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The rigid and flexible road pavements in terms of life cycle costs

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Abstract

The cost of road pavement construction, its durability and reliability depends on many factors, including: the scope and detail of the technical design, quality of work but also the scope of works related to its maintenance, conservation and operation. Determining the amount of rational expenses, in terms of the life cycle cost of the pavement, requires determination and consideration of the above issues, already at the planning and design stage. In many cases, the ordering party analyzes only the initial investment costs, omitting the operating expenses for the pavement in the long term. The article points out the link between decisions taken at the planning and design stages and expenses incurred at the stage of maintenance and use of road pavement. The authors analyse and compare life cycle costs for two technologies of making road pavement - flexible (asphalt pavement) and rigid (portland cement concrete - PCC) and three categories of road traffic. Referring to the methodology included in [1], the authors present an example of the LCC analysis and determine the individual cost components: construction, renovation and maintenance during the period of 30 years. The analysed costs were determined based on the expert knowledge and current price publications.
The authors draw attention to the fact that low costs incurred by the ordering party at the stage of investment implementation, in the course of use and maintenance of the pavement, entail significant expenses in the long-term. The authors also indicate difficulties related to the estimation of the cost of the road pavements life cycle.
The main reasons include the lack of designers' knowledge about the technology of pavement repairs and related costs, as well as the lack of a simple model for calculating life cycle costs, which is a tool for supporting investment decisions and indicating the optimal solution already at the design stage.

Keywords: road pavement construction; life cycle costs; LCC analysis; flexible pavement (asphalt); rigid pavement (concrete);

1. Introduction

The basis for making any investment decision, including the construction of road infrastructure, is the Life Cycle Cost Analysis. Its scope covers the purchase, ownership and liquidation costs of the structure. In the light of the obligation to rationally spend public funds, entities responsible for road infrastructure are obliged to demonstrate that the activities carried out are highly effective. Therefore, they are looking for tools of economic analysis that will help in choosing the right solution. The LCC method makes possible to estimate the costs of alternative solutions for new projects, but also those already in operation, indicating variants generating the lowest costs over the life span.

The policy of sustainable development of the economy currently implemented in the EU is directed for activities related to environmental protection. According to this idea, at the stage of designing new road constructions, the cost of their construction, rebuilding and maintenance for a long time should be taken into account. All solutions that have no negative impact on the environment, including recycling, energy saving and efficient use of raw materials are widely promoted. Road projects are supported, which are characterized by low costs in the course of their operation. It is estimated that taking into consideration the life cycle in the road pavement design may contribute to a reduction of up to 5% of annual expenses for their maintenance.

The aim of the article is to analyse and compare lifecycle costs for two technologies of making road pavements -

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flexible (asphalt pavement) and rigid (PCC pavement), including construction, renovation and maintenance costs over a period of 30 years. On this basis, the authors indicate the optimal solution from the road pavement life cycle costs point of view and the assumed traffic category.

2. The application of LCC in the road construction

The costs of maintaining and using road pavement constitute a large part of the annual expenses of companies responsible for the above activities. The frequency and scope of maintenance and repair works in a given period related to the maintenance and use of a given type of road surface depends on its lifetime. They are affected by accepted design standards, the quality of the constructed structure and the strategy and quality level of the carried out maintenance activities. Determining the road surface optimal life cycle cost requires estimating the size of the above components.

A characteristic feature of the road infrastructure implementation is a high initial investment, but also assumed long service life, which can be extended through systematic repairs and proper maintenance. The task of road infrastructure is to meet the need for safe and economical people and goods transport, while ensuring certain quality standards (e.g. the resistance to slippage) and requirements (e.g. smooth ride, low impact on the environment). The task of the owners and managers of the road infrastructure is to ensure proper traffic conditions for the period of its operation. However, the traditional approach to design often does not take into account the requirements and costs of maintaining road pavement.

