Asphalt mixture performance and testing

End result verification for performance based project delivery

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Abstract

With the introduction of the European Standards for asphalt in 2008 the Netherlands has chosen the fundamental approach for the specification of properties of asphalt concrete. In this approach the mechanical properties of the asphalt are determined by laboratory type testing; a standard set of fundamental asphalt tests. The results are declared on the Declaration of Performance of the asphalt and are direct input for pavement design calculations. A major disadvantage of the fundamental approach, however, is that the responsibility of the asphalt producer for the specified mechanical properties ends at the gate of the asphalt plant. This is in full contradiction with the common knowledge that asphalt concrete only develops its mechanical properties in practice after transport, application and compaction. Nowadays quality control of a finished asphalt pavement is still based on the evaluation of only empirical properties which might have worked in the past for the very limited types of asphalt composed of straight run bitumen, but do not suffice any more in the current practice with different types of bitumen production, polymer modifications and the large scale introduction of additives and bioproducts. Since 2014 the Dutch contractor Boskalis started working on a new framework for performance based evaluation of constructed pavements. This framework is based on the use of fundamental asphalt tests as is done for the determination of the performance based mix specifications for CE marking. One of the most important boundary conditions is that all tests within this framework can be performed on asphalt cores and a direct comparison of the mechanical properties of the type test and the constructed asphalt can be done. For the comparison of the fatigue behavior a dissipated energy based analysis method was developed. The first results of the practical use of this framework are presented in this paper.

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1. BACKGROUND

1.1. Context

The type test consists of a fixed set of tests specifically selected for each type of mix. When the CE Marking was introduced in 2008, the Netherlands opted for a fundamental approach to these mix specifications. Since then, asphalt has been specified based on mechanical properties that are representative of the actual behaviour of the material in the road. These fundamental properties, resulting from the type test, now serve as direct input for the pavement design. As a result, the pavement dimensions are perfectly matched to the properties of the asphalt used and are therefore more efficient in terms of costs and aspects alike.

The missing link in the chain is the relationship between the measured mechanical/fundamental properties used in the design and the asphalt properties attained in the field. Information about differences between attained and laboratory properties is important, both for determination of design safety factors and because it enables to demonstrate that the designed and achieved pavements are at least equivalent in terms of the established safety factors and tolerances. At present, quality control of the processed asphalt is still largely based on empirical rather than fundamental properties, which means that discussions at the time of delivery of the work are still too focused on values that no longer are relevant to the quality of the work.

Due in part to the large-scale use of reclaimed asphalt, composite fillers, modified binders, and all kinds of aggregates in asphalt, the current quality control based on composition and degree of compaction says too little about the functional quality of paved asphalt. Clients are therefore increasingly concerned about whether the delivered product will provide the contractually agreed performance levels. The development and, above all, practical implementation of End Result Verification is therefore necessary.

1.2. Aim of End Result Verification

End Result Verification means assessment of whether the delivered product is in conformity with the specifications, within tolerances to be further defined, in accordance with the type test, on the basis of fundamental tests of the asphalt after incorporation.

2. METHODOLOGY FOR END RESULT VERIFICATION

In 2014, Sluer and Stigter [1] discussed four viable methodologies for End Result Verification. Verification of the asphalt quality through conduct of the same fundamental tests as for the type test on material from the field was the preferred option. Relevant properties and suitable tests have therefore been selected for the End Result Verification of incorporated asphalt. Table 1 shows an overview of the selected properties and tests.

One of the important advantages of the chosen methodology is that it allows a direct comparison of fundamental properties. After all, most test set-ups, specimen sizes, and test conditions are identical. It follows from table 2.1 that, except for the fatigue resistance and stiffness modulus, a direct comparison can be made between the specified and attained asphalt quality. Only the properties determined by the four-point bending test (4PB) are compared, to the same properties, but then as determined by the Cyclic Indirect Tensile Test (CIT-CY). After all, it is very impractical and even undesirable to cut and remove prismatic samples from the completed work for testing in the laboratory. As such, special care is required for determination of the stiffness modulus and fatigue resistance.

Table 1: Tests for end result specification and verification of asphalt concrete

PROPERTY	TYPE TEST	END RESULT VERIFICATION
	TEST	TEST
Target composition	--	Extraction
(Target) density	Dry and underwater weighing	Dry and underwater weighing
Strength/Water sensitivity	Static Indirect Tensile Test	Static Indirect Tensile Test
Resistance against permanent deformation	Triaxial test	Triaxial test
Fatigue resistance	Four-point bending test	Cyclic Indirect Tensile Test
Stiffness modulus @ 20 °C & 8 Hz	Four-point bending test	Cyclic Indirect Tensile Test
Master curve stiffness mortar	DSR Frequency sweep	DSR Frequency sweep

The stiffness modulus and fatigue resistance of asphalt are determined in the type test by means of the four-point bending test (4PB). The tests are conducted on prismatic specimens (beams) with dimensions of 50x50x450 mm. Stiffness and fatigue tests on paved asphalt are preferably conducted on cylindrical specimens, which can be produced with a core drill. During the last two years, experience has been gained in determining the stiffness modulus and fatigue resistance of asphalt by means of the cyclic indirect tension test (CIT-CY) to cylindrical specimens Ø100-150 mm. Various research results show strong similarities between the stiffness modulus of asphalt determined with CIT-CY on cylindrical specimens and the stiffness modulus determined on beams in the 4PB test. Differences between CIT-CY and 4PB stiffness are generally limited to +10% on average. It is therefore likely that this difference can be largely attributed to differences in the nature of the tests and that these differences can be encapsulated in a 'conversion factor'. This will require additional research.

However, a direct comparison of the CIT-CY fatigue resistance and that measured by 4PB tests during the type test was not possible. The current, conventional fatigue analysis method does not allow this, because it is based on the development of mechanical parameters, such as stiffness and strain, during the fatigue test to define damage in the specimen. The effect of the differences in the nature of the tests, i.e. displacement-driven (4PB) versus force-driven (CIT-CY), means that these mechanical parameters are only representative for the development of damage within the specific conditions of the test.

For this reason, Boskalis Nederland conducted research into alternative fatigue resistance analysis methods. The findings of this study show that the application of energy concepts is a more suitable basis for the assessment of fatigue [2]. In particular, the Shen and Carpenter theory [3], in which the Ratio of Dissipated Energy Change (RDEC) is considered as a damage indicator, has proved to be a good basis for the development of a fatigue analysis that facilitates the direct comparison of 4PB and CIT-CY fatigue tests [4, 5]. This form of fatigue analysis would make End Result Verification possible in this way.

End Result Verification can now be used on the basis of two strategies. The results of the CIT-CY study on asphalt cores from the field can be compared to:

- A reference determination of CIT-CY stiffness and fatigue resistance in the type test based on the conventional fatigue analysis.
- The results of the 4PB stiffness and fatigue study in accordance with the type test by means of a fatigue analysis based on dissipated energy, QRS-RDEC[1].

