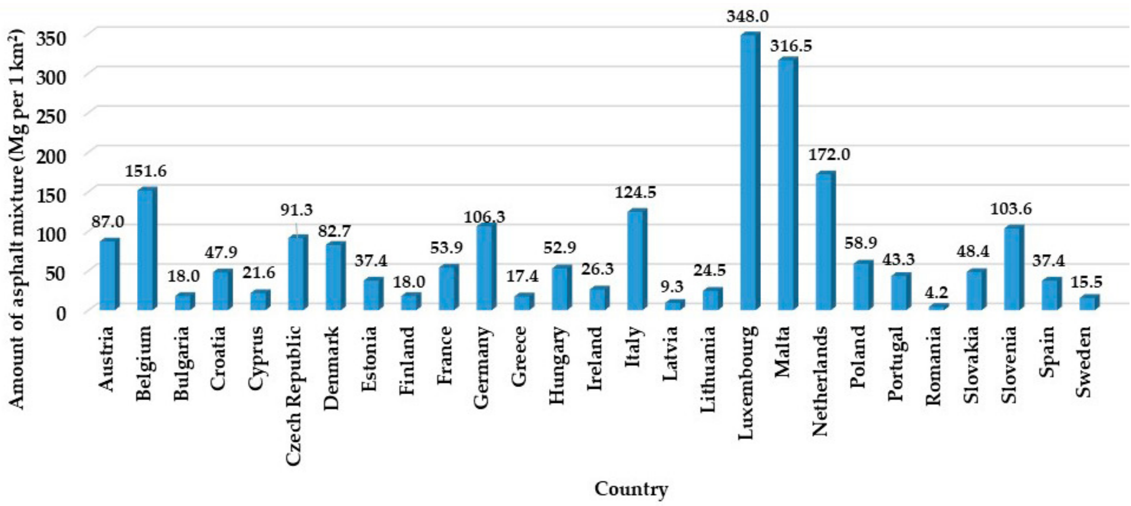


Figure 5. Total production of asphalt mix per 1 km$^2$ of an EU member state area, in 2021

Source: authors' work based on European Asphalt Pavement Association (2021).

## Sustainability in the road construction sector

Nowadays, the idea of sustainable development is present in every sector of the economy. It combines not only economic and social aspects but also environmental ones. The environmental aspect concerns broadly understood ecological issues and, in particular, relates to minimising the use of natural resources, reducing $CO_2$ emissions and reducing the level of waste generated. The concept of sustainable development is also becoming more and more popular in the road industry. The following contribute to this, among others: high energy inputs necessary to produce aggregate needed for road construction and the need to manage large amounts of generated C&D waste. It was, therefore, necessary to take actions aimed at reducing the costs related to the use of energy and minimising the consumption of natural resources. Therefore, it is necessary to develop and implement new technologies that use waste generated in road construction (Nandal et al., 2023). The most desirable method of managing waste generated in the road construction sector is its reuse in the production of mineral-asphalt and concrete mixtures. Waste materials can also be used to produce other road infrastructure elements, e.g. acoustic barriers made of waste concrete blocks (Amarilla et al., 2021).

In the road sector, there has recently been a systematic increase in interest in concrete surfaces, which, due to the assumptions of sustainable development, are a good solution for the structure of communication networks. The ideas of sustainable development should be taken into account already at the stage of designing the facility and selecting materials, as well as at the stage of optimising technological and organisational work. Concrete, due to its properties, is a material that meets the criteria of sustainable construction. It is renewable, durable, does not require any special maintenance, is highly resistant to fire and weather conditions, and is produced near the construction site from local materials, minimising the hassle of transport. During the production of concrete mix, it is possible to

