Research Article

Optimization of Life Cycle Extension of Asphalt Concrete Mixtures in regard to Material Properties, Structural Design, and Economic Implications

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Design of ACM life cycle is defined with respect to traffic load acting on the pavement and road class for a period of about 20 years. In practice, reconstruction is usually pending until the end of the life cycle after which the reconstruction takes place and the original materials are replaced by new materials. Life cycle of the pavement construction in road structure is significantly longer than that of the ACM; it is therefore necessary to consider ACM from a long term viewpoint, that is, exceeding their life expectancy. This paper describes a methodology which consists of analytical calculations, experimental measurements, and optimization of the ACM life cycle with the use of a rehabilitation action to provide new physical properties of pavement surfacing in different periods of the original life cycle. The aim is to attain maximal economic effectiveness, by minimizing financial costs for rehabilitation and maintenance and economic costs of road user. Presented method allows deriving optimal life cycle from various rehabilitation alternatives for particular ACM with the fact that all the necessary parameters are derived from specific experimental measurements and calculations. The method is applicable to all types of ACM materials; however, for each material, it is necessary to carry out the necessary measurements and tests. The article describes the methodology and case study results for a particular type of ACM material.

1. Introduction

Modelling of ACM life cycle applied in the pavement construction depends on the rehabilitation implementation method (mill-and-replace/recycle, overlays, etc.), but also it is from time in which rehabilitation was carried out. For the LCCA (Life Cycle Cost Analysis), life expectancy of ACM layer and degradation functions of original and new layers are the critical parameters. It can be said that the credibility or accuracy of LCCA analysis is directly proportional to the accuracy of life expectancy calculation of the ACM layer and the degradation functions. Given that ascertainment of necessary data is quite complicated and requires access to computational methods and experimental devices, usual input data of the LCCA are generally known data, that is, software where these data are incorporated but are not available for the user to verify [1–3]. In fact, however, the ACM layers compose different asphalt, different thicknesses,

and different aggregate, in various mixing ratios. The pavement is also subject to various climatic conditions and maintenance methods, especially during winter maintenance. Therefore, their behaviour over long periods of time differs quite significantly and their generalization is a cause of great uncertainty.

Method based on the design and evaluation of ACM rehabilitation in the framework of the life cycle requires a combination of analytical and computational models and experimental measurements on sections which are subject to traffic loading in real-life operation. In the analytical part, methods are proposed to calculate the design of the pavement construction with ACM surfacing, fatigue characteristics are defined as trend lines of ACM life expectancy, and computation models are defined for calculation of the life cycle and economic efficiency of all proposed variants. Experimental part consists of an experiment to determine the basic material and fatigue characteristics and deformation trend lines.

FIGURE 1: Flowchart: Life cycle extension of the ACM.

Life cycle of ACM materials in the pavement construction is defined through the analytical calculation method of pavement construction, where life expectancy is derived through the fatigue characteristics of materials used. However, the ACM life cycle itself can be defined by means other than fatigue characteristics, for instance, permanent deformation expressed through pavement unevenness and foremost rutting (transverse unevenness).

Based on ACM life cycle defined through the material fatigue and permanent deformation expressed by unevenness, it is possible to design rehabilitation variant-recycling or overlay at different times within the life cycle. These variants extended the original life cycle. In terms of efficiency, variants of the rehabilitation are evaluated by means of Cost Benefit Analysis (CBA) and mathematical optimization model. The flowchart encompassing processes described in this paper is shown in Figure 1.

2. Experimental Pavement Model

The proposed methodology allows analysing each type of ACM layer individually and calculating the LCA for particular conditions. In addition to triaxial bending machine for the measurement of ACM fatigue characteristics, experimental accelerated pavement testing facility was constructed for ascertainment of degradation functions which allows deriving degradation trend lines for particular ACM in particular climatic conditions. These precise results are then applied to the LCA calculation method, economic efficiency evaluation,

FIGURE 2: Pavement structure.

and optimization. Therefore, experimental pavement section was built on 1:1 scale, on which heavy truck axle acted as a simulated traffic load prescribed as equivalent single axle load.

