

Review

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Review

Evaluation of Transition Effects Using Composite Material from Polymer Waste in Integral Bridges

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Abstract: In the article, the authors presented the problem of the transition effect in bridge engineering, its causes, negative consequences, and suggested a solution involving the use of integral bridges with the embankment through a spatial bars structure using reinforced composite polymer material. Integral bridges are designed to collaborate with road or railway embankments in bearing loads. Additionally, their application minimizes maintenance and construction costs while enhancing durability. Current solutions in bridge engineering were described. It is predicted that the presented concept will reduce the amount of plastic waste and contribute to the long-term use of materials. The article emphasized the importance of sustainable development, recycling, and the potential application of substitute materials.

Keywords: civil engineering; integral bridges; transition zone; transition effect; reinforced polymer composite; recycling

1. Introduction

The combination of adverse phenomena such as excessive deformations, dynamic impact, wear and tear and damage at the junction between an embankment and a bridge structure is defined as the transition effect. It occurs at points where different types of permanent way or pavement are connected, laid on various substrates (e.g., soil subgrade, engineering structures) [1,2]. The transition effect is a complex phenomenon, as illustrated in Figure 1, showing the most significant causes of its occurrence, including permanent settlements at abutments (usually smaller) and embankments (usually larger), progressing over time with unequal values for individual elements, and momentary deformations from live loads (deflection of girders, rails, and substrate deformations). Among the surface-related causes, differences in stiffness between the ballast and ballastless tracks, as well as varying stiffness parameters across the transverse direction, can be listed. It includes also primary geometric irregularities of rails and inaccurate alignment of the gradeline on and outside the facility. Causes related to the structure include, but are not limited to, primary geometric irregularities, deformations, settlement, and increased stiffness. Causes related to the substrate involve poor sub-ballast compaction, excessive stiffness differences between sub-ballast and substrate, sub-ballast contamination, and improperly chosen geotextiles. Due to different settlement values at the abutment and embankment, a so-called "threshold" is formed, which leads, among other reasons, to additional dynamic loads on the structure and excessive permanent deformations of the surface, amplifying dynamic effects and causing increased wear and tear and damage to pavement, track superstructure, substrate, and structure. Designing and constructing bridges with their associated embankments require special attention. These structures are often placed in locations where there are poorly compacted, young alluvial sediments, and sometimes clayey or peaty soils, which undergo significant settlement [3]. The issue of ensuring uniform support on the road or railway at the junction of an engineering structure and a deforming earthwork concerns most existing and renovated structures of this kind, to a lesser extent new lines, where the issue of non-uniformity can be largely prevented through the use of appropriate designs [4].

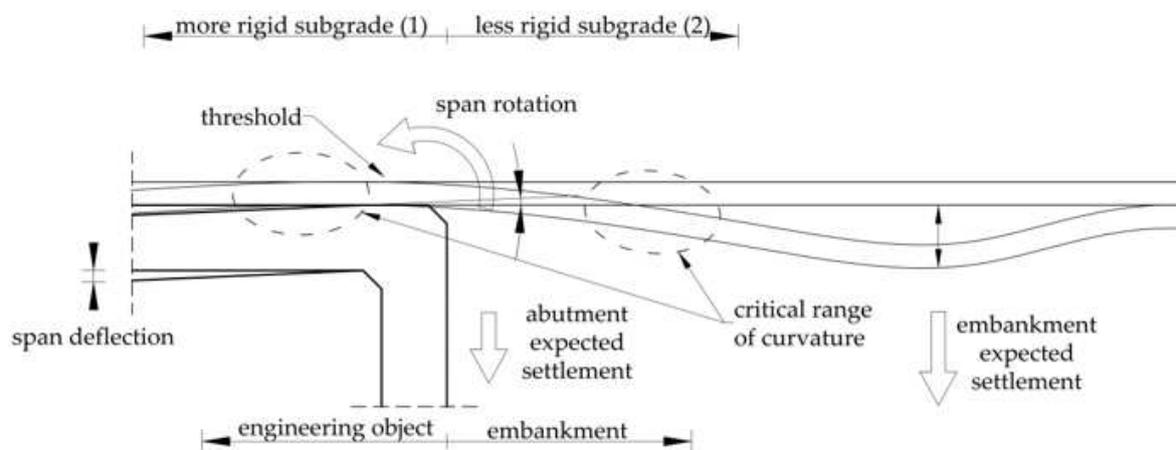


Figure 1. Figure explaining the transition effect.

1.1. Engineering aspect

So far, clear requirements and solutions ensuring a gradual change in the substrate's stiffness for transition zones and reducing the effects of increased rolling stock actions in engineering structure areas have not been defined [4]. Currently, a commonly used solution to mitigate substrate stiffness changes is the transitional slab. However, analyzing the most common damages during the "lifetime" of structures, such as road pavement cracks and track superstructure deformations, suggests that the transitional slab might not be an entirely effective solution as it doesn't ensure a sufficiently gradual change in substrate stiffness (flexibility) [5]. Currently, very different design solutions for transition zones on railway lines are provided, but they do not include a comprehensive assessment of the transition effect.

In contrast to roads where transitional slabs are frequently used, they are not popular for railway lines. Instead, geosynthetics, draining and vibration-isolating mats, synthetic resins, stabilized soil blocks, reinforcement using stone columns or micropiles, dogging, chemical stabilization of sub-ballast, extending and widening substructures, and using stiffening rails within track rails are employed. Contemporary solutions sometimes also involve the use of reinforced concrete slabs.

Engineers often grapple with the durability issue of bridge structures. According to EC 0, bridges fall under category (class) S5, which implies an approximate design service life of at least 100 years. There are also structures over 200 years old still in use. Hence, the aspect of durability and safety of the structure while limiting construction and operation costs is crucial.

The elements with the shortest lifespan in bridge structures are expansion joints and bearings. The most advanced ones can operate for only about 30 years [6]. While piers and girders determine the bridge's load-bearing capacity, equipment elements significantly influence its durability and maintenance costs. The immediate cost of equipment element installation constitutes around 15-20% of the bridge construction cost. Their contribution to maintenance and repairs is often much higher, frequently exceeding 50% [7].

The question arises whether there is a type of bridge structure without a transition slab, expansion joints and bearings? These are frame structures, particularly integral bridges [5–14]. These are single or multi-span structures with a continuous deck connected to the abutment. The connection between the abutment and the deck can be rigid or semi-rigid, depending on the structural solution of the connection. The abutment can be articulated on the foundation or supported on piles. The fundamental structural solutions for these bridges are decks integrated with abutments based on shallow direct foundations, solid abutments, or partially integrated ones.

An integral bridge is a specific type of bridge structure designed to collaborate with an embankment in a way that minimizes the negative effects of the transition effect. The interaction

between the integral abutment and the embankment is crucial to ensuring comfort and safety for its users.

Figure 2 shows an example of an integral bridge. In such cases, the embankment soil is often reinforced. As mentioned earlier, this type of structure does not have expansion joints, bearings, or transitional slabs. The integral abutment is usually incorporated into the road or railway embankment, reducing the bridge's impact on the environment and ensuring smooth and safe road or railway traffic.

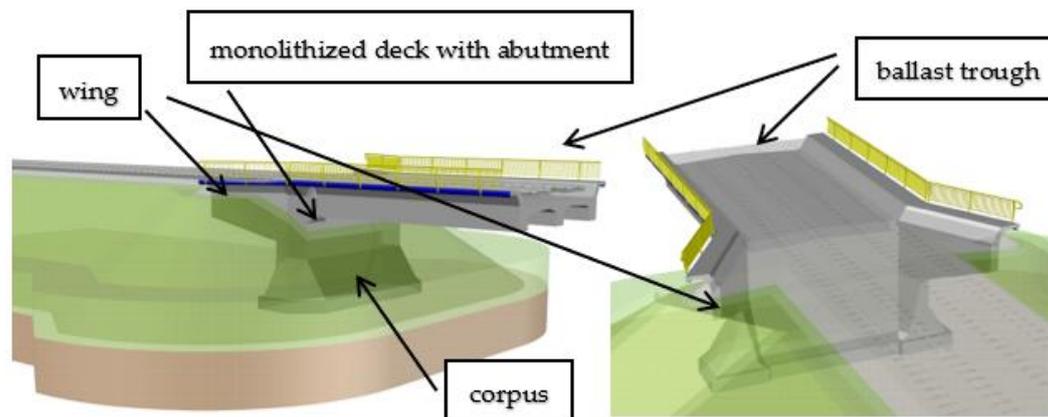


Figure 2. 3D model of an example integral bridge.

The longitudinal forces arising from the thermal expansion or contraction of the bridge deck are transmitted to the abutments and to the soil behind the abutment [15]. In the design assumption, the abutment does not necessarily have to absorb the entire horizontal forces due to thermal effects, as part of them will be transferred to the embankment, which will be integrated into the cooperation [15]. Therefore, the crucial aspect is the connection between the abutment and the embankment.

In calculating the ground reactions behind the abutment, the total length of the bridge is significant, determining the extent of its expansion or contraction due to temperature changes. However, the number of intermediate supports has no effect on the magnitude of the bridge's expansion or contraction, and hence, this number doesn't influence the size of the ground reaction [7].

In integral bridges, forming a slip plane to stimulate movements in the upper layers of embankment soil is essential to minimize vertical displacements that affect the magnitude of the transition effect [7]. Intermediate supports, typically reinforced concrete, can be articulated on the foundation or based on one or several rows of piles. Spans for structures with integrated supports usually range around 60 meters, sometimes reaching 80-100 meters. The number of piers can vary, and the lengths of the longest integral bridges can exceed 350 meters (Happy Hollow Bridge, Tennessee, USA).

Integral bridges are designed with the assumption that only minor settlements of the end supports of the structure and embankments are permissible for using this solution in a given location. It is essential to note that this assumption significantly restricts the application of integral bridges.

