A Life Cycle Cost Approach based on the Calibrated Mechanistic Asphalt Pavement Design Model

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ABSTRACT:

Life Cycle Cost Analysis (LCCA) provides cost estimation over the life time of a project and thereby helps road administrations, designers, and contractors with choosing an economical design. Calculation of the costs can be based on a pavement design model, such as the Calibrated Mechanistic model (CM), in order to capture the mechanical behaviour of the asphalt pavement. This study aimed to develop an approach for performing comparative LCCA in order to find the most economical design alternative in terms of the total cost for the pavement design life. The integrated LCCA-CM approach was used to evaluate different design alternatives with different rehabilitation intervals for asphalt pavements.

KEY WORDS: Life Cycle Cost, Calibrated Mechanistic Design Model, Asphalt Pavements

1. Introduction

Roads are one of the most important parts of the infrastructures and they play a key role in development of the society all around the world. Despite having a crucial part in national economy, road network systems imply high economic burdens on the road agencies. In order to keep the quality of the roads above an acceptable level, large amount of investments for rehabilitation and maintenance activities are necessary. The case of not being able to provide those funds will result in a poor road's safety and operational condition.

Life Cycle Cost (LCC) is the total discounted cost for construction, operation, maintenance, and disposing of a facility during its defined life time. Life Cycle Cost Analysis (LCCA) is an economic evaluation method to obtain the total cost of construction, operation, maintenance, and demolition for a property during its life time [8]. By providing cost estimation over the life time of a project for initial construction cost and all the related costs for rehabilitations and maintenances, LCCA helps the designers, road administrations, and contractors with choosing the most economically efficient design for the roadways. Thus LCCA can be used as a basis for more optimized investments [1]. The American Association of State Highway and transportation Officials of 1986 and 1993 describe the different costs that must be considered in LCCA. The agency and the user costs associated with pavement projects and also economic evaluation methods and discount rate is also discussed in the guide [2]. The center for Transportation Research (CTR) developed the Flexible Pavement System, a methodology and software to compare the total design life costs for different alternatives [4].

In order to perform LCC on roads a prediction on the life time of the road, corresponding thicknesses of structural layers as well as the eventual rehabilitations are required. To calculate the asphalt design thickness for an assumed number of years, the Calibrated Mechanistic design (CM) model can be used. This study aimed to develop an approach for performing comparative LCCA in order to find the most economical design alternative in terms of the total cost during the pavement design life. In this approach a LCCA was performed based on design predictions by the CM flexible pavement design model. A case study was performed to compare design alternatives with different rehabilitation intervals to determine the optimum design in terms of LCC.

2. Calibrated Mechanistic Design

The HMA Fracture Mechanics model predicts crack initiation and propagation based on viscoelastic fracture mechanics principles [5]. Within the model Energy Ratio (ER) is introduced as a function of dissipated creep strain energy, which is used as an indicator to distinguish between pavements that exhibit cracking and those that do not (Equation 1). The minimum required ER as a function of traffic level and reliability is defined as optimum energy ratio (ER_{opt}) [7].

$$ER = DCSE_f / DCSE_{min} \quad [1]$$

The initiation and propagation of cracks in asphalt pavements can be predicted by comparing the Dissipated Creep Strain Energy to failure ($DCSE_f$) against the minimum Dissipated Creep Strain Energy $DCSE_{min}$ of the mixture. Dissipated $DCSE_f$ is defined as the non-elastic part of fracture energy as shown in Figure 1.