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use, after appropriate processing, various types of waste in the form of additives or admixtures. Many years of research on improving the properties of concrete have often shown that the use of recyclates in appropriate quantities increases its strength parameters, which is beneficial in the long-term use of road surfaces. Better mechanical parameters and reduced costs of producing surfaces using waste lead to an increase in the number of kilometres of the concrete road network, both expressways and local government roads (Jackiewicz-Rek & Konopska-Piechurska, 2013; Karthikeyan et al., 2023). An interesting alternative to replacing primary raw materials, i.e. fine sand in the concrete mix, is the use of industrial waste (such as floor stickers, fillers, pre-mixed mortars, plasters, and putties) in combination with aggregate from the processing of C&D waste. The optimal amount of industrial waste (by-products) depends strictly on the properties of the C&D waste used in the mixture. The use of a mixture of industrial waste and C&D waste has a positive impact on the development of a circular economy, but it is important to provide concrete producers with documented information regarding the origin and composition of waste materials. Waste materials should not raise any doubts or concerns about their quality (Bergonzoni et al., 2023).

Continuous development of technology allows the implementation of innovative C&D waste management strategies. An interesting technological solution is the reuse of rubber waste in asphalt and concrete road surface projects. In the case of the former, modified asphalt increases the driving comfort of road users by reducing the noise level and also allows for reducing the costs associated with the production and installation of noise barriers. In the context of concrete technology, the addition of steel fibres from used tyres allows for obtaining concrete with better mechanical properties. The use of steel fibres from recycled tyres, depending on the amount and degree of fragmentation, can increase the compressive strength of concrete by over 10% and the bending strength by over 50% in relation to unreinforced (control) concrete (Moasas et al., 2022).

Table 1. The literature summary of identified types of construction and demolition waste, along with their use in the road construction sector

| No. | Type of waste | Application | Literature item |
|---|---|---|---|
| 1. | Reclaimed asphalt | Construction and repair of asphalt surfaces, construction of upper and lower structural layers of the surface (hot and cold recycling), construction of the surface layer of rigid (concrete) surfaces, soil stabilization, use as aggregate for the production of concrete mix, preparation of the foundation layer | Al-Ali and Kuwait (2023), Masi et al. (2022), Rout et al. (2023), Ungureanu et al. (2020), Xiao et al. (2023) |
| 2. | Reclaimed concrete | Construction of road substructure, construction layers of concrete surfaces, use as concrete aggregate in the construction of concrete surfaces, bicycle paths and sidewalks | Al-Ali and Kuwait (2023), Fanijo et al. (2023), Kox et al. (2019), Malazdrewicz et al. (2023) |
| 3. | Concrete rubble | Construction of a pedestrian bridge, construction of structural layers of concrete road surfaces | Devènes et al. (2022), Wagih et al. (2013) |
| 4. | Rubber waste | Production of rubberized asphalt, production of mineral-asphalt mixtures for the construction of bituminous surfaces | Bocci and Prosperi (2023), Ibrahim et al. (2023) |
| 5. | Plastics | Production of mineral-asphalt mixtures for the construction of bituminous surfaces, strengthening the subsoil and road substructures | Ashish et al. (2023), Miranda et al. (2023), Ibrahim et al. (2023), Saberian et al. (2023), You et al. (2022) |

The use of additional waste materials for road construction, both in asphalt and concrete technology, allows for obtaining surfaces with better strength properties, which reduces the costs associated with carrying out frequent renovations and increases the safety of road users (Abdy et al., 2022; Almokdad & Zentar, 2023). Table 1 presents a literature summary of the most frequently used recyclates in the road industry, along with their application in individual areas of road infrastructure. In addition to reclaimed asphalt and concrete, recyclates made of waste plastic, in particular polyethene and polypropylene, enjoy great popularity. The use of polyethene and polypropylene waste improves

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the mechanical properties of concrete, but legal and technological restrictions prevent the use of this type of solution on a large global scale (Shamsuyeva & Endres, 2021).