2.1. Determination of reference CIT-CY stiffness and fatigue in type test

The determination of stiffness and fatigue resistance can be added to the Performance Based Specification (type test) by means of CIT-CY. This determination allows direct comparison of test results from cylindrical lab-fabricated specimens and cores (see figure 1). This strategy is undesirable, as it would require expansion of the type test and associated higher costs. Moreover, the properties of the completed work cannot be made suitable for use in residual life cycle calculations, not even by means of conversion factors. An advantage of this method is that the relationship between the measured CIT-CY and 4PB stiffnesses can be expanded.

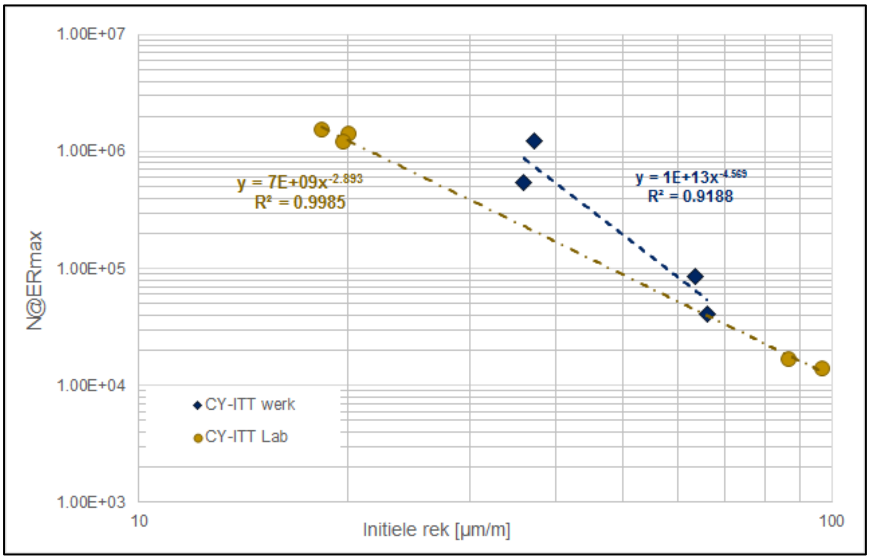

Figure 1: Direct comparison CIT-CY fatigue result Lab vs. Field

[1] Analysis method based on RDEC as introduced by Shen & Carpenter [3] but revised by QRS, Quality, Research & Support, the knowledge department of Boskalis Nederland.

2.2. Direct comparison of CIT-CY and 4PB with QRS-RDEC analysis

In this strategy, the 4PB stiffness and fatigue resistance, as determined in the type test, serve as a reference for verification of the completed work. Such a direct comparison of the 4PB and CIT-CY fatigue resistances is possible by conducting the analysis of the data based on the progression of the dissipated energy during a fatigue test. Since in this scenario there is no need for expansion of the type test, this is preferable to the strategy described above.

The search for alternative analysis methods for fatigue of bituminous bound mixes began several years ago. Indeed, the current method repeatedly proved in practice to be unsuitable for use on mixes with PMB. Boskalis Nederland has since developed an analysis methodology, QRS-RDEC, with which the fatigue behaviour of mixes with penetration bitumen and PMB can be assessed in an objective and uniform manner, regardless of the test set-up and load conditions. With this method it is possible to directly assess the attained fatigue properties of an asphalt mix from the field on the basis of fatigue tests on cores in relation to the fatigue properties established in the type test. The method is based on the theory of Shen and Carpenter concerning the Ratio of Dissipated Energy Change, RDEC. For a more detailed explanation and application of Shen and Carpenter's theory, consult sources [3, 4 and 5].

2.2.1. Original theory of Shen & Carpenter [3]

In 2007, Shen and Carpenter developed an analysis method with which the fatigue behaviour of asphalt can be described on the basis of the RDEC, Ratio of Dissipated Energy Change. The RDEC is a parameter that results from a mathematical calculation of the dissipated energy. What the RDEC actually describes is the rate at which the dissipated energy changes between successive load cycles. According to Shen and Carpenter, this difference in energy between load cycles is the main cause of fatigue and the associated damage. Dissipated energy that does not cause damage is eliminated from the RDEC determination. The RDEC value therefore indicates the contribution of each subsequent load application to the resulting damage. When plotted, the RDEC curve has a specific shape, consisting of three distinct zones, as shown in figure 2.

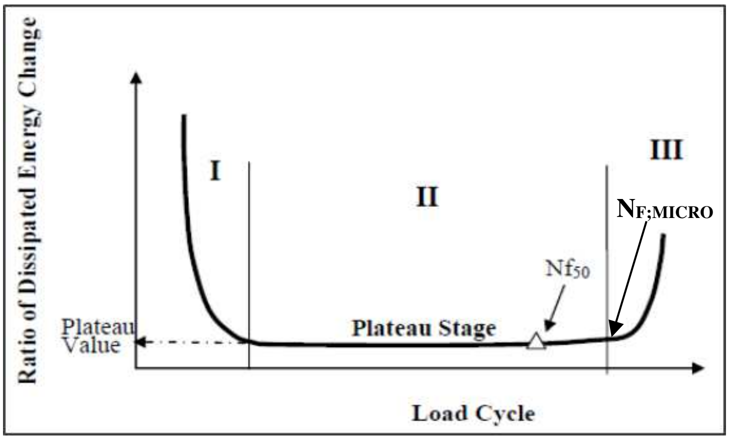

Figure 2: RDEC [Shen and Carpenter, 2007]

After initial stage I, the test enters plateau stage II, in which the value of RDEC is nearly constant. A constant amount of energy is converted to damage, in the form of heat and micro-cracks, during each loading cycle. The RDEC value during this stage is called the ‘plateau value’, PV. This PV is a material characteristic that depends on the mix design and the applied load. According to Shen and Carpenter, PV is deemed to be a fundamental material parameter that can be used to describe the fatigue behaviour of asphalt, regardless of the test set-up and load. In stage III, the RDEC shifts from a constant value to a rapidly increasing value. This transition is associated with the propagation of micro-cracks to macro-cracks. After a certain number of load repetitions, the RDEC reaches a maximum. When this occurs, the failure criterion ‘fracture’ is reached.

According to Shen and Carpenter, there is a linear relationship on a log–log scale between fatigue life and PV for asphalt mixes. Shen and Carpenter identified the end of life as the number of load repetitions at a stiffness reduction of 50%, N0.5G*. The PV is the value of the RDEC at N0.5G*. Rather than an N0.5G*-ε relationship, the fatigue resistance of asphalt is therefore expressed as an N0.5G*-PV relationship. Shen and Lu [6] provide a more detailed explanation as to why the choice for an N0.5G*-PV relationship would be justified.

In general, it is argued that a material with higher PV suffers more damage from repeated loading than a material with a lower PV. As the number of load repetitions increases, the damage suffered will increase more rapidly than in materials with a lower PV. In addition, a relatively high PV generally indicates that the fatigue resistance, i.e. the occurrence of fatigue cracks, is lower.