As a result of the growing demand for transport, the number of vehicles and the volume of traffic on the roads increases. This results in increased degradation of road infrastructure elements, air pollution and noise emission (deterioration of health and quality of life of local residents) and increased sensitivity of road systems to traffic disruptions caused by maintenance works (renovation, repairs, replacements), collisions and road accidents [2]. The functionality of the road infrastructure is expressed above all in ensuring the continuity of its operation in the assumed period. Continuity of operation is based on the constant provision of appropriate quality parameters for road users to transfer and receive information, drive a vehicle, safety etc. Managing the functionality of road infrastructure means maintaining its high level of readiness to operate by monitoring basic parameters (e.g. the degree of degradation of the surface, loss of its technical parameters), also changing as a result of maintenance and renovation. The scope and frequency of conducting works related to the maintenance and use of road pavement are essential elements affecting their functionality and operating costs [3].

The costs of maintaining and using road infrastructure are of interest many research centres around the world [2,4,8]. The life cycle cost analysis is the process of evaluating the overall economic value of a project by analysing initial costs and discounted financial outlays incurred over a longer period. The comprehensive LCC analysis includes initial costs (road construction), costs related to maintenance and use (renovation, repair, replacement, maintenance, reconstruction and restoration) but also costs incurred by road users, such as delays due to repair and maintenance work (loss of time) or accidents and traffic collisions.

Factors which, according to the authors, have an impact on the costs associated with the maintenance of road pavement activities, are [4]:

- season of the year (winter, summer),
- road conditions,
- accepted standard of maintenance,
- the course of the road: straight section, road curve,
- the type of road,
- the intensity of vehicles (average annual daily intensity of vehicles),
- the type of passing vehicles,
- the load-bearing capacity and durability of the surface,
- permissible speed on the road section,
- the number of lanes on the road,
- regional conditions.

For the analysis of two variants (flexible and rigid pavement) to estimate the component costs (acquisition, ownership) the following methods were applied:

- the engineering method of cost estimation (direct product testing, component after component),
- the method of cost estimation by analogy (the estimation based on the experience of experts with similar products and technologies),

- the parametric cost estimation method (available parameters and variables were applied to develop the cost estimation dependency).

3. Assumptions adopted for the analysis

In order to make an analysis, the authors adopted the assumptions described below.
1. Two basic types of pavement constructions were analysed:
- type 1 – the flexible pavement with asphalt layers and the base course layer made from unbound mixture materials,
- type 2 – the rigid pavement with portlant cement concrete (PCC) slabs and the base course layer made from materials treated with hydraulic binders.

2. Individual types of pavement constructions were proposed in accordance with the current Polish catalogues of typical pavement constructions that have been applicabled since 2014 [5, 6, 7].

Table 1. The diagram of the pavement structure layers of flexible pavement and improved subgrade layer, after [5]

Pavement structure	Upper layers of the pavement structure	Wearing course layer	
		Binder course layer	
		Base course	The upper layer of the base course
			The bottom layer of the base course
	Bottom layers of the pavement structure	Subbase layer	
		Frost protection layer	
Subgrade	Layer of improved subgrade		
	Native soil in cutor embankment (fill), qualified to one of the subgrade classification from G1 to G4		

source: own study based on [5].

Table 2. The diagram of pavement structure layers of rigid pavement and improved subgrade, after [6]

Pavement structure	Upper layers of the pavement structure	PCC concrete slab
		Sliding layer
		Base course layer
	Bottom layers of the pavement structure	Subbase layer
		Frost protection layer
Subgrade	Layer of improved subgrade	
	Native soil in cutor embankment (fill), qualified to one of the subgrade classification from G1 to G4	

source: own study based on [6].

Table 3 The list of layers thicknesses of flexible and rigid pavements for KR6 traffic category, after {5, 6]

The flexible pavement with asphalt wearing course and base course with the unbound aggregate (cm)		**The rigid pavement** with Portland Cement Concrete slab in the wearing course and base course with mixture treated by hydraulic binder (cm)	
Heavy traffic - traffic category KR6			
22.0 – 52.0 mln axles of 100 kN during the design period of 30 years		**42.63 – 101.25 mln axles of 100 kN during the design period of 30 years**	
4 cm	The wearing course layer of asphalt mixture	27 cm	The wearing course layer – PCC with dowels
8 cm	The binder course layer of asphalt mixture	-	The slippery layer: geotextile
16 cm	The base course layer of asphalt concrete	18 cm	The base course layer of aggregate mixture bound with a hydraulic binder C 8/10
20 cm	The sub-base layer of unbound aggregate mixture	15 cm	The basic sub-base layer of a mixture bound with a hydraulic binder C5/6
15 cm	The sub-base layer of aggregate mixture bound with hydraulic binder	20 cm	Capping layer of unbound aggregate mixture
20 cm	Capping layer of unbound aggregate mixture	25 cm	Improved subgrade stabilized with hydraulic binder or lime
25 cm	Improved subgrade stabilized with hydraulic binder or lime		
83 cm	Subgrade	81 cm	Subgrade