Table 2. A list of publications on identified construction waste in European Union countries from the last 10 years

| Country EU Member State | Type of waste | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Reclaimed asphalt | Reclaimed concrete | Reclaimed tar | Concrete rubble | Brick rubble | Mix construction debris | Basalt grit | Recycled stone material | Rubber waste | Recycled plastics |
| Austria | 10 | 2 | 0 | 0 | 1 | 1 | 0 | 0 | 13 | 82 |
| Belgium | 34 | 2 | 1 | 7 | 1 | 0 | 0 | 3 | 21 | 110 |
| Bulgaria | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 18 | 3 |
| Croatia | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 3 | 19 | 12 |
| Cyprus | 0 | 1 | 0 | 2 | 1 | 0 | 0 | 0 | 3 | 6 |
| The Czech Republic | 32 | 15 | 0 | 9 | 5 | 0 | 0 | 5 | 73 | 89 |
| Denmark | 12 | 2 | 0 | 1 | 1 | 0 | 0 | 2 | 15 | 49 |
| Estonia | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 5 | 5 |
| Finland | 5 | 3 | 1 | 0 | 0 | 0 | 0 | 2 | 28 | 95 |
| France | 92 | 18 | 0 | 10 | 3 | 1 | 0 | 8 | 96 | 232 |
| Germany | 65 | 3 | 3 | 12 | 8 | 1 | 0 | 10 | 101 | 338 |
| Greece | 20 | 6 | 0 | 1 | 1 | 0 | 0 | 3 | 16 | 43 |
| Hungary | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 23 | 39 |
| Ireland | 4 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 8 | 32 |
| Italy | 235 | 41 | 1 | 25 | 24 | 2 | 0 | 27 | 140 | 565 |
| Latvia | 15 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 10 | 40 |
| Lithuania | 11 | 0 | 0 | 1 | 0 | 0 | 0 | 1 | 16 | 12 |
| Luxembourg | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 2 | 6 |
| Malta | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 3 |
| Netherlands | 61 | 10 | 0 | 10 | 1 | 0 | 0 | 5 | 51 | 109 |
| Poland | 54 | 31 | 2 | 18 | 8 | 2 | 1 | 6 | 206 | 136 |
| Portugal | 31 | 11 | 0 | 10 | 7 | 0 | 0 | 11 | 61 | 111 |
| Romania | 9 | 1 | 0 | 3 | 0 | 2 | 0 | 2 | 84 | 90 |
| Slovakia | 11 | 2 | 0 | 1 | 0 | 0 | 0 | 1 | 37 | 48 |
| Slovenia | 5 | 1 | 1 | 1 | 0 | 1 | 0 | 1 | 6 | 22 |
| Spain | 69 | 10 | 0 | 8 | 4 | 1 | 0 | 15 | 161 | 339 |
| Sweden | 4 | 5 | 1 | 0 | 0 | 0 | 0 | 4 | 25 | 78 |

Source: authors' work based on Scopus Preview (2023).

Based on data from the SCOPUS database from the last 10 years, a table was prepared of the number of publications in which the topic of construction waste recycling was discussed in individual Member States of the European Union (Table 2) (Scopus Preview, 2023). As shown in the data presented in Table 2, most publications in the last decade concern the recycling of plastics (2 694 publications) and rubber waste (1 239 publications). The least interest among scientists concerned the use of basalt grit (1 publication) and reclaimed tar (10 publications). It is worth noting the large number of publications in Poland in the analysed thematic area. This is the only country where there have been publications on each type of identified waste. The interest of scientists in this country, as elsewhere in the world, was largely focused on rubber waste (206 publications) and plastic waste (136 publications), and to a small extent in relation to the recycling of basalt grit (1 publication) and reclaimed tar and mixed construction rubble (2 publications each).

## Materials and Methodology

The general research scheme is presented in Figure 6. The first stage of the research was to assess the possibility of applying recycling activities in the Polish road construction sector. For this purpose, a SWOT (acronym for Strengths, Weaknesses, Opportunities and Threats) analysis was carried out. These attributes also function as 4 categories to which selected criteria (data) are assigned. The data presented in this study were obtained on the basis of literature and local sources (survey research in recycling companies).