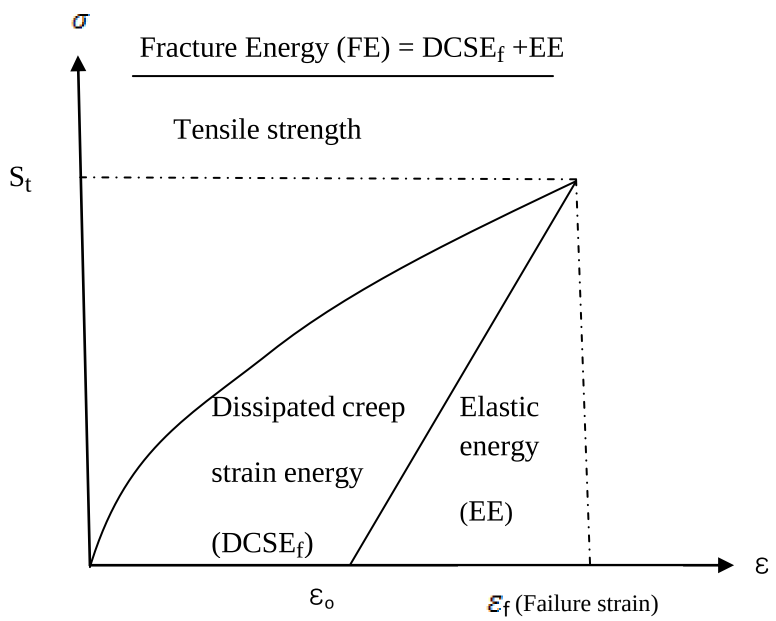

Figure 1. *Illustration of Dissipated Creep Strain Energy*

According to the HMA fracture mechanics the minimum dissipated creep strain energy ($DCSE_{min}$) of asphalt mixtures represents a fracture damage threshold. Below the threshold damage is considered to be healed after a resting period. When the damage exceeds the threshold crack initiation or growth will occur which is not going to be healed in the resting period. In order to calculate $DCSE_{min}$ the tensile stress (σ_t), tensile strength (S_t), and the creep compliance parameters m and D_1 need to be determined, see Figure 2. The design premise is to obtain the AC layer thickness which has an energy ratio corresponds to ER_{opt} [10]. The design model which is evaluated and calibrated for Sweden [3] is used in this study. The model was based on linear elastic analysis, and the failure mechanism taken into account was cracking.

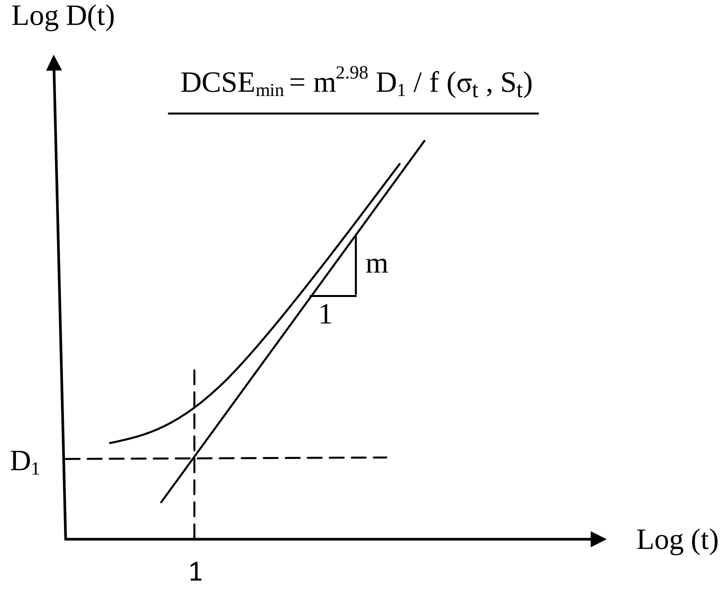

Figure 2. *Illustration of Creep Compliance curve and DCSE*

3. Life Cycle Cost Analysis (LCCA)

LCCA is a method to evaluate the overall economic efficiency of competing alternates by incorporating the initial cost and discounted future costs over the design life of the pavement [6]. As well as being used as a decision support tool for selecting pavement type, LCCA can also be used to evaluate different rehabilitation strategies. The first step in LCCA is then to identify the design alternatives. Each pavement design alternative consists of an initial design and time dependent maintenance or rehabilitations activity [6].The total LCC consists of the agency costs and the road user costs. The agency cost is the direct costs related to the construction and maintenance of the project and user costs are those related to delay and Vehicle Operating Cost (VOC) during the maintenance activity. The road user's costs included in LCCA are those related to queuing, and delays during the rehabilitation activities. The user cost can be calculated based on the required time for the rehabilitation activity the level of traffic at the time of the rehabilitation activity and corresponding delay and vehicle operating costs.