3. For each type of pavement structure (type 1 – asphalt pavement, type 2 – PCC pavement), typical constructions for heavy traffic (traffic category KR6), medium (traffic category KR4) and light traffic (category of traffic KR2) were adopted.

4. The arrangement of the flexible pavement structure layers is presented as in Table 1. The variant in cut (with high groundwater level and poor soil conditions) is analysed. A rigid pavement construction system was adopted and presented in Table 2.

5. For the purpose of stablishing the LCC, the authors analyzed three selected representative traffic categories - according to [5, 6, 7], representing heavy traffic (KR6 traffic category), medium traffic (KR4 traffic category) and light traffic (KR2 traffic category).

6. The construction of the flexible pavement (asphalt layers) - the upper layers of the pavement structure for the traffic categories: KR6, KR4 and KR2 were adopted in accordance with [5, 8].
The thickness and layer systems for three selected traffic categories (KR6, KR4, KR2) adopted in the LCC analysis taking into account the catalog requirements are presented in Table 3, 4, 5.

Table 4 The list of layers thicknesses of flexible and rigid pavements for KR4 traffic category, after [5,6]

The flexible pavement with asphalt wearing course and base course with the unbound aggregate (cm)		**The rigid pavement** with Portland Cement Concrete slab in the wearing course and base course with mixture treated by hydraulic binder (cm)	
Medium traffic - traffic category KR4			
2.5 – 7.3 mln axles of 100 kN during the design period of 30 years		**6.39 – 15.99 mln axles of 100 kN during the design period of 30 years**	
4 cm	The wearing course layer of asphalt mixture	23 cm	The wearing course layer – PCC with dowels
6 cm	The binder course layer of asphalt mixture	-	The slippery layer: geotextile
10 cm	The base course layer of asphalt concrete	20 cm	The base course layer of aggregate mixture bound with a hydraulic binder C5/6
20 cm	The sub-base layer of unbound aggregate mixture	15 cm	The subbase course layer of aggregate mixture bound with a hydraulic binder C3/4
15 cm	The sub-base layer of aggregate mixture bound with hydraulic binder	20 cm	Capping layer of unbound aggregate mixture
20 cm	Capping layer of unbound aggregate mixture	25 cm	Improved subgrade stabilized with hydraulic binder or lime
25 cm	Improved subgrade stabilized with hydraulic binder or lime	79 cm	Subgrade
75 cm	Subgrade		

Table 5 The list of layers thicknesses of flexible and rigid pavements for KR2 traffic categories, after [5, 6]

The flexible pavement with asphalt wearing course and base course with the unbound aggregate (cm)		**The rigid pavement** with Portland Cement Concrete slab in the wearing course and base course with mixture treated by hydraulic binder (cm)	
Light traffic - traffic category KR2			
0.09 – 0.5 mln axles of 100 kN during the design period of 30 years		**0.15 – 0.75 mln axles of 100 kN during the design period of 30 years**	
4 cm	The wearing course layer of asphalt mixture	24 cm	The wearing course layer – PCC with dowels
8 cm	The binder course layer of asphalt mixture	30 cm	The sub-base layer of unbound aggregate mixture
20 cm	The sub-base layer of unbound aggregate mixture	22 cm	Capping layer of unbound aggregate mixture
22 cm	Capping layer of unbound aggregate mixture	24 cm	Improved subgrade stabilized with hydraulic binder or lime
24 cm	Improved subgrade stabilized with hydraulic binder or lime	76 cm	Subgrade
54 cm	Subgrade		

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4. The comparative analysis of LCC for flexible and rigid pavements

The LCC analysis presented in this article is carried out in accordance with the methodology described in [1]. The time horizon was defined for the purpose of the analysis - adopted for 30 years and then the cost components were determined. The costs discussed in the article were determined on the basis of expert knowledge, current price publications and market data.

