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COMBINING THE AMERICAN AND EUROPEAN MIX DESIGN APPROACHES:
utilization of NCHRP performance indicators for analysis of CEN-test results

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ABSTRACT

In the Netherlands, the functional approach described in the 2008 European Asphalt Concrete standards was selected, specifying mixtures by their stiffness, fatigue resistance, permanent deformation, moisture sensitivity and limited composition data. The requirements for the functional specifications were based on the existing experience with a large number of mixes. Since the introduction of the standards, unexpected developments like improved performance in all functional tests with increasing RAP content, led to questions about the predictive quality of the laboratory determined functional characteristics for field performance and the potential causes of a mis-match between lab and practice. These questions led to a large, long term project in the Netherlands (NL-LAB) in which the functional characteristics are determined in the process of construction projects. They are determined on (I) material mixed and compacted in the lab, (II) mixed in the plant and compacted in the lab and (III) mixed in the plant and compacted in the road. These tests will eventually provide insight in the effect of mixing and compaction. The pavement sections are monitored in time, to allow the link with pavement performance. The sections will be sampled during their service life to see changes occur in their functional properties. For the road industry, that tries to guarantee pavement performance by accurate selection of materials, the possibility of design information based on both laboratory and in situ results would be beneficial.

Two mixes for base layers with different mix compositions and amounts of RAP are analysed using formalistic expressions originating from Design Guide Level II for estimation of various performance indicators. This project uses expressions to analyse the differences between the mixes in the three cases described above. It addresses the possibility of utilizing these expressions during preliminary mix design to guide the selection of mix composition parameters towards a desired optimum.

INTRODUCTION

It is always a crucial point in every mix design to optimize the performance of a mix on the basis of the mixture components (aggregate type, bitumen stiffness, aggregate gradation). Furthermore, the increasing use of RAP in Hot Mix Asphalt (HMA) requires a more detailed study of its effect on the intended performance. Certainly, laboratory tests are crucial in this process even if they are expensive and of time consuming nature. For these reasons their number should be limited. Formalistic expressions for estimation of various performance indicators could help road authorities and engineers in coming up with a preliminary choice of aggregate and bitumen type for further laboratory investigation.

At European level, the indirect tensile test (IDT) (EN 12697-23, 2003) (*2*) and the triaxial cyclic compression test (TCCT) (EN 12697-25, 2005) (*3*) are two of the tests used in the European Standard Specification EN for HMA mixture characterization. It is well-known that the mechanical response of the HMA samples is strongly related to the mechanical-physical characteristics of the single components (bitumen, aggregate and voids). Therefore, several formalistic relations for tensile stress at failure and permanent strain have been developed over the years. In general, they are based on linear regression between the various mix composition parameters. Nevertheless, after appropriate calibration, their utilization for the estimation of HMA mixture properties has become standard in engineering practice. The first step of this research was to evaluate the applicability for European mixes of the formalistic expressions available for Level II design in NCHRP 1-37A (*1*) on the basis of laboratory tests.

Generally, the performance of a mixture is not affected by one parameter alone. A large set of mixture variables in fact influence its performance and as reported by the Project 1-37A (*1*) formula, not always linearly. Also, it is well known that the properties realized in the actual pavement will vary and may differ from those found in laboratory tests. In this paper the essential influences of the various composition-related factors are investigated in detail using statistical and back-calculation analyses to identify the significant variables to be included in the relationship between measured and back-calculated values.

The characteristics of two mixes have been determined during all the phases of design and construction (from laboratory investigation to field compaction) from construction projects on two important Dutch roads: Highway A4 and Provincial Road N345. The following cases will be discussed in this contribution:

- Case I: Lab-Lab (the specimen have been produced and compacted in the laboratory by means of gyratory compactor);
- Case II: Plant-Lab (HMA has been transported from the plant to the laboratory and there gyratory compacted);
- Case III: Field (HMA has been transported from the plant to the field and there compacted by means of roller compactor).

The variables considered in the NCHRP report (*1*) were utilized for the starting phase of the research, aiming to determine suitable coefficients for the European conditions. In a later stage, the sensitivity of all the variables was studied: some variables were considered not relevant for the case of study and new variables were added. Details about the back-calculation procedures that were developed and the verification of the reliability of the different formulae for the evaluation of ITS and permanent strain is discussed.

NCHRP DESIGN GUIDE

In the NCHRP Design Guide 1-37A(*1*) the formula for the indirect tensile strength (ITS) is stated as:

$$ITS = 7416{,}712 - 114{,}016 * V_a - 0{,}304 * V_a^2 - 122{,}592 * VFA + 0{,}704 * VFA^2 + 405{,}71 * \log(Pen_{77}) - 2039{,}296 * \log(A) \quad (1)$$

where:

- ITS = Indirect Tensile Strength at -10ºC (psi);
- V_a= Air voids (%);
- VFA = Voids filled with asphalt (%);
- Pen_{77}= Binder penetration at 25ºC (mm/10);
- A = Viscosity-temperature susceptibility intercept.

The Design Guide (*1*) procedure requires the determination of the tensile strength at -10ºC and a load rate of 51 mm per minute. The R^2 quoted in the Design Guide for these parameters is 0.62.