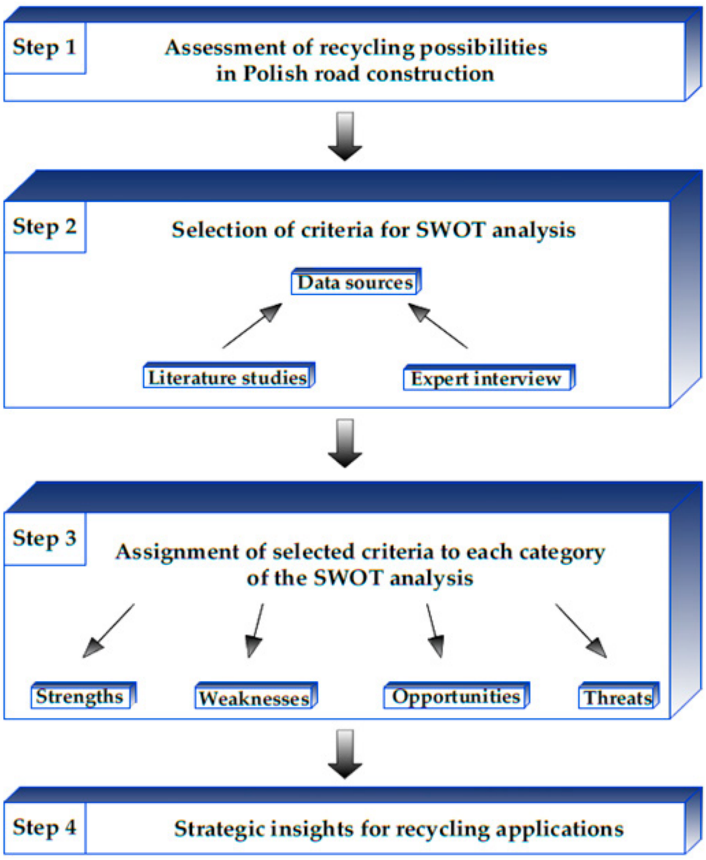


Figure 6. The general research scheme

The SWOT analysis was performed in accordance with the assumptions of the research methodology described in the work (Piercy & Giles, 1989; Puyt et al., 2020). Each category included 5 key features subjected to analysis. Then, appropriate weight (degree of importance) and rating were assigned to each criterion in accordance with the author's assumptions (based on literature sources and data from recycling companies). The sum of the weights in each category was 1, while the rating scale ranged from 1 to 3, where:

1 – low level,
2 – medium level,
3 – high level of a given feature.

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A summary of the categorised features of recycling activities and their weight, rating and weighted value is presented in Table 3. On this basis, weighted values were calculated and then summed. After completing appropriate mathematical calculations, one of the strategies that should be adopted in the matter under discussion was determined. There are four types of strategies (Pickton & Wright, 1998):

- aggressive (maxi-maxi) – when strengths and opportunities predominate,
- conservative (maxi-mini) – strengths and threats predominate,
- competitive (mini-maxi) – weaknesses and opportunities predominate,
- defensive (mini-mini) – weaknesses and threats predominate.

Table 3. Categorized data for SWOT analysis along with their assessment

| Strengths | | | | Weaknesses | | | |
|---|---|---|---|---|---|---|---|
| Criteria | Rating | Weight | Weighted value | Criteria | Rating | Weight | Weighted value |
| Lower energy consumption in carry out the recovery process | 2 | 0.2 | 0.4 | Technological difficulties | 3 | 0.25 | 0.75 |
| Possibilities of repairing | 1 | 0.15 | 0.15 | Lack of appropriate | 3 | 0.25 | 0.75 |
| damaged surface | 3 | 0.2 | 0.6 | infrastructure | 2 | 0.2 | 0.4 |
| Saving natural resources | 2 | 0.15 | 0.3 | Formal and legal constrains | 1 | 0.15 | 0.15 |
| Reducing greenhouse gas | 3 | 0.3 | 0.9 | Waste contamination | 1 | 0.15 | 0.15 |
| SUM | | 1 | 2.35 | SUM | | 1 | 2.2 |
| Opportunities | | | | Threats | | | |
| Criteria | Rating | Weight | Weighted value | Criteria | Rating | Weight | Weighted value |
| Development of road infrastructure | 3 | 0.2 | 0.6 | Increased costs of laboratory tests | 2 | 0.25 | 0.5 |
| Reducing traffic noise | 1 | 0.1 | 0.1 | Improper waste treatment | 1 | 0.2 | 0.2 |
| Improving durability of roads | 3 | 0.25 | 0.75 | No possibility of recovery of every type of waste | 1 | 0.1 | 0.1 |
| Increasing the RTS level | 3 | 0.25 | 0.75 | Limited possibilities for | 3 | 0.3 | 0.9 |
| Savings on investment costs | 2 | 0.2 | 0.4 | developing recycling | 2 | 0.15 | 0.3 |
| SUM | | 1 | 2.6 | SUM | | 1 | 2.0 |