Aware that the transitional slab does not entirely solve the transition effect issue and causes other negative effects, manifesting as pavement and track superstructure damages, designers of integral bridges opted for better cooperation between the embankment and the structure, abandoning the transitional slab [7]. The assumption of minor settlements in integral bridges mitigated the transition effect issue but significantly limited their applicability.

When entering a bridge, a vehicle must cross a transition zone. During its design, engineers must consider that the road or rail and the bridge itself may have different mechanical properties, such as stiffness, density, and Young's modulus. If the foundation at the entrance to the bridge is too stiff, it can lead to excessive stress in the bridge structure and increased risk of damage. Conversely, if the foundation is too soft, it may cause excessive settling of the bridge and a change in its geometry,

which can result in hazardous situations for users. The mismatch usually occurs between a too compliant embankment and a too rigid bridge structure. Regulations seem to focus separately on the settling of individual elements, overly stiffening the structure (restrictively limiting deformations and settling) while overlooking the fact that soil structures will always settle more than those built from concrete and steel. Hence, it is reasonable to extend the bridge structure into the transition zone and connect it with a system that ensures efficient load transfer and smooth settling changes.

Reinforcing the ground behind the abutment is often used in bridge engineering to relieve the abutments. This is done by forming a block construction from reinforced soil, using geosynthetic materials, for instance. It can relieve the abutment bodies and wings of newly built bridges as well as existing ones. However, the resulting void between the back wall of the abutment and the embankment creates a discontinuity that can negatively impact operational qualities, increasing the transition effect.

By reducing the pressure on the abutment, its dimensions can be reduced, thus minimizing the difference in stiffness (compliance) between the surfaces. Ensuring load transfer cooperation and standardized settling is crucial. Geosynthetic reinforcement itself is not used due to its low stiffness compared to the abutment. However, these two mediums can cooperate effectively. This type of solution has been studied, among others, by Horvath [16].

The purpose of reinforcing the ground (or using layers) is to increase soil shear strength and reduce ground pressure on the abutment [7]. By reinforcing the embankment soil, uneven settling can be controlled. In the case of a significant increase in pressure on native soil, there is a risk of uneven settling or loss of stability. Using a reinforced platform allows for even distribution of settling [17]. The platform's effectiveness can be increased by using high-strength geosynthetic geogrids, with tensile strength up to 1600 kN/m, which vertically absorb, distribute, or dissipate loads onto the soil [17].

The problem of the transition effect, caused by the varying compliance (stiffness) of the pavement foundation in the transitional section onto the bridge, remains a current challenge for bridge engineers and continues to be researched and analyzed [10,11,13–16,18–28]. Intensity in addressing this issue has decreased in recent years, yet with increasing speed limits and tonnage, the problem is escalating. In the case of railways, any unevenness in the track profile gains importance due to the possibility of jolting rolling stock, uneven wear on rail heads, or damage or dislodgement of track beds. For traditional roads, damage occurs to the surface, followed by subsequent structural elements. The ever-growing volume of waste poses challenges to humanity. Seeking multi-faceted solutions contributing to the common good is the essence of engineers' and scientists' efforts. The issue of transition zones (and the transition effect within) in bridge engineering involves the use of numerous different solutions that are not standardized and have limited impact on reducing the set of adverse phenomena, such as excessive deformation, dynamic effects wear, and damage to surface elements, foundation, and the structure itself. There is an opportunity to propose solutions involving the use of processed waste in the construction of transition zones connecting abutments to embankments, where materials made from waste can fulfill their function and contribute to reducing environmental pollution.

Ensuring the durability of bridge structures places specific requirements on the durability of individual elements. Despite the increasingly modern solutions in bearing and expansion joint construction, reality verifies that production, assembly, and maintenance costs are significantly rising. There are also increasing demands for the qualification of personnel involved in assembly, maintenance, and replacement of individual elements during the operation of these structures. The growing number of structures poses increasing maintenance difficulties, necessitating the search for "simple" solutions. Integral bridges can be considered as such.

1.2. Environmental aspect

An effect of the increasing affluence of societies is the intensive growth in the quantity of waste generated. According to the World Bank report [29], currently, approximately 2 billion tons of solid waste are produced each year. Experts also predict that in about 30 years, we might expect nearly a

doubling of garbage production. The enormous volume of waste poses a significant burden on the natural environment. Statistics indicate that an average resident of the European Union generates 530 kg of waste per year [30], of which approximately only 48% is processed. The share of polymer waste in recycling is only 25% [31].

Polymer materials are processed many times, which further reduces the need for limited resources, such as oil or gas, from which they are produced. However, it is important to note that with each subsequent recycling of polymer raw materials, their mechanical properties deteriorate. Essentially, after two cycles of plastic use (use - recycling - use), the material is no longer suitable for rational processing; its strength properties become too low [32]. It is desirable, therefore, to find a long-term use for waste material.

Comparing them to everyday items, the use of processed materials, especially in civil engineering like in bridge construction, ensures their long-term use, often exceeding 100 years. This fact can significantly reduce the carbon footprint of everyday products that eventually become waste. The issue of managing the increasing amount of waste from polymers has gained particular significance in recent decades, and if properly utilized, these can become valuable resources.

Special attention needs to be paid to waste from high-molecular-weight plastics. Their largest source is packaging. According to data [33], only about 19.5% of plastic waste is sorted. This fact guarantees a constant demand for solutions allowing for recycling.

According to the PlasticsEurope Foundation report [34] from 2022, in 2021, global production increased by 4% to over 390 million tons, indicating a strong and continuous demand for plastics. However, Europe faces many challenges. The latest data shows that China's share in global plastic production continues to grow (reaching 32% in 2021), while Europe's share - totaling 57.2 million tons in 2021 - continues to decline (reaching 15%). In 2021, the recovery of plastic waste in the 27 EU27+3 countries exceeded 5.5 million tons, post-consumer plastic waste used in new products and parts accounted for about 10% of plastic recycling and increased by about 20% compared to 2020 [34]. According to the cited report, global plastics production increased from 365.5 million tons in 2018 to 390.7 million tons in 2021. Plastic recyclates accounted for 30 million tons and 32.5 million tons respectively. A slight increase in the share of recyclates from 8.2% to 8.3% can be observed [35]. In 2022, in the EU27+3 group of countries, out of 17.9 million tons of plastic packaging, 17% was landfilled, 46% was recycled, and 37% was recovered for energy [35]. In two countries, Belgium and the Netherlands, the intended goal of complete elimination of landfilling of plastic waste was almost achieved [34].

In the EU27+3 group of countries, the percentage of waste going to landfills continues to decrease, but progress in this area is slow, especially in countries with a low level of plastic waste recovery. Half of the EU member states recover less than 30%. Every year, 25% of plastic waste in the EU27+3 still goes to landfills [36]. In Europe, 37% of plastic waste is incinerated in modern incinerators [34]. The above data is presented in Figure 3; the charts are based on information contained in [34,35]. A study by Zero Waste Europe showed that even the most modern incinerators emit dioxins and other harmful pollutants [37,38]. This situation encourages intensified efforts to increase the amount of recycled materials [36].

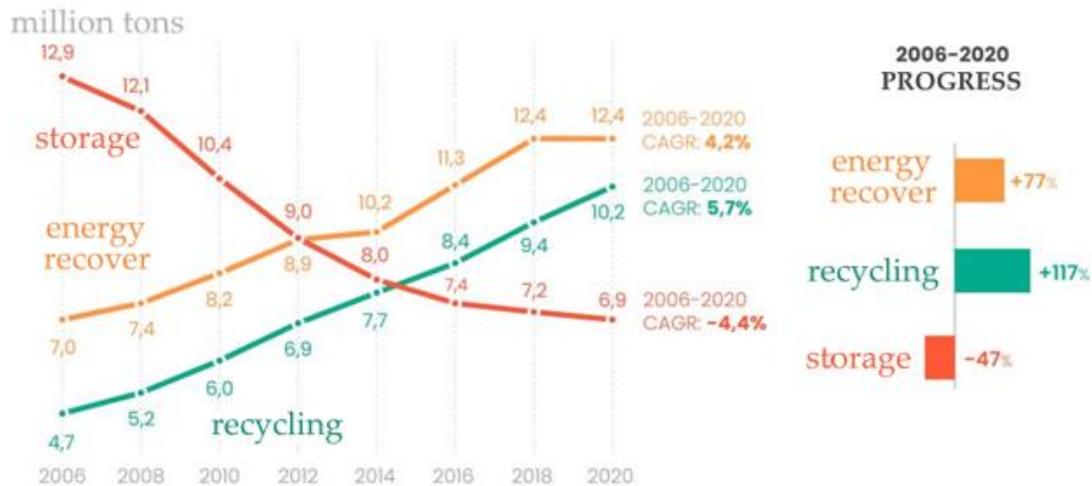


Figure 3. Progress in the management of post-consumer plastic waste (EU27+3).

Many of the countries accepting waste perform poorly in plastic waste management rankings. According to the World Bank, in developing countries, "over 90% of waste often ends up in illegal landfills or gets burned [39]." Every product of plastic ever produced still exists today. Since 1950, 2 million tons of plastic have been created worldwide [34]. In studies [40], Roland Geyer et al. estimate that about 79% of all plastic waste ends up in landfills or directly in the natural environment. Ten million tons of plastic enter the oceans every year.

The cost of pollution is estimated in billions of dollars annually [41]. In 2019, an international research team published in the *Marine Pollution Bulletin* data stating that each ton of plastic waste in the oceans represents destroyed resources valued at up to \$33,000. Scientists did not account for the indirect impact on tourism, transportation, and health. Considering these aspects, the social and economic costs of plastic waste in the oceans may be significantly underestimated [41].

The main challenges hindering plastic recycling are the quality and price of recycled products compared to their virgin counterparts. This is due to the complex process and various difficulties to overcome [42]. This includes sorting technology, specific challenges related to mechanical recycling like thermo-mechanical degradation or degradation over the product's lifespan, and the immiscibility of polymer mixtures. Plastic processors require large amounts of recycled plastics produced to tightly controlled specifications and at competitive prices [43]. However, plastics can be easily customized to meet the functional or aesthetic needs of any manufacturer, complicating the recycling process and increasing its cost while affecting the quality of the final product [43].