The Design Guide (*1*) also provides an expression for the viscous creep compliance. It is obtained by taking into account the correlations of creep tests with volumetric and mixture properties of an asphalt mix. The formula for the creep compliance at time *t*, as published in the Design Guide (*1*), is given as:

$$D(t) = D_1 \cdot t^m \quad (2)$$

where D_1, m = creep parameters.
The expression used for D_1 is:

$$\log(D_1) = -8.5241 + 0.01306\, T + 0.7957 \log(V_a) + 2.0103 \log(VFA) - 1.923 \log(A_{RTFO}) \quad (3)$$

where:

- T = Test temperature (°F);
- V_a = Air voids (%);
- VFA = Voids filled with asphalt (%);
- A_{RTFO} = Intercept of binder Viscosity – Temperature relationship for the RTFO condition.

For the *m* parameter, the expression is:

$$m = 1.168 - 0.00185\, T - 0.01126\, VFA + 0.00247\, Pen_{77} + 0.001683\, Pen_{77}^{0.4605}\, T \quad (4)$$

where:

- T = Test temperature (°F);
- V_a = Air voids (%);
- VFA = Voids filled with asphalt (%);
- Pen_{77} = Penetration at 77 ºF = $10^{290.5013-\sqrt{81177.288+257.0694*10^{(A+2.72973*VTS)}}}$ (mm/10);
- A = Viscosity-temperature susceptibility intercept;
- VTS = Slope of binder Viscosity – Temperature relationship.

MATERIALS

Mixes from Highway A4 (Amsterdam-Zandvliet) near Steenbergenand and from Provincial Road N345 (Apeldoorn-Zutphen)in the Dutch network were analyzed. Aggregate type, gradation and reclaimed asphalt types and percentage were different. The A4 specimens contained 50% of reclaimed asphalt while those from N345 contained 60%. Specimens were tested in the laboratory originating from: (Case I) laboratory production and gyratory compaction, (Case II) plant production and gyratory laboratory compaction and (Case III) plant production and field compaction. For each mixture the average values of the considered variables in the back-calculation phase are reported in Table 1.

TABLE 1 Average Value of Variables

		Density [g/cm^3]	V_a [%]	VFA [%]	A	Pen_{25} [mm/10]	R&B [°C]	Bitumen [%]
Case I	A4	2.387	3.90	76.68	0.044	27.0	58.8	4.03
	N345	2.397	3.07	81.50	0.034	15.0	76.2	4.30
Case II	A4	2.377	4.08	76.37	0.044	24.0	60.0	4.26
	N345	2.388	4.38	74.31	0.037	16.0	71.0	4.50
Case III	A4	2.407	3.01	81.42	0.044	27.0	58.6	4.22
	N345	2.445	0.84	94.43	0.046	30.0	56.2	4.40

According to the European Standard EN 12697-23 (*2*), the test conditions for the IDT are 15ºC and a load rate of (50±2) mm/min. In this paper the ITS is expressed in MPa. The triaxial cyclic compressive test has been carried out at 40 ^{o}C (104 ºF) with a confinement stress (σ_c) of 0.05 MPa and an amplitude (σ_v) of 0.2 MPa. This results in a peak load of the discontinuous sinusoidal compressive stress of 0.45 MPa in accordance to the European Standard EN 12697-25 (*3*), the principle of the applied stress signal is give in Figure 1.

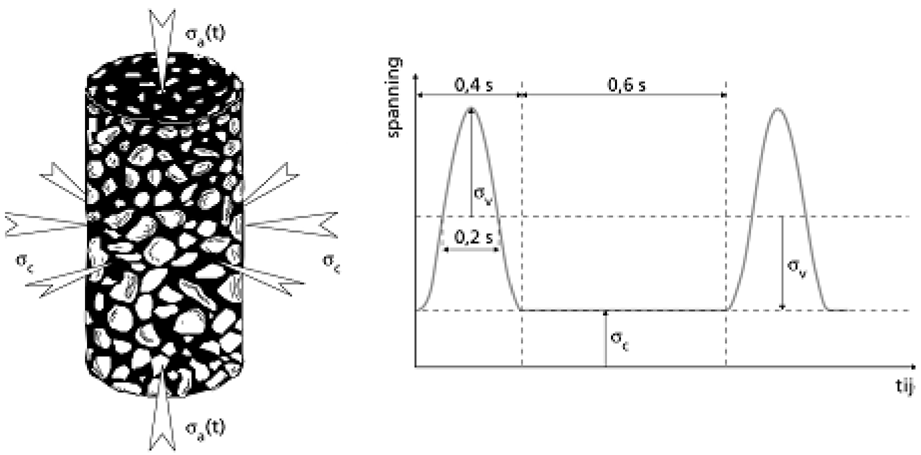


FIGURE 1 Schematic of the stress signal in time.