The second part of the research was focused on identifying construction waste and assessing the possibility of its reuse in road construction. Input data, based on literature sources, was then summarily compiled in Table 3. Each type of waste was assessed in the context of the possibility of reuse for a specific layer of concrete and bituminous road surface or other elements of road infrastructure:

- the surface course of asphalt surface,
- binder layer of asphalt surface,
- base and sub-base layers,
- lower layers of the pavement structure,
- layers of improved substrate (capping layer),
- layers of concrete pavements,
- embankments,
- non-structural concrete elements,
- elements of the drainage system.

The following acronyms were used in the assessment:

- UF – waste useful in implementation,
- US – waste unsuitable for implementation,
- PU – waste potentially useful, requiring further research.

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The subsequent stage of the research was to calculate percentage indicators reflecting the level of usefulness of a given waste in the analysed area.

## Results and Discussion

Based on the SWOT analysis (Table 3), we can see that the strengths of recycling in road construction (2.35) prevail over weaknesses (2.2), and the "opportunities" with a value of 2.6 over the "threats" category with a value of 2.0. It is worth noting that the obtained weighted values do not differ much from each other, with a difference of only 0.6 between the lowest and the highest values. Based on the results, the necessary strategy was determined, as shown in Figure 7.

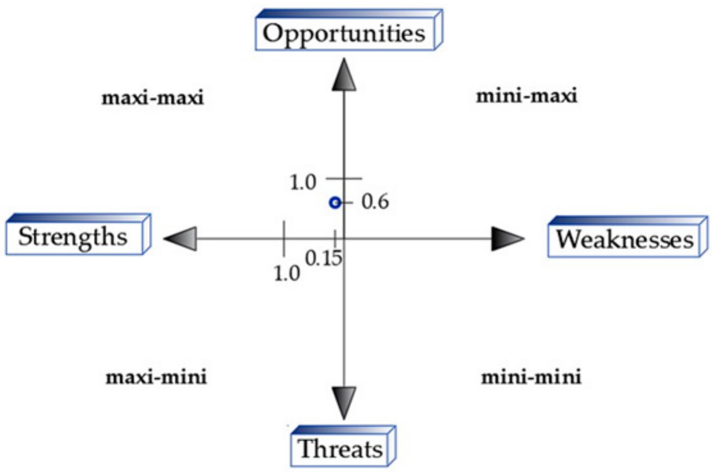


Figure 7. Chart of the strategy for recycling in road investments

The research results allowed us to conclude that the use of the recycling process in linear construction projects is a very desirable phenomenon, mainly for ecological and road safety reasons. Therefore, to obtain the best possible results, the best option is an aggressive strategy (maxi-maxi), which will enable to use to the greatest degree the advantages and will strengthen the correlation between strengths and opportunities categories".

In the environmental aspect, waste management in the area of road construction enables significant savings in natural resources by, for example, using recycled aggregates necessary to produce a new mix and reducing emissions of greenhouse gases by decreasing energy consumption of the construction process. Research works conducted in other countries have shown that the use of recyclates in the production of new material improves its properties, which in turn decreases the number of necessary renovations and, consequently, less spending on related costs (Pereira & Vieira, 2022). In the study Sapkota et al. (2023), the authors conducted research related to the use of recycled aggregates for the production of asphalt mixture. The results showed an increase in the stiffness of the proposed material ranging from 45% to 145%, as well as an increase in Marshall stability from 80% to 99%, which translates into higher strength of the entire pavement structure and has a direct impact on road safety. Durable pavement construction, which does not imply the need to carry out renovation activities within a short period of operation, has a significant impact on reducing the number of road accidents, which was discussed in (Brycht, 2021). A well-made surface also decreases traffic noise, which improves the comfort of use. In addition to the numerous advantages of recycling activities and related opportunities in the road industry, there are also certain limitations. Technological difficulties are reflected in the lack of appropriate machines and devices necessary for waste treatment. This is often related to the high costs of purchasing specialised equipment and the lack of appropriate infrastructure. It is worth paying attention to the still insufficient knowledge of participants in the construction process and the small number of specialists in this field, which translates into irregularities in waste processing. Unfortunately, laboratory research on improving the possibilities of their reuse generates high costs and requires a lot of time.