Green energy still faces challenges, especially in wind energy, where durable, lightweight materials like carbon fibers are needed for producing turbine blades. However, their rapid consumption and the lack of comprehensive solutions for processing these materials pose societal problems [44–56]. From 80% to 90% of wind turbine installations can be recycled (concrete, steel, copper, and silica). The remaining 10% to 20% represents a critical issue in disposing of the materials used to build them [44,45]. This concerns the materials in the blades, known as fiber-reinforced polymers (FRPs), often made of glass, carbon, aramid, or basalt fibers. In the EU, demand for FRPs grew sharply from 5,000 tons in 1991 to 346,000 tons in 2015. It is estimated that by 2030, 4 million tons of fiber-reinforced polymers will be used for zero-emission wind energy production in the European Union. **Current recycling methods proposed do not solve the rapid increase in the amount of this type of waste [44].**

Currently proposed actions in this area include: prevention, involving services and repairs of turbine blades to enable their extended use; reusing them in other sectors of the economy, producing items like small architectural elements, playgrounds, furniture, and similar products. However, low processing capabilities and the dust generated during processing are issues; recovery through chemical or thermal treatment, which is currently unprofitable; disposal through landfilling and

incineration, which do not solve the problem and are banned in many countries; additionally, they are not in line with the principles of a circular economy [44].

In Germany alone, where 30,000 wind turbines are currently operating, by 2024, 70,000 tons of materials from turbine blades are expected to be scrapped. Most of these devices will then be dismantled. The German Federal Environment Agency calls on the government and regional authorities to quickly develop regulations and procedures for recycling decommissioned turbines [45]. Wind turbines installed in the United States in the late 1990s are gradually being decommissioned after 25 years of operation. A massive graveyard of buried turbine blades from decommissioned turbines is located in Casper, Wyoming. Until recently, a morally questionable practice occurred on a large scale, where dismantled wind farms were sold to markets in Eastern and Southeastern Europe, Russia, Africa, Asia, and Latin America. However, requirements in these countries are constantly increasing, and most are no longer interested in acquiring old technology that requires significant investment in maintaining such installations [45,50,53–55]. Extracting fibers using pyrolysis and using them as dispersed reinforcement in polymer materials will certainly help manage large quantities of this specialized waste to some extent.

Currently, the simplest and most effective way of waste disposal appears to be the use of materials in civil engineering as construction materials. Construction accounts for the use of 4 million tons of recyclables in new products for EU27+3 countries, which constitutes 46% of plastic recyclables [36]. The demand for materials for constructing embankments is very high. For standard embankment heights near bridge structures, this amounts to tens of cubic meters per meter of embankment using materials with a long period of use, as shown in Table 1.

Table 1. Dependence of the volume of the embankment depending on its height per 1 m.

height of the embankment [m]	narrow embankment for a single-track line [m³/mb]	narrow embankment for a double-track line [m³/mb]
3	19.47	19.90
5	36.25	36.68
8	70.03	70.46
12	131.18	131.61
20	308.67	309.10

2. Keyword analysis

Before delving into a detailed analysis of available literature related to the proposed topics in this publication, a scientometric analysis was conducted based on publicly available library catalogs. This analysis aimed to highlight the major scientific trends and areas requiring in-depth research. It facilitates the creation of visualizations for data analysis and establishes connections between sources, keywords, authors, and articles within a specific research area. Researchers from various fields of science utilize scientometric analysis [57–61].

Currently, scientists have access to a substantial collection of library catalogs promoted by various publishers. Below are the results of the analysis for widely accessible and most reliable databases, Scopus, and Web of Science [61,62]. Scopus is a scientific database managed by Elsevier, providing information about published scientific works such as articles in scientific journals, books, conference materials, and patents. As of November 2023, the database contained over 93 million records, encompassing more than 28,000 active titles published by over 5,000 publishers [63]. Additionally, it indexed around 327,000 books.

The indexed works in the database cover natural sciences, engineering, medical, social, humanities, and arts [63]. Web of Science, also a scientific database managed by Clarivate, contains similar information about published scientific works. As of November 2023, it contained over 211 million records, including books, articles, and other materials [64]. The thematic scope of the indexed works in this database is also similar. The data search was conducted in November 2023, using

keywords such as 'civil engineering, integral bridges, transition zone, transition effect, reinforced polymer composite, recycling.'

Due to the multifaceted nature of this article, the explored topics covered various fields, including civil engineering, material engineering, chemical engineering, chemical sciences, environmental engineering, environmental sciences, and resulted in the following Table 2, presenting results for individual combinations of keywords. While analyzing the results, it is worth noting that the orders of magnitude of the presented results from different databases correspond with each other, with minor exceptions. These differences may arise from the search criteria offered. Unlike Scopus, Web of Science did not have a defined limit to searching only titles, abstracts, and keywords. It is crucial to highlight that as the number of keywords increases, the search results drop to zero. This clearly indicates that the presented scope requires further research.

Table 2. Keyword association results summary.

selected keywords		number of searches by	
		Scopus	Web of Science
civil engineering		1,748,102	1,057,904
integral bridges		6,195	5,314
transition zone	1	75,613	65,590
transition effect		593,443	476,006
reinforced polymer composite		56,775	57,048
recycling		245,488	240,686
civil engineering + integral bridges		149	1,000
integral bridges + transition zone	2	9	10
integral bridges + transition effect		50	64
reinforced polymer composite + recycling		1,515	2,049
civil engineering + integral bridges + transition zone		0	5
civil engineering + integral bridges + transition effect		0	7
transition zone + transition effect + reinforced polymer composite	3	40	51
transition zone + reinforced polymer composite + recycling		4	10
integral bridges + transition zone + transition effect + recycling	4	0	0
civil engineering + transition zone + transition effect + recycling		5	320
integral bridges + transition zone + transition effect + reinforced polymer composite + recycling	5	0	0
civil engineering + integral bridges + transition zone + transition effect + reinforced polymer composite + recycling	6	0	0

The initial high values of association results do not clearly reflect the content relationship presented in the publications with this study. Often, the overlap of two keywords is far from sufficient. Only with three keywords do single articles begin to share common parts.

Data from Scopus and Web of Science databases for selected searches (3 and 4 keywords) were exported in comma-separated values (CSV) format for importing into the appropriate software tool. Mapping and visualizing the academic network were created using the VOSviewer software version (developed by the Centre for Science and Technology Studies of Leiden University, Leiden, Netherlands). VOSviewer is a software tool used to construct and visualize bibliometric networks based on citations, bibliographic couplings, co-citations, or co-authorship relations [65].

The visualization of co-occurrence networks of keywords, their relationships, and the density associated with the frequency of their correlations were examined and presented in Figures 4 and 5.

The size of the keyword node denotes its frequency, while its location represents its co-occurrence in publications. To enhance clarity in the presented data, the engineering material part related to integral bridges was separated and displayed in Figure 4. The entirety of connections is shown in Figure 5a, with a detailed engineering part in Figure 5b, which was subdued due to the material scope.

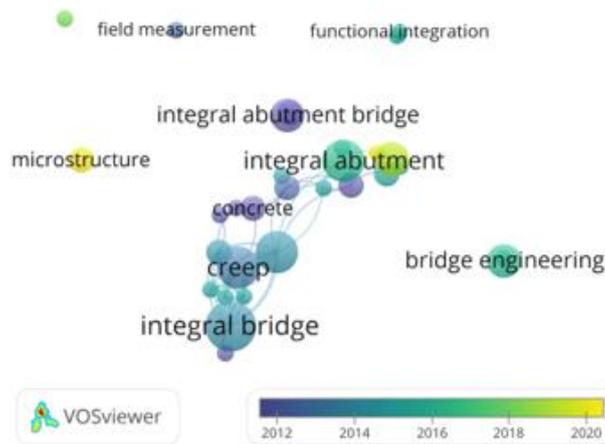


Figure 4. Visualize the incidence and relationship of individual keywords created using VOSviewer showing additionally date of publication (accessed on 11.2023).

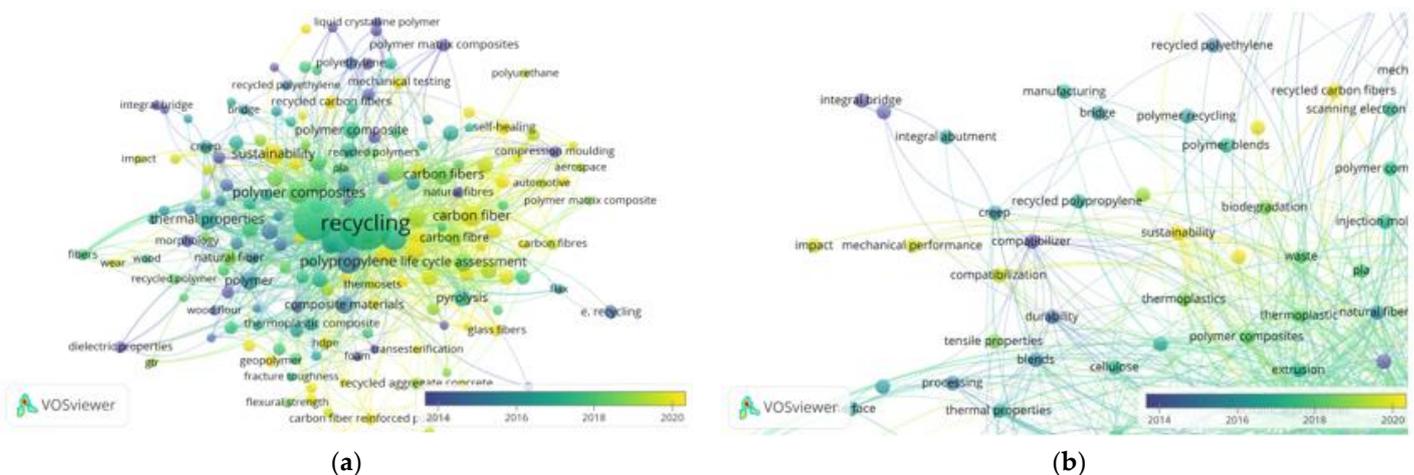


Figure 5. Visualize the incidence and relationship of individual keywords created using VOSviewer showing additionally date of publication (accessed on 11.2023).