2.2.2. Shift of the end of life criterion – $N_{F;MICRO}$

The Shen and Carpenter method provides a valuable, objective parameter – in the form of the plateau value – for assessment of the formation of damage in a specimen. However, 50% stiffness reduction is also considered a failure criterion in this method. When applying the N_{F50} criterion to DSR fatigue tests of mortars with polymer modified binders, however, results are obtained that explicitly raise the question whether an end of life criterion based on 50% stiffness reduction is a realistic and uniform starting point for fatigue tests on asphalt mixes and mortars with all the binders that occur in practice (figures 3-5).

The figures each show the result of an individual mortar fatigue test worked out in accordance with the RDEC method described by Shen and Carpenter [3]. Incidentally, while the binder in each figure varies, the compositions of the mortars are the same. The figures show that the number of load repetitions at 50% stiffness reduction, N0.5G*, is not within the plateau zone for all the mortars; in some cases, it is in stage III (figure 3). Moreover, the mortar in figure 5 reaches half stiffness relatively quickly, at the beginning of the plateau zone, but still has considerable residual life. From these observations the conclusion can be drawn that the calculated plateau value does not describe the same physical condition, namely the end of fatigue life, for every mortar. The PV – N0.5G* relationship therefore gives a distorted picture of the fatigue behaviour of the tested mortars. The question this raises is whether the 50% stiffness reduction criterion is a realistic criterion for describing the end of fatigue life, if the course of the RDEC shows that no significant increase in dissipation growth has yet occurred.

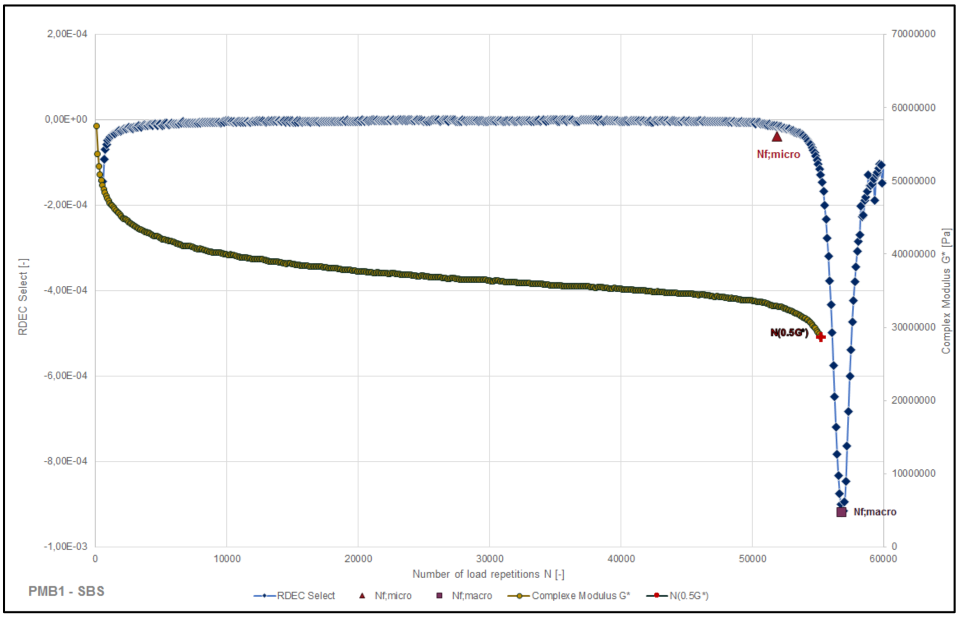

Figure 3: Dissipated energy, RDEC PMB1 – N0.5G* in stage III

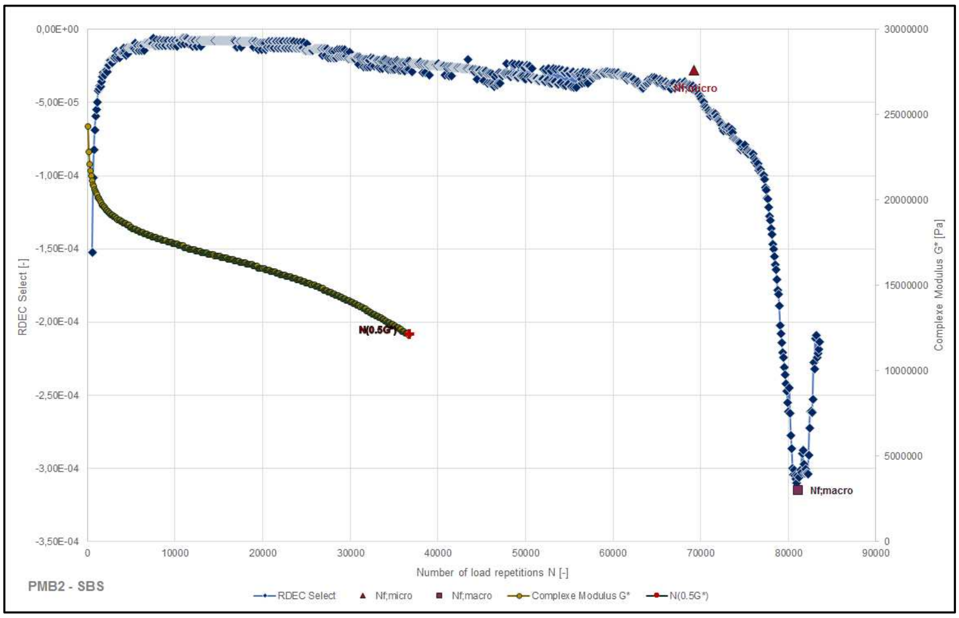

Figure 4: Dissipated energy, RDEC PMB2 – N0.5G* in stage II

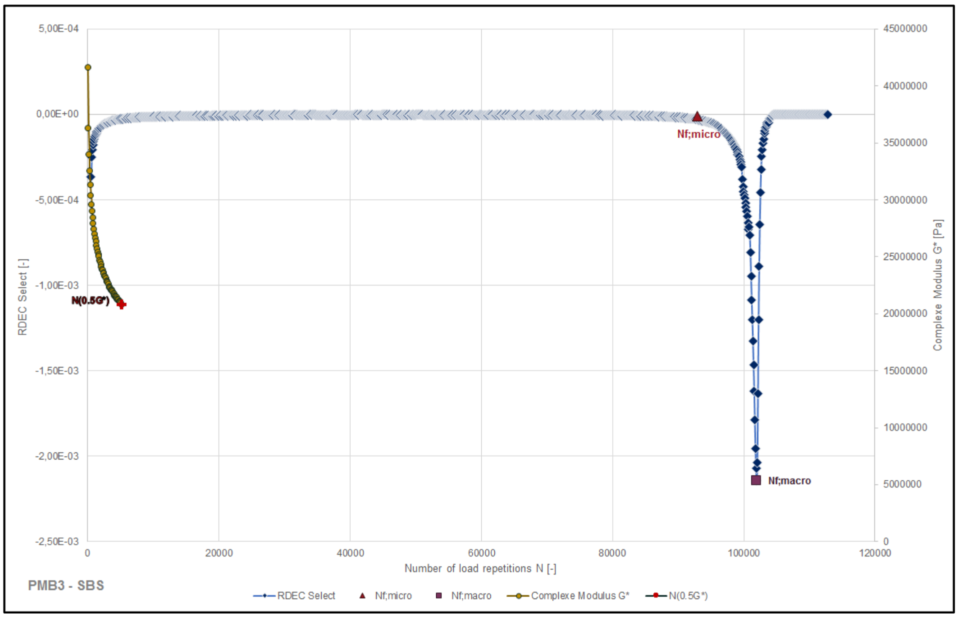

Figure 5: PMB3 – RDEC, Stiffness reduction and N0.5G* in stage I

The fact that mixes with PMB as binder still have residual life after halving the stiffness means that at that time the most heavily loaded cross-section has not yet been weakened to such an extent that each subsequent load repetition causes a significant propagation of the fatigue damage or crack formation. A more appropriate failure criterion would therefore seem to be the propagation of fatigue damage from micro scale to macro scale.