ITS PARAMETER DETERMINATION

As shown in the previous section the formulae given by the NCHRP project 1-37A(*1*) are composed by expressions of variables with associated multipliers. A general relationship between the variables and their multipliers for the ITS is :

$$ITS = A_1 + A_2 * V_a + A_3 * V_a^2 + A_4 * VFA + A_5 * VFA^2 + A_6 * \log(Pen77) + A_7 * \log(A) \quad (5)$$

where:

- *ITS* = Indirect Tensile Strength at -10ºC (psi);
- A_1...A_7 = multipliers;
- V_a, *VFA, log(Pen77), log(A)* = physical variables.

Back-Calculation of Multipliers

Introducing *M* as the matrix of physical variables (*VFA*, *Pen77*, *etc.*) and *A* the vector of unknown multipliers, the ITS equation can be expressed as:

$$[ITS] = [M] * [A] \tag{6}$$

Every row in matrix *M* represents a separate measurement which results in a corresponding ITS value, so that it holds that:

$$\begin{bmatrix} ITS \\ \vdots \\ ITS \end{bmatrix} = \begin{bmatrix} 1 & V_a & V_a & VFA & VFA^2 & Log(Pen77) & \log(\mathrm{A}) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & V_a & V_a & VFA & VFA^2 & Log(Pen77) & \log(\mathrm{A}) \end{bmatrix} * \begin{bmatrix} A_1 \\ \vdots \\ A_7 \end{bmatrix} \tag{7}$$

M must be composed of a number of rows at least equal or greater than the number of multipliers A_i. A total of 31 tests results were available in this study. Utilization of all 31 test results in the back-calculation procedure rendered the above system of equations over-determined and necessitated the use of Least Squares for its solution (*4*). As mentioned before, the formula for the ITS value vector consists of the multiplication of the matrix of physical variables *M* and the multiplier vector A as:

$$[ITS] = [M] * [A] \tag{8}$$

Pre- and post multiplying both sides with $([M]^T*[M])^{-1}[M]^T$ and after some mathematical manipulations it results

$$[A] = ([M]^T * [M])^{-1} * [M]^T * [ITS] \tag{9}$$

which enables the determination of A_i-s on the basis of the ITS test values.

After obtaining the new calculated vector of ITS values it is possible and necessary to make a comparison between the measured values during tests and the back-calculated ones. The calculation of errors is of fundamental importance for the comparison between the experimental and back-calculated ITS values and especially for the evaluation of the level of interdependence of the physical variables used for the calculation of ITS. Computation of the error between predicted and computed ITS values is important for the verification of the suitability of the multipliers A_i as determined via the back-calculation procedure.

TCCT PARAMETER DETERMINATION

For the analyses of the resistance to permanent deformation, the European Standard EN 12697-25 (*3*) provides two formulations, a linear one and an exponential function. Both depend on the number of loading cycles. In this paper the exponential form for the plastic strain is adopted:

$$\varepsilon_N = A \cdot n^B \tag{10}$$

where *A* and *B* are coefficients and *n* is the cycle number.

A triaxial cyclic compressive test (TCCT) is used instead of the creep test used in the Design Guide (*1*). In this study, the spirit of the Design Guide (*1*) formula was maintained but the actual equation was recast to represent the results of TCCT. The Design Guide (*1*) correlation between total strain, creep stress and creep compliance in time is given by the following expression:

$$\frac{\varepsilon(t)}{\sigma} = D_1 \cdot t^m \tag{11}$$

This equation can be transformed into its logarithmic form as:

$$\log\big(\varepsilon(t)\big) = \log(\sigma) + \log(D_1) + m \cdot \log(\mathrm{t}) \tag{12}$$

Similarly a general relationship between the physical variables and their multipliers can be setup for the parameter D_1 in logarithmic form:

$$\log(D_1) = \beta_0 + \beta_1 \cdot T + \beta_2 \cdot \log(V_a) + \beta_3 \cdot \log(VFA) + \beta_4 \cdot \log A \tag{13}$$

where:

- T = Test temperature (°F);
- V_a = Air voids (%);
- VFA = Voids filled with asphalt.
- A = Intercept of binder Viscosity – Temperature relationship;
- $\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$= multipliers.

For the *m* parameter, the expression is reported as:

$$m = \vartheta_0 + \vartheta_1 \cdot T + \vartheta_2 \cdot VFA + \vartheta_3 \cdot Pen_{77} + \vartheta_4 \, Pen_{77}^{\alpha} \cdot T \quad (14)$$

where:

- Pen_{77}= Penetration at 77 °F;
- $\vartheta_0, \vartheta_1, \vartheta_2, \vartheta_3, \vartheta_4$= multipliers.

A set of modifications are made in the following to this equation to recast it in a form suitable for TCCT. The first assumption concerns the loading stress. In the TCCT a pulse load is utilized instead of a constant load. In this study, the choice is made to relate the creep stress to the maximum stress of the pulse load:

$$\sigma = \sigma_{a,max} \quad (15)$$

The second assumption is that the creep test time *t* can be substituted by the time required for n load cycles, each of 1 sec duration. Finally, in contrast to the Design Guide, it is assumed that Eq. 12 is suitable to describe the development of plastic strain as it progressively develops with increasing number of cycles.