In order to carry out the cost analysis, the following assumptions were made:
- initial expenses, i.e. acquisition costs, taking into account: trench excavation for the structure together with the preparation of the foundation, costs of loading, transporting and utilizing the material from the excavation,
- excavations are carried out in frost susceptibility soil with the transport of the excavated soil up to 3 km with the formation and leveling of slopes on the deposit,
- the calculation includes the costs of the implementation and maintenance of the thick-layered horizontal marking on the surfaces,
- costs of maintenance, including costs of carrying out the following works: for the PCC pavement - reconstruction of the horizontal marking with the removal of the old marking and priming the area, winter maintenance - snow removal by the plow with salt sprinkling - assumed 120 times in the season, repair costs of the accepted range and conducted with the assumed frequency,
- the pavement construction cost calculations were made for a road segment of a given traffic category (KR6, KR4, KR2) and an area of 10,000 m²,
- the calculated unit prices take into account the costs of purchasing materials – i.e. costs related to the transport to the place of installation,
- the average unit prices were determined on the basis of information contained in selected Polish price publications [9, 10, 11] and information from the Polish market and individual calculations,
- a discount rate of 1.75% was assumed.

Based on the experience of domestic and foreign entities managing the maintenance of road infrastructure, assuming that the analysed road surfaces work in similar climatic conditions, the following strategies for their maintenance were adopted.

1. For flexible pavement and heavy traffic category - KR6:
- the replacement of the wearing coarse layer - 100% of the structure wearing course layer after 10 and 20 years of use,
- the replacement of all asphalt layers - 100% of the asphalt layers after 30 years of use,
- the partial repairs of the pavement - 1% of the pavement area after 2, 3, 12, 13, 22, 23 years of use, 2% of the pavement area after 4, 14, 24 years of use, 3% of the pavement area after 5, 15, 25 years of use, 4% of the pavement area after 6, 16, 26 years of use, 5% of the pavement area after 7, 17 years of use, 10% of the pavement area after 8, 18, 28 years of use and 15% of the pavement area after 9, 19 and 29 years of use,
- leveling the pavement surface - 3% of the surface after 5, 15 and 25 years,
- maintenance of horizontal marking - 100% of the construction area of 5, 10, 15, 20, 25 and 30 years and 2.5% of construction after 7, 14, 21 and 28 years of use,
- winter maintenance: 120 times during the winter season for 30 years.

2. For rigid pavement and heavy traffic category - KR6:
- partial replacement of the PCC slabs with the base course (demolition of the pavement, profiling of the subgrade, conversion of concrete debris into useful material, reconstruction of the concrete surface) - 2.5% of the surface after 7, 14, 21 and 28 years of use,
- complete replacement of the pavement with the base course - 100% of the pavement structure after 30 years of use,
- crack sealing - 1% of the pavement area after 7, 14, 21 and 28 years of use,
- keeping the horizontal markings - 100% of the pavement surface area of 5, 10, 15, 20, 25 and 30 years and 25% of the structure after 3, 8, 13, 18, 23, 28 years of use,
- winter maintenance: 120 times during the winter season for 30 years.

Appropriate maintenance strategies were also adopted for traffic caregories KR4 and KR2.
The list of acquisition, maintenance and cumulative costs over 30 years for 1 m² of flexible and rigid pavement for the KR6, KR4 and KR2 traffic categories is given in Table 6.

