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HIGH AIR-VOID VOLUME IMPLICATIONS FOR ASPHALT CONCRETE SERVICE-LIFE AND PRICE PENALTY

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ABSTRACT

In road industry, the construction of asphalt concrete layers is a dynamic process that, if not properly done, will lead to problems compromising the pavement performance. One of the most common problems is poor compaction leading to air-void volume above the maximum acceptable. This study discusses the impact of compaction/density deficiencies and presents an innovative model to calculate the asphalt pavement service-life loss in a simple and objective way, and in line with the road construction managers needs to calculate price penalty for contractors. The model was optimized for dense graded asphalt concrete, that typically has a maximum acceptable air-void volume between 4% and 7%.

KEYWORDS

Asphalt Concrete, Density, Air-Void Volume, Service-Life, Modelling, Contract, Penalty

INTRODUCTION

Asphalt pavements constitute a critical factor for road transportation infrastructure worldwide. Its long-term cost is continuously rising with the increasing of prices of its components, especially bitumen, gravel and labor.

The density is one of the most important parameters in construction of asphalt concrete (AC) layers and its proportion of air-voids is probably the single most important factor that affects performance and service-life for asphalt pavements; thus the compaction is an important factor that affects pavement performance in terms of durability, fatigue life, resistance to deformation (rutting), strength and moisture damage [1] [2].

The failure in obtaining the required density for AC layers is a rather common problem and requires a scheme for evaluating the loss in service-life and an appropriate price reduction penalty for contractors. There are surprisingly few studies or consolidated technical procedures to evaluate the impact in the pavement performance or how to calculate a suitable price penalty for those cases. Hence, in lieu of guiding documents unnecessary and painful negotiations between transportation agencies and contractors are frequent.

The present study is a practical and objective approach to calculate the service-life loss for dense graded asphalt concrete caused by deficiency in too low density, that is, air-void volume higher than the maximum specified in the applicable standards or as contracted. The reduced life can then be used as a parameter to specify contract penalties.

LITERATURE REVIEW

A review of available studies conducted in 2016 at the National Center for Asphalt Technology (NCAT), on the densification/compaction of AC and its implications for durability and service-life, found 5 studies citing fatigue service-life implications and 7 studies citing rutting. In general terms, this literature review found that an 1% decrease in air-voids was estimated to improve the fatigue performance of asphalt pavements between 8.2% and 43.8%, to improve the rutting resistance by 7.3 to 66.3%, and to extend the service-life by conservatively 10%. Based on these results, NCAT conducted a life-cycle cost analysis (LCCA) for AC with two alternatives of density, 92% and 93%. The LCCA results show that the user agency would see a net-present-value cost savings of $88,000 on a $1,000,000 paving project (or 8.8%) by increasing the minimum required density by 1%. Higher AC density also has impacts on road operation, maintenance and road users' cost [3].

In Australia, the Pavement Work Tips No.17 published the results of an interesting study where an asphalt concrete mixture with different air-void volumes was tested. It shows the increasing of air-voids from 5% to 8% leads to fatigue life reduction of about 50% (Fig. 1), a reduction of AC modulus by 20% (Fig. 2) and an increase of about 75% in rutting depth (Fig. 3) [4].

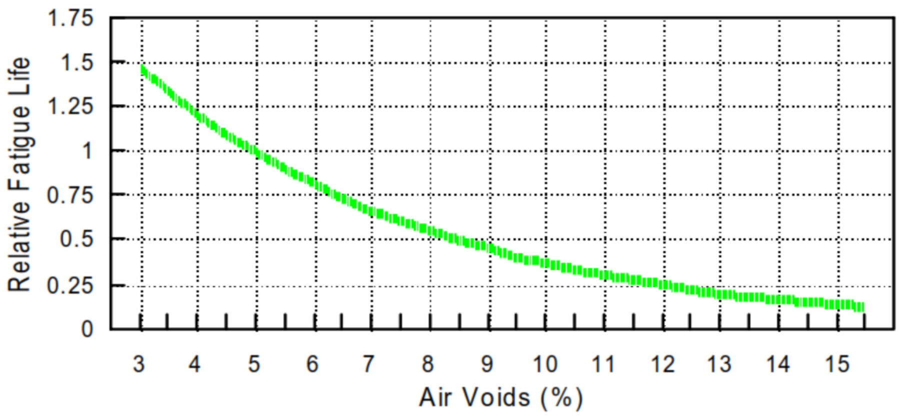

Fig. 1 – Fatigue life versus air-voids for asphalt concrete [4]