Data from a total of 39 test specimens were available. As in the case of the ITS, on the basis of Eq. 13 and Eq. 14 and the available data, two systems of equations can be formulated:

$$[\log D_1] = [S] * [\beta] \quad (16)$$

$$[m] = [T] * [\vartheta] \quad (17)$$

Back-Calculation of Multipliers

Solution of the above two over-determined systems of equations provides the values of the [β] and [ϑ] multipliers. Use of the Least Squares technique is necessary because of the over-determined nature of the systems. Following the same numerical procedure as in the case of ITS, [β] and [ϑ] multipliers are determined as:

$$[\beta] = ([S]^T * [S])^{-1} * [S]^T * [\log D_1] \quad (18)$$

$$[\vartheta] = ([T]^T * [T])^{-1} * [T]^T * [m] \quad (19)$$

Once [β] and [ϑ] are known, the values of D_1 and *m* can be calculated as:

$$\log(D_1)_{calc} = \beta_0 + \beta_1 \cdot T + \beta_2 \cdot \log(V_a) + \beta_3 \cdot \log(VFA) + \beta_4 \cdot \log A \quad (20)$$

$$m_{calc} = \vartheta_0 + \vartheta_1 \cdot T + \vartheta_2 \cdot VFA + \vartheta_3 \cdot Pen_{77} + \vartheta_4 \, Pen_{77}^{\alpha} \cdot T \quad (21)$$

and the plastic strain can be determined on the basis of mix composition via Eq. 12.

RESULTS

Indirect Tension Test

For the indirect tension test three different combinations of mix composition variables were analyzed. The difference between them lies in the number and type of variables that were utilized for response prediction.

- Test case 7:

$$ITS = 22.383 + 2.740 * V_a - 0.294 * V_a^2 - 0.705 * VFA + 0.006 * VFA^2 - 3.022 * \log(Pen) + 0.897 * \log(\mathrm{A}) \quad (22)$$

- Test case 13:

$$ITS = 17.624 + 2.672 * V_a - 0.279 * V_a^2 - 0.633 * VFA + 0.005 * VFA^2 - 2.655 * \log(Pen) \quad (23)$$

- Test case 29:

$$ITS = 26.937 - 0.107 * V_a - 0.055 * V_a^2 - 2.846 * \log(Pen) - 8.016 * Density \quad (24)$$

where:

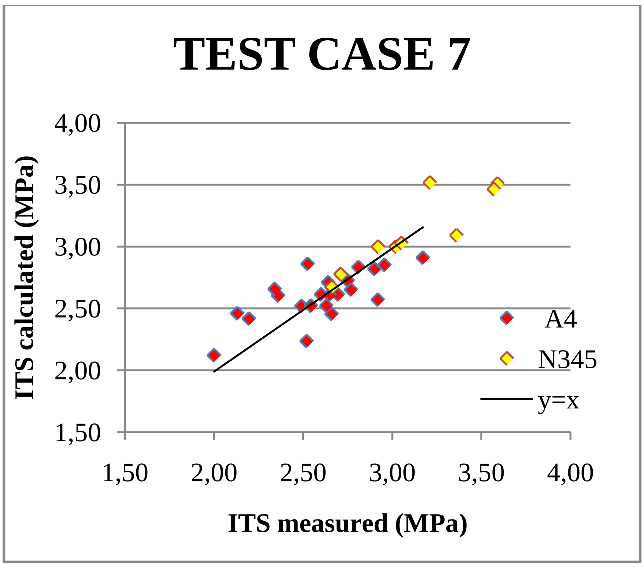
- ITS value is expressed in MPa and it refers to a test temperature of 15ºC;
- V_a is the specimen percentage of voids (%);
- *Pen* is the bitumen penetration at 25ºC (mm/10);
- *VFA* stands for Voids Filled with Asphalt (%);
- *Density* is the density of the specimens (g/cm^3).

For each Test case, the list of coefficients of the individual physical variables is shown in Table 2. All 3 sources of material samples (Case I, II, III) were individually examined.

TABLE 2 Calculated Multipliers

TEST CASE 7					
CASE I		CASE II		CASE III	
A_1	465.443	A_1	-224.407	A_1	33.526
A_2	42.244	A_2	-7.962	A_2	4.271
A_3	-5.432	A_3	1.003	A_3	0.235
A_4	-24.316	A_4	9.403	A_4	3.425
A_5	0.159	A_5	-0.061	A_5	-0.014
A_6	82.460	A_6	-28.041	A_6	-64.942
A_7	-197.643	A_7	60.314	A_7	102.584
TEST CASE 13					
CASE I		CASE II		CASE III	
A_1	857.513	A_1	-340.213	A_1	-165.223
A_2	42.244	A_2	-7.962	A_2	4.271
A_3	-5.432	A_3	1.003	A_3	0.235
A_4	-24.316	A_4	9.403	A_4	3.425
A_5	0.159	A_5	-0.061	A_5	-0.014
A_6	-3.561	A_6	-3.614	A_6	-23.427
TEST CASE 29					
CASE I		CASE II		CASE III	
A_1	8.731	A_1	22.262	A_1	162.392
A_2	5.471	A_2	4.202	A_2	-2.154
A_3	-0.740	A_3	-0.600	A_3	0.136
A_4	-4.793	A_4	-4.066	A_4	-33.034
A_5	-3.954	A_5	-8.902	A_5	-44.545