Because the RDEC describes the increase in crack formation, the points above can be expressed in terms of RDEC as follows: 'The fatigue damage in asphalt with PMB can still be "safely" in the plateau zone after the stiffness has been halved. At that time, crack formation only manifests itself on a micro scale and has minimal influence on the performance of the asphalt on a macro scale. A more appropriate failure criterion would therefore seem to be the transition from constant RDEC to increasing RDEC.'

Based on the results of research, Boskalis has chosen to use NF;MICRO as the uniform end of life criterion for all fatigue tests. Research has shown that for each asphalt mix there is a unique linear relationship between log PV and log NF;MICRO [4,7]. An external verification of the research results showed that the PV- NF;MICRO relationship describes the fatigue behaviour of asphalt more accurately than the current NF;50-ε relationship. Moreover, based on data from two asphalt mixes, penetration bitumen and PMB, it could be demonstrated that on a log–log scale the relationship between PV and NF;MICRO can be optimally described by one joint regression line for the 4PB and the CIT-CY test. This shows that, despite the difference in their natures, 4PB and CIT-CY tests provide the same information concerning the fatigue behaviour of asphalt. This breakthrough makes it possible to compare results from the type test (4PB) with the results from the completed work (CIT-CY) in an unbiased manner. After completion of this study, an analysis procedure was developed, with which the QRS-RDEC analysis can be performed in a uniform and objective manner in Excel.

2.2.3. Determination of $N_{F;MICRO}$ by means of cumulative standard deviation (CuSTD)

In order to establish the PV- $N_{F;MICRO}$ relationship from individual RDEC curves, two parameters must be determined per fatigue test:

- $N_{F;MICRO}$ – The number of load repetitions for which the transition from stage II to stage III takes place.
- PV – Plateau value, the average value of RDEC in stage II

It is important to determine these parameters as accurately and reliably as possible, because in a subsequent step a relationship is established by fitting all combinations of log ($N_{F;MICRO}$), log (PV) for the specimens of a particular mix.

Determination of the plateau value PV

The RDEC is a mathematical calculation of the dissipated energy (DE) and describes the rate at which the difference in DE shifts between successive load cycles. In a 4PB test, the DE follows a descending S-shaped curve. The resulting RDEC is therefore always negative. The CIT-CY is force-driven, and therefore the DE follows an ascending S-shaped curve. The RDEC calculated from CIT-CY is therefore always positive. For this reason, absolute values of RDEC were used for 4PB and CIT-CY in the initial analyses. However, the verification study showed that this can lead to significant overestimation of the PV value. The degree to which this occurs depends on the mean in combination with the distribution in the non-absolute values of RDEC in the flat section in stage II of the bathtub curve. In several cases the overestimation of PV was large (>0.50), and it also varied from one specimen to another. This has an adverse effect on the reliability of the resulting PV– $N_{F;MICRO}$ relationship.

There were two solutions to this problem: either using an analysis method that calculates PV from DE rather than RDEC or making RDEC less sensitive to overestimation. In a comparative study, a number of analyses were then conducted on the same data set using selected calculation methods. This analysis showed that the ‘exponential method’, in which the PV is calculated from the exponential part of the DE curve, provides exceptionally good results. However, this approach requires iterative statistical methods and is therefore more difficult to program in Excel. Because it is of great importance that the analysis method can be made broadly available, the decision was taken to develop a method that can be programmed in Excel and compare its results with those from the exponential method. The overestimation of RDEC mainly occurs when the values fluctuate above and below zero. In these cases, the DE measurements are so widely scattered that they are not uniformly ascending/descending for successive load cycles. To make RDEC less sensitive to overestimation, the decision was taken to first filter the DE values by means of a moving average. This approach was successful: after smoothing, the problem with overestimation of the PV value had been resolved [7].

Determination of $N_{F;MICRO}$

The analysis of the $N_{F;MICRO}$ values calculated with all the selected methods showed that the results were reasonably similar in all cases. The failure point or transition from RDEC stage II to RDEC stage III was in no way affected by the RDEC determination method. The determination was not yet automated, however, and therefore more prone to errors. In the current analysis method the determination of $N_{F;MICRO}$ is automated, by determining the number of load repetitions at the minimum of the cumulative standard deviation of the RDEC (figures 6 and 7).