To identify clusters for Figure 4 among over 550 author keywords in separate publications, those appearing a minimum of 2 times were selected, reducing the number of analyzed words to 40. This demonstrates a significant diversity of topics and areas. Words that were entirely unrelated thematically were excluded from the visualization, leaving around 30. In the case of Figure 5, the number of analyzed keywords was 354. Many weakly connected words imply their infrequent occurrences, being referenced only a few times with other analyzed words from different texts. This indicates the vast fragmentation within the research area.

The visualization can not only assist in finding trends but also aid future authors in selecting presented keywords to find published data on specific topics.

The results presented in Figures 5a and 5b indicate that topics related to bridge engineering have been less frequently addressed in recent years. Popular areas in publications seem to revolve around recycling and the use of reinforced polymers. However, there is a lack of keyword connections between bridge-related topics and the use of reinforced polymer composites, not to mention the

transition effect, for which there is a minimal number of keywords. The analysis presented clearly indicates the necessity for further research in the highlighted subject matter.

3. General purpose of research

The aim of this review article is to showcase the current solutions in bridge engineering, focusing on reducing the transition effect and emphasizing the significance of the problem. Additionally, the issue of plastic recycling in the context of utilizing them as an advanced material base for construction has been outlined.

4. Research area

The research area focused on assessing transition effects using post-consumer polymer materials is multifaceted. In today's world, solving individual problems in the short term is challenging. When advancing knowledge in one field, it is essential to consider whether materials available in other areas might be useful for solutions. Therefore, construction itself generates a large demand for materials and can effectively utilize materials that are considered waste in other sectors.

This study addresses aspects such as:

- *Engineering Aspect:* Current projects do not entirely solve the issue of stiffness discontinuity (flexibility) in the subgrade for linear structures approaching bridges. According to the authors, further progress supported by appropriately developed materials and the spatial structure of the joint construction will undoubtedly enrich contemporary bridge engineering with new design solutions that could reduce the transition effect. Introducing a new medium into the structure will affect the behavior of the structural abutment system and directly link it to the embankment. It will enhance load transfer through a complex structure onto different material centers and provide a smoother change in stiffness (flexibility) of the subgrade for linear structures.
- *Environmental Aspect:* The new material and its application area offer opportunities to utilize large amounts that accumulate in landfills or are incinerated. It is important to note that these materials could be reused (to be confirmed by planned future research). Due to their longevity anticipated in engineering constructions, the properties of processed waste will serve future generations. Pursuing the idea of sustainable development involves seeking applications for waste considered inefficient, difficult, or costly to process. This fact guarantees a constant demand for solutions enabling recycling.

5. Detailed overview related to the essence of the studies

5.1. Outline

The presented literature review covers several fundamental aspects. Successively, the topics related to transition zones in bridge engineering, the application and principle of operation of integral bridges, as well as the properties and use of polymers in bridge engineering will be addressed. Each of the aforementioned concepts will be thoroughly explained and described in the respective sections below.

5.2. *The importance of the connection between the abutment and the embankment in shaping the transition zone.*

The transition zone is the area where the embankment meets the bridge structure, also referred to as the embankment-abutment interaction zone [66,67]. It is one of the most critical locations along a road or railway line. Due to the fact that usually the unit stresses acting on the ground beneath the embankment base are smaller than those under the abutment foundation slab of the bridge, the settlements of the abutment will be larger, causing unevenness in the grade line [68]. It is impractical to ensure the same settling for the entire embankment over many kilometers as for the rigid bridge abutment. Hence, a limited zone has been defined where a change in stiffness must occur.

As mentioned in the introduction, delineating the transition zone is necessary due to the transition effect occurring at the end of this zone, marking the boundary of elements with significantly different stiffness. The essence of using transition zones is to minimize the difference in deformation (settlement) between the bridge structure and the embankment during the operational period [68]. This is one of the key challenges faced by engineers in preparing a design [68]. The embankment adjacent to engineering structures should be protected to equalize settlements at the junction with the support and prevent irregularities in the road pavement or rail track superstructure. An example of a solution commonly used is the transition slab, depicted in Figure 6. Its concept involves softening the stiffness by supporting it unilaterally on a rigid abutment on one side and through resilient embedding in the embankment on the other side. The presented solution is demonstrated for integral abutments.

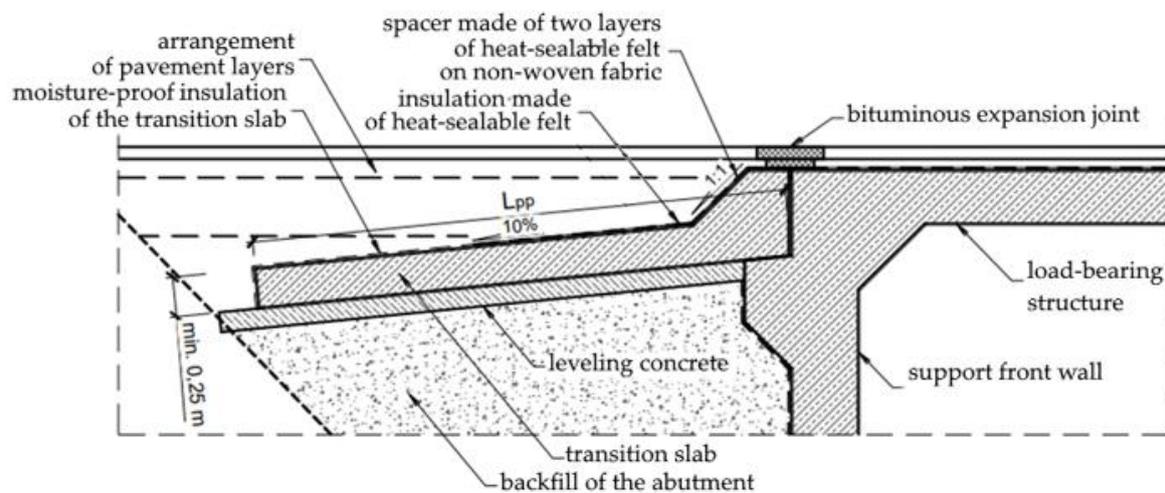


Figure 6. Longitudinal section through an example of an integral abutment.

The analysis of the most frequent damages during the 'lifespan' of a structure, such as cracks and deformations, suggests that the transition slab is not entirely a suitable solution as it does not provide a sufficiently gradual change in the substrate's stiffness (flexibility) [5]. This statement is vividly illustrated by photographs taken on numerous bridge structures, with selected examples shown in Figure 7 [69], and it is also supported by the content presented in publications by several authors [5,70–78].

By reviewing the available literature and observing existing bridge structures, it becomes evident that surface damages occur at the beginning of the transition zone, where the transition slab starts. Road pavement cracks mark the onset of gradual road degradation and over time can pose a danger to vehicles. However, for trains, there are even more risks involved. The track geometry always degrades faster in transition zones than in open tracks, causing significant irregularities (dips) [74]. Such irregularities in geometry can lead to substantial forces, potentially damaging track components, compromising passenger comfort, and even causing derailment [79–82].



Figure 7. Damage to road pavement and rail track superstructure at the beginning of the transition zone, where transition slabs were used.

The connection of the bridge structure with the embankment, depending on the length of the structure, the shape of the space under the structure, the type of obstacle and the terrain conditions, may be made through massive abutments (8a), wall abutments (8b), box frame walls (8c), pillars (8d.) or frame columns (8e) provided in the embankment, supports of the span (8f) inserted into the embankment [66,70].

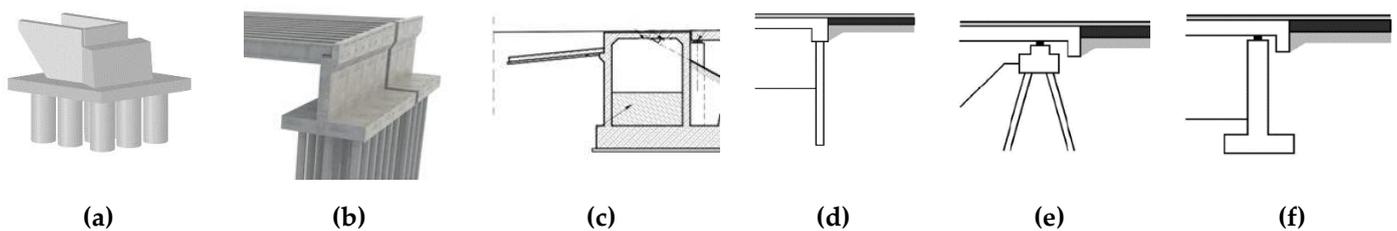


Figure 8. Types of abutments.

The stability of mutual interactions should be ensured, especially in bridge structures where elastic deformations of supports are used to accommodate the elongation of load-bearing structures, aiming to eliminate sliding bearings. Integral bridges are examples of such structures. Measures adopted to achieve this include proper shaping and compaction of embankments; installation of transition slabs between the structure and embankment; using reinforced soil for embankment construction; modification of the subsoil; speeding up of subsoil consolidation; and technological procedures (such as simultaneous embankment construction with support building, supporting girders on bearings after settlement due to their self-weight and embankment weight). Expansion joints between the load-bearing structure and the abutment are employed to protect road pavement from cracking and rail track superstructure from unwanted deformation [66,67].