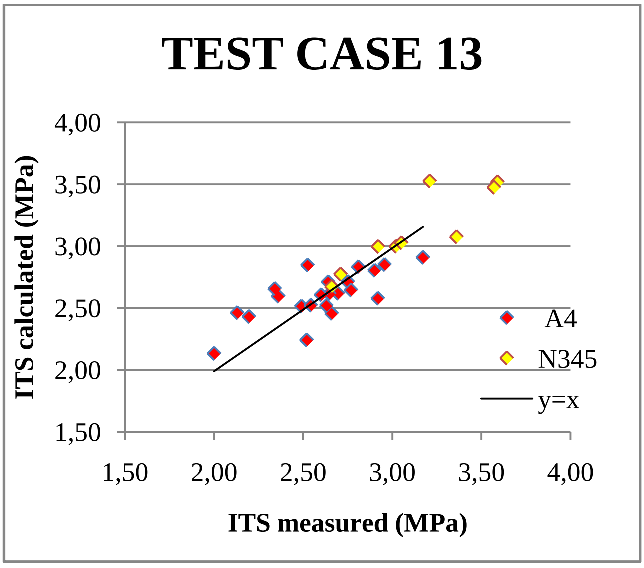
From Table 2 it is clear that the calculated multipliers for mixes produced by different processes i.e. lab produced vs. plant produced vs. field produced, were different and indicate the influence of mix production and compaction on mix response. The respective *R-squared* values are for Test 7: 0.93, 0.74 and 0.92, for Test 13: 0.93, 0.74 and 0.92, for Test 29: 0.88, 0.70 and 0.87. The difference between Test case 7 and Test case 13 is the parameter A. It is clear from the comparison of the R^2 for the three cases analyzed that it is not a significant parameter for the evaluation of ITS. The parameters of Eq. 22 were determined by utilizing the results from all available specimens independent of mix production process. The numerical values of the parameters are shown in the insert of Figure 2. The corresponding *R-squared* is 0.76 which indicates a satisfactory prediction reliability level for the model.



TEST CASE 7	
A_1	22.383
A_2	2.740
A_3	-0.294
A_4	-0.705
A_5	0.006
A_6	-3.022
A_7	0.897

FIGURE 2 Test case 7 Measured and calculated ITS; multipliers.

From the results of Test case 7, it became apparent that the viscosity-temperature susceptibility intercept had very little influence on the predictions. For this reason, in Test case 13 it was ignored. All other variables were as in Test case 7. The numerical values of the computed parameters are shown in the insert of Figure 3. Similarly to the previous case the *R-squared* is also 0.76. From the spread of the data along the equality line it is clear that the calculated coefficients are capable of predicting realistic ITS values without the need to include the temperature-viscosity susceptibility intercept in the formulation.

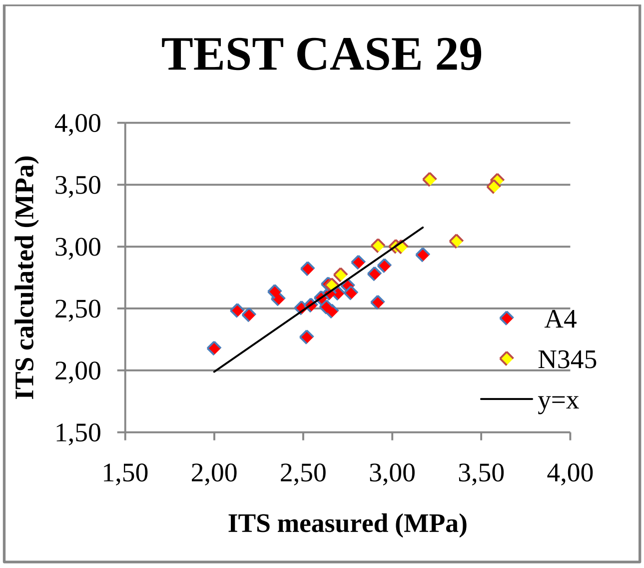


TEST CASE 13	
A_1	17.624
A_2	2.672
A_3	-0.279
A_4	-0.633
A_5	0.005
A_6	-2.655

FIGURE 3 Test case 13 Measured and calculated ITS; multipliers.

Having removed the viscosity-temperature susceptibility intercept from the list of physical variables, it was decided in Test case 29 to explore the possibility of substituting

VFA with density. Among these two parameters, the latter is easier to determine and it is contained in the evaluation of the VFA. Therefore the latter was chosen and the best R^2 was obtained considering a linear dependency between ITS and density. The numerical values of the computed parameters are shown in the insert of Figure 4. Similarly to the previous case the *R-squared* was also 0.76.



TEST CASE 29	
A_1	26.937
A_2	-0.107
A_3	-0.055
A_4	-2.846
A_5	-8.016

FIGURE 4 Test case 29 Measured and calculated ITS; multipliers.

