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COMMUNICATIONS

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LIFE CYCLE EXTENSION OF A PAVEMENT STRUCTURE

The pavement structure, namely pavement surfacing must meet the criteria required to provide operational service during the whole life cycle of the pavement. Surfacing design composed of layer strengths and proposed materials is defined by design method which calculates the stress state during long-term transport and environmental conditions. The designed surfacing life cycle is defined in respect to traffic load acting on the pavement and road class for a period of about 20 years. Given the practical aspects of road administration, pavement reconstruction is usually due only at the end of the life cycle, when the original materials are replaced by new materials and the layer strength is re-evaluated. Since the overall life cycle of the whole pavement is significantly longer than that of the surfacing, it is necessary to consider possibilities to extend the life cycle of the surfacing either through various technologies, i.e. reinforcement, overlays or recycling. Timing of execution of such action plays a paramount role, and it has impacts on future financial flows of road administrator as well as economic aspects of transportation for the whole society. This paper describes analytical calculations and experimental measurements of surfacing materials, as well as accelerated pavement testing process needed for ascertainment of operational performance of a pavement construction during its life cycle. Finally, a case study encompassing the whole method is presented.

Keywords: *Pavement management system, life cycle extension, pavement surfacing, accelerated pavement testing.*

1. Introduction

Life cycle of a pavement surfacing should be modelled in advance of a pavement construction and it should be a corner stone of a successful long term administration of given road section. Design and evaluation of pavement surfacing 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, fatigue characteristics are defined as trend lines of asphalt material surfacing life-expectancy, 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.

Life Cycle of surfacing 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 surfacing life cycle itself can be defined by other means than fatigue characteristics, for instance, permanent deformation expressed through pavement unevenness, foremost rutting (transverse unevenness).

Based on surfacing 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 extend the original life cycle. In terms of efficiency, variants of the rehabilitation are evaluated by means of Cost Benefit Analysis (CBA) and mathematical optimisation model.

2. Experimental Pavement Model

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, this is called accelerated pavement testing (APT). The general principle of APT testing is to apply artificially inducted load similar to real life traffic load in a compressed time period, thus providing an expedited means of evaluating factors associated with traffic-pavement interaction. APT is essentially a full-scale laboratory test during which loaded truck wheels are used to traffic sections of full-scale road pavement constructed using conventional techniques.

In order to define surfacing lifecycle 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 [1] for a minimum level of traffic load - $2x10^6$ design axles. The pavement design of built experimental pavement

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section is shown in Fig. 1. Subgrade is simulated by a rubber layer on concrete with equivalent modulus of E_{def} 100 MPa. The complete APT tester is shown in Fig. 2. It is a Semi-mobile linear APT facility with axle load of 57.5 kN moving at 2.22 m.s^{-1}.

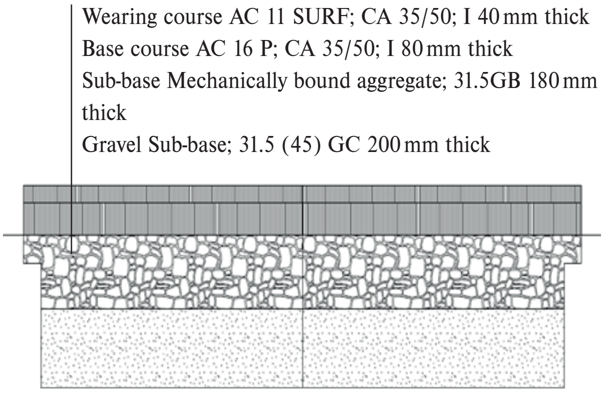

Fig. 1 Pavement Structure

Fig. 2 APT tester

Pavement structure layers are designed from generic materials defined in national standards. Table 1 contains material characteristics ascertained by the initial physical–measurement of surfacing materials. Two point bending test was used for this purpose. These values fall within the required interval for this particular type of pavement.