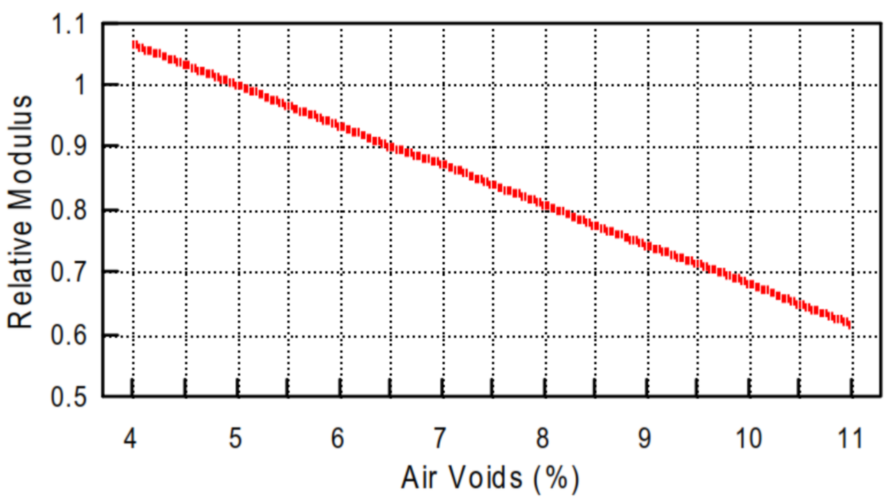

Fig. 2 – Relative modulus versus air-voids for asphalt concrete [4]

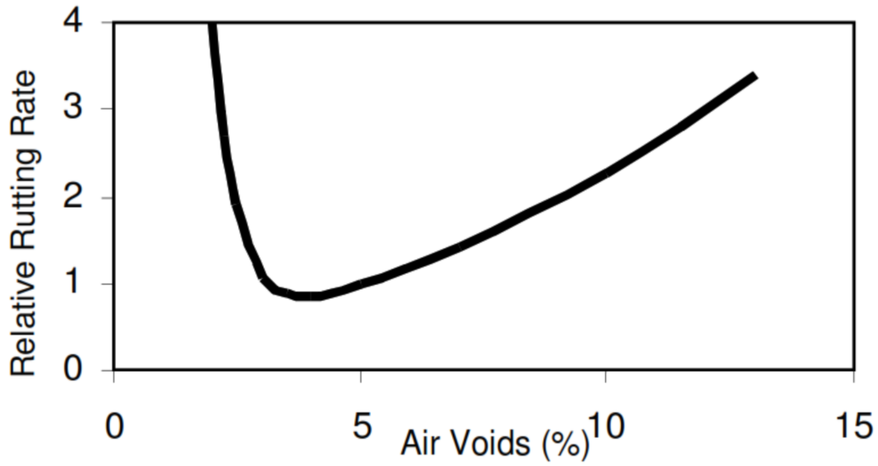

Fig. 3 – Relative rutting versus air-voids for asphalt concrete [4]

In United States, the Kentucky Transportation Center (KTC) conducted a research to identify factors affecting the asphalt concrete density and its influence on long term pavement performance. It was found that reducing the air-voids from 11% to 7% leads to an increase of 50% in fatigue life [5].

A summary of studies showing the impact of 1% increase in air-voids for was presented by Aschenbrener at the FHWA Asphalt Mixture - Expert Task Group meeting in 2016 [6]. It shows a reduction in AC fatigue life between 8.2% and 43.8% (Tab. 1) and an increasing in rutting depth between 7.3% and 66.3% (Tab. 2).