Triaxial Cyclic Compression Test

For the triaxial cyclic compression test four different combinations of mix composition variables were analyzed.

- Test case 1:

$$\log D_1 = 0.1054 \cdot T - 1.7670 \cdot \log V_a - 7.5199 \cdot \log VFA - 2.9947 \cdot \log A \quad (25)$$

$$m = 0.1726 + 0.0025 \cdot V_a - 0.0008 \cdot VFA + 0.0013 \cdot Pen_{77} \quad (26)$$

- Test case 2:

$$\log D_1 = -0.0790 \cdot T - 1.2627 \cdot \log V_a - 11.0295 \cdot \log VFA - 3.1094 \cdot \log A + 10.7454 \cdot Density \quad (27)$$

$$m = 11.7994 - 0.2188 \cdot V_a - 0.0283 \cdot VFA + 0.0010 \cdot Pen_{77} - 3.6187 \cdot Density \quad (28)$$

- Test case 3:

$$\log D_1 = -0.0756 \cdot T - 1.1903 \cdot \log V_a - 10.9344 \cdot \log VFA - 5.7066 \cdot \log A + 12.3746 \cdot Density + 0.0006 \cdot (Pen_{77} \cdot R\&B) \quad (29)$$

$$m = 15.3469 - 0.3272 \cdot V_a - 0.0452 \cdot VFA + 0.0225 \cdot Pen_{77} - 4.2495 \cdot Density - 0.0006 \cdot (Pen_{77} \cdot R\&B) \quad (30)$$

- Test case 4:

$$\log D_1 = -0.1630 \cdot T - 0.6130 \cdot \log V_a - 8.0746 \cdot \log VFA - 0.5499 \cdot \log A + 6.8926 \cdot Density + 0.0015 \cdot (Pen_{77} \cdot R\&B) + 1.1463 \cdot bitumen\% \quad (31)$$

$$m = 11.8591 - 0.2370 \cdot V_a - 0.0310 \cdot VFA + 0.0489 \cdot Pen_{77} - 2.8850 \cdot Density - 0.0014 \cdot (Pen_{77} \cdot R\&B) - 0.1680 \cdot bitumen\% \quad (32)$$

where:

- T is the test temperature (°F);
- V_a is the specimen percentage of voids (%);
- *VFA* stands for Voids Filled with Asphalt (%);
- *A* is the intercept of binder Viscosity – Temperature relationship;
- *Density* is the density of the specimens (g/cm^3);

- *Pen_{77}* is the bitumen penetration at 77 ºF (mm/10);
- *R&B* is the temperature of the softening point (°F);
- *% bitumen* is the percentage of bitumen in the specimen.

As for ITS, the difference between them lies in the number of physical variables that were utilized for response prediction. For each Test case the list of multipliers of the individual variables is shown in Table 3. All 3 sources of material samples (Case I, II, III) were examined.

TABLE 3 Calculated Multipliers

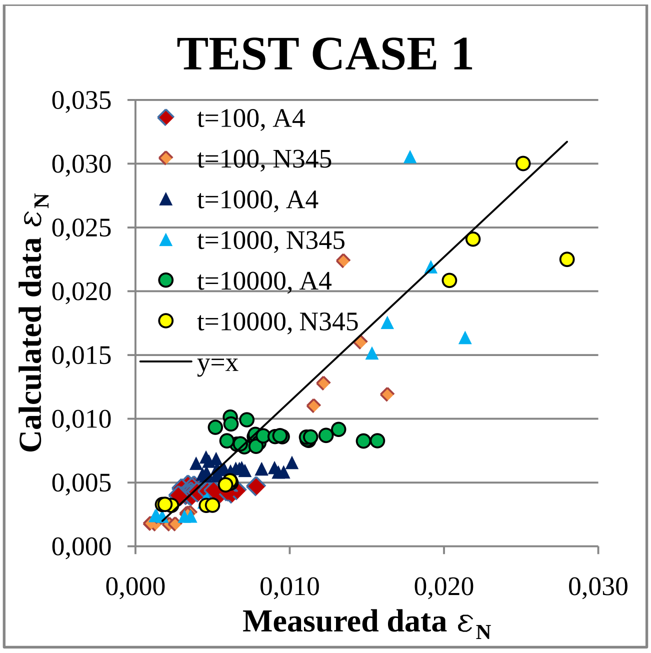
TEST CASE 1					
CASE I		CASE II		CASE III	
β_1	-0.8039	β_1	0.7260	β_1	-0.3736
β_2	10.7442	β_2	-9.5991	β_2	0.5396
β_3	38.9802	β_3	-40.4160	β_3	12.6002
β_4	3.3159	β_4	1.4703	β_4	-4.6667
ϑ_0	-12.9430	ϑ_0	-16.5398	ϑ_0	-1.5513
ϑ_1	0.6589	ϑ_1	0.8265	ϑ_1	0.1050
ϑ_2	0.1339	ϑ_2	0.1779	ϑ_2	0.0142
ϑ_3	0.0099	ϑ_3	-0.0110	ϑ_3	0.0082
TEST CASE 2					
CASE I		CASE II		CASE III	
β_1	-1.0619	β_1	-0.8262	β_1	-0.2444
β_2	13.0481	β_2	9.1896	β_2	0.4793
β_3	45.3106	β_3	13.1621	β_3	-1.0649
β_4	3.3251	β_4	4.7692	β_4	12.3518
β_5	5.6857	β_5	22.5510	β_5	14.8624
ϑ_0	4.5454	ϑ_0	-72.7789	ϑ_0	-4.7126
ϑ_1	0.1775	ϑ_1	2.3608	ϑ_1	0.1390
ϑ_2	0.0542	ϑ_2	0.4467	ϑ_2	0.0151
ϑ_3	0.0081	ϑ_3	-0.0043	ϑ_3	0.0147
ϑ_4	-3.9581	ϑ_4	12.3220	ϑ_4	1.1658