3. Asphalt Concrete Material Layer

3.1. Complex stiffness modulus

Measurement of complex stiffness modulus of a surfacing layer in the pavement structure was carried out according to national standard which is in compliance with European Union Standards [2]. Measurement of the complex stiffness modulus is performed with utilisation of short-term alternating harmonic load. It expresses the proportion of the maximum amplitudes of excitation tension and deformation induced by it and their phase shift. On the basis of measurements performed for different

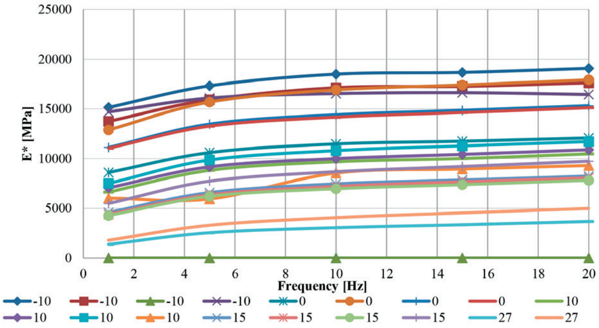

Fig. 3 E relation to frequency and temperature*

Material Characteristics of Pavement Layers Table 1

Layer	Complex modulus	Strength	Poisson number	Layer Thickness
AC 11 SURF	10891 MPa	3.2 MPa	0.3	40 mm
AC 16 P	8317 MPa	2.4 MPa	0.33	80 mm
MBA, 31.5 GB	586 MPa	0.1 MPa	0.25	180 mm
Gravel Sub-base, 31.5	365 MPa	0.07 MPa	0.3	200 mm
Sub-grade	100 MPa	-	0.3	-

Complex modulus of AC11 measured at different frequencies Table 2

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

temperature values ascertained are presented in Table 2 and Fig. 3.

3.2. Sub-base Layers

The measured values on sub-base layers are performed using an LDD and Clegg that, after conversion based on the equation (1) according to [3], were adjusted to CBR (California Bearing Ratio) values. The results are shown in chart in Fig. 4.

$$CBR_{STN721016} = 0.78 * CIV^{1.12} \tag{1}$$

Where:
CIV - Clegg impact value.

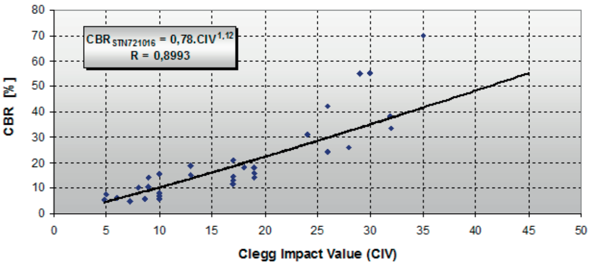

Fig. 4 Clegg and CBR Relationship

Subsequently, the CBR values were converted according to equation (2) [4] to (E_N) value with the use of following formula:

$$E_N = 17.6 * CBR^{0.64} \tag{2}$$

3.3. 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 [5].

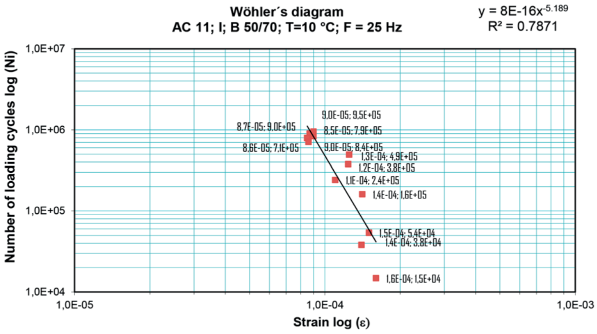

Fig. 5 Wohler diagram for AC 11 SURF

The results of research [6] carried out in the ambit of fatigue characteristics are presented in Fig. 5 and Table 3.

Values of fatigue parameters for mix AC 11 SURF — Table 3

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

4. Ascertainment of the Life Cycle

The life cycle of a surfacing layer 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 (Asphalt Concrete Material) 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 [7 and 1]. This method imposes structural value for the surfacing 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.

$$SV \geq \frac{\sigma_{ri}}{SN * R_i} \tag{3}$$

Where:
SV - structural value
σ_{ri} - radial stress,
R_i - strength,
SN - fatigue characteristic.

The calculated radial stress in the surfacing layer is calculated on the basis of the thickness of the layers, complex modulus and Poisson number by means of calculation in the layered elastic half space model [8]. 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 tonnes (2P = 100 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 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, i.e. constant temperature above + 10 °C.