Tab. 1 - Fatigue life versus air-void volume [6]

Study	Lab/field	Mix type	Air-voids evaluated	Reduction in fatigue life for 1% air-voids increase
UC Berkeley (1969)	Lab	British Std	4 - 14%	20.6%
		CA Fine	5 - 8%	43.8%
		CA Coarse	2.5 – 7%	33.8%
UCB (1996)	Lab	CA Dense Graded	1 - 3%	15.1%
			4 - 6%	
			7 - 9%	
WesTrack (2002)	Lab	Fine	4, 8, 12%	13.5%
		Fine-Plus		13.3%
		Coarse		9.0%
	Field	Fine/Fine-Plus		21.3%
		Coarse		8.2%
AI (2010)	Lab	9.5 mm Dense	4 – 11.5%	9.2%

Tab. 2 - Fatigue life versus air-void volume [6]

Study	Lab/field	Mix type	Air-voids evaluated	Final field ruth depth (mm)	Increase in ruth depth for 1% air-voids increase
WesTrack (2002)	Field	Fine/Fine-Plus	4, 8, 12%	9 - 35	11.5%
		Original Coarse		13 - 36	9.6%
		Replacement Coarse		12 - 26	66.3%
		Fine/Fine-Plus/Coarse		9 - 36	7.3%
		Replacement Coarse		12 - 26	10.9%
AI (2010)	Lab	9.5 mm Dense-Graded	4 – 11.5%	N/A	22.7%

In 2015 Wang and others developed a procedure based on life-cycle cost analysis (LCCA), for price reduction for in-place air-void of asphalt pavements, using data of projects constructed in New Jersey from 1995 to 2005 and pavement condition index (PCI) extracted from the pavement management system. Empirical pavement performance models were developed with sigmoidal functions and Monte Carlo simulations were used to capture the uncertainty of overlay service-life. This is a quite complex approach where the price reduction may be affected by the considered maintenance strategy and other variables [7].

In 1989 Linden and others [8] published the "*Effect of Compaction on Asphalt Concrete Performance*" with the results of an extensive research to evaluate the loss of service-life of dense graded asphalt concrete due to air-voids. The study comprised three data-sets, (1) from a literature review, (2) a robust research at the American State Highway Agencies (SHA) and (3) data from the Washington State Pavement Management System (WSPMS). According to the authors "*the rule-of-thumb that emerges is that each 1 percent increase in air-voids (over a base air-void level of 7 percent) results in about a 10 percent loss in pavement life*". The conclusions of this research are suitable only for the cases where the maximum acceptable air-void volume base-line is 7%; for all other cases such a rule can be subject of discussions and disputes [8].

AIR-VOID VOLUME MEASUREMENT AND CALCULATION

The required air-void volume usually is specified in contracts or standards as an envelope, with minimum and maximum acceptable characteristic values. For example: minimum characteristic air-voids = 2%, and maximum characteristic air-voids = 6%.

The way the characteristic air-void volume is calculated is another important aspect to be considered. The voids are usually measured in extracted cores or with nuclear densometer, that is an evaluation by sampling. Given such sampling nature the results must be evaluated from a statistical perspective, for every constructed pavement lot. At Fiji Roads Authority, for example, the way the characteristic values are calculated is specified at the standard FRA 5100:2020 considering the available number of measurements/cores, the standard deviation and the producer risk [9]. Other agencies usually adopt similar procedures.

MODEL DEVELOPMENT

In an ideal world all AC layers will be constructed with the air-voids inside the required envelope, but this frequently does not happen, forcing project managers and contractors to negotiate a price reduction. Despite to be an important problem, surprisingly there are almost no studies proposing technical parameters for price reduction that are easy to implement and also reflect the true cost for the loss of the predicted life.

In the present study an innovative model to calculate the AC service-life loss for any air-void requirement in the typical range of dense graded AC (4% to 7%) is presented. This model can also be used as a parameter for price reduction. The model was constructed by performing a reanalysis of two data-sets synthesis, literature review and SHA survey (Tab. 3), originally published by Linden and others [8], that are considered the ground truth. This generalized model allows to by-pass the limitation of the original authors' conclusion, that have a fixed base-line of 7% for air-voids.