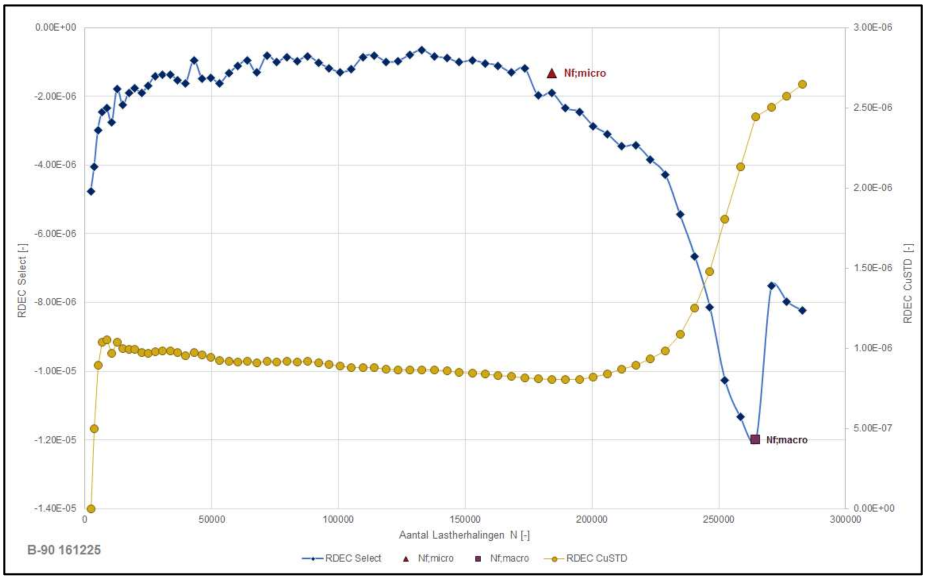

Figure 6: RDEC and CuSTD RDEC incl. Nf;micro and Nf;macro for 4PB test

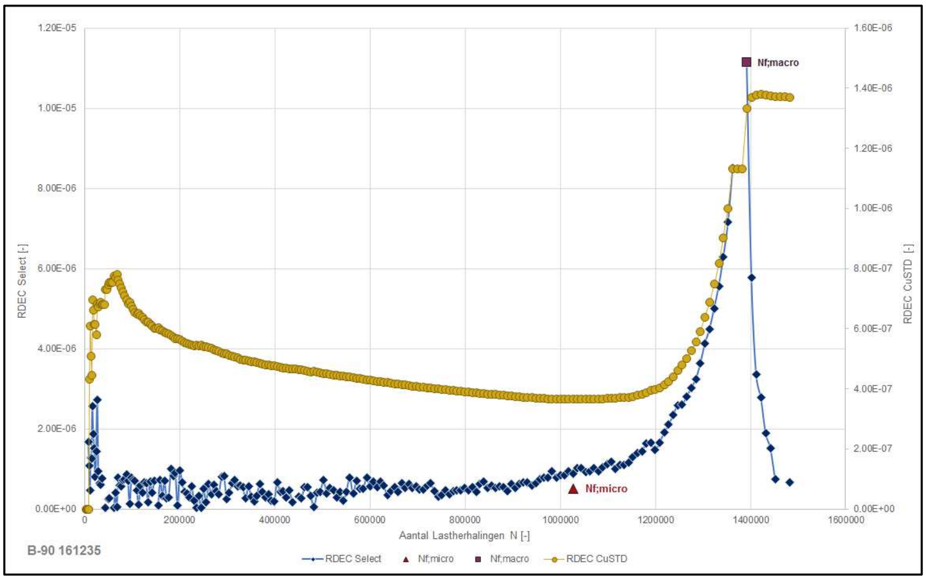

Figure 7: RDEC and CuSTD RDEC incl. Nf;micro and Nf;macro for CIT-CY

3. RESULTS OF END RESULT VERIFICATION

Since the establishment of the database for End Result Verification, End Result Verification has already been carried out on the basis of the preferred strategy for a number of projects. This chapter presents the results of this verification.

3.1. Case I: The subbase course – mix 252 A4 Steenbergen

3.1.1. NL-LAB – FEC 2.0

In 2012/2013, the FEC 2.0 study was conducted within the framework of NL-LAB. The aim of this study was to determine the extent to which the fundamental properties of asphalt actually attained in the field correspond to the specified properties on the basis of a type test. Table 2 shows the results of the study for plant-mixed mix 251-1, both compacted in the field and in the laboratory at Boskalis and Strukton. It should be noted that in order to determine the stiffness and fatigue resistance of the completed work, beams were cut from the road and tested in the 4PB set-up.

It follows from the results that, for the same mix composition and building materials, the fundamental properties attained for the asphalt subbase course of the A4 Steenbergen project are better than those established in the type test. This conclusion is based on the study results in table 2, which show that the resulting required asphalt thickness on the basis of the properties attained in the field is in all cases less than the required design thickness on the basis of the properties of the type test. This means that it is possible to attain asphalt with fundamental properties equivalent to those established in the type test of the mix concerned, provided that the following conditions are met:

- Mix composition TT ≈ mix composition in the field, and
- Properties of building materials TT ≈ properties of building materials in the field, and
- Density TT ≈ density in the field

Table 2: Results NL-LAB FEC 2.0

		TYPE TEST	BOSKALIS		STRUKTON	
		MIX 251-1	PLANT-MIXED	FIELD	PLANT-MIXED	FIELD
PRODUCTION		TT	Mill	Mill	Mill	Mill
COMPACTION		TT	Roller	Field	Plate compactor	Field
DENSITY	[kg/m^3]	2355	2398	2417	2383	2418
STIFFNESS	[MPa]	8402	9592	9850	8611	9781
$\varepsilon 6$	[µm/m]	102.6	108.3	106.9	96.9	110.8
K_2		-5.968	-6.997	-5.315	-5.798	-4.968
ITS	[MPa]	-	2.61	3.02	2.62	2.60
ITSR	[%]	86	87	106	93	93
f_C	[µm/m/N]	0.1	0.2	0.2	0.1	0.2
$H_{ASPHALT}$	[mm]	312	223	260	278	276

3.1.2. End Result Verification mix 251-1 – A4 Steenbergen

The mix used in the FEC 2.0 study is frequently used as a subbase or base course. The mix has also been used in the A4 Steenbergen project. Cores drilled from the pavement were used for End Result Verification of mix 251-1. The results of this verification are presented in tables 3 to 5.

Table 3: End Result Verification of density

PROPERTY		TYPE TEST	END RESULT VERIFICATION FIELD
Target compaction	[kg/m^3]	2355	--
Specimen density	[kg/m^3]	--	2373
Mix density	[kg/m^3]	2504	--
Void content	[%v/v]	6.0	--

Table 4: End Result Verification of mix composition

TYPE TEST				END RESULT VERIFICATION	
TARGET COMPOSITION		COMPOSITION AFTER EXTRACTION		COMPOSITION FIELD	
Sieve	Through sieve	Sieve	Through sieve	Sieve	Through sieve
C31.5		C31.5	100.0	C31.5	100.0
C22.4	99.2	C22.4	99.2	C22.4	99.4
C16		C16		C16	91.0
C11.2	78.0	C11.2	78.0	C11.2	76.2
C8		C8		C8	61.8
C5.6		C5.6		C5.6	54.1
2 mm	43.0	2 mm	44.0	2 mm	44.3
0.5 mm		0.5 mm		0.5 mm	28.2
0.180 mm		0.180 mm		0.180 mm	10.8
0.063 mm	6.0	0.063 mm	6.3	0.063 mm	5.9
Bitumen 'in'	4.3	Bitumen 'in'	4.3	Bitumen 'in'	4.2

Table 5: End Result Verification of fundamental properties

PROPERTY		TYPE TEST	END RESULT VERIFICATION
			FIELD
ITS retained	[MPa]	--	2.71
Triaxial f_c	[µm/m/N]	0.12	0.14
4PB S E_{mix}@8Hz&20ºC	[MPa]	8402	
CIT-CY S E_{mix}@8Hz&20ºC	[MPa]		12618
FATIGUE ANALYSIS RDEC			
4PB F logPV-log$N_{F;MICRO}$ relationship		-0.97x – 0.50	
	R^2	0.97	
CIT-CY F logPV-log$N_{F;MICRO}$ relationship			-0.81x – 1.20
	R^2		0.96
FATIGUE ANALYSIS CONVENTIONAL			
4PB F $N = k_1 \cdot \varepsilon^{K2}$		$N_f = 10^{18.00} \cdot \varepsilon^{-5.97}$	
	R^2	0.62	
CIT-CY F $N_f = C_1 \cdot \varepsilon_{EL;INI}{}^{C2}$			$N_f = 0.220 \cdot \varepsilon_{EL;INI}{}^{-4.57}$
	R^2		0.92