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The subject matter related to the development of decision-support models in construction activities provides a wide scope for discussion and further research. The variety of dependencies and conditions for the implementation of construction projects implies the need to test different approaches that may prove useful in the analysed area (Szafranko & Harasymiuk, 2022). The presented SWOT analysis is treated as a tool supporting the decision-making process. It enables determining the criteria and individual goals for a given construction project, serving as a project management instrument. It is an auxiliary tool in the decision-making process and a complement to other methods, so it should not be treated as a determinant.

In the analysed case, a company that assumes similar starting criteria and a priority goal should adopt an aggressive strategy. The resulting graph shows the strategy that should be adopted with specific priority criteria in order to achieve the intended effect, which is determined by the maximum use of the potential of the project in question. SWOT analysis is a universal tool that allows you to adapt the criteria to the specific operating conditions of a given company. The research conducted in the article and the results obtained constitute an introduction to further considerations on conducting recycling activities in the road industry. However, at this stage, they confirm the validity of using construction waste to build Polish roads, which is an added value for road companies, primarily in the information context, which may actually contribute to more frequent recycling activities and building ecological awareness of all members of the construction process.

Depending on the legal conditions of the project being implemented, the levels of weights and ratings assumed in the initial phase of the analysis may vary in individual countries. Future research could address these limitations by considering a broader, more diverse research context, particularly with regard to comparing results across national contexts. Additionally, when applying the study's findings, governments should carefully adapt the recommendations to their specific environmental, economic and technological landscape, ensuring that they are consistent with local sustainability goals and construction industry standards. This approach may contribute to the implementation of the obtained research results in practice. The second stage of the research focused on identifying the most frequently generated construction waste and assessing the possibility of using it in particular areas of the road industry, as presented in Table 4.

Table 4. Assessment of the possibilities of recycling identified construction waste

| Type of waste | The structural layer of the pavement or road element | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Surface course of asphalt surface | Binder layer of asphalt surface | Base and sub-base layers | Lower layers of the pavement structure | Layers of improved substrate (capping layer) | Layers of concrete pavements | Embankments | Non-structural concrete elements | Elements of the drainage system |
| Reclaimed asphalt | UF | UF | UF | UF | UF | PU | PU | US | PU |
| Reclaimed concrete | PU | PU | UF | UF | UF | UF | PU | UF | UF |
| Reclaimed tar | US | US | US | UF | US | US | US | US | US |
| Concrete rubble | PU | PU | PU | UF | UF | UF | UF | UF | UF |
| Brick rubble | US | US | UF | UF | UF | PU | UF | UF | PU |
| Mixed construction debris | US | US | US | UF | UF | US | UF | US | US |
| Basalt grit | UF | UF | UF | UF | UF | UF | UF | UF | UF |
| Stone material | UF | UF | UF | UF | UF | UF | UF | UF | UF |
| Rubber waste | UF | UF | UF | UF | UF | PU | UF | PU | UF |
| Plastics | PU | PU | UF | UF | UF | UF | UF | UF | UF |

Based on the above list of assessments, percentage indicators were calculated, reflecting the level of usefulness of a given waste for individual construction layers of the surface and other road ele-

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ments, which accounted for 100% of the calculations. Then, the percentage share of each identified waste was calculated in terms of suitability for the implementation of individual elements of road infrastructure (in relation to the 9 analysed application areas). The obtained results are presented in Figure 8.