The base data (Tab. 3) was plotted and a power trendline equation was calculated (Fig. 4). The trendline equation was then used as basis for engineering an adaptative mathematical formula by doing intensive computer-based simulations. The final developed and optimized model is presented in Eq. 1. It has three components and considers the life loss at the constructed air-void volume (Eq. 2.a), the theoretical life loss at the maximum acceptable air-void volume (Eq. 2.b) and an adjusting component (Eq. 2.c) that was optimized to improve the model's accuracy. The adjusting component (Eq. 2.c) was constructed in a way that keeps the model's mathematical consistency, showing service-life loss equal to zero (L = 0) when the contracted and constructed air-voids are equal (A = B). To evaluate the model's performance, its predictions compared the base data are shown in Fig. 5.

The situations where the model is needed and can successfully be used are shown in Tab. 4. It is important to mention the model is not suitable to evaluate the pavement service-life loss resulting of constructed characteristic air-void volume smaller than the minimum acceptable; for those cases other procedures must be used.

Tab. 3 – Base data for model's development [8]

Source	Air-void volume (%)	Pavement life reduction (%)
Literature review [8]	8	10
	9	20
	10	30
	11	40
	12	50
SHA Survey [8]	7	7
	8	13
	9	21
	10	27
	11	38
	12	46

$$\boldsymbol{L = \left(0.00663 \cdot B^{3.61035}\right) - \left(0.00663 \cdot A^{3.61035}\right) + \left[\left(\frac{B}{A}\right)^{2.15} - 1\right]}$$

Where:

A: Maximum acceptable air-void volume according to the applicable standard or contract (%)

B: Air-void volume of the constructed asphalt concrete (%)

L: Asphalt concrete service-life loss (%)

Eq. 1 – Model to calculate the service-life loss for dense graded asphalt concrete

Tab. 4 – Scenarios where the model is valid and/or needed

Scenario	Interpretation
B > A	the model is suitable to calculate service-life loss and price penalty
B = A	the model will report service-life loss equal to zero
L ≥ 100	the AC pavement will have a marginal service-life only
B ≤ A	there is no service-life loss because of air-void volume (model's calculation is not needed)
B is smaller than the minimum acceptable characteristic air-void volume	this model is unsuitable

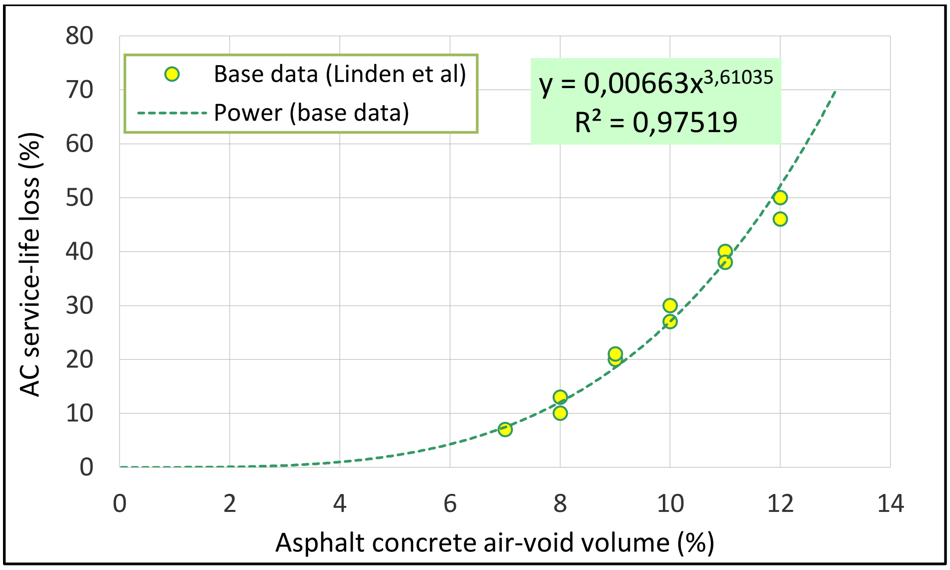

Fig. 4 – Asphalt concrete service-life loss according to the air-void volume

$$L = \overset{\textbf{a}}{\boxed{\left(0.00663 \cdot B^{3.61035}\right)}} - \overset{\textbf{b}}{\boxed{\left(0.00663 \cdot A^{3.61035}\right)}} + \overset{\textbf{c}}{\boxed{\left[\left(\frac{B}{A}\right)^{2.15} - 1\right]}}$$

