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Analysis of the costs of construction and maintenance of rigid and flexible pavements

Abstract: The costs of construction and the future maintenance of expressways and motorways have a significant impact on the choice of technologies for their construction. The subject of the article is the analysis of the costs of construction and maintenance of rigid (concrete) and flexible (asphalt mixtures) pavements in Poland. The construction technologies and maintenance scenarios in service were analysed for selected pavement constructions of rigid and flexible motorways and expressways. The costs of construction and maintenance of these pavements in national conditions were determined. The fourth quarter of 2015 was adopted as the initial price level. On the basis of the analysis of the costs of construction and maintenance of the analysed structures, the advantage of rigid constructions made of cement concrete was demonstrated, especially in the aspect of the surface maintenance. The cost assessment was carried out for 30 years of exploitation. The concrete pavements on the road network in Poland have been used for over 20 years. They are present both on low-class roads and on the highest-class roads, i.e. motorways and expressways.

Keywords: Concrete pavement; Asphalt pavement; Construction costs; Maintenance costs

Introduction

The current age is characterized by increased environmental concerns. This applies to both adverse environmental impacts and the consumption and use of materials, including the construction of road surfaces. The subject of evaluation of "environmentally-friendly" aspects of the production of road construction materials is a broad subject covering both the social, economic and direct costs of the investor. Discussions on the costs of these surfaces are observed in the road administrations of many countries in Europe and in the world. The surface structure may include costs related to the microclimate impact, costs of lighting the artificial pavement at night, costs affecting the fuel consumption of the vehicle, costs of waste and recycled materials, costs of recycling the surface at the end of the period of use.

Various Life Cycle Cost Analysis [4], [3] for LCA - Life Cycle Inventory - Life Cycle Inventory, LCC - Life Cycle Costing - The cost of the Life Cycle. The LCA procedure is based on assessing the environmental impact of a product or service over the life of a product or service. The LCA calculation process includes the definition of objectives and scope, resource analysis, environmental impact assessment and interpretation of results. A product in the LCA technique can be either a specific object or the entire production process or service. The essence of this method is to focus not only on the assessment of the final result of a given technological process but also on the assessment and assessment of the consequences of the

entire process for the natural environment. The assessment process is continuous - as the new data flow and the quality of the data is verified. These problems are regulated by PN-EN ISO 14040: *2009 Environmental management - Life cycle assessment - Principles and structur*e.

The LCI procedure is the stage of collecting the data needed to implement the LCA. It is a "simple" process of calculating and "booking" all elements included in the assessed system - for example, resources, materials, energy, water, emissions to air, water, soil divided into individual substances, etc. This analysis is potentially very complex because it covers all processes throughout the supply chain (e.g. extraction of raw materials, individual stages of the production process, transport, etc.). The process includes data collection and calculation procedures, quantifies the inputs and outputs for a given product system during its life cycle. The collection of data takes place in order to compile an extensive balance of all energy and chemical elements are taken from the environment, those that enter the system, and which leave the system as emissions to the environment.

The LCC procedure is the sum of all costs incurred during the product's life cycle ("from cradle to grave" - investment, renovation, manufacturing, use and decommissioning). LCC only covers direct financial costs incurred in connection with the operation of the product or the performance of the service, without taking into account environmental impact (i.e. LCA).In the US road administration since 2008, the LCC procedure has been applied in 33 states. In Poland, so far, this type of study and analysis is missing.

This publication focuses on the direct costs associated with the construction and maintenance of rigid and vulnerable pavements. The analyzes include simple calculations taking into account the longer service life of both pavements according to the level of prices from 2015.

The adopted technical assumptions for the analysis of construction costs

For the analysis of construction costs, pavement constructions from catalogs were adopted, i.e. from the "Catalog of typical structures of flexible and semi-rigid pavements" from 2014 and the "Catalog of typical rigid pavement constructions" from 2014. For both types of construction, the assumption was made that typical solutions of the lower layers of the structure and the layer of the improved substrate are the same. It was assumed that the second module on the upper surface of the auxiliary foundation is 120 MPa. Substrate type was assumed as TYPE 1-G1. Therefore, no construction costs were calculated for this type of ground reinforcement. The service life of 30 years is assumed for both types of pavement construction. Two options were adopted in traffic load analysis.

Option 1

It was assumed that the analyzed structures will carry 90,000,000 standard axes with 100 kN pressure. This value was assumed because the structures susceptible to the KR7 category traffic were designed for approximately 90,000,000 axes of 100 kN. For rigid pavements for the KR7 traffic category, the calculated axle count of 100 kN is 220,000,000. The number of 90,000,000 axles of 100 kN for rigid surfaces means the movement of category KR6.