TEST CASE 3					
CASE I		CASE II		CASE III	
β_1	-1.6451	β_1	-0.1545	β_1	-0.1992
β_2	13.0472	β_2	9.1896	β_2	0.4793
β_3	45.3082	β_3	13.1621	β_3	-1.0649
β_4	-31.1910	β_4	45.8878	β_4	15.2125
β_5	5.6834	β_5	22.5510	β_5	14.8624
β_6	0.0086	β_6	-0.0096	β_6	-0.0005
ϑ_0	2.7252	ϑ_0	-34.4077	ϑ_0	-2.6017
ϑ_1	0.1784	ϑ_1	2.3608	ϑ_1	0.1390
ϑ_2	0.0543	ϑ_2	0.4467	ϑ_2	0.0151
ϑ_3	-0.1041	ϑ_3	2.7573	ϑ_3	0.1274
ϑ_4	-3.9460	ϑ_4	12.3220	ϑ_4	1.1658
ϑ_5	0.0030	ϑ_5	-0.0727	ϑ_5	-0.0033
TEST CASE 4					
CASE I		CASE II		CASE III	
β_1	-1.3847	β_1	-1.0104	β_1	-0.2886
β_2	13.0472	β_2	9.1896	β_2	0.4793
β_3	45.3082	β_3	13.1621	β_3	-1.0649
β_4	-49.1128	β_4	42.5175	β_4	11.9565
β_5	5.6834	β_5	22.5510	β_5	14.8624
β_6	0.0060	β_6	0.0033	β_6	-0.0046
β_7	-11.7336	β_7	15.4325	β_7	2.6777
ϑ_0	-0.5084	ϑ_0	-59.9699	ϑ_0	-4.1973
ϑ_1	0.1784	ϑ_1	2.3608	ϑ_1	0.1390
ϑ_2	0.0543	ϑ_2	0.4467	ϑ_2	0.0151
ϑ_3	0.0189	ϑ_3	-0.7392	ϑ_3	0.0202
ϑ_4	-3.9460	ϑ_4	12.3220	ϑ_4	1.1658
ϑ_5	0.0003	ϑ_5	0.0160	ϑ_5	0.0003
ϑ_6	1.0383	ϑ_6	-4.2656	ϑ_6	-0.2789

R-squared values were calculated at three instants of time (100, 1000, 10000 seconds) and it can be stated that the greater the time instant, the higher the *R-squared*. Table 2 reports the multipliers obtained means by the back-calculation.

In Test case 1 the variables provided from the NCHRP (*1*) were utilized, but for *Log* D_1 has been taken into account temperature (T) while for *m* the constant value (K). Furthermore it has not been taken into account $T*Pen_{25}^{\alpha}$ because of the exponential was set for the creep test conditions. For this reason also Test case 2, 3 and 4 present these characteristics. The *R-squared* values are 0.81, 0.88 and 0.93 in Case I, 0.19, 0.47 and 0.77 in Case II, 0.92, 0.92 and 0.93 in Case III. Test case 2 differs respect to Test case 1 only for *Density*: it can be seen that only the Case II has an improvement in terms of R^2, with values of 0.39, 0.67 and 0.90; Case I and Case III have slightly difference than the previous Test case. A combination of Pen_{77}**R&B* was added in Test case 3 leaving the same variables of Test case 2. The resulting parameters do not give a significant contribution. In all Cases *R-squared* values don't change. Finally, in Test case 4 the percentage of bitumen was added to the previous Test case 3. The contribution of this variable is relevant in Case II: *R-squared* is 0.41, 0.69 and 0.91.*R-squared* values of Case I and Case III were similar to the Test case 3.