4. Suggested approach

An approach suggested using the outputs from the CM design model to achieve the initial construction cost and also the future rehabilitation costs. The calculation for the construction cost is based on the unit cost for the asphalt, and the optimum design thickness of the asphalt layer for a specific case. The rehabilitation cost can be obtained in correspondence to the required thickness of the overlay and the unit cost of overlay. Different alternatives can be selected with deferent rehabilitation intervals. The total costs during the design life for each alternative consists of the initial construction cost, summation of the rehabilitation costs, and the user costs (Figure 3).

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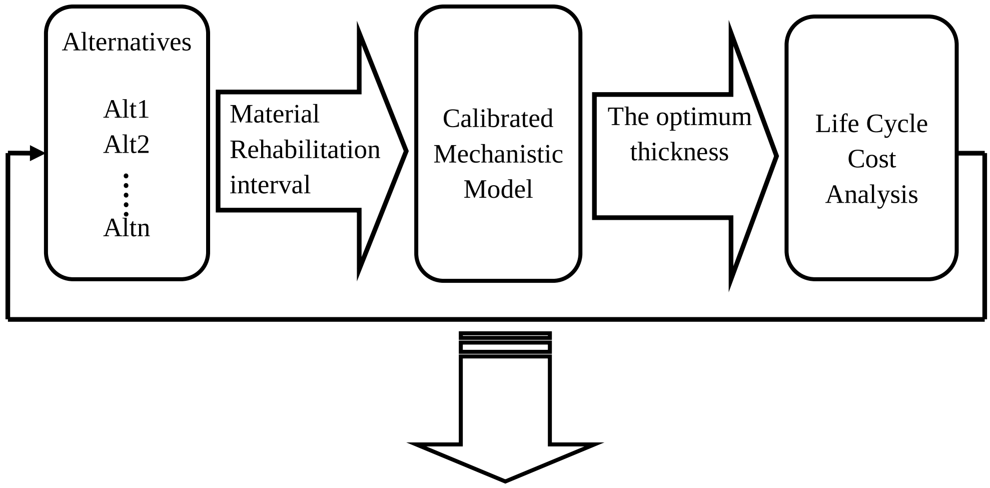

Figure 3. *Integration of LCC and CM*

5. Case Study

In this study three different alternatives were compared considering their Net Present Value (NPV). The analysed pavement profile consists of 50 mm wearing course above the asphalt layer, 80 mm base course, and a 420 mm sub base (Figure 4). The wearing course is asphalt concrete ABT 11 which is dense graded mixture with a maximum aggregate size of 11 mm. The AC layer assumed to be AG 22 which is an asphalt-bound base layer with a maximum aggregate size of 22 mm. The binder is B160/220, and the binder content assumed to be 6% and 4,5% for ABT11, and AG22 subsequently. The mean annual air temperature was assumed to be 5℃ which can be representative for climate in the central part of Sweden, and was assumed to be constant throughout the design life.

The design premise for each alternative was first to find the optimum thickness of the AC-layer AG 22 below the wearing course ABT 11, and then the overlay ABT 11 thicknesses for the rehabilitation activities.