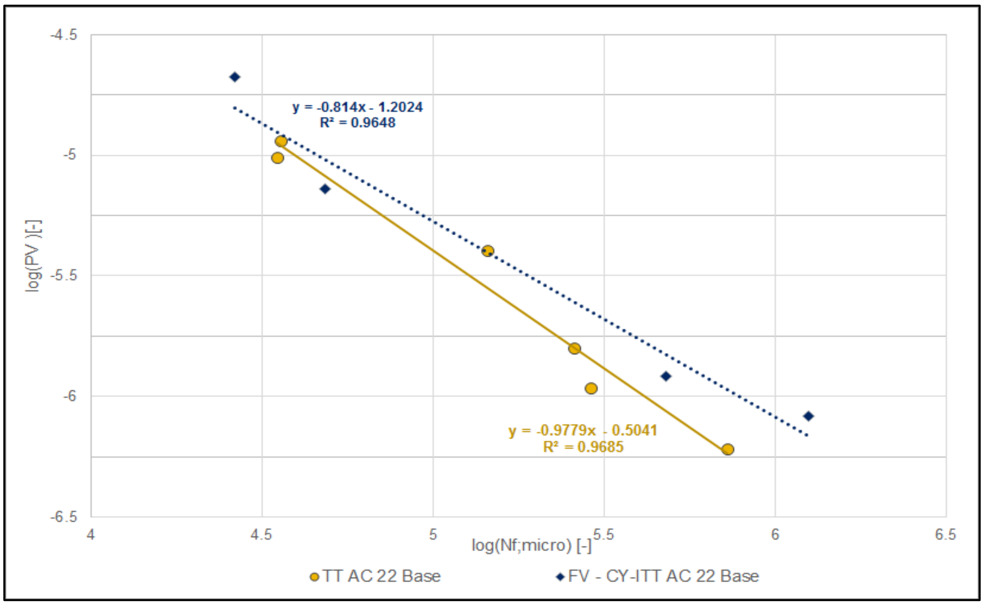

Figure 8: PV-N$_{F;MICRO}$ fatigue relationships TT (4PB) and work (CIT-CY) – Case I

3.2. Case II: Two paving methods versus type test

Tables 6 to 8 show the results of End Result Verification for one mix at two sites. An AC22 base mix was incorporated in different ways at these two sites.

Table 6: End Result Verification of density

PROPERTY		TYPE TEST	END RESULT VERIFICATION	
			PROJECT A	PROJECT B
Target compaction	[kg/m³]	2368	2368	2368
Specimen density	[kg/m³]	2377	2353	2355
Mix density	[kg/m³]	2470	2475	2475
Void Content	[%v/v]	3.8	5.0	4.1

Table 7: End Result Verification of mix composition

TYPE TEST				END RESULT VERIFICATION			
Target composition		**Composition after extraction**		**Composition project A**		**Composition project B**	
Sieve	Through sieve	Sieve	Through sieve	Sieve	Through sieve	Sieve	Through sieve
C31.5	100.0	C31.5	100.0	C31.5	100.0	C31.5	100.0
C22.4	98.0	C22.4	100.0	C22.4	100.0	C22.4	99.4
C16		C16	93.3	C16	92.1	C16	95.1
C11.2	80.0	C11.2	83.7	C11.2	81.0	C11.2	81.8
C8		C8	68.1	C8	68.5	C8	54.4
C5.6		C5.6	57.4	C5.6	58.8	C5.6	59.7
2 mm	43.0	2 mm	41.5	2 mm	44.9	2 mm	45.6
0.5 mm		0.5 mm	29.0	0.5 mm	30.4	0.5 mm	31.9
0.180 mm		0.180 mm	13.8	0.180 mm	13.9	0.180 mm	15.2
0.063 mm	6.4	0.063 mm	6.7	0.063 mm	6.5	0.063 mm	7.1
Bitumen ‘in’	4.3	Bitumen ‘in’	4.3	Bitumen ‘in’	5.3	Bitumen ‘in’	4.4

Table 8: End Result Verification of fundamental properties

PROPERTY		TYPE TEST	END RESULT VERIFICATION	
			PROJECT A	PROJECT B
ITS retained	[MPa]	2.00	1.93	2.01
Triaxial f_c	[µm/m/N]	0.23	0.25	0.18
4PB S E_{mix}@8Hz&20ºC	[MPa]	7525		
CIT-CY S E_{mix}@8Hz&20ºC	[MPa]		10993	11277
FATIGUE ANALYSIS RDEC				
4PB F logPV-log$N_{F;MICRO}$ relationship		$-0.94x - 0.96$		
R^2		0.86		
CIT-CY F logPV-log$N_{F;MICRO}$ relationship			$-1.08x - 0.05$	$-0.72x - 1.96$
R^2			0.98	0.91
FATIGUE ANALYSIS CONVENTIONAL				
4PB F $N = k_1 \cdot \varepsilon^{k2}$		$N = 10^{17.02} \cdot \varepsilon^{-5.29}$		
R^2		0.74		
CIT-CY F $N_f = C_1 \cdot \varepsilon_{el;ini}{}^{C2}$			$N_f = 10^{11.78} \cdot \varepsilon_{el;ini}{}^{-4.75}$	$N_f = 10^{13.30} \cdot \varepsilon_{el;ini}{}^{-3.73}$
R^2			0.87	0.92