Option 2

For this option, it was assumed that pavement constructions will transfer a certain number of vehicle silhouettes. The following traffic volume has been adopted:

- trucks without trailers-1200 per day per belt,
- trucks with trailers - 3300 a day for a belt,
- buses-200 a day for the belt.

Converting the above structure to standard axes of 100 kN over a 30-year period, the following were obtained:

Susceptible surfaces - 79 670 000 axes 100 kN - movement category-KR7.

Stiff surfaces - 148 360 000 axes 100 kN - movement category-KR7

In addition, it was assumed that for susceptible structures, layers of asphalt-type mix - SMA and asphalt concrete type - AC meet the requirements of WT-2 2014. *Asphalt mixtures for national roads. Technical requirements.*

Mechanically stabilized crushed aggregate meets the requirements of WT-4 2010. Mixtures unrelated to national roads. Technical requirements.C5 / 6 bound mixtures meet the requirements of WT-5 2010. *Mixtures not related to national roads. Technical requirements.*

Stiff surfaces are made of C35 / 45 cement concrete and 5,5 MPa bending strength and XF4 exposure class. The concrete is a two-layer, upper layer of the so-called discovered aggregate.

The foundation of mechanically stabilized broken aggregate meets the requirements of WT-4 2010. *Mixtures unbound for national roads. Technical requirements*.

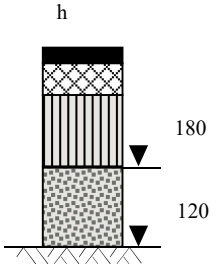
Asphalt concrete foundation meets the requirements of WT-2 / 2014. *Asphalt mixtures for national roads. Technical requirements*.

The substructures of C8 / 10 bound mixtures meet the requirements of WT-5 2010. Hydraulic binder mixtures for national roads. Technical requirements.

For rigid pavements, it was assumed that OST, approved by GDDKiA, applies.

Flexible structures for the KR7 movement

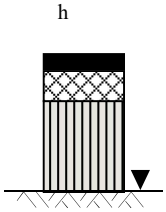
Vulnerable pavement constructions, which were adopted for the analysis of construction and maintenance costs for KR7 traffic, are presented in Figures **1**, **2**, **3**. The structures with the underlying foundation of mechanically stabilized broken aggregate, asphalt concrete mix, and cement-bonded mix were analyzed.



Wear layer - SMA acc. WT2
Binding layer - AC16W acc. WT2
Foundation layer - AC22P acc. WT2

Foundation layer - crushed-stone aggregate mech. stab. $C_{90/3}$ acc. WT2

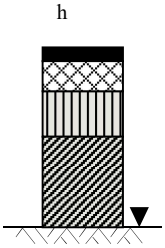
1. Flexible structure with the foundation of mechanically stabilized crushed-stone aggregate type A1-KR7 on the TYP1-G1 substrate



Wear layer - SMA acc. WT2
Binding layer - AC16W acc. WT2

Foundation layer - AC22P acc. WT2

2. Flexible structure with the foundation of asphalt concrete mixture type B-KR7 on the TYP1-G1 substrate



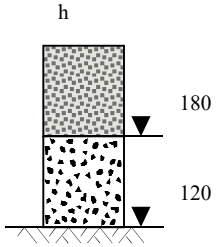
Wear layer – SMA acc. WT2
Binding layer - AC16W acc. WT2
Foundation layer - AC22P acc. WT2

Foundation layer - a compound bonded with hydraulic binder $C_{5/6}$

3. Flexible construction with the foundation of the cement-bonded mixture type C-KR7 on TYPE1-G1 substrate

Rigid structures for traffic KR6 and KR7

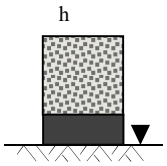
In the case of rigid pavement constructions, which were taken to analyze the costs of construction and maintenance, two categories of traffic KR6 and KR7 were included. It should be recalled that the number of standard axles of fixed surfaces for KR6 corresponds to the number of axes of pavements susceptible to KR7. Schemes of these structures are shown in Figures **4** - **9**. Structures with the same basic substructures as for flexible surfaces were analyzed.