In order to define ACM life cycle in the pavement construction and the application of technological variants of rehabilitation, a standard pavement type usual for a primary road was designed. The pavement was designed according to standard methodology [4] for a minimum level of traffic load: 2×10^6 design axles. The entire pavement was subsequently built in the laboratories of the Department of Construction Management at the University of Zilina. The experimental model of pavement construction is shown in Figure 2.

Pavement structure layers are designed from generic materials defined in national standards. The pavement itself is

TABLE 1: Material characteristics of pavement layers.

Layer	Complex modulus	Strength	Poisson number	Layer thickness
AC 11 O	10891	3.2 MPa	0.33	40 mm
AC 16 P	8317	2.4 MPa	0.33	80 mm
MBA, 31.5 GB	586	0.1 MPa	0.30	180 mm
Gravel subbase, 31.5	365	0.07 MPa	0.30	200 mm
Subgrade	100	—	0.35	—

a generic light flexible pavement commonly used for regional roads. Table 1 contains material characteristics ascertained by the initial physical measurement of surfacing materials.

2.1. Asphalt Concrete Material Layer

2.1.1. Complex Stiffness Modulus. Measurement of complex stiffness modulus of ACM in the pavement structure was carried out according to national standard which is in compliance with European Union Standards [5]. Complex stiffness modulus (E^*) is a material temperature and time variable characteristic of viscoelastic deformation under short term oscillating stress load. It is the proportion of maximal amplitude of excitation stress and the induced strain in steady harmonic oscillation with respect to their mutual phase shift. It represents the attenuation by asphalt bound materials. The frequency is determined by the length of the amplitude (T) in volts (V). The frequency (f) is calculated as follows:

$$f = \frac{1}{T} [\text{Hz}]. \quad (1)$$

The test results are evaluated separately for each selected test temperature and frequency. The result is the arithmetic average of several complex modulus measurements and phase shift (φ), at a given temperature and frequency. Complex modulus is a ratio of stress (σ_0) and deformation (ϵ_0) at steady, harmonically variable oscillation in consideration of their mutual time shift [6].

$$E^* = \frac{\sigma_0}{\epsilon_0} = (E_1^2 + E_2^2)^{1/2}, \quad (2)$$

where E^* is complex stiffness modulus, E_1 is real component that characterizes the elastic properties, and E_2 is imaginary component that characterizes viscous properties.

Measurement of the complex stiffness modulus is performed with utilization of short term alternating harmonic load. It expresses the proportion of the maximum amplitudes of excitation tension ($0s$) and deformation induced by it ($0e$) and their phase shift (j). On the basis of measurements performed for different temperatures, E^* values for frequencies of 1–20 Hz were ascertained; these are listed in Table 2.

2.2. Subbase Layers. The measured values on subbase layers are performed using an LDD and Clegg that, after conversion

TABLE 2: Complex modulus of AC11 measured at different frequencies.

Temperature °C	E^* [MPa]				
	Frequency Hz				
	1	5	10	15	20
−10	14532	16449	17390	17524	17715
0	10919	13261	14248	14664	15112
10	7060	9171	10002	10430	10891
15	4686	6721	7577	8026	8463
27	1581	2919	3556	3944	4334

FIGURE 3: Clegg and CBR relationship.

based on (3) according to [7], were adjusted to CBR (California Bearing Ratio) values. The results are shown in chart in Figure 3.

$$\text{CBR}_{\text{STN721016}} = 0,78 * \text{CIV}^{1,12}, \quad (3)$$

where CIV is Clegg impact value.

Subsequently, the CBR values were converted according to (3) [8] to (E_N) value with the use of the following formula:

$$E_N = 17,6 * \text{CBR}^{0,64}. \quad (4)$$

3. Fatigue Characteristics

Fatigue characteristics are used in the assessment of pavement resilience against repeated loading. Test temperature for the endurance test is 10°C and the frequency of cyclic loading is 25 Hz. The test is carried out at a constant bend of the test sample during the test. Fatigue tests were carried out according to the European standard [9]. Results of the fatigue test are in the form of a Wöhler diagram.

$$\log \epsilon_{0j} = a_j + b \log N, \quad (5)$$

where ε_{0j} is maximum amplitude of proportional deformation in the test conditions at the beginning of the measurement, a_j, b are parameters measured during the fatigue tests being the stress lines coefficient in the range of N , and N is the number of load repetitions.