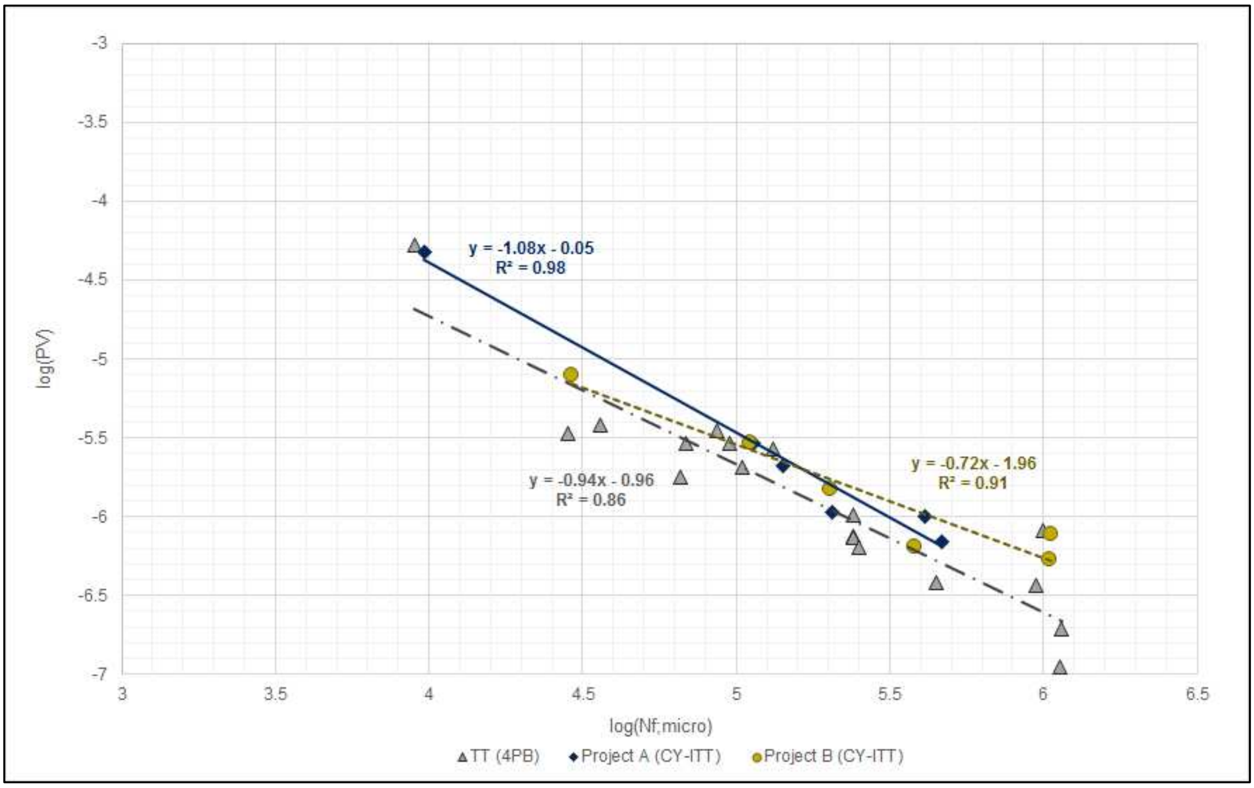

Figure 9: PV- $N_{F;MICRO}$ Fatigue relationships TT, Project A and Project B – Case II

3.3. Discussion

From the reported results it can be deduced that End Result Verification of paved asphalt in relation to the fundamental properties of the same mix as determined in the type test is possible. It is therefore demonstrably possible to attain asphalt with fundamental properties equivalent to those established in the type test of the mix concerned, provided that the conditions formulated on the basis of the NL-LAB study are met.

In addition, it has been demonstrated that the empirical properties alone are insufficient for assessment of the actual quality of a constructed asphalt surface. Exceeding the stated, mix-specific tolerance bands for these empirical properties does not necessarily lead to less desirable fundamental properties and vice versa. In these specific cases, it has been demonstrated that a deficit (Case I) and an excess (Case II) of the desired bitumen content, outside the applicable tolerance bands, does indeed have a measurable influence on the fundamental properties but that this influence does not always have to be significant in relation to the actual quality of a pavement.

In contrast to the other determined properties, the fatigue resistance of 4PB and CIT-CY is normally not directly comparable. The analysis based on the RDEC, a mathematical calculation of the dissipated energy, does make direct comparison possible. It follows from the graphs in figures 8 and 9 that the fatigue resistance of the paved asphalt is better than that measured in the type test. This means that the actual fatigue life of the pavement in both example projects will always be at least equal to or longer than the design life. Case 1 also shows that the conclusions drawn for fatigue on the basis of 4PB testing on bars from specimen plates from the field and the conclusions drawn on the basis of the End Result Verification methodology are consistent.

4. FROM END RESULT VERIFICATION TO FUNCTIONAL DELIVERY

The foregoing demonstrates that End Result Verification of completed asphalt pavement constructions is now possible. The ultimate goal is to use End Result Verification for Functional Delivery. Functional Delivery is the use of End Result Verification for contractual assessment and acceptance of completed asphalt work. For the successful practical application of End Result Verification for Functional Delivery, four important aspects require further attention:

1. Evaluation and standardization of test guidelines and test conditions
2. Recalibration and establishment of design safety in relation to construction tolerances
3. Development of a theoretical predictive model for business control purposes
4. Establishing a database for long-term monitoring and validation of Functional Delivery

4.1. Evaluation and standardization of test guidelines and test conditions

In addition to development and/or adaptation of the CIT-CY test for measuring the stiffness and fatigue of asphalt for End Result Verification, the CIT-CY and triaxial test, in particular, must be thoroughly evaluated and verified in order to standardize the test conditions, test execution, analysis and reporting method, and equipment. This may require analyses based on a theoretical finite element model of the tests and a verification study in the laboratory.

4.2. Recalibration and establishment of design safety in relation to construction tolerances

For the successful introduction of End Result Verification for quality control of asphalt in contracts, it is an absolute necessity that research is conducted into the tolerances to be used for approval/rejection in relation to the safety margins used in pavement design.

The determination of the tolerances to be applied to the measured asphalt properties in End Result Verification is directly related to the recalibration of the safety margins in the design. After all, the safety margins for the material properties in the pavement design form the basis for the tolerances to be used in the practical implementation. Quantitative determination of the fundamental properties actually delivered, through End Result Verification, also opens new avenues for fair (or fairer) settlement of deficiencies in delivered asphalt pavement quality and even bonus systems for delivered asphalt pavements that demonstrably meet or exceed the specified quality. After all, by entering the properties determined using the material from the field in the design calculations, a possible surplus of life can be demonstrably established. With the objective quantitative assessment of the attained properties of an asphalt mix it offers, End Result Verification also provides new possibilities for rewarding a contractor when average expected values for the properties are exceeded.

It should be possible to check whether the number of permissible axle load repetitions for the attained asphalt falls within a required tolerance band for a number of as yet to be determined representative load levels. This is indicated by the red arrows in figure 10. Table 9 shows that the actual life is less than the attained design life based on the type test for just one of the tested load levels (highlighted in yellow). If the design safety factors were established such that, for example, the attained Nperm,design must be ≥0.7*Nperm,design for all load levels, this delivery would be accepted. In the case of a deficiency, if the requirement were 0.8*Nperm,design for example, a contract provision could establish whether the work would be rejected or a penalty imposed on the basis of the shorter life predicted to be actually attained. On the other hand, if the number highlighted in yellow had been 1.25, there would also be justification for the contractor to be entitled to a bonus based on the 25% longer predicted life delivered.