Concrete slab C35 / 45, doweled and anchored

Foundation layer – crushed-stone aggregate mechanically stabilized $C_{90/3}$

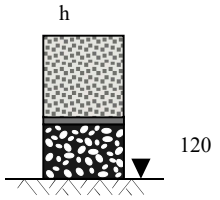
4. Rigid structure with the basis of mechanically stabilized crushed-stone aggregate type I-KR6 on the TYP1-G1 substrate



Concrete slab C35/45, doweled and anchored

Foundation layer – AC22 acc. WT2

5. Rigid structure with the foundation of a mineral-asphalt mixture type II-KR6 based on TYP1-G1 substrate

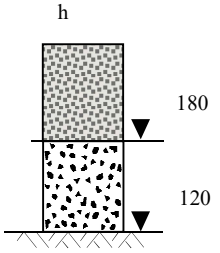


Concrete slab C35/45, doweled and ancho

Slip layer - surface fixation

Foundation layer - a compound bonded with hydraulic binder $C_{8/10}$

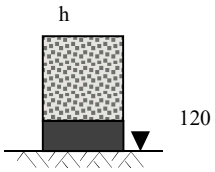
6. Rigid structure with the foundation of a mixture bound with hydraulic binder type III-KR6 on the TYP1-G1 substrate



Concrete slab C35 / 45, doweled and anchored

Foundation layer - crushed-stone aggregate mechanically stabilized $C_{90/3}$

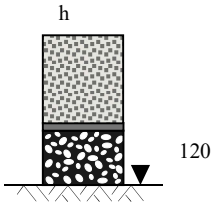
7. Rigid structure with the basis of mechanically stabilized crushed-stone aggregate type I-KR7 on the TYP1-G1 substrate



Concrete slab C35/45, doweled and anchored

Foundation layer - AC22 according to WT2

8. Rigid structure with the asphalt concrete mix type II-KR7 based on type TYP1-G1



Concrete slab C35/45, doweled and anchored

Slip layer - surface fixation

Foundation layer - a compound bonded by hydraulic binder$C_{8/10}$

9. Rigid structure with the foundation of a mixture bound with hydraulic binder type III-KR7 on the TYP1-G1 substrate

Construction costs

The calculation of construction costs for the S-class road section has been made for the expressway with a length of 1 km and a width of 10 m, ie 10,000 m2. In addition, in construction costs for comparative purposes, we omit for all analyzed structures all costs related to the transport of both input materials for the plant and finished materials to the place of incorporation. The issues related to horizontal marking in both cases were completely omitted. R, M and S prices as well as purchase costs, intermediate costs and profit indicators were adopted on the basis of current rates according to Sekocenbud (fourth quarter of 2015), therefore transport costs were omitted based on purchase costs according to Sekocenbud (fourth quarter of 2015). Average prices for engineering works were accepted.

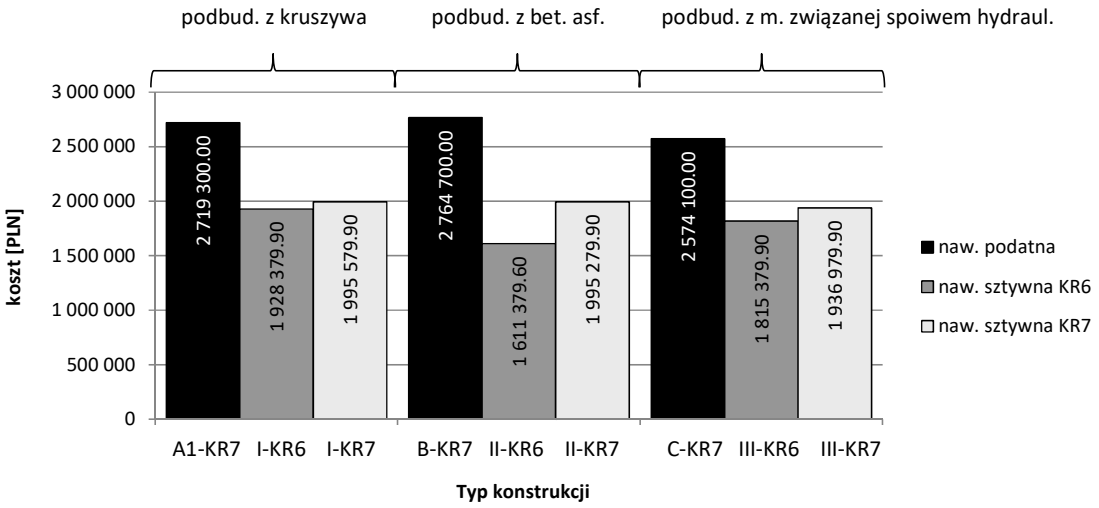
Due to the lack of data in Sekocenbud, based on the interview with the contractors, it was assumed that the cost of a set of machines for concrete pavement with support is 5000.00 PLN/h. The capacity is about 50 mb/h - the cost of building 1 m2 is at the level of 10 PLN.