The characteristics of the fatigue are in the equation where the average size of deformation derived from stress lines derived after 10^6 loading cycles in microstrain ($\mu\text{m/m}$).

$$\log\left(\frac{\varepsilon_6}{10^6}\right) = a_j + 6b, \quad (6)$$

where a, b are fatigue parameters and ε_6 is average deformation derived from fatigue curve after 10^6 loading cycles in microstrain [$\mu\text{m/m}$].

The number of loads corresponding to the initial deformation in the test sample under specified conditions can be ascertained as

$$N = 10^6 \left(\frac{\varepsilon_6}{\varepsilon_0}\right)^B, \quad B = -\frac{1}{b}, \quad (7)$$

where B are the fatigue characteristics in the range of 3 to 10.

The results of research [6] lit 6 carried out in the ambit of fatigue characteristics are presented in Figure 4 and Table 3.

4. The Calculation of the Life Cycle

The life cycle of ACM can be defined through the means of bearing capacity evaluation on the basis of the stress and fatigue characteristics up until the point of a breakdown. In addition, however, the ACM is subject to permanent deformation as a result of traffic loading, which may cause the loss of operational capability defined by the standard prior to its failure caused by fatigue. These deformations manifest as plastic deformations.

4.1. Bearing Capacity. Calculation of the life cycle is possible on the basis of the calculation method for the design of pavement structure [4, 10]. This method imposes structural value for the ACM layers which is expressed by comparing the calculated radial stress on the bottom of the considered layer with the strength in the same layer. That in view of the repeated loading is reduced by a fatigue factor S_N .

$$SV \geq \frac{\sigma_{ri}}{S_N * R_i}, \quad (8)$$

where SV is structural value, σ_{ri} is radial stress, R_i is strength, and S_N is fatigue characteristic.

The radial stress in the ACM layer is calculated on the basis of the thickness of the layers, complex modulus, and Poisson numbers by means of calculation in the layered elastic half-space model [11]. Calculated stress (σ_{ri}) is based on the effects of repeated loading, which is expressed in terms of the design axle load with the axle weight of 10 tons ($2P = 100 \text{ kN}$). Behaviour and properties of the materials used in the pavement construction pertain to certain climatic conditions; therefore under standard processes three different periods are considered during which the resiliency and elastic

TABLE 3: Values of fatigue parameters for mix AC 11 O.

Parameter	a	$1/b$	$\varepsilon_6 \cdot 10^{-6}$	r^2
Fatigue parameters	-15.0754	-0.1927	86.77	0.7871

FIGURE 4: Wöhler diagram.

modulus change. In our case, the modelling of the pavement construction behaviour happens in constant conditions persisting in laboratory where the experimental pavement section is built. These constitute medium conditions, that is, constant temperature above $+10^\circ\text{C}$.

Fatigue characteristic (S_N) is expressed via parameters (a) and (b) which represent the shape of the Wöhler curve and the expected traffic load (N).

$$S_N = a - b * \log N_C, \quad (9)$$

where a, b are fatigue characteristics.

On the basis of fatigue characteristic measurements (Section 3) for AC 11 O mixture, the values of fatigue coefficients a, b are

$$\begin{aligned} a &= 1, \\ b &= 0.11. \end{aligned} \quad (10)$$

The life cycle of ACM in the pavement construction can be expressed through (1), on the basis of the stress calculation in pavement construction and strength and fatigue characteristics. The structural value must be less than 1, in order for the stress not to exceed the resiliency value. If it is exceeded, the ACM is at the end of its useful life and breaks down. The length of life cycle therefore defines stress in the ACM layer and a decrease of strength depending on the traffic load expressed by the fatigue characteristics. For this reason, stress calculations were made for the pavement construction and its characteristics for the duration of the whole life cycle. In Table 4, stress values are listed in various stages of the life cycle depending on the number of loads and complex modules, whose values also decrease depending on the repeated loading. In Figure 5, trend line of stress state, as well as the decrease of strength resiliency due to the fatigue ACM layer, is presented.