Eq. 2 – Components of the engineered model

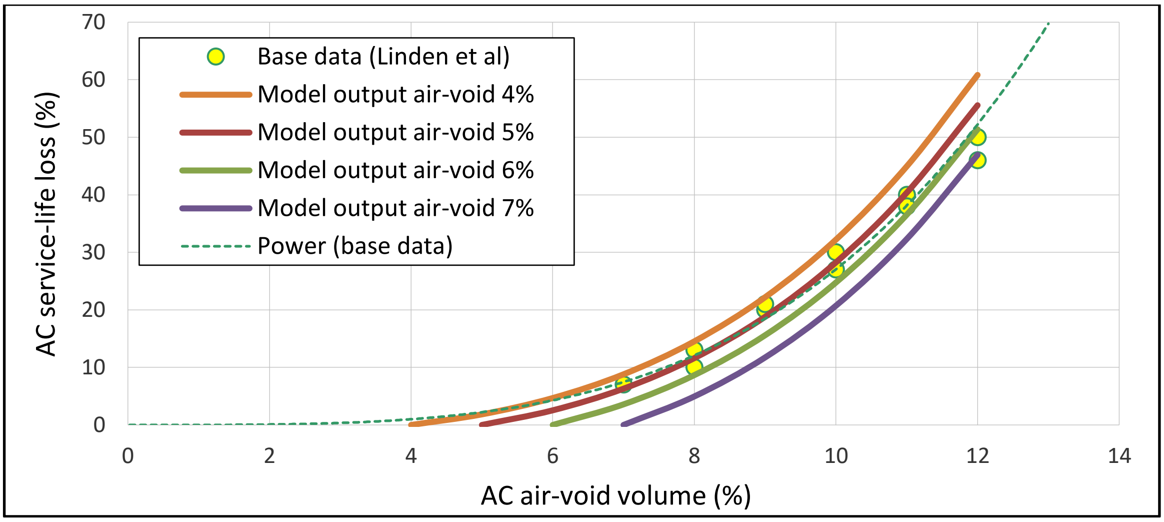

Fig. 5 – Base data versus model output (Eq. 1) for maximum allowed air-void volume of 4% to 7%

EXAMPLE OF SERVICE-LIFE LOSS CALCULATION AND PRICE PENALTY

In this example is considered a contract rate of \$100.00/m^2 for the AC meeting the contract requirement of a maximum characteristic of air-void volume of 6%, but the constructed pavement was found with a characteristic air-void volume of 8%, for the analyzed construction lot. (This example does not consider other problems that eventually are present, such as bitumen content outside the required range, aggregate grading outside the envelope, AC thickness smaller than contracted, and others.)

A = 6

B = 8

Eq. 1:

$$L = (0.00663 \cdot 8^{3.61035}) - (0.00663 \cdot 6^{3.61035}) + \left[\left(\frac{8}{6}\right)^{2.15} - 1\right]$$

$$L = 8.66$$

Conclusion: the asphalt concrete lost 8.66% of its expected service-life. Remaining service-life is 91.34%.

Price penalty

Rate for AC with maximum characteristic air-void volume of 6%:	\$ 100.00/m^2
Penalty because of constructed air-void volume is 8%:	8.66%
Rate to be paid for AC after penalty:	\$ 91.34/m^2

CONCLUSION

A consensus exists among researchers and departments of transportation regarding the negative impact of high air-void volumes on the asphalt concrete service-life and, for road construction projects, the need to apply a price penalty for contractors. The existing studies on the subject are few and usually don't provide an objective and practical way to evaluate the impact of excessive air-voids on the pavement performance nor calculate a price penalty.

The developed model can be used with success to calculate the service-life loss of dense graded asphalt concrete resulting of air-void volume above the maximum allowed by contracts or standards, and to calculate contract price penalties for such cases.

The mode is not suitable for cases where the constructed AC has air-void volume lower than the minimum acceptable, and does not consider other problems that may be present in the same pavement, such as bitumen content outside the required range, aggregate grading outside the envelope, AC thickness smaller than contracted, and others that also affect the service-life and may lead to price penalties.

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