Table 1 shows indirect costs, purchase, profits and labor accepted for analyzes.

Tab. 1. Summary of indirect costs, purchases, profits and labor accepted for analyzes

period	Indirect costs, %	Purchase costs, %	Profit, %	Labor, %
IV kw 2010	64,70	8,20	11,70	13,76
• IV QTR 2011	64,30	8,60	11,40	13,91
• IV QTR 2012	63,60	8,60	11,00	13,90
• IV QTR 2013	62,80	8,30	10,50	13,61
• IV QTR 2014	63,00	7,80	10,30	13,62
• IV QTR 2015	62,80	7,50	10,30	13,90

On the basis of the above assumptions, the results of calculation of construction costs for the analyzed pavement structures for 2015 were obtained, which are presented in Fig. **10** taking into account various types of foundations.



10. List of construction costs for flexible and rigid pavements for 2015

It is worth noting that for a given type of foundation, the costs of constructing the KR7 susceptible pavement are higher compared to the rigid surfaces for KR6, as well as KR7. This applies to costs for the three types of substructures. The ratios of the cost of pavement susceptible to rigid roads for KR6 are respectively: 1.41 (foundation from aggregate), 1.72 (foundation from asphalt concrete) and 1.42 (foundation from a mix bounded by a hydraulic binder), compared to the rigid surface for traffic KR7: 1.36 (foundation made of aggregate), 1.39 (foundation of bituminous concrete) and 1.33 (foundation of a mixture bound with hydraulic binder.)

Maintenance of the surface

Technological operations (maintenance strategy) were adopted on the basis of national experience and other road administrations whose surfaces work in similar climatic conditions as Poland (France, Germany, USA).

The strategies for maintaining susceptible surfaces are different in different road administrations. An example is a strategy applied in France [1], where strategies for

maintaining susceptible and semi-rigid pavements for various traffic categories were given. The strategy of susceptible surfaces maintenance consists in replacing wear and bonding layers in periods of 8-9 years. The German catalog [5] also indicated conservation strategies involving the use of new layers.

This paper proposes a scenario of susceptible surface maintenance presented below, using national experience, mainly on the A4 motorway in Poland.

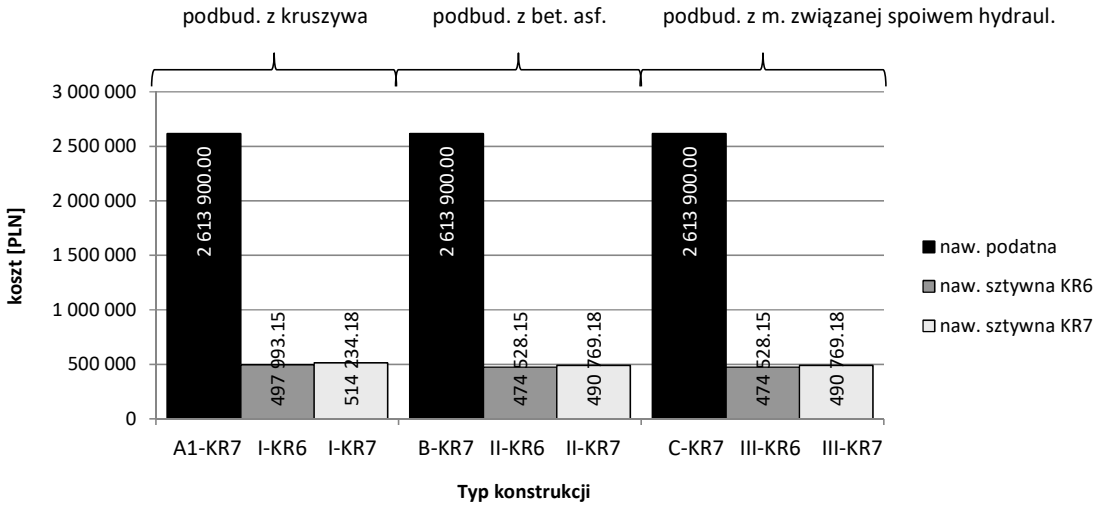
a. After 9 years, replace the wearing layer
b. After 18 years, 40% replacement of wear and bonding layer
c. After 18 years, exchange 60% of the wearing layer
d. After 27 years, replacement of 60% of the bonding and wear layer
e. After 27 years, replacement of 40% of the wearing layer
f. After 30 years, fatigue life of the pavement structure remained, according to 1 option, 23 million axes 100 kN according to the option 2 - 10 million axes 100 kN