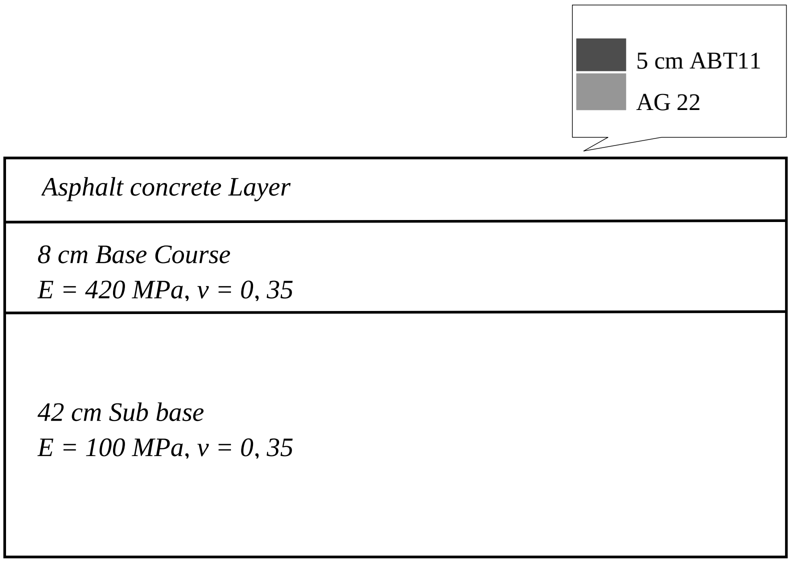

Figure 4. *The pavement profile for the analyzed alternatives*

Three alternatives were chosen with 6, 9, and 18 years rehabilitation intervals during the design life. The first alternative required rehabilitations at the 6^{th} and 12^{th} year and the second alternative required rehabilitation at the 9^{th} year. In each rehabilitation activity a layer of ABT11 was assumed to be added to the pavement. The thickness of the overlay corresponded to the ER equal to ER_{opt} at the design life of the overlay.

The Swedish distribution of costs per ton for asphalt material, regarding both the asphalt layer and overlay was investigated and showed to follow a normal distribution curve (Figure 5). The cost distribution is a function of different factors, such as cost of material (Bitumen, aggregate), transport costs, costs of storage and manufacturing, establishment costs, safety, existing pavement features, existing pavement. The cost of bitumen is probably the most important factor as the mixture with higher bitumen content has a higher average cost (Figure 5).

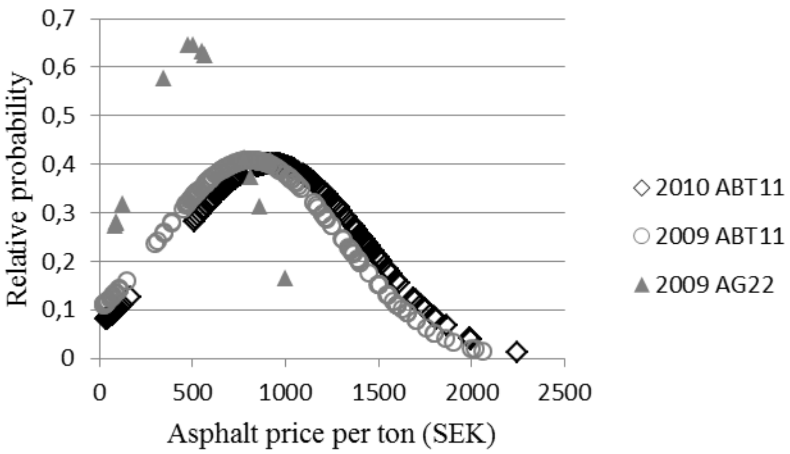

Figure 5. *Price distributions for asphalt layer and overlay*

The initial thickness of the asphalt layer AG22 for each alternative was calculated corresponding to the ER equal to ER_{opt} at the first rehabilitation activity. The overlay thickness ABT11 was obtained according to the required ER at the next rehabilitation activity or the end of the design life. The pavement life curves for the compared alternatives show the initial thickness and the overlay thickness for the asphalt layer as a function of material properties, Reliability (R), and number of Equivalent Single Axel Loads (ESALs)in each rehabilitation interval (Figures 6-8). The axel load for a dual tire was assumed to be 25 KN, and tire pressure was 800 kPa. Each curve which represents the degradation of the pavement reaches to the minimum required ER before the rehabilitation activity. By adding an overlay the ER increased to a new ER_{opt} which corresponded to the level of traffic in the rehabilitation interval.