The life cycle itself expressed by utilization structural values in accordance with (1) is shown in Figure 6. Calculations

TABLE 4: Radial stress and strength resiliency values in ACM layers based on Ni.

The number of Ni	0	1.5×10^6	3×10^6	4.5×10^6	6×10^6	7.5×10^6
AC 11 O E* (MPa)	10891	5998	5759	5620	5521	5445
AC 16 P E* (MPa)	8317	4580	4398	4291	4216	4158
Stress (MPa)	0,978132	0,634328	0,613133	0,600401	0,591348	0,584278
Strength (MPa)	2,4	0,769512	0,690040	0,643552	0,610568	0,584984

FIGURE 5: Relationship between stress in ACM depending on repeated loading and decrease of ACM strength resiliency depending on the fatigue trend function.

FIGURE 6: Life cycle of ACM in the pavement construction depending on the number of loading cycles.

show that the life cycle of ACM in the testing pavement section is defined by 7.5 million of design axle passes. In this case, the annual traffic load will be max. 375 000 design axle loads and the life expectancy will be 20 years.

4.2. Permanent Deformation. Detailed knowledge regarding degradation characteristics in given climatic conditions and traffic loading can be attained only through experimental measurements. Credibility of LCA is dependent on the accuracy of these trend lines. Permanent deformations are induced by traffic loading and external environment conditions such as temperature, humidity, and radiation. The material deteriorates to a point where it is no longer suitable from the viewpoint of operational characteristics and thus

FIGURE 7: Life cycle of ACM in the pavement construction depending on the number of loading cycles.

FIGURE 8: Transverse unevenness.

ends its life cycle [12]. In contrast to fatigue and its relation to the residual life expectancy, which can be expressed by different coefficients [8], for example, this cannot be done for permanent deformation. It is foremost because of the fact that ACM is not, during deformation, in elastic nor in plastic state and the calculations are extremely sensitive to variety of conditions from the external environment. Therefore, experimental measurements are used to record pavement shape changes, and by means of mathematic models environmental conditions are directly derived [13, 14]. In our research, deformation characteristics were obtained through measurements on the experimental pavement section after 50, 100, and 150 thousand loads. Deformations are shown in Figure 7. Trend line of deformation in relation to load was derived and it is shown in Figure 8.

5. Extension of the Life Cycle

The life cycle represents number of load repetitions acting on ACM layer up to the state of breakdown. For economic

TABLE 5: Stress calculations before and after rehabilitation.

Year	5	10	15	20	25	30	35	40
ACM layer thickness increase (mm)	36	52	62	71	—	—	—	—
AC 11-overlay E^* (MPa)	10891	10891	10891	10891	5445	5445	5445	5445
AC 11 O E^* (MPa)	5945	5682	5551	5445	5354	5304	5248	5205
AC 16 P E^* (MPa)	4540	4339	4239	4158	4088	4051	4008	3975
Stress prior to rehabilitation (Mpa)	0.751838	0.664456	0.620544	0.584984	0.48615	0.4465	0.42012	0.40146
Stress prior to rehabilitation (Mpa)	0.508571	0.464004	0.429907	0.40146	0.477312	0.428528	0.404145	0.382118

FIGURE 9: Rehabilitation design at various stages of the life cycle.

reasons, however, it may not be the cheapest or most efficient to wait until the very end of the ACM life cycle; rehabilitation at earlier date may be more efficient. In our case, the rehabilitation of ACM denotes improvements by means of overlay or mill-and-replace action, which restores the original properties of ACM layer and thus shifts the layer to the beginning of its life cycle [15]. This extends the life cycle of up to 20 years. In terms of analytical computational structural method, the rehabilitation manifests itself by increased complex modulus of ACM and by adjusted thickness of the layer i . In Table 5, proposal rehabilitation is shown for three time periods of the life cycle, including rehabilitation at the end of the initial life cycle. The rehabilitation design lays in various increases of ACM layer thicknesses in relation to current state of the ACM material based on analytical calculation method [4]. The elastic modulus of ACM layer is shown for each rehabilitation action year and the calculated stress before and after rehabilitation. Rehabilitation design in thickness increase (millimetres), rehabilitation year, and extension of life expectancy are shown in Table 5. Graphically, individual variants of extended life in different years are shown in Figure 9.