As in the case of pavements susceptible to rigid pavements, maintenance strategies have also been developed. An example of this is France [1] or Germany [5]. In [6] various treatments are given that are used when maintaining concrete surfaces. An essential maintenance procedure for concrete pavements is the replacement of fracture protection materials. These treatments are carried out every 8-9 years. Other damages include plate cracks, grain losses, etc. According to AASHTO recommendations, the upper limit of cracked boards is 15%. At the same time, it is assumed that at a 90% confidence level within 20 years the number of broken boards cannot exceed 5%. Cracks in the boards can be flooded with a filling compound and sealed. For the purpose of this work, it was assumed that the broken plates will be replaced. Of course, this raises the cost of maintenance and operation, however, is on the safe side when it comes to the analysis of the cost of living. The scenario of maintaining concrete pavements is presented below.

a. After 9 years, replacement of longitudinal and transverse joint seals
b. After 18 years, replacement of 5% of plates
c. After 18 years, replacement of longitudinal and transverse joint seals
d. After 24 years, exchange of 3% of plates
e. After 27 years, replacement of longitudinal and transverse joint seals
f. After 27 years, replacement of 5% plates
g. After 30 years, fatigue life of the pavement structure according to option 1 load about 12 million axes 100 kN and according to option 2 - 70 million axes 100 kN.

The paper does not take into account the costs of roughing concrete surfaces. This was done deliberately because there is a lack of experience and necessity of roughening in Europe and Poland in the case of concrete pavements in the so-called outdoor aggregate technology. Such technology is recommended in this work as effective both in terms of ensuring appropriate friction conditions and noise impact. However, if there is a need to introduce such a procedure, it can be added to the given statements, taking into account after the 18 years of operation, the amount of PLN 80,000 per 10,000 m^2. However, the introduction of the above amount does not change the general conclusions regarding the maintenance of concrete pavements.

Figure **11** presents a comparison of maintenance costs of the analyzed structures, comparing them with similar types of substructures.

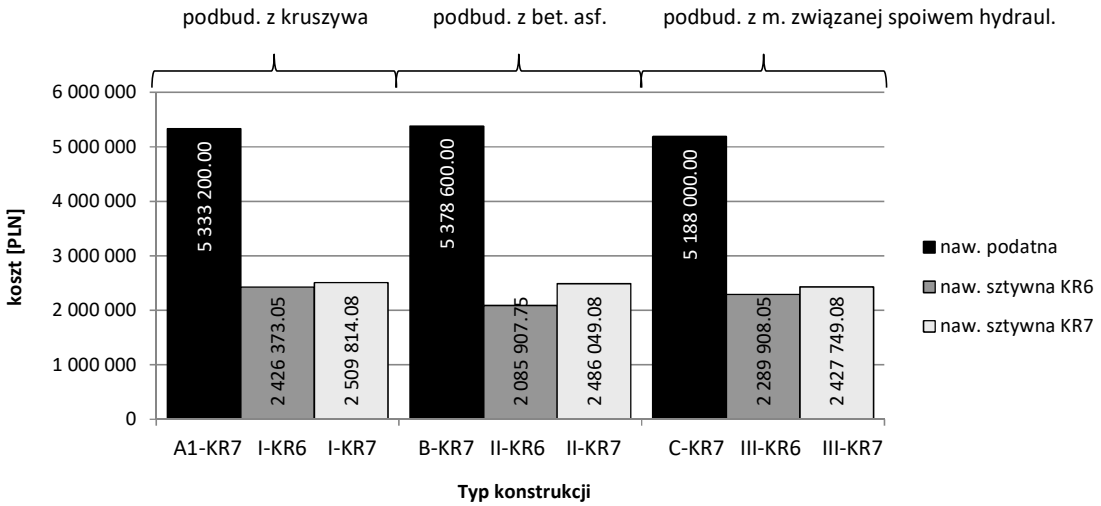


11. Summary of total costs of maintaining susceptible and rigid pavements for 2015

It is worth noting that for a given type of foundation, the costs of susceptible pavement maintenance are definitely higher compared to the rigid surfaces for KR6 and KR7. The ratios of the cost of pavement susceptible to roads that are rigid to the KR6 traffic are 5.25 (the aggregate foundation), 5.51 (asphalt bitumen foundation) and 5.51 (the foundation related to the hydraulic binder), compared to the KR7 rigid pavement: 5.08 (foundation of aggregate), 5.33 (foundation of bituminous concrete) and 5.33 (foundation of a mixture bound with hydraulic binder).