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Table 6. The comparison of initial expenses - purchase costs (including earthworks and horizontal markings) and total maintenance costs

The flexible pavement with asphalt wearing course and base course with the unbound aggregate			**The rigid pavement** with Portland Cement Concrete slab in the wearing course and base course with mixture treated with hydraulic binder		
The initial costs (road construction) in [PLN/m^2]	The maintenance costs for a period of 30 years in [PLN/m^2]	LCC (acquisition and maintenance over a period of 30 years) [PLN/m^2]	The initial costs (road construction) in [PLN/m^2]	The maintenance costs for a period of 30 years in [PLN/m^2]	LCC (acquisition and maintenance over a period of 30 years [PLN/m^2]
KR6					
355,39	1280,14	1635,53	345,71	1342,30	1688,01
KR4					
304,92	1067,72	1372,64	333,70	1148,27	1481,97
KR2					
200,04	559,15	759,19	270,60	833,16	1103,76

source: own study

For the flexible and rigid pavement as well as for traffic categories KR6 and KR4 (i.e. heavy and medium traffic), the total life cycle costs (i.e. the sum of acquisition and maintenance costs) are similar (Table 6, Figure 1). In each of these two cases, the total costs are slightly higher for the rigid pavement. A clear difference in the compared total lifecycle costs for both types of surface occurs for the KR2 category (i.e. the light traffic) - Table 6, Figure 1. The total cost of acquisition and maintenance over a 30-year of a rigid pavement is 45.4% higher than total cost for flexible pavement (Table 6, Figure 1).

According to research (Table 6) for the KR6 traffic category, the initial investment for the flexible pavement is higher than the initial investment for the rigid pavement. It should be emphasized, however, that concrete pavements require regular work related to maintaining expansion joints in a good technical condition. These treatments usually concern only a few percent of the boards surface. For asphalt surfaces, maintenance procedures are only carried out in the event of damage, and the wear layer should be replaced in accordance with the accepted maintenance scheme.

The conducted economic analysis shows that for all included traffic categories (KR6, KR4, KR2), slightly higher lifecycle costs for rigid pavement are observed (Figure 1).

The life cycle costs of road pavements are closely related to the length of their exploitation period, the scope and frequency of maintenance and repair activities, the maintenance standard of the road used by its manager and the function and importance of the road. However, it should be noted that the costs of maintaining flexible and rigid pavements for the traffic categories KR6, KR4 and KR2 in the longer term (e.g. 30 years) are significant in comparison with the costs of their purchase. They constitute over 70% of the total cycle costs of the construction life cycle (Figure 2).

The results of the LCC analysis, for selected traffic categories and two technologies for the construction of different type road pavements indicate that this method in practice should be one of the basic criteria for the selection of the optimal solution, i.e. an economically justified variant of undertaking the implementation.

5. Conclusions

The research and analyses carried out by the authors justify the formulation of the following statements and conclusions.

1. The use of LCC analysis at the concept stage, defining and designing the road pavement offers great opportunities to reduce costs throughout their life cycle. The problem, however, is obtaining reliable information regarding the operation costs and the surface removal. Currently, there are no uniform technical regulations in Poland on the recommended scenarios for road surface maintenance in the longer term. Therefore, a long-term experience of road managers and entities responsible for the maintenance of road infrastructure can be a valuable source of information on the scope and costs of maintenance and repair of pavement constructions. Taking into account their knowledge and experience at the design stage, performing and maintaining different types of surfaces, in accordance with certain standards and requirements, should ensure good functional features of the structure throughout the assumed lifetime.