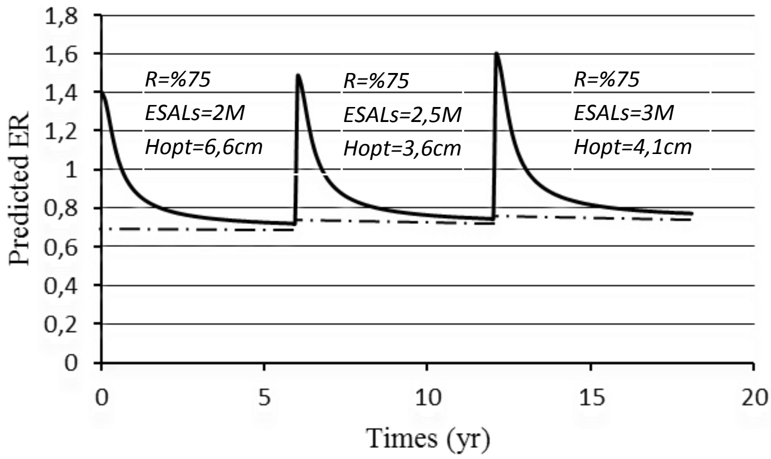

Figure 6. *Pavement life curve for 6 years rehabilitation intervals.*

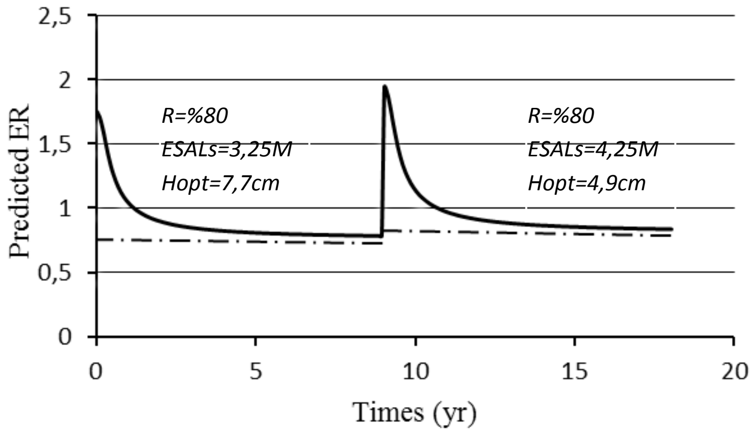

Figure 7. *Pavement life curve for 9 years rehabilitation intervals delete*

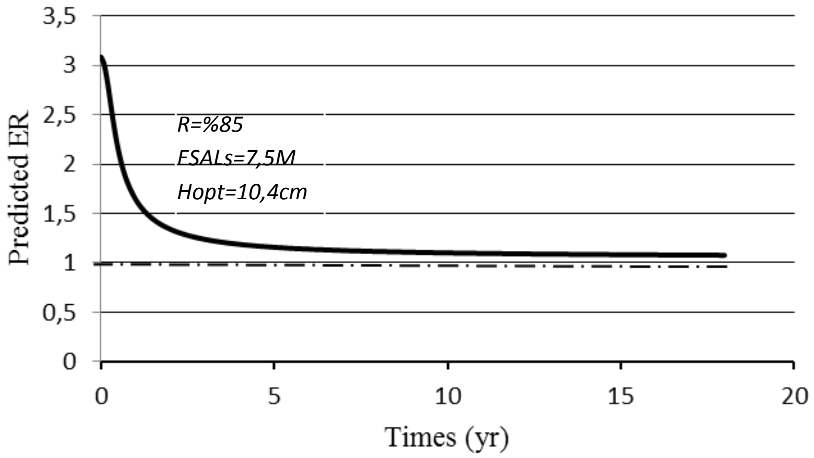

Figure 8. *Pavement life curve for no rehabilitation*

The construction cost and undiscounted rehabilitation cost for each alternative was calculated based on the average cost from the Figure 5. According to the results the alternative with thicker initial asphalt layer and no rehabilitation resulted in lowest total cost (Figure 9).