Total costs after 30 years

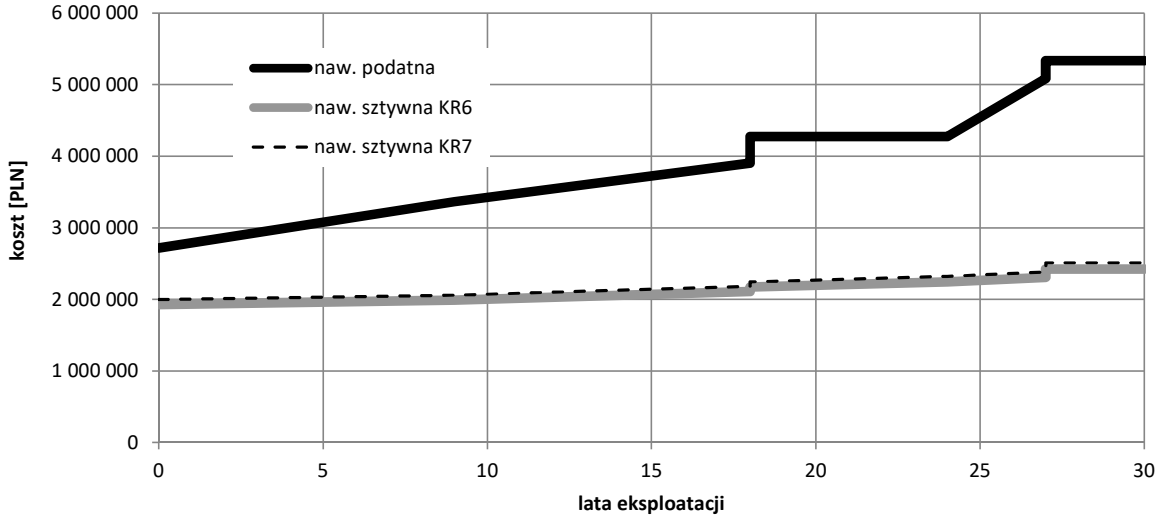
Figure **12** presents a comparison of total costs after 30 years of analyzed structures, comparing them with similar types of foundations for the initial year 2015.



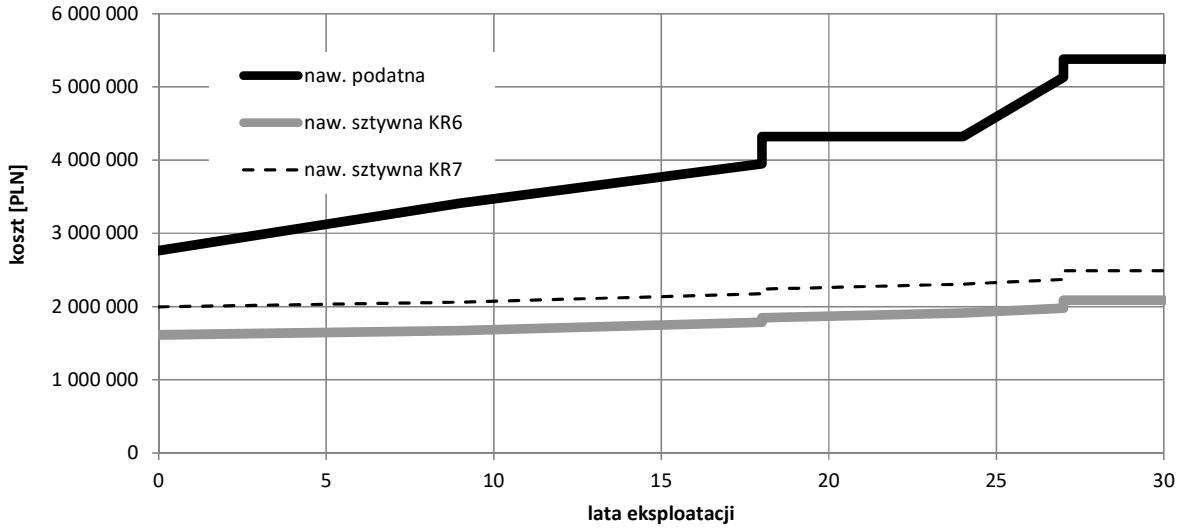
12. Summary of total costs after 30 years of operation for susceptible and rigid pavements for 2015.