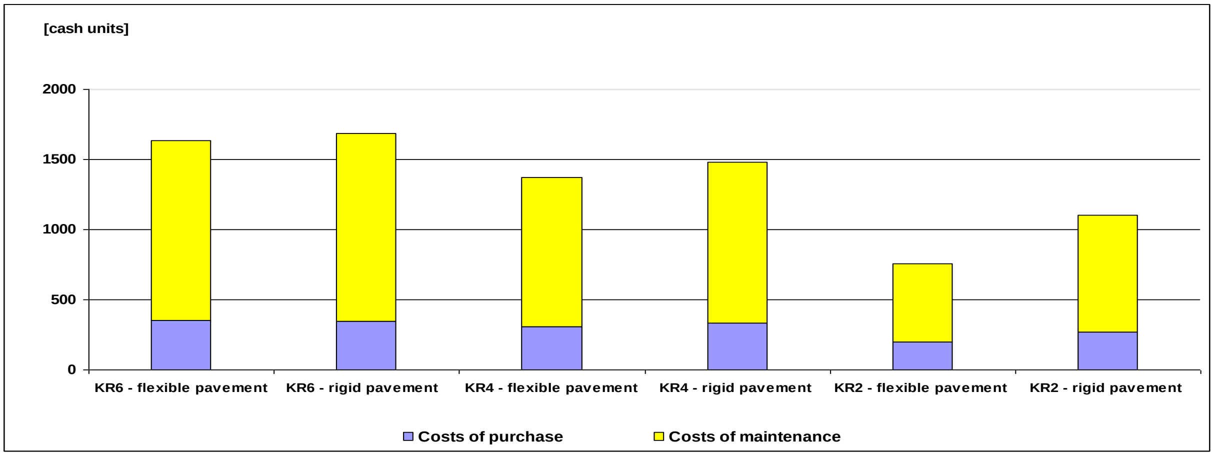

Fig. 1 Costs of purchase and maintenance for 30 years for flexible and rigid pavement, including KR6, KR4, KR2 traffic categories
source: own study

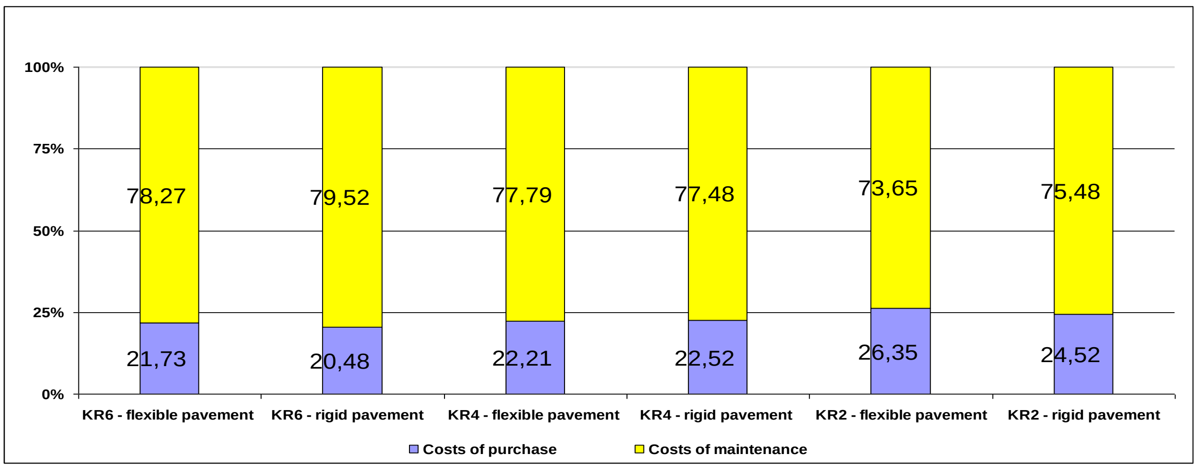

Fig. 2 Proportions of purchase and maintenance costs over a period of 30 years in the total life cycle cost for flexible and rigid pavement, including traffic categories KR6, KR4, KR2.
source: own study

2. An important element in the estimation of the road pavement life cycle costs is the precise definition of activities of various nature, which may have an impact on the reduction or increase of costs and determining the correlation between them. An important element of the LCC analysis is to determine the lifetime of the surface (e.g. 30 years) and the amount of the discount rate. Input data formulated in this way can be processed using a specific calculation model. The obtained results should be verified.
3. The proposed approach to the selection of the optimal variant in the road pavement implementation, fully fits in the idea of environmental protection and sustainable development of the economy promoted in the EU. In each of the analysed cases, the performance and maintenance of a flexible pavement in the long run is associated with a smaller investor's expenses. Particular savings in the long term are visible for the KR2 light traffic category. The total cost of purchase and maintenance of a rigid pavement in 30 years is 45.4% higher than the cost of maintaining flexible pavement during this period.
4. According to [1] the life cycle cost estimation is the most effective at the early stage of product design. There is the possibility of effective optimization of the solution. It is also recommended to update information in the next phases of the life cycle in order to identify areas that generate significant costs during the maintenance phase.
5. The presented analysis concerns only the life cycle costs of the pavement. However, it should be emphasized that the analysis should be extended by LCA (Life Cycle Assessment). According to the standard [12] the life cycle is defined as "subsequent and related stages of the product, from obtaining or producing raw material from natural resources to its final disposal". An important activity of the LCA analysis is to conduct a detailed balance of the use of materials and energy. Performing such a study contributes to reducing the negative impact of the product on the

environment at the stage of manufacturing, incorporation and use, but also measurable financial savings by increasing the efficiency of energy and raw materials use [13]. Therefore, the LCC analysis combined with LCA will allow to indicate unambiguously which of the road and pavement presented construction technologies is the optimal choice in terms of costs and environmental impact. Such analysis is the direction of further research carried out by the authors.