In bridge structures, crossing rivers and watercourses is always associated with the risk of riverbed erosion and changes in ground level directly in contact with the bridge support. The transmission of loads to the subsoil is significantly influenced by repeated, cyclic, and variable loads [83]. The practical application of new soil strengthening technologies beneath embankments also introduces new risks to the overall stability of the structure. The transition zone at the embankment-abutment junction is particularly vulnerable. This issue is not new; it was previously addressed in early post-war standards (see PN-69/B-02482, PN-83/B-02482). In recent years, this problem has been extensively highlighted in literature and numerous conferences [19–22,84–89]. It is worth noting that the most significant issues in this area often occur during execution due to gaps in evaluating intermediate schemes during design phases [83].

Several scientific publications describe the behavior and dynamic response of embankments, including transition zones [23,77,90,91]. Due to the recent increase in train speeds and transported tonnages, many researchers have undertaken studies, their dynamic effects and vibrations transmitted to the engineering object and embankment [92–95]. This aspect is crucial for the safety and durability of bridges as dynamic forces generated by vehicle movement focus primarily in this area. The complex vehicle-soil-bridge system is where the bridge structure reacts with soil properties such as load-bearing capacity, shock resistance, and displacement. Understanding the interaction between embankment and bridge is essential for the design, construction, and maintenance of bridges.

Implementing engineering structures combined with embankments on weak ground is a complex task. Evaluating the load-bearing capacity and stability of road or railway embankments is the initial step [96–98]. Structures embedded within the embankment are usually supported on piles in challenging conditions [68,99,100].

Placing the structure on deep (pile) foundations results in minimal settlements [68], whereas allowable settlements for adjacent embankments can reach several dozen millimeters [96,98,99,101]. If the transition zone is not adequately design or if settlements are not uniform, unacceptable irregularities in road might emerge, which are unacceptable to users. This aspect is more critical for railway lines [67,96,97].

Presently, bridge design involves complex models encompassing the entire structure, considering mutual influences of parts with different stiffness and loads [89]. However, in the initial stages of such projects, simpler computational tools were used to analyze individual structural components. Paradoxically, conservative assumptions were adopted due to significant uncertainty. Consequently, actual settlements were much smaller than calculated, leading to uneven levels among intersecting parts and necessitating costly elimination of the resulting discrepancies. It is worth noting that requirements for limiting settlement differences [4,66,67], and the consequent design work, do not consider time-variable settlements such as soil consolidation.

The analysis of deformations and mutual displacements of different parts of the same structure or neighboring structures is crucial. Both excessive and insufficient displacements are undesirable. Phasing of construction and the interaction between structures built at different times must be taken into account. Advancements in knowledge, research capabilities, and computational methods emphasize deformation analysis, displacements, and assessing serviceability limit states, pushing the issue of load-bearing capacity into the background [99]. Unlike previous practices, where in some cases only load-bearing capacity was analyzed, settlement matters were hidden in calculations through design assumptions.

To reduce embankment and abutment settlement differences in the transition zone, often, embankment soil reinforcement is necessary [66–68,75,102–104]. Road and railway embankments, as well as bridge abutments, can be designed as reinforced soil structures [66,67]. In such structures, active forces and external loads are partly transferred through friction by soil and partly by reinforcement anchored in the ground. Additional reinforcement at the bottom of the embankment, extending beyond the outline of the transition slab, is often used to minimize ground settlement differences [68]. Materials commonly termed geosynthetics are employed for soil reinforcement [17,105,106]. There are various types of geosynthetics used based on specific needs, including geogrids, geotextiles, geomembranes, and geocomposites [17]. This topic has been well-described by numerous authors [107–119]. Reinforced soil structures can be applied in bridge constructions, particularly as a reinforced soil block separated from the front and side walls of the abutment, bearing the embankment pressure; as a retaining structure forming the abutment walls; and as foundation support for piers.

Reinforced soil structures, serving as retaining structures, can be executed using passive systems, where soil reinforcement comprises both structural elements (reinforcement wraps embedded within the reinforced soil block) and auxiliary components (anchoring inserts placed between the structural reinforcements), which anchor the protective elements of the wall. The protective wall and reinforced soil block constitute separate structures, enabling their independent

construction. Alternatively, active systems incorporate reinforcing soil inserts anchored in the wall's protective elements (reinforcing-anchoring inserts). Simultaneously, protective elements functioning as formwork for subsequent layers of fill material are placed alongside the formation of the reinforced earth block. For abutment elements, utilizing reinforced soil structures in a passive system is recommended due to the lesser impact of embankment settlements [102–106].

Flat steel strips, ribbed steel bars, polyethylene geogrids, polymer strips, or strips made of polyester fibers with a polyethylene coating serve as soil reinforcement. The reinforcement connects with protective elements using systemic connectors. The use of geosynthetics in constructing transition zones holds significant potential. Reinforcing the subsoil of the embankment and increasing its stiffness will reduce the transition effect.

The relevance of transition zone themes and the phenomena within them are confirmed by ongoing research [120,121]. The cited articles and their description of the interaction between embankment soil and the bridge indirectly relate to the collaboration of these elements in response to the transition effect load. An important conclusion is the lack of examination of structures that facilitate and enhance the cooperation between the bridge structure and the embankment.

5.3. Integral bridges as a justified choice

Bridge construction history dates back several thousand years [122]. Bridges are an integral part of infrastructure and have played a pivotal role in civilization's development. With technological advancements and heightened demands for durability and safety, engineers seek increasingly superior solutions and construction materials. Bridges stand among the most significant engineering structures, serving as essential components of transportation infrastructure, facilitating access across natural obstacles like rivers, valleys, as well as artificial barriers, ensuring convenient and safe passage to human settlements. They form a fundamental factor in societal development by enabling the transportation of goods and people [122–127].

Bridge structures must be stability and the necessary load-bearing capacity to meet traffic intensity and load requirements. They must also be durable and safe for users [128,129]. Hence, the construction materials used must meet stringent strength requirements, including resistance to variable and dynamic loads, corrosion, and weather conditions [128,129].

Since the late twentieth century, experts have debated how to repair, renew, and modernize transportation infrastructure in Central Europe [130]. Over the past 25 years, there has been a focus on utilizing modern engineering technologies and decision-making processes to solve typical and regional environmental problems in land transport, especially roads and bridges.

Integral bridges are structures devoid of connections and bearings. Hence, they are less susceptible to natural and human-induced threats while requiring minimal maintenance throughout their service life. Most conventional bridges is equipped with components compensating for distortions and displacements. Additionally, water, salts, and other de-icing agents can seep through expansion joints, leading to corrosion in bearings, load-bearing structures, sidewalk parapets, and other bridge elements. The absence of expansion joints in integral bridges reduces repair and maintenance costs throughout their service life [131,132], aligning with the urgent global need for low-maintenance transportation infrastructure [133].

The absence of intricate devices present in typical bridge structures requires no or minimal maintenance. Furthermore, integral bridges, when integrated into highways or railway lines, enhance riding comfort due to the absence of expansion joints and provide better horizontal stiffness perpendicular to the longitudinal axis of the bridge. This reduces the likelihood of rail misalignment [131]. Moreover, modern integral bridges exhibit resilience during earthquakes owing to their monolithic construction. This has been corroborated in publications like [131–136]. Thanks to these advantages, such structures can be appealing to entities managing transportation infrastructure.

The challenge in evaluating existing structures and applying them lies in the interaction between the bridge and embankment soil. In many cases, this interaction is misunderstood due to the inherent nonlinear behavior of soil during what's known as operational interaction, significantly altering stresses in the embankment soil due to abutment displacements [133]. A step toward better

understanding this phenomenon involves interpreting the support and embankment soil state at the beginning of dynamic excitation based on earlier interactions during operation and assessing the stiffness and strength of existing cushioning properties of supports under dynamic loads [133]. Typical geometry of an integral support and typical embankment soil is studied using fully constrained simulations, assuming a viscoelastic-plastic stress model for the soil (coupled approach) under static and dynamic loads [133].

Despite numerous advantages, designing and constructing integral structures poses a challenge, with primary limitations in widespread application arising from the interaction between the abutment and embankment soil. This interaction results in permanent vertical displacements of embankment soil and passive soil pressure increase against the abutment [132]. Surprisingly, the literature has not reached consensus on whether this is a beneficial or detrimental effect. Identified discrepancies in literature point toward a conceptual gap in design and evaluation, requiring further research [132].

5.4. Properties and use of polymers in bridge structures

In recent years, increasing environmental pollution and the depletion of natural resources have presented new challenges to civil engineers. Advances in science and technology allow for the utilization of polymers as structural materials in the construction of bridges and embankments, which may contribute to improved durability, corrosion resistance, and cost-effectiveness. Older structures, built using masonry technology, as well as those made of concrete and steel, require numerous analyses, such as acoustic emission to assess and monitor bridge integrity [137] or well-known non-destructive testing of bridges using acoustic and radar impulses [138,139]. Nowadays, most bridges are built using concrete and steel [128,137], employing well-established computational models and analyses. However, many new designs are being conceptualized as composite systems [140–144], or concrete structures reinforced with polymer fibers from carbon, glass, aramid, or even basaltic materials [145]. These are structures still being explored, and their behavior in the future remains unknown.

Polymers are materials with complex chemical structures, consisting of long chains of molecules called polymers, linked together through the process of polymerization [146–150]. The size and shape of monomers influence polymer properties [146–148]. Due to their exceptional properties, polymers are increasingly being used as structural materials in bridge construction [151,152].

Growing environmental awareness and the need to reduce the construction industry's impact on the environment encourage the search for alternative materials, such as polymers. The diagram illustrating the global production structure of plastics in 2021 shown in Figure 9 was developed based on data from the PlasticEurope Foundation report [36]. By analyzing the structure of global plastics production (Figure 9), taking into account their frequency [36] and mechanical properties [153–156], we can identify several types of polymers that can be successfully applied in bridge engineering.