Figures **13, 14, 15** show the cumulative construction and maintenance costs. Taking into account both the initial costs related to the construction and costs in subsequent years of operation, it was found that all types of rigid constructions intended for the KR7 and KR6 traffic are cheaper than the corresponding types of flexible surfaces. In the further period of operation, the maintenance costs of susceptible surfaces increase significantly and the

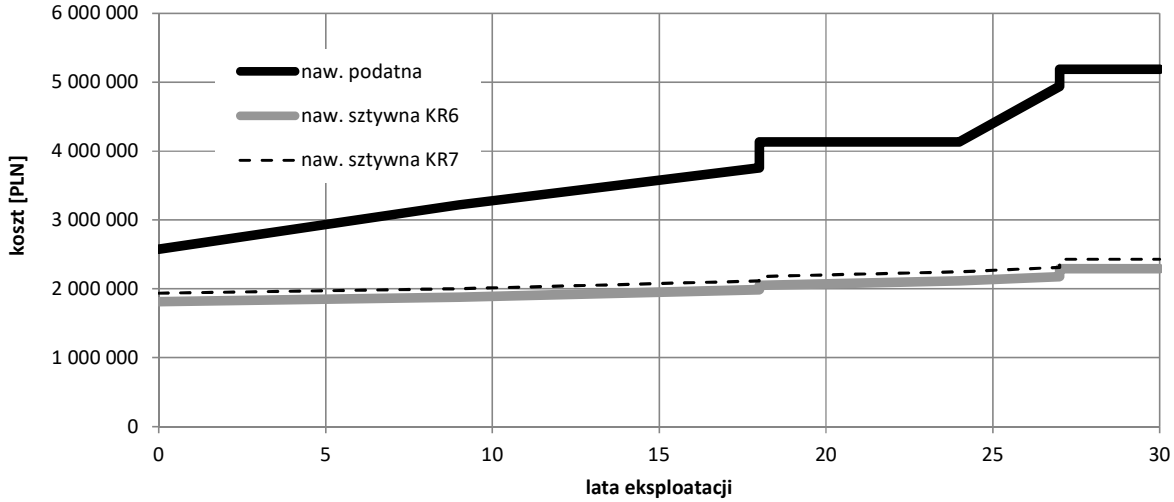
differences are relatively larger. For the surface on the foundation of aggregate, the total costs of the compliant surface are more than twice as high as those for traffic KR6 (2.20) and KR7 (2.12). For the surface on the foundation of asphalt concrete, the difference for the rigid surface for traffic KR6 is also even greater (2.58), while for KR7 it is 2.16. In the case of the foundation of a mixture bound with a hydraulic binder, the differences are: for the rigid surface for KR6 2.27, and for KR7 2.14. It is worth noting that the decisive influence here is the costs of surface maintenance, which are over five times higher for susceptible surfaces compared to rigid ones. The costs of pavement construction have a smaller impact. The average annual cost of susceptible surfaces is about 87 thousand. PLN per year, while rigid surfaces around 16 thousand PLN for a year. The difference is more than five times. Of course, for assumptions made for this analysis.



13. Cumulative costs for susceptible and rigid pavements on aggregate foundations, 2015



14. Cumulative costs for susceptible and rigid surfaces on the asphalt concrete substructure, 2015



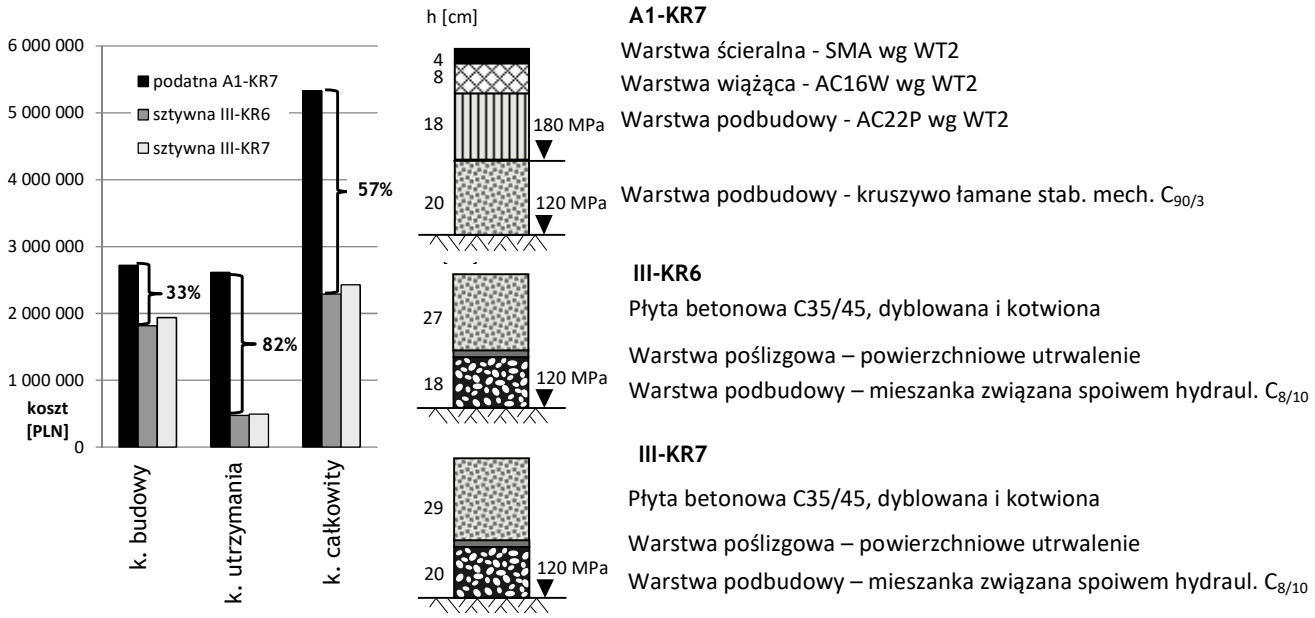
15. Cumulative costs for susceptible and rigid pavements on the substructure of the cement bound mixture, 2015