6. Optimization and Economic Efficiency

The gist of optimization lies in selection of rehabilitation variant and year which maximizes economic efficiency and thus is optimal. For calculation of economic efficiency, rehabilitation

costs, increased maintenance costs, and increased user costs have to be considered in case of postponed rehabilitation or for variant without any rehabilitation. Maintenance and user costs increase proportionally during the entire life cycle with operational capability of the pavement surface. The optimal time of rehabilitation can be calculated with the use of Cost Benefit Analysis in which the extension of the original life and related maintenance and user costs are taken into account. Optimization is a mathematical relationship including all costs and ACM layer operation.

6.1. Cost Benefit Analysis. The economic efficiency analysis is carried out with the use of Cost Benefit Analysis (CBA). CBA evaluates positive impacts, benefits, related to improved operational parameters of the pavement in comparison to costs for applied rehabilitation actions. The Payback Period (PP), Internal Rate of Return (IRR), and Net Present Value (NPV) are economic indicators of CBA.

Benefits Generated by Rehabilitation Actions. Identification and calculation of benefits generated through rehabilitated ACM are a key factor for economic efficiency calculation. Benefits are calculated as a difference in road user costs before the rehabilitation action and decreased costs stemming from improved pavement parameters as a result of the rehabilitation action. Benefits may be internal or external. Internal benefits are the road user costs which consist of vehicle operating costs and travel time costs. External benefits are savings from emission, noise, and accident rate reduction. The road users costs which are under our research work are the vehicle operation costs, which include fuel consumption, lubricant consumption, car maintenance, wearing of tires, and travel time of cargo and passengers. To be able to calculate the value of benefits HDM coefficients are employed [3]. Road user costs are a function of the following factors:

$$RUC = VOC + TTC = f(TCH, OC, PCH, VFCH), \quad (11)$$

where RUC are road user costs [€]; VOC are vehicle operating costs [€]; TTC are travel time costs [€]; TCH is traffic characteristic, intensity and composition of traffic; OC is operational capacity; PCH are physical characteristics, horizontal and vertical alignment and category of the communication; VFCH is vehicle fleet characteristic, category of vehicles and their technical level (lorries up to 3.5 tons; lorries 3.5–12 tons, lorries over 12 tons; cars and buses).

TABLE 6: The results of the rehabilitation, maintenance, and user costs.

Variant	Variant scenario	Rehabilitation 5th year	Rehabilitation 10th year	Rehabilitation 15th year	Rehabilitation 20th year
Rehabilitation action	—	Overlay 36 mm	Overlay 52 mm	Overlay 62 mm	Overlay 71 mm
Investment cost	0€	69 084€	99 788€	118 978€	136 249€
Maintenance cost	846 938€	858 066€	941 350€	1 162 456€	1 581 330€
Road agency cost	846 938€	927 150€	1 041 138€	1 281 434€	1 717 579€
Road user costs					
Vehicle operating cost	8 316 431€	9 995 382€	11 689 165€	13 594 956€	16 045 362€
Travel time cost	822 241€	973 891€	1 125 826€	1 290 801€	1 569 194€
Total road user cost	9 138 673€	10 969 273€	12 814 991€	14 885 757€	17 614 555€
Life cycle length	20	25	30	35	40
Optimization index	0	475 857	461 871	461 920	483 303
CBA					
NPV	—	20 333€	26 739€	14 527€	1 438€
IRR	—	48.30%	155.10%	139.40%	99.50%
PP	—	6	11	15	20

Road user benefits are calculated as savings, that is, difference between higher road user costs prior to the rehabilitation action and lower road user costs after the rehabilitation action. Each rehabilitation method has its expected serviceability, defined by its pavement performance functions:

$$RUB = \sum_{t=1}^z [(RUC_{DS} - RUC_{DN}) \cdot k_{DEG} \cdot k_{ATG}]_t, \quad (12)$$

where RUB are road user benefits [€]; RUC_{DS} are road user costs in “do something” variant [€]; RUC_{DN} are road user costs in “do nothing” variant [€]; k_{DEG} is coefficient of function predicting condition of the pavement; k_{ATG} is annual transportation growth coefficient.