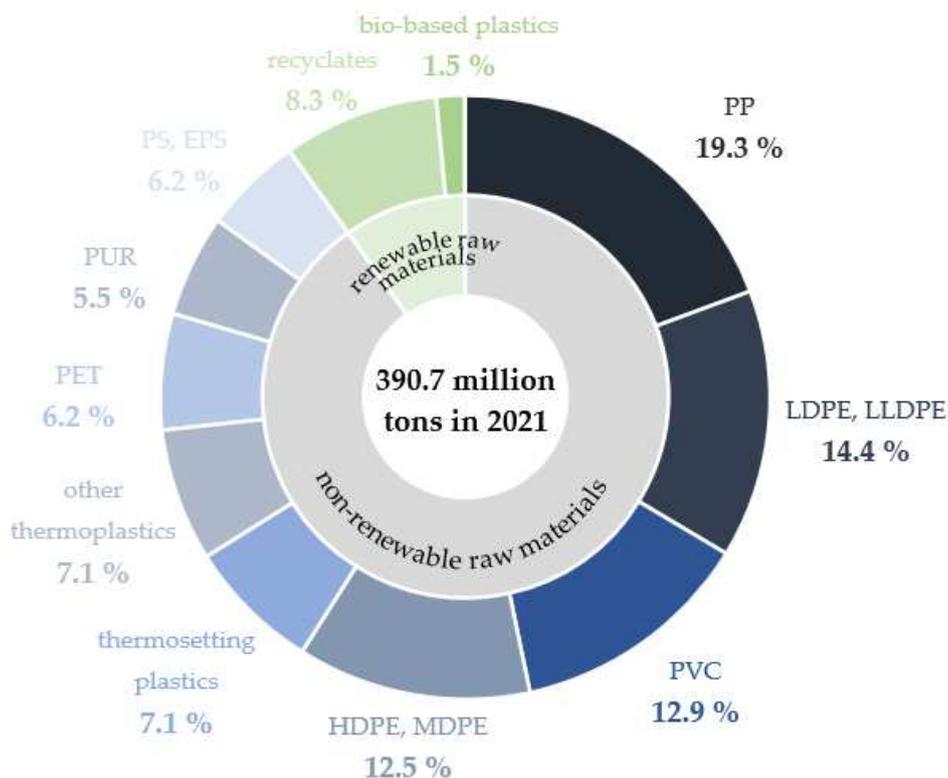


Figure 9. Structure of global plastics production.

Polymers are used as insulation material, adhesives, components, surfacing, reinforcement, and barriers [149,151,152]. They are relatively easy to shape into various forms and sizes, allowing adaptation to the individual needs of a project, making them highly versatile construction materials. Moreover, polymers are readily available and widely used across various industries [33–36,151,152], making them more cost-effective than traditional construction materials.

Polymer composites are employed in bridge construction due to their lightweight nature, strength, and durability [142–144]. They are also corrosion-resistant, which is particularly crucial for bridges near water bodies or in high-humidity areas and for underground structural elements. Despite numerous advantages, using polymers in bridge construction also has some drawbacks. One of the significant drawbacks is their lower resistance to high temperatures [145]. Polymers are less resistant to heat compared to traditional construction materials like steel or concrete. However, in certain applications, the risk of fire hazards for the structure might be minimal, or the polymer material might be adequately protected by non-combustible materials (e.g., soil or concrete). Another drawback is their reduced resistance to mechanical damage [145]. This aspect can be critical due to the cyclic and long-term dynamic loads that bridge structures experience. A detailed analysis of polymer behavior and their performance in such specific environments should be required.

5.4.1. Examples of polymers and their applications

In recent years, there has been increasing attention given to thermosetting polymers such as epoxy, polyester, and epoxy resins [157,158]. Thermosetting polymers are characterized by their high mechanical strength and corrosion resistance, making them attractive construction materials in bridge building [159,160]. Moreover, these thermosetting polymers resist environmental factors like UV radiation, contributing to the durability of structures [161,162].

Polymers have been used in bridge construction for many years [140–142,151]. One of the initial uses of polymers in construction was the use of saturated polyesters to reinforce wooden bridges [163–165]. Presently, polymers are used in the form of laminates reinforced with fiberglass or carbon fiber in bridge construction [163–173]. Another application of polymers in bridge building is their use

as construction materials [140,142,143]. Polymers can also be used to increase bridges' resistance to dynamic forces [174,175].

Polymers like fiber-reinforced polymer composites, especially glass fiber-reinforced polymer (GFRP), can be used in bridge structures to enhance flexibility and resistance to seismic damage [176]. Another application is using polymers as anti-slip materials [177,178]. Polymers like polyurethane or rubbers are employed to enhance traction on bridge surfacing, enhancing safety for pedestrians and vehicles. Finally, polymers can be used as fiber-reinforced materials to improve the strength and durability of bridges [164–173], for instance, epoxy resins reinforced with glass or carbon fibers.

The reinforcement of structures with polymer materials has long been popular [164–173]. These materials, such as carbon, glass, and aramid fibers, possess excellent mechanical properties like high strength and rigidity, allowing their usage in various applications [145]. Carbon fibers are among the most commonly used polymer-based materials for reinforcing structures [145,168,179,180]. They exhibit high tensile strength and a high modulus of elasticity. Being lightweight, carbon fibers can reduce the overall weight of a structure without compromising its load-bearing capacity.

The process of reinforcing structures with carbon fibers usually involves placing a mat or mesh of carbon fiber on the structure's surface and saturating it with epoxy resin, bonding the carbon fibers to the structure [168,179,180]. This process can be applied to reinforce concrete structural elements such as columns and beams, as well as wooden and metallic elements.

In the case of reinforcing structures with glass fibers, the process is similar. While glass fibers have slightly lower strength than carbon fibers, they are more cost-effective and flexible, allowing their use in reinforcing more complex structural shapes [145,163,164].

Aramid fibers like Kevlar are also popular materials for structural reinforcement [145,181]. These fibers are highly durable and possess outstanding resistance to abrasion and perforation. Reinforcing structures with polymer-based fiber materials can improve their strength in extreme conditions like earthquakes, hurricanes, and tornadoes. Due to their strength and rigidity, these materials are excellent candidates for use in construction projects such as bridges.

In summary, polymers are incredibly significant materials in bridge construction, and their application is crucial for enhancing the safety, durability, and load-bearing capacity of bridge structures.

5.4.2. Recycling polymers - use in bridge construction

Polymers obtained from waste can be used in the construction of bridge structures. One example of utilizing waste polymers is the production of plastics from secondary raw materials like PET bottles, which can be used to create unsaturated resins applied in bridge construction [182,183]. Another instance is the use of PET from recycling, in the form of sheets, to improve the strength parameters of sandy soil [184]. Ongoing efforts also explore realistic alternatives to classical materials used as reinforcements, such as steel or fiber-reinforced polymers, aiming to produce cheaper and more environmentally friendly structural elements with similar or superior performance during use. PET tapes and polyester yarn tapes could effectively compete with currently used materials. They are among the most commonly used materials in the packaging industry, boasting high tensile strength comparable to steel and being easily recyclable [185].

Currently, there is a developing trend in using biopolymer fibers derived from organic organisms reinforced with polyester fibers (PES) in manufacturing construction materials that could be employed in bridge construction [186,187]. These examples clearly indicate that polymers derived from waste hold promise in construction, reaffirming the relevance of addressing this issue.

Numerous scientific articles exist on the recycling of polymer fibers. One such example involves recycling carbon fibers from wind turbine blades [44–48,52]. The use of post-recycled fibers to reinforce polymers, which are intended to become the building blocks of spatial rod structures, will be effective and environmentally justified.

5.4.3. Polymers in the construction of bridges and embankments

Polymers have been extensively used in bridge and embankment construction for a long time [17,105–112,140,142,177,180]. Their application is known in hydro-insulation and surfacing [188–190]. For reinforcing embankments, geopolymers (geosynthetics) are particularly effective, especially in transition zones [17,105–119]. Initially, soil reinforcement was done using steel bars. The primary drawback of this solution, mainly in terms of durability, was corrosion of the reinforcement. The use of reinforced concrete layers is also considered more historical. Currently, soil reinforcement primarily involves various forms of geotextiles [7] due to their advantageous properties and application aspects. Geosynthetics are synthetic materials used in geotechnical engineering to improve soil properties and geotechnical structures [7,191]. Geotextiles are one type of geosynthetic characterized by low unit weight and high tensile strength [17].

Geotextiles for soil reinforcement constitute a kind of mat made from synthetic fibers, usually polypropylene, bonded together in the technological process of their production. It is essential to ensure suitable strength and deformation parameters (ductility) [7]. There are various solutions for constructing embankments using geotextiles. One popular approach involves using geogrids as reinforcement beneath the embankment. This solution increases soil bearing capacity and reduces its deformation. Another method is using geotextiles as a separation layer between different soil layers or as a filtration layer, preventing soil washout from the embankment by water, improving embankment stability, and reducing erosion risk. Geotextiles used for embankment reinforcement at abutments cannot act as a diffusion barrier for air and water and must withstand low and high temperatures. They must also resist aggressive compounds (especially bases and acids), fungi, and decay [7].

A comprehensive analysis of geosynthetic reinforcement at the embankment base can be found in A. Duszyńska's work [17] and related studies [105–119]. It focuses on geosynthetic reinforcement in geotechnical structures, specifically the use of geogrids in embankment bases. The work presents results from laboratory tests and numerical analyses aimed at evaluating the effectiveness of using geogrids in reinforcing earth embankment bases. The author compares the geotechnical strength of structures using geogrids and those without, considering different soil conditions and loads.

The research findings indicate that employing geogrids in reinforcing soil embankment bases enhances the structure's load-bearing capacity and reduces deformation. The author also compares the costs of using geogrids against traditional reinforcement methods, which can be significant from an economic perspective. The study provides a new perspective on geogrid applications in geotechnics and presents research results that contribute to improving the efficiency and durability of soil structures. All these solutions use geotextiles to improve embankment properties and increase its durability. The use of geotextiles in embankment construction is extensively described in scientific literature and engineering practice, and the choice of a specific solution depends on soil conditions and design requirements.