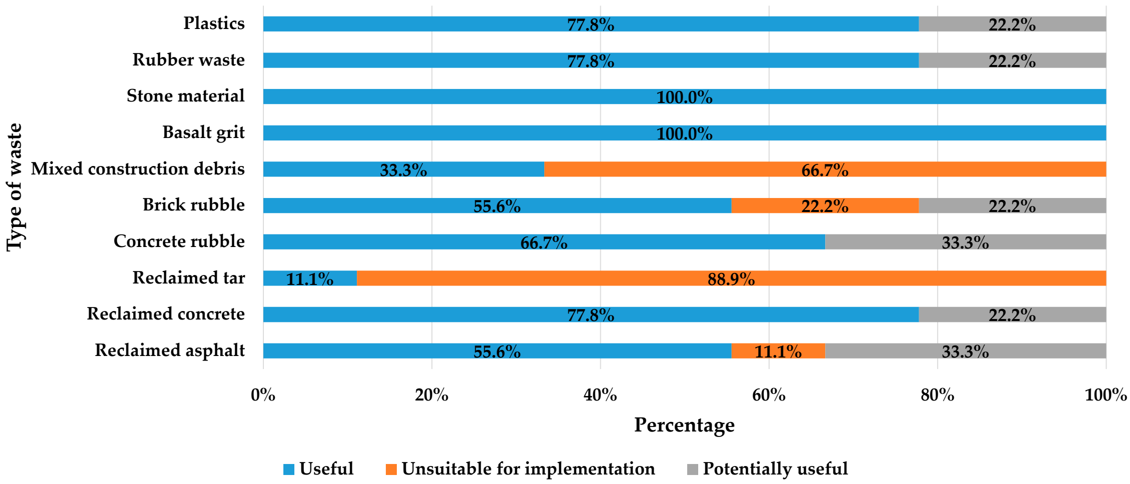


Figure 8. Percentage indicators of the suitability level of identified construction waste

Based on the research results, it was found that 80% of the identified construction waste is suitable for reuse in most of the analysed cases. The material most suitable for recycling turned out to be basalt grit and stone material (100%). Basalt grit, due to its high resistance to precipitation UV radiation as well as high and low temperatures, will work well as an aggregate for the production of mineral-asphalt and concrete mixes. Stone waste originating from the crushing of stone structural elements, paving stones, kerbs and the demolition of unbound sub-base can be used in particular as a raw material for lower layers of the surface structure.

Recently, the practice of reusing asphalt granules, i.e. crushed reclaimed asphalt obtained from milled bitumen surfaces, has become more popular in Poland. However, the use of this reclaimed material is still very limited in our area compared to other countries. Reclaimed asphalt is mainly used for roadside hardening, forest roads and road sub-bases. Research has shown that it is possible to use it when making structural layers of asphalt surfaces (55.6%). It can be successfully used for the production of mineral-asphalt mixes, as well as for surface maintenance purposes (Ołdakowska & Ołdakowski, 2021). Asphalt granules can be reused after appropriate analysis, which involves determining the thickness and type of milled layers, the type of mix, binder and aggregate in the old layer. It is very important to determine whether there is a tar binder, which makes it impossible to carry out the "hot" recycling process and only allows the "cold" method, e.g. in mineral-cement-emulsion (MCE) mixtures. This type of waste can be used for the lower layers of pavement structure, thus the low ratio of 11.1%.

The equivalent of reclaimed asphalt in concrete pavements is reclaimed concrete, obtained by crushing worn out concrete elements. It is widely used in the construction of concrete road surfaces as well as elements of the drainage system and embankments (77.8%). Recently, numerous studies have been carried out to improve the properties of concrete modified with rubber and also polymer waste. Plastics and rubber are currently among the most popular recyclates used in construction industry, also due to the fact that large amounts of this type of waste remain in landfills. According to research, as much as 77.8% of this waste has attributes useful in road construction. Unfortunately, despite many different options of reusing it, the plastic recycling process is very expensive and severely limited due to technological shortcomings.