Calculation of economic efficiency for the experimental pavement section was performed on the basis of rehabilitation, maintenance, and user costs for different variants according to Figure 8. Quantification of road user costs was made for arterial road with usual traffic flow with yearly equivalent axle loads described in previous chapters. The results are shown in Table 6. Rehabilitation costs are market averages, and user costs were quantified with the use of Highway Development and Management Software endorsed by the World Bank.

6.2. Optimization Model. Based on the trend line for service life and economic efficiency model for optimization of costs was created. Optimization model allows for the estimation of “optimal time” for rehabilitation. Constantly evolving mathematical model [16] for the calculation of optimal time has three parts: pavement rehabilitation costs, maintenance costs, and user costs. Optimal time is calculated as the sum of construction costs for the rehabilitation, maintenance costs, and user costs before rehabilitation and after the action. This

sum of costs is divided by the number of years of newly extended service life. This is shown in (13). The model shows that the later we carry out the reinforcement, the more expensive the rehabilitation will be in terms of construction and user costs. Rehabilitation prior to the optimal time will produce little change to the user cost and small extension of service life. Even greater precision of this calculation optimal life is attained if we take into account the maintenance costs for variants with and without the rehabilitation. Optimization index is computed for each year of the whole service life.

$$OI = \frac{(RC + MC_{BR} + MC_{AR} + UC_{BR} + UC_{AR})}{Tt}, \quad (13)$$

where OI is optimization index; RC are rehabilitation costs [€]; MC_{BR} are maintenance costs [€]; MC_{AR} are maintenance costs [€]; UC_{BR} is sum of user costs before rehabilitation [€]; UC_{AR} is sum of user costs after rehabilitation [€]; Tt is the number of years of extended service life.

The optimization calculation was performed using economic efficiency data from Table 6. Two possibilities were considered, the first one includes the rehabilitation and maintenance costs, and the other one incorporates also the user costs.

The results, lowest optimization index value, indicate that the optimum results are obtained when the rehabilitation action is carried out in 10th year of the original life cycle; the rehabilitation type required is an overlay of 50 millimetres. Optimization index values and OI min value in particular are shown in Figure 10.

7. Conclusion

This paper describes topical issues of Asphalt Concrete Mixture life cycle assessment and optimization of this process on a case study for particular ACM layer. It elaborates

FIGURE 10: Optimization index calculation. (a) CBA without user cost; (b) CBA with user costs.

on the whole process of the calculation and derivation of characteristics for the selected type of ACM. It was proven that with the use of this methodology it is possible to characterize any ACM and its optimal life cycle. All the necessary characteristics are obtained by means of our own measurements and thus apply for the particular combination of material, climatic conditions, and traffic conditions. The actual definition of the life cycle—and the description of its characteristics—requires a design of methodology that consists of analytical computation methods and actual measurements on experimental pavement sections. This paper describes how the combination of these methods can be used to define life cycle and how different rehabilitation technologies performed in different periods of the life cycle can be evaluated when modelling life cycle extension. The aim of presented calculations and experiments is the finding of optimal time of rehabilitation of ACM surfacing layer, thus finding method to extend the life cycle for the lowest sum of economic costs. In first chapters of the paper, detailed analytical calculation method for pavement material design is described and its application for determining service life is presented. Experimental pavement section is described on which measurements were made to support this life cycle analysis method. The input physical and fatigue characteristics of the materials are described for materials constituting ACM surfacing layer of the experimental pavement section. These characteristics are shown in more detail, in order to provide the reader with application framework of these methods. Subsequently, the calculation of ACM life cycle and its extensions are presented. Values that are necessary to measure during pavement operation are derived from experimental pavement model. Economic calculations are made using common methods with the computation model of the World Bank. Optimization procedure is the result of research works.

Competing Interests

The authors declare that they have no competing interests.

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