An interesting application of polymers is their use in epoxy injection for repairing cracks in bridge structures [192]. One of the most intriguing applications can be found in scientific work concerning an innovative method of reinforcing ground behind abutments using geopolymer injection [193]. This procedure enhances load-bearing capacity, stiffness, improves embankment and structure cooperation, and enhances durability.

It is crucial to relate the mentioned aspect to the transition effect. Ensuring the safety of the structural design itself and appropriately designing the connection between the bridge structure and the embankment are significant aspects in the process of bridge construction. Excessive embankment settlements are one of the main causes of failures in this transition zone [194,195], often leading to numerous damages (e.g., expansion joints).

Commonly used embankment reinforcement methods mostly rely on soil replacement, subsoil consolidation, mechanical stabilization, vibratory and dynamic methods, deep-seated reinforcements, or the use of geosynthetics [196–198]. Using typical methods during renovations usually requires dismantling the pavement and conducting extensive earthworks, significantly increasing not only the costs but also hindering the operation of the structure during the works.

Geopolymer material injection provides a non-intrusive alternative to traditional substructure work and piling.

Studies on the application of dispersed reinforcement in concrete in the form of fibrous polymers have focused on mechanical properties and durability when used as concrete reinforcement [180,181,186,187,199]. The results indicate that fibrous polymers increase the strength and durability of concrete. Polymer reinforcement materials are typically provided in the form of mats or meshes, which can be easily cut and adapted to the dimensions of the surface to be reinforced. In the case of concrete, the fibrous polymer reinforcement material is usually placed inside the concrete mass before laying, allowing for better interaction between the materials.

For high abutments and abutments founded on piles, as well as ground behind the abutment with a low internal friction angle, horizontal forces play a significant role. These forces can be reduced by using polypropylene blocks resembling honeycomb patterns and expanded polystyrene (EPS) blocks - styrofoam, for embankment construction [7,200].

In engineering, a solution for the embankment behind abutments involves using geosynthetic reinforcement and styrofoam blocks to simultaneously reduce ground pressure on abutments and control settlement adjacent to the abutments [16]. The use of EPS geof foam as a filling material between viaducts and abutments has been described in several publications [7,16].

Several concepts have been developed so far for creating composite materials using fiber-reinforced polymers [163–167]. Glass, carbon, aramid, or basalt fibers are used as dispersed fibrous reinforcement in these materials [151]. Research on such fiber-reinforced materials can be found, among others, in studies [33,34,201–204].

Currently, there is ongoing research on the impact of reinforcing PET material with carbon fiber on its mechanical and thermal properties. Research has shown this to be a material with the best tensile strength properties among polymers commonly found in waste [33,34]. Due to its good recyclability and simplicity, it is one of the most commonly processed waste polymers [33,34].

5.4.4. Polymers - use in reducing the transition effect

Polymers are applied in engineering structures to reinforce the subgrade, increasing its stiffness (while decreasing its susceptibility) and reducing the transition effect, primarily through injection masses. In China, studies are being conducted on the use of polymer reinforcement in railway subgrades within transition zones at the approaches of engineering structures to mitigate the transition effect. The technology involves injecting a polyurethane polymer mass. Research and experimentation on this solution have been conducted by, among others, Q. Wei et al. [205] and C. Zhao et al. [206]. The research results demonstrated increased subgrade stiffness and reduced transition effect.

A. Brzeski also focused on combining polymers with aggregate, creating a type of synthetic rock. Besides the obvious advantage of recycling, this solution allows for obtaining a material with controlled stiffness, resistant to weather conditions, fire-resistant, elastic, durable, non-permanently deformable, and environmentally neutral [207].

The examples cited clearly demonstrate that polymers possess numerous positive properties applicable in bridge construction. The utilization of recycled polymers in bridge engineering has not yet been thoroughly investigated, creating opportunities for valuable research.

6. Description of the concept of reducing the transition effect using a spatial polymer bar structure

In reference to the aforementioned issues, the authors propose the design of a composite material composed of a polymeric matrix reinforced with recycled carbon fiber. It is anticipated that from a material with a rationally chosen spatial geometry, a structure ensuring lasting cooperation between the abutment and the embankment can be designed, thereby expanding the possibilities of integral bridges, minimizing the requirement for limited settlements, and reducing the transition effect. A visualization of the preliminary concept is shown in Figures 10 and 11. Proper shaping of the near-abutment zone, as well as the abutment structure with anchored rod elements enforcing the

abutment's interaction with the embankment and the surrounding zone, will provide a gradual change in the subsoil's stiffness along the transition zone, consequently reducing the transition effect [208].

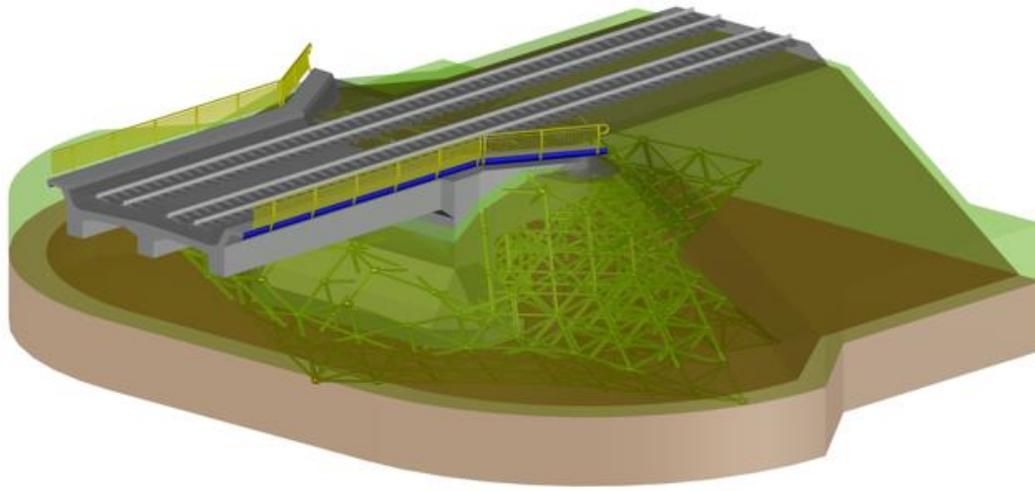


Figure 10. A preliminary 3D model of the concept of a bar structure connecting the integrated bridge abutment with the embankment, forcing the cooperation of material centers.

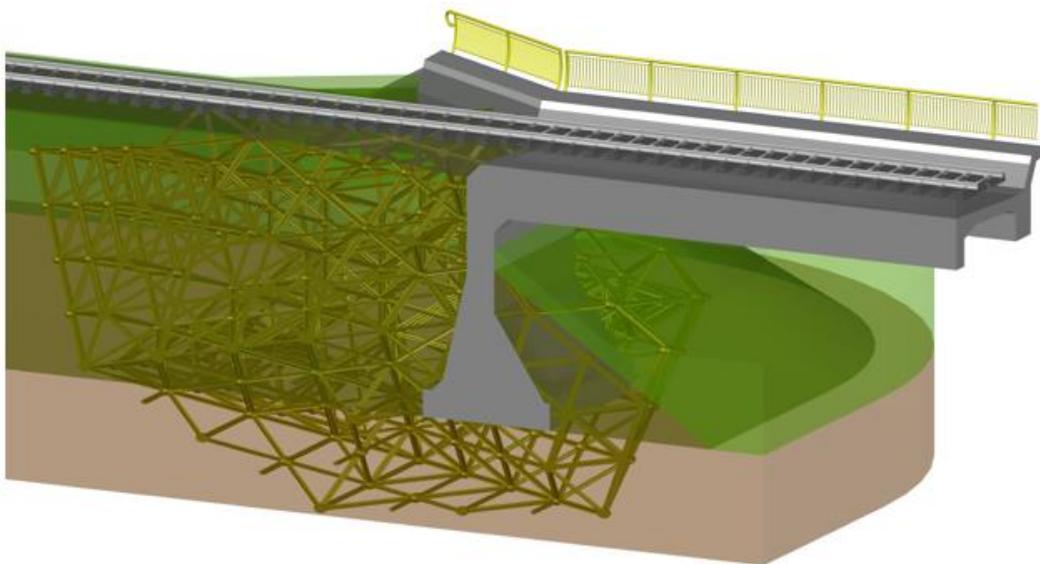


Figure 11. A preliminary 3D model of the concept of a bar structure connecting the integrated bridge abutment with the embankment, forcing the cooperation of material centers.

The geometry of the bar structure arises from the analysis of finite element method (FEM) computational models of various engineering structures. Tetrahedral elements make the computational models to rigid. Due to this phenomenon, designers tend to avoid such elements in constructing accurate models that reflect reality. The phenomenon described above is planned to be applied more effectively to stiffen the embankment soil. Design the presented configuration began with triangles, which were then transformed into tetrahedra, further evolving into a spatial mesh based on a regular dodecahedron.

As widely known, we cannot create a spatial mesh from regular tetrahedra. The closest geometric solid whose elements would resemble tetrahedra is indeed a regular dodecahedron, where the components consist of equilateral triangles with a similar ratio to the equilateral triangle. Hence, the appearance of the presented mesh. The genesis of its formation is shown in Figure 12. This is one

of the initial concepts that will be further analyzed and confirmed by subsequent work. However, such a mesh has an additional advantage—it radiates outward radially in all directions from the central point. If such a point were designed at the center of the abutment mass, the effect of the generated cooperation could be impressive.