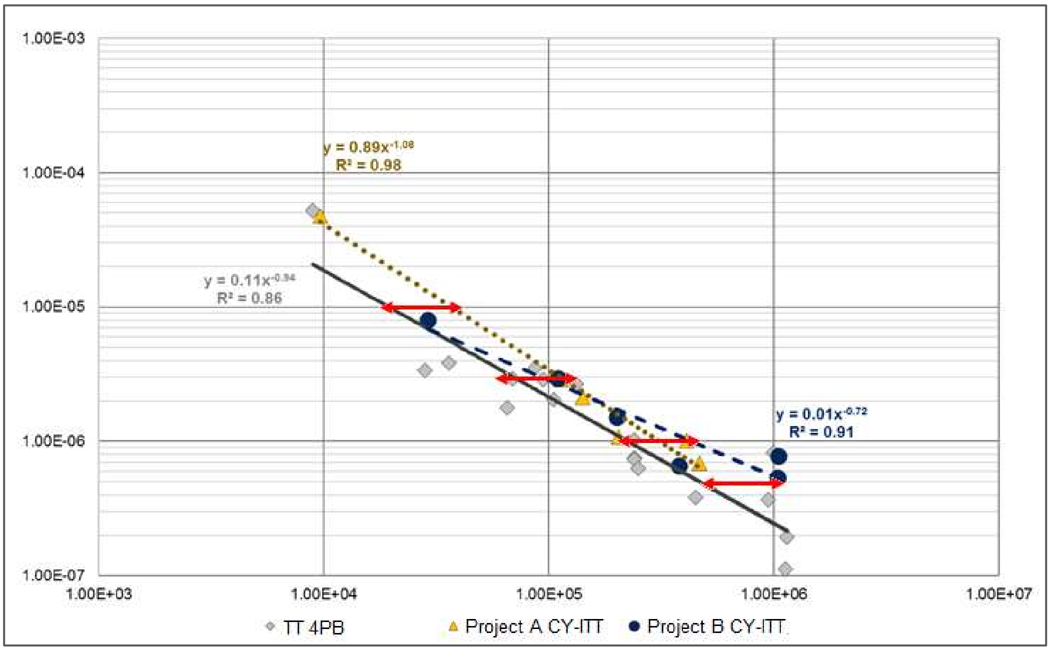

Figure 10: Comparison of life – TT based on PV-$N_{F;MICRO}$ relationship

Table 9: Comparison of relative life vs TT

$N = Ax^B$	TT	Project A	Project B			
A	0.11	0.89	0.01			
B	-.94	-1.08	-0.72			
PV	**N_{TT}**	**$N_{PROJ.A}$**	**$N_{PROJ.B}$**	**N_{TT} /N_{TT}**	**$N_{PROJ.A}$/ N_{TT}**	**$N_{PROJ.B}$/ N_{TT}**
1.00E-05	1.99E+04	3.83E+04	1.47E+04	1.00	1.92	0.74
2.00E-06	1.10E+05	1.70E+05	1.37E+05	1.00	1.54	1.24
1.00E-06	2.31E+05	3.23E+05	3.59E+05	1.00	1.40	1.56
5.00E-07	4.82E+05	6.13E+05	9.41E+05	1.00	1.27	1.95

4.3. Development of a theoretical predictive model for business control purposes

Based on years of experience with type testing of asphalt, it is known that the properties of freshly produced and incorporated asphalt still develop (i.e. improve) strongly in the first weeks. For End Result Verification, it is therefore very important to consider the moment when the tests are conducted in comparison with the moment when the specimens are tested during the type test of the mix concerned. It is currently assumed that the tests for End Result Verification should preferably be carried out in the period between six and eight weeks after incorporation of the asphalt. If, for the assessment of a project, it is desirable to have insight into the attained quality more quickly, predictive models can be used for an initial assessment (see step 1 in figure 11). The fact is that these predictive models require further development and validation through additional research. As part of the development of End Result Verification, the stiffness of the bitumen or mortar is therefore also measured with the DSR (see table 1) in order to be able to predict the fundamental properties and generate data for further development of the predictive models.

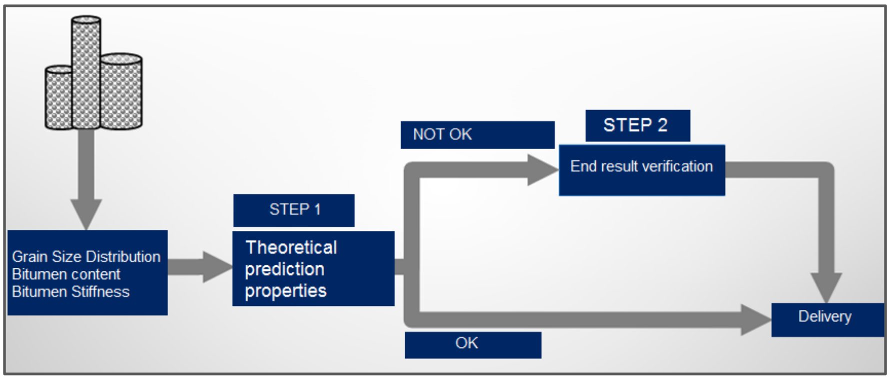

Figure 11: Possible proposal – methodology for End Result Verification

4.4. Establishing a database for long-term monitoring and validation of Functional Delivery

In order to validate the drastic changes in asphalt road construction practice in the Netherlands since 2004, a long-term monitoring programme is required. This programme will investigate the extent to which design methodologies and attained pavement properties actually lead to attainment of performance, within an acceptable margin of reliability, in conformity with the pavement design. The results of this monitoring programme will then form the basis for further development and refinement of the theoretical technical framework for asphalt pavements. In contrast to the large-scale and above all costly SHRP monitoring programme in the past, the costs of such a monitoring programme can be drastically reduced through the use of new registration and measurement systems based on GPS positioning. An important system for managing construction and monitoring data is, for example, Pavement Information Modelling (PIM), which was put into use by contractors at the end of 2018.

For the verification and validation of the methodology for End Result Verification, it is absolutely vital that practical experience is gained and a structured database is compiled in order to facilitate and accelerate further development. In order to facilitate and finance this, stakeholders (clients, research institutes, contractors, engineering firms etc.) are being sought who are willing to participate in data collection in a fixed format for an extended period of time for the purpose of fine tuning the system for End Result Verification.

5. CONCLUSIONS & RECOMMENDATIONS

From the reported results it can be deduced that End Result Verification of incorporated asphalt in relation to the fundamental properties of the same mix as established in the type test is demonstrably possible. The methodology is now deployable in the event of disputes about delivered asphalt quality, because direct and reliable comparisons can be made between the actual work and the type test for all fundamental properties through use of the QRS-RDEC method. The results also support the conclusions drawn on the basis of the NL-LAB study. In addition, after consideration of two practical examples of End Result Verification, it follows that exceeding the stated, mix-specific tolerance bands for empirical properties does not necessarily lead to less desirable fundamental properties and vice versa. The added value of this End Result Verification framework to the current, empirical framework is therefore evident. In connection with this, a number of important aspects relating to the details of the design of the verification framework need to be worked out in more detail. Recommendations made concerning the further improvement and validation of the End Result Verification framework are:

- Evaluation and standardization of test methods, test guidelines, and analytical methods.
- Implementation of a change in the end of life criterion used for specification of the fatigue resistance, from N0.5G* to $N_{F;MICRO}$. The practical consequence of this is that, from now on, fatigue tests conducted for the purpose of a type test must always be continued until fracture.
- Development of a theoretical model for prediction of fundamental asphalt properties (for business control purposes).
- Further population of the End Result Verification database already created during the pilot project.
- Expansion of the database through the addition of long-term monitoring.

In the near future, the aim is to use End Result Verification for Functional Delivery. It has been shown that the results of End Result Verification are very suitable to serve as a basis for the design of a billing system that does justice to the fundamental, technical framework. In order to facilitate Functional Delivery, it is important that:

- The dialogue is started on the form and formulation of conditions for End Result Verification which should already be included in contracts.
- The current design safety is reviewed and reassessed in relation to the construction tolerances.

The most important recommendation to the Dutch road construction collective is to join forces and, through the 'Functional Delivery' project under the banner of the Asfalt-Impuls programme [8], further develop the framework for End Result Verification and Functional Delivery for regular use in practice.

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