Among the presented areas of potential waste reusage, the greatest potential is shown by projects with subgrade layers and lower structural layers of the pavement and embankments. As much as 60% of the identified waste can be recycled in certain areas of road construction. The presented detailed analysis relating to the Polish context of the use of construction and demolition waste in road

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infrastructure provides a number of important information in relation to the general approaches presented so far in the literature. This study goes beyond theoretical analysis and proposes practical solutions and implications for the road construction industry, especially in the context of Polish regulations and market requirements. The assessment of the recycling potential of identified various types of construction waste may be helpful in developing reference documents for the domestic construction industry dealing with the construction of bituminous and concrete roads. The obtained results can also be implemented when preparing documents for other member states of the European Union. However, further research is necessary, especially with regard to local legal, environmental and technological conditions in individual Member States.

## Conclusions

The research shows that recycling activities are widely used in the road industry. They are not only important in terms of environmental protection, but also increase the level of road traffic safety and improve the durability of the entire road surface structure. They help reduce the use of natural resources and minimise the generation of huge amounts of waste from construction, demolition and renovation works. The obtained results of the SWOT analysis confirmed the validity of using construction waste to build Polish roads. However, there are certain financial, technological and legal limitations both in the country and in the European Union countries. Appropriate legislation should be introduced to remove these barriers and Member States should pursue policies to support improved recycling practices in road construction. Currently, the level of recycling in Poland in the analysed research area is low, and without appropriate regulations, it will not increase. A low level of production of recycling mixtures (below 100 Mg/1 $km^2$ of their area) is observed in 74.1% of EU countries. The highest level is recorded in Luxembourg (348.0 Mg/1$km^2$), and the lowest is in Romania (4.2 Mg/1$km^2$). However, from year to year, people are becoming more and more aware of environmental issues. The presented SWOT analysis is a useful tool helping in the process of decision-making while implementing construction projects. Participants in the construction process pay increased attention to the ecological aspect at every stage of the construction of linear structures. Up to 80% of the construction waste identified in the study is suitable for reuse as raw material for pavement layers and other road infrastructure elements. The most useful waste is basalt grit and stone material (100%), and the least useful is reclaimed tar (11.1%). Reclaimed asphalt has been used more and more often in recent years, the usefulness of which has been estimated at 55.6%. The research results imply the need to conduct further research on improving methods of recycling and reusing C&D waste. Moreover, they indicate the economic potential of recycled materials on the road construction market, as the recovery and recycling of used materials can bring economic benefits to the road construction industry. The obtained results are very important from the point of view of information policy and may be useful to guide future research and encourage engineers to implement them in sustainable construction practices.

### The contribution of the authors

Conceptualization, M.U. and N.B.; methodology, M.U. and N.B.; software, N.B.; formal analysis, M.U.; investigation, resources, M.U. and N.B.; writing-original draft preparation, N.B.; writing-review and editing, M.U.; visualization, N.B.; supervision, M.U.

The authors have read and agreed to the published version of the manuscript.

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## ANALIZA SWOT MOŻLIWOŚCI RECYKLINGU ODPADÓW BUDOWLANYCH W POLSKIEJ INFRASTRUKTURZE DROGOWEJ

STRESZCZENIE: W ostatnich latach obserwuje się znaczny wzrost poziomu generowanych odpadów z budowy i remontów (C&D). W krajach Unii Europejskiej stanowią one rocznie ok. 40% wszystkich generowanych odpadów. Odpady C&D gromadzone na składowiskach odpadów nierzadko wpływają negatywnie na środowisko naturalne. Rozwiązaniem tego problemu jest ich powtórne wykorzystanie przy robotach kubaturowych oraz drogowych. Obecnie branża drogowa jest jednym z najlepiej rozwijających się sektorów budowlanych, co stwarza duże możliwości recyklingowe. Celem artykułu jest identyfikacja odpadów wraz z oceną możliwości ich ponownego wykorzystania przy budowie dróg za pomocą analizy SWOT. Aż 80% zidentyfikowanych odpadów budowlanych nadaje się do ponownego wykorzystania. Najbardziej użytecznym odpadem jest grys bazaltowy i materiał kamienny (100%), najmniej użytecznym jest smoła z odzysku (11.1%).

SŁOWA KLUCZOWE: analiza SWOT, odpady budowlane, odpady remontowe, recykling, drogi