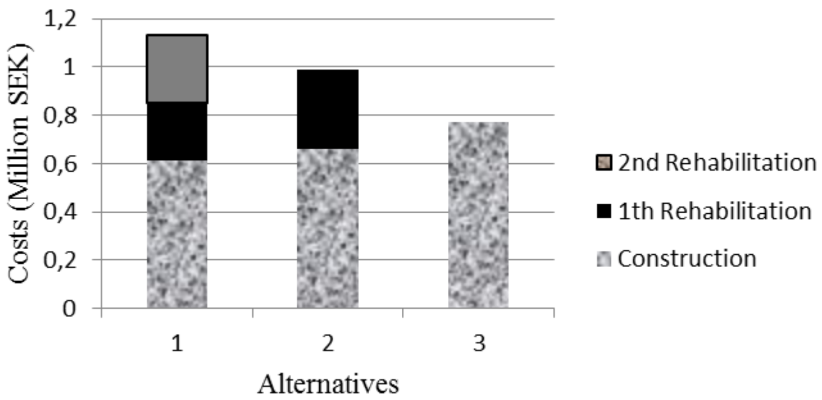

Figure 9. *Undiscounted costs for alternatives: (1)6 years rehabilitation intervals. (2) 9 years rehabilitation intervals (3) No rehabilitations*

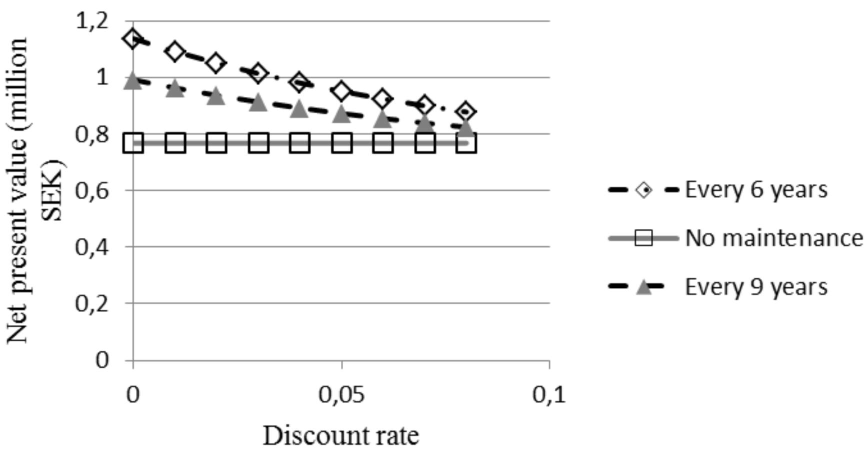

Figure 10. *Sensitivity of the total cost to the discount rate*

According to the sensitivity analysis higher interest rate benefited the alternatives with lower initial costs. However, even when assuming a high discount rate the alternative with no rehabilitation during the 18 years of design life had the lowest total NPV (Figure 10).

Since the study aimed to be a comparative LCC and including the traffic cost would favour the alternative with no maintenance the traffic cost has not been included in the case study. Although the user cost during the maintenance activities is an important part of the road life cycle and should be considered in standalone LCC studies.

6. Conclusions

Utilization of the CM design model for asphalt pavements enables a prediction of the pavement LCC based on the pavement performance as determined by the mechanical properties of the mixture. An approach was suggested in which a comparative LCCA, with input from the CM design model, is performed in order to find the most economical design alternative in terms of the total cost during a pavement design life. When the approach was used in a case study it was observed that designing a thicker pavement which requires less frequent rehabilitation activities could result in a lower total cost. However, this result was sensitive to the interest rate.

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