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

$$S_N = a - b * \log N_c \tag{4}$$

where:
a, b – fatigue characteristics.

On the basis of fatigue characteristic measurements (chapter 3.1) for AC 11 SURF mixture, the values of fatigue coefficients a, b are:

a = 1, b = 0.11 (5)

The life cycle of ACM in the pavement construction can be expressed through the equation (1), on the basis of the stress calculation in pavement construction, 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 surfacing layer is at the end of their useful life and collapses. The length of life cycle therefore defines stress in the surfacing 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.

The life-cycle itself, expressed by utilisation of Structural values in accordance with equation 1 is shown in Fig. 6. Calculations show that the life cycle of a surfacing 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, which, for given traffic intensity, equals to life expectancy of 20 years.

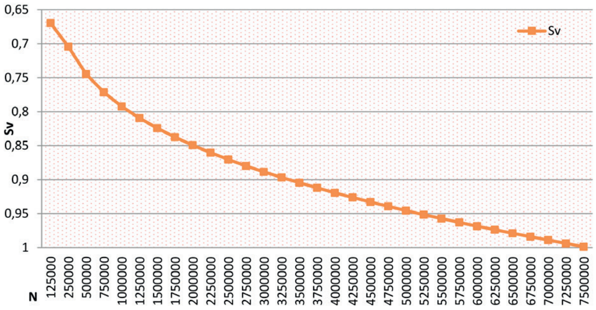

Fig. 6 Life cycle of surfacing in the pavement construction depending on the number of loading cycles

4.2. Permanent Deformation

Permanent deformations are induced by traffic loading and external environmental conditions such as temperature, humidity, radiation, etc. The material deteriorates to a point where it is no longer suitable from the viewpoint of operational characteristics, and thus ends its life cycle [9]. In contrast to fatigue and its relation to the residual life expectancy, which can be expressed by different coefficients [10], e.g. this can not be done for permanent deformation. It is foremost because of the fact that surfacing layer is, during deformation, neither 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 mathematical models environmental conditions are directly derived [11, 12 and 13]. 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 Fig. 7. Trend line of deformation in relation to load was derived and it is shown in Fig. 8.

Radial Stress and strength resiliency values in ACM layers based on Ni — Table 4

The number of Ni	0	1.5x10^6	3x10^6	4.5x10^6	6x10^6	**7.5x10^6**
AC 11 SURF 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

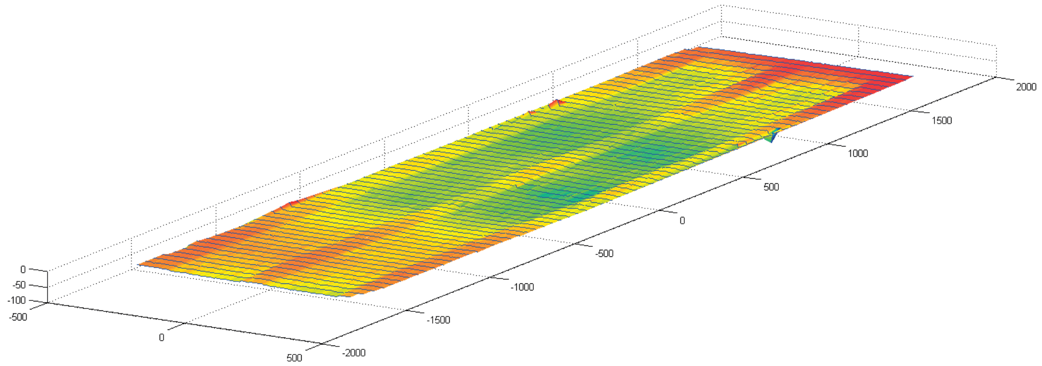

Fig. 7 Life cycle of surfacing in the pavement construction depending on the number of loading cycles - permanent deformations