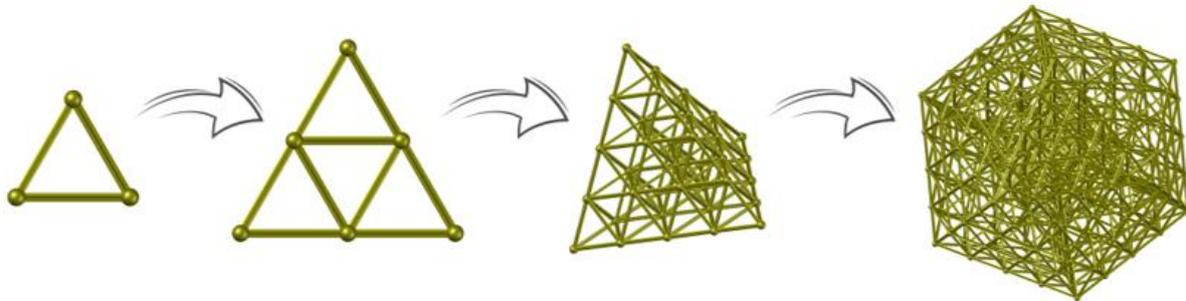


Figure 12. The origins of the grid concept.

Due to their exceptional properties, polymers are increasingly being used as construction materials for bridge structure. The application of polymers as construction materials or their components is the best proof of how the construction industry can adapt modern materials to its own needs. An example of such adaptation is Fiber Reinforced Polymer (FRP) composite materials, where polymers are reinforced with fibers [150,199].

In composite materials, glass, carbon, basalt, or aramid fibers are used as reinforcing fibers [6,143,145,179]. In recent years, polymers have gained popularity due to their lightweight, durability, corrosion resistance, flexibility, and ease of shaping. Polymers are used in various structural elements of bridges, such as girders, cables, beams, and spans. For instance, the use of carbon fiber, one of the most popular polymers in bridge construction, is a good example. Carbon fibers are highly resistant while remaining lightweight, making them an ideal material for bridge structures. The use of carbon fiber helps reduce the mass of the structure, subsequently lowering production, transportation, and assembly costs.

PET (polyethylene terephthalate or poly(ethylene terephthalate)) is a waste plastic material with excellent strength properties [149,151,156,204,209]. It is the most commonly processed material. However, as mentioned earlier, it is not feasible to rely entirely on recycled raw material because with each processing, the long polymer chains fragmentize, causing a loss in strength properties. Therefore, adding virgin material in the recycling process is necessary to maintain the required strength properties. Consequently, it is evident that there will always be a continuous influx of material for processing. Hence, finding a long-term use for the material to extend its service life is crucial. It appears that PET, as a matrix for carbon fibers, has potential applications [156,204,209,210]. The real strength (relative to density) in Table 3 shows that it could be a more efficient material than steel. In most structures, it is the self-weight that constitutes the majority of the loads, if it is significantly optimized thanks to innovative light and durable materials, engineers will be able to create more advanced structures.

Table 3. Comparison of the properties of reinforced recycled polymers to steel.

material	tensile strength	density	real strength
[-]	[MPa]	[g/cm ³]	[kNm/kg]
PET reinforced with glass fiber in a ratio of 55 %	196	1,80	108,9

PET reinforced with carbon fiber in a ratio of 30%	220	1,45	151,7
Steel S235JR	360 - 510	7,85	45,9 - 65,0
Steel S355	470 - 630	7,85	59,9 - 80,3

The primary requirement in constructing a bridge abutment along with an embankment is to ensure smooth passage between these entities. Irregularities not only accelerate vehicle wear but also pose a danger to those traveling at high speeds. They also contribute to increased dynamic forces exerted on bridge structures by vehicles. Reducing the pressure from reinforced ground fill involves the occurrence of frictional forces between the ground and the reinforcement. Regardless of increasing the soil's shear strength and reducing the pressure on the abutment, reinforced ground provides a more even distribution of deformations. This is particularly crucial in the case of integral bridges, where due to temperature changes, displacements of the ground behind the abutments alter direction multiple times [7].

Polymers are actively utilized to reduce the transition effect. An example is the use of polyurethane material as an adhesive that gradually stiffens the subgrade along the transition zone. To achieve a gradual change in stiffness, Chinese scientists proposed using a polyurethane-bound sub-ballast [205,206]. In this scheme, the bonding surface of the aggregate with the polyurethane determined the variation in subgrade stiffness. This solution was adapted in China for the transition zone of a railway line at the entrance to a tunnel, where the ground changed from flexible to the rigid concrete of the portal.

Polymers are employed as reinforcing materials in various construction projects, and there is substantial scientific research confirming their strength properties [140,141,180,211]. The above literature demonstrates that polymers can have numerous applications in the construction of bridge abutments and embankments, both as structural materials and auxiliary substances. It is worth noting that there is not an abundance of scientific studies linking recycled polymers with bridge construction, particularly with abutments, embankments, and transition zones. This area remains niche and requires interest from scientists.

7. Future and perspectives

In future research on the proposed solution, a critical aspect will be the integration of the abutment with the ground using reinforcing bars, along with selecting the composite's composition and shaping the geometry of the bar structure to achieve the required stiffness. The authors are currently exploring the possibility of processing PET polymer (polyethylene terephthalate) with reinforcing fibers. In the PET recycling process, primarily used for new bottle production, issues arise from contaminated materials (adhesives, labels, chemicals) that can't be used in products intended for food contact. Consequently, it is essential to find solutions where such limitations do not apply.

The use of polymers as construction materials or their components is a testament to how the construction industry can adopt modern materials to meet its needs. An analogy to such adaptation is the composite materials with a polymer matrix and fibrous reinforcement (FRP – Fiber Reinforcement Plastics).

Material recycling (using minimally processed material) can significantly manage large quantities of waste (Table 1) and ensure their utility for an extended period. Material recycling represents ways to utilize waste material in line with sustainable development principles, also enabling the production of construction material with unique properties. Its natural application area is in transportation infrastructure, where natural materials can be replaced by high-quality recycled materials.

The construction of transportation infrastructure involves increasingly larger structures. This leads to increased vertical loads on the ground and, in the case of bridges and retaining structures,

additional horizontal forces (pressure). The most commonly applied solutions to these problems are costly ground reinforcement techniques (such as piling, various types of columns) or enhancing slope stability and retaining structures (using ground anchors or nails). Moreover, the availability of high-quality natural materials (coarse sands, gravels, aggregates) is often limited, and their transportation over significant distances is uneconomical. An alternative, more cost-effective solution to these issues might involve the use of substitute materials.

The resources of polymer waste are continually growing. The planned material's utilization in the construction and modernization of roads, railways, and broadly understood bridge structures can be particularly efficient. Employing polymers as one of the building blocks of engineering structures, ensuring long-term usage, will undoubtedly aid the poorest countries in managing their waste. The solution primarily lies in designing a spatial bar structure that expands the integral bridge abutments and their connection with the embankment to establish load transfer cooperation and limit differential settlements.

8. Research gaps

There is a clear gap in the potential use of composites made from recycled materials in shaping transition zones in integral bridges. The future perspective aims to propose a new design solution for the bridge support structure based on the system of integral bridges, where the abutment will be closely linked to the embankment. In the future, a spatial structure will be designed and analyzed, ensuring cooperation between the structures. Through this, the change in the stiffness (flexibility) of the subgrade along the length of the structure and transition zones will be gradual, predicting a significant reduction in the transition effect.

Another probable outcome of the research will be an expanded scope for the use of integral bridges, which won't be significantly restricted by the requirement for minimal settlements under the bridge supports and embankment. As mentioned, elements such as transition slabs, expansions, and bearings are not present in this type of structure. The absence of these elements will have a favorable impact on reducing the construction and maintenance costs of bridge structures.

It is anticipated that the designed structure will be composed of a composite made of polymer reinforced with dispersed fibers, with a direct and clearly defined correlation between the composition and the 'stiffness' of the resulting material. The 'stiffness' of the material and its geometric arrangement will directly influence the stiffness of the designed embankment structure.

The priority selection of components involves utilizing waste in the form of polymers in recycle form and recycled fibers. The anticipated use of these raw materials will significantly reduce the carbon footprint and effectively utilize materials (the expected durability of bridge structures is at least 100 years). The scope of the study will, in the near future, encompass a comprehensive exploration of the issue, starting from theoretical analysis of computational models and concluding with laboratory research and a description of the proposed solution.

9. Summary

The issue of transition zones and the transition effect in bridge engineering is associated with the use of various solutions that lack standardization and have a limited impact on reducing the discussed phenomenon. This topic has been known for quite some time. With the development of transportation, increasing cargo tonnages, and rising speeds, research in this area becomes necessary. There's a visible opportunity to propose solutions involving the utilization of processed waste in constructing zones connecting abutments with embankments. However, it's crucial to emphasize that polymers, including reinforced polymers, especially those made from recyclables, are not widely used in bridge construction, and their impact on reducing the transition effect hasn't been thoroughly explored. The idea of sustainable development, recycling, and environmental aspects should be incorporated into every field.

In the article summary:

1. It has been highlighted the relevance of the transition effect problem in bridge structures and the need for exploring new solutions. It has been proposed a solution related to integral bridges,

- allowing the avoidance of expansion joints and bearings, which positively impacts durability and maintenance costs. Transition slabs often do not completely eliminate this and may cause damage;
2. It has been emphasized the importance of sustainable development, especially in the context of plastic waste management, drawing attention to the recycling potential in construction, the use of composite materials based on recyclables reinforced with fibers in bridge engineering, contributing to waste reduction and sustainable utilization of recycled materials;
 3. It has been Indicated that the possibility of using substitute materials, appropriately processed and shaped, might find application in bridge engineering, representing a cheaper and more ecological alternative to traditional solutions;
 4. It has been highlighted PET (polyethylene terephthalate) as having the best strength properties among waste plastics and exhibiting good capabilities for creating composites with fibers.

It has been presented a prospective approach to bridge design, considering technical, durability, and environmental aspects through the utilization of innovative solutions and materials, which could lead to more sustainable and efficient construction practices in the future. The presented topic is related to a doctoral thesis, and at this stage, concepts aligned with sustainable construction trends and the principles of the 6Rs are being formulated.

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