Taking into account the costs of surfacing types currently under construction in Poland, i.e. flexible - A1- KR7 - SMA + AC + AC + KŁ and concrete - KR6 - BC + C8 / 10 and - KR7 - BC + C8 / 10, construction costs and total maintenance costs like this:

Flexible, construction costs - PLN 2,719,300 - A1 KR7
Concrete, construction costs - PLN 1,815,379.80 - III KR6
Concrete, construction costs - PLN 1 936 979.90 - III KR7
Flexible, total costs - PLN 5 337 600, 00 PLN - A1 KR7
Concrete, total costs - PLN 2 287 919.66 - III KR6
Concrete, total costs - PLN 2 432 454.34 - III KR7

Fig. **16** presents a graphical interpretation of the above calculations of construction and maintenance costs for flexible and rigid pavements, most often currently being built in Poland.

Analyzing the results, it can be seen that the costs of constructing and maintaining concrete pavements are much lower than those of the susceptible ones. The cost of constructing concrete pavements is about 30% lower. However, the cost of living is about 80% lower. The total cost is about 50% lower.



16. Costs of construction and maintenance of the most-frequently-built pavements in Poland, 2015

Summary

The analysis of the costs of construction and maintenance of flexible and rigid pavements presented in the article indicates that the construction costs of both pavements are similar, and minor differences may result from price fluctuations of the main materials (asphalt and cement) and changing economic conditions in the country and the world. Significant differences are in terms of maintenance. In this case, rigid surfaces are definitely cheaper. The strategies for surface maintenance were mainly taken into account on the basis of data from the A4 motorway, on which both susceptible and concrete surfaces are exploited for around 20 years. Although rigid plates have not been replaced yet, American experience indicates the need for this type of intervention in severely degraded situations. In the case of typical damage to susceptible surfaces, both wearing and binding layers are exchanged in more or less the proportions specified in the article. The French administration has similar experiences. According to American experiences [2], trends in price changes of concrete pavements are stable and almost unchanged compared to asphalt prices, which are unstable. In the USA, during the last 50 years, the prices of concrete pavement have dropped by 20%, while asphalt prices increased by 95%. In 2013, in the US, the costs of constructing concrete pavements were 10 to 20% lower than those of compliant surfaces.

The authors are aware of the shortcomings that appear in this study in which many factors have not been taken into account. However, the study wanted to draw attention to the need for an objective approach to the use of different technologies without the mutual elimination of them. The only criterion should be the technical and economic justification for the use of selected technologies.

Source materials

[1]French Design Manuel for Pavement Structures, Guide Technique. LCPC, SETRA, 1997
[2]Guide for mechanistic-Empirical Design of New and Rehabilitated Pavement Structures. Final Reports. Part 3- Design and Analysis, NCHRP, TRB, NRC March 2004
[3]Life Cycle Cost Analysis Procedures Manual State of California Department of Transportation Pavement Standards Team and Division of Design 2007-2010
[4]Life Cycle Cost Analysis US287/US81. Montague County. Texas Department of Transportation.
[5]RSTO 01 – Richtlinien fur die Standardisierung des Oberbaues von Verkehrsflachen. FSV, Ausgabe 2001
[6]Szydło A., Nawierzchnie z betonu cementowego. Teoria, wymiarowanie, realizacja. Polski cement, Kraków 2004