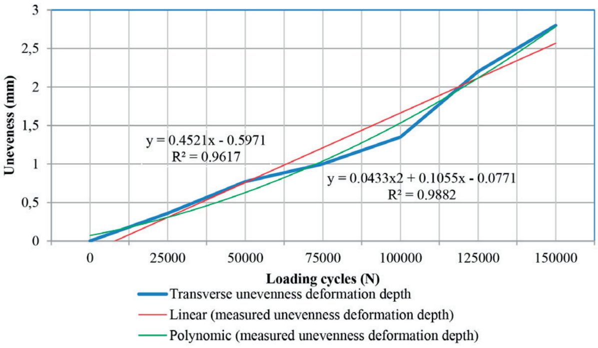

Fig. 8 Transverse Unevenness

5. Extension of the Life Cycle

The life cycle represents number of load repetitions acting on surfacing layer up to the state of a breakdown. For economic reasons, however, it may not be the cheapest or most efficient to wait until the very end of the surfacing life cycle, rehabilitation at earlier date may be more efficient. In our case, the rehabilitation of surfacing denotes improvements by means of overlay or mill & replace action, which restores the original properties of surfacing layer thus shifts the layer to the beginning of its life cycle [14]. 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 surfacing layer and by adjusted thickness of the layer i. In Table 5, proposed rehabilitation is shown for three time periods of the life cycle

Stress Calculations Before and After Rehabilitation Table 5

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 SURF 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

– rehabilitation performed in year 5, 10, 15 and rehabilitation at the end of the initial life cycle in year 20. Thus there are four scenarios: Rehabilitation in 5th year, Rehabilitation in 10th year, Rehabilitation in 15th year and Rehabilitation in 20th year. The rehabilitation design constitutes various increase of surfacing thicknesses (without milling) in relation to current state of the surfacing material based on analytical calculation method [1]. The elastic modulus of surfacing 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 Fig. 9.

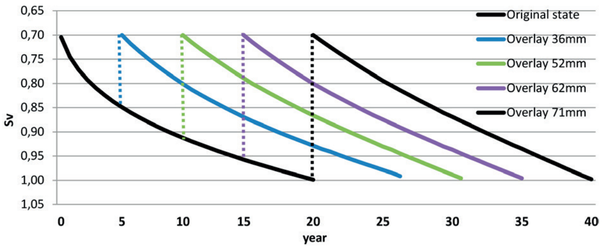

Fig. 9 Rehabilitation Design at Various Stages of the Life Cycle

6. Societal aspects and economic efficiency

The aim is to select rehabilitation variant and year which maximises economic efficiency, i.e. generates the most value for money. 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. Optimisation is a mathematical relationship including all costs and surfacing layer operation.

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.

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 Fig. 9. Quantification of road user costs was made for arterial road with usual traffic flow with yearly equivalent axle loads described in the previous chapters. The results are shown in Table 6. Rehabilitation costs are market averages, and user costs were quantified with the use of HDM-4 (Highway Development and Management Software) endorsed by the World Bank.

For quantification of user costs, vehicle fleet composed from personal car Skoda Octavia 1.6 TDI, light utility vehicle Fiat Ducato, medium truck Iveco Eurocargo, heavy truck Volovo FM9, articulated truck Volvo FH 12 + trailer Schwartzmuller and Bus Karosa C956. Their technical and economical parameters (unit

The results of the rehabilitation, maintenance and user costs Table 6

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
Optimisation 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

cost) were predefined in the HDM-4 calibration file for Slovak republic (unit cost were adjusted for year 2016). Vehicle travel speed was computed in the HDM-4 software, the road section was of average curvature (15 deg.km^{-1}) and level (2 m.km^{-1}). Speed limit was set to 90 km.h^{-1}. Vehicle operation costs and Travel time costs were subsequently calculate based on this imput. Accident cost were excluded from the computation since accident class of the road section wasn't influenced by the rehabilitation.

7. Conclusion

This paper describes topical issues of rehabilitation magnitude selection and timing of rehabilitation to ensure life cycle extension of pavement surfacing with consideration to economic efficiency of this process. The methods described in this article are based on analytical computation methods and actual measurements on experimental pavement section with the use of accelerated pavement testing. These methods are used to defined life cycle and ascertain how different rehabilitation technologies performed in different periods of the life cycle, this can be evaluated when modelling life cycle extension of the pavement surfacing. The aim of presented calculations and experiments is the search for optimal technology and time of rehabilitation, i.e., identification of methods to extend the life cycle for the lowest sum of economic costs. The calculations of surfacing life cycle and its extensions which are presented in this article are exemplificative, yet applicable in real life conditions. 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.

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