6. Among the fundamental practical problems related to defining the life cycle costs of road pavements, it should be mentioned the concentration of contracting parties only at the initial cost related to their performance, without taking into account the costs associated with their maintenance. Documents have been developed in many countries around the world, indicating methods for calculating life cycle costs. These experiences can be a benchmark for defining the methodology of conducting LCC analysis for road infrastructure in Poland.

7. Despite numerous limitations (including determination of individual components of costs, requires multidisciplinary and extensive field, laboratory and simulation research at the national and regional level), the LCC analysis can be applied to assess the effectiveness of various variants of acquisition of new road pavement or modernization of existing ones. It provides transparent information about the possible consequences of the solutions under consideration, taking into account the durability period and the parameter of the pavement's reliability.

References

[1] PN-EN 63300-3-3 Reliability Management Part 3-3: Application Guide, Life Cycle Cost Estimation (2006).

[2] M. Budzyński, W. Kustra, R. Okraszewska, K. Jamroz, J. Pyrchla, The use of GIS tools for road infrastructure safety management, in: *E3S Web of Conferences*, Vol. 26, p. 00009, EDP Sciences (2018).

[3] B. Grzyl, E. Miszewska-Urbańska, M. Apollo, The life cycle cost of a building from the point of view of environmental criteria of selecting the most beneficial offer in the area of competitive tendering, in: *E3S Web of Conferences,* Vol. 17, p. 00028, EDP Sciences (2017).

[4] B. Grzyl, A. Kristowski, K. Jamroz, A. Gobis, A., Methods of estimating the cost of traffic safety equipment's life cycle, in: *MATEC Web of Conferences,* Vol. 122, p. 02003, EDP Sciences (2017).

[5] GDDKiA, Katalog Typowych Konstrukcji Nawierzchni Podatnych i Półsztywnych, Zarządzenie nr 31 Generalnego Dyrektora Dróg Krajowych i Autostrad z dnia 16.06.2014 r.

[6] GDDKiA, Katalog Typowych Konstrukcji Nawierzchni Sztywnych, Zarządzenie nr 30 Generalnego Dyrektora Dróg Krajowych i Autostrad z dnia 16.06.2014 r.

[7] J. Judycki, P. Jaskuła, M. Pszczoła, D. Ryś, M. Jaczewski, J. Alenowicz, M. Stienss, New polish catalogue of typical flexible and semi-rigid pavements, in: *MATEC Web of Conferences*, Vol. 122, p. 04002, EDP Sciences (2017).

[8] J. Judycki, P. Jaskuła, M. Pszczoła, D. Ryś, M. Jaczewski, J. Alenowicz, B. Dołżycki, M. Stienss, Analizy i projektowanie konstrukcji nawierzchni podatnych i półsztywnych, Wydawnictwa Komunikacji i Łączności, Warszawa (2014).

[9] Biuletyn cen robót drogowych, mostowych i torowych BCD, Sekocenbud (first quarter of 2018).

[10] Biuletyn cen robót przygotowawczych BCP, Sekocenbud (first quarter of 2018).

[11] Biuletyn cen robót ziemnych i inżynieryjnych BRZ, Sekocenbud (first quarter of 2018).

[12] PN-EN ISO 14044: Environmental management. Life cycle assessment. Requirements and guidelines (2009).

[13] D. Kowalski, B. Grzyl, A. Kristowski, The Cost Analysis of Corrosion Protection Solutions for Steel Components in Terms of the Object Life Cycle Cost, *Civil and Environmental Engineering Reports* 26.3 (2017).