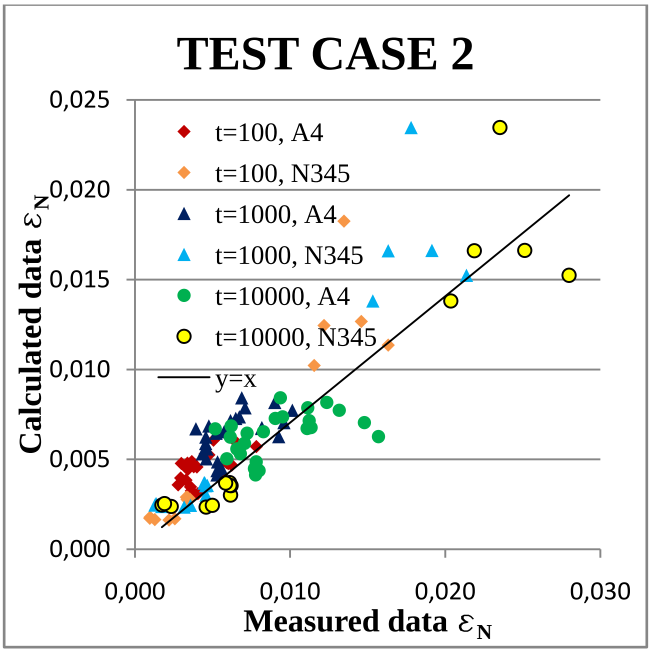
The calculated parameters were obtained including the total number of specimens for all Test cases. The results are reported in Figure 5, 6, 7 and 8. Compared to Case I, II and III where the *R-squared* improved with increasing number of cycles, the contribution of the total number of specimens resulted to a decrease of *R-squared* with increasing number of cycles.



TEST CASE 1	
β_1	0.1054
β_2	-1.7670
β_3	-7.5199
β_4	2.9947
ϑ_0	0.1726
ϑ_1	0.0025
ϑ_2	-0.0008
ϑ_3	0.0013

FIGURE 5 Test case 1 Measured and calculated ε_N; multipliers.

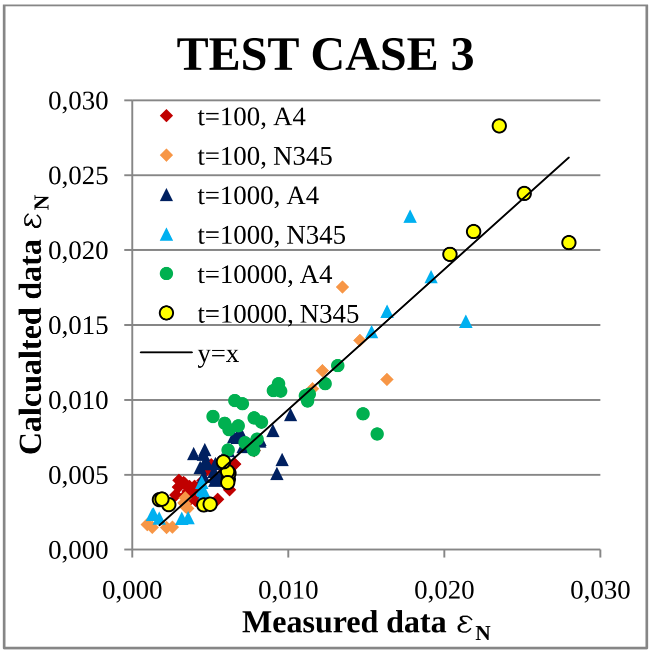
Figure 5 shows the data point distribution and the parameters calculated in the Test case 1. The *R-squared* value is 0.78 at 100 seconds, 0.77 at 1000 seconds and 0.73 at 10000 seconds.



TEST CASE 2	
β_1	-0.0790
β_2	-1.2627
β_3	-11.0295
β_4	3.1094
β_5	10.7454
ϑ_0	11.7994
ϑ_1	-0.2188
ϑ_2	-0.0283
ϑ_3	0.0010
ϑ_4	-3.6187

FIGURE 6 Test case 2 Measured and calculated ε_N; multipliers.

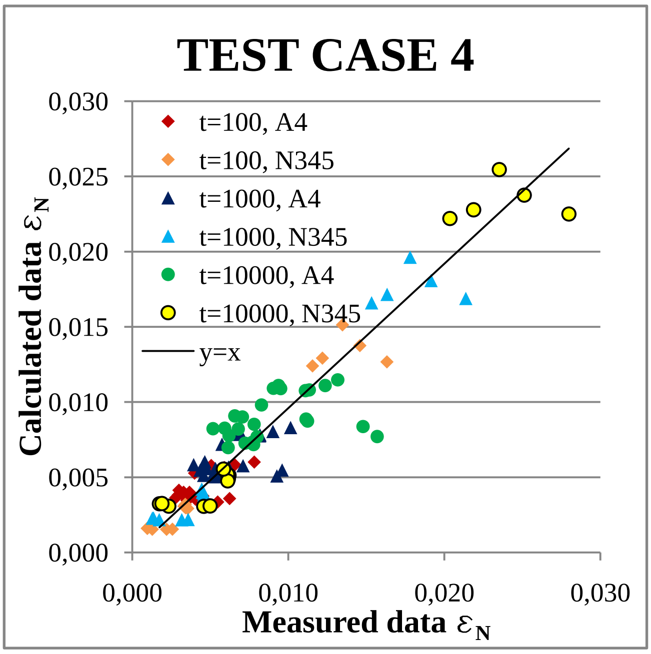
The set of new calculated parameters (Figure 6) gives *R-squared* values better than the Test case 1. *R-squared* is 0.84 at 100 seconds, 0.83 at 1000 seconds and 0.82 at 10000 seconds. Also it can be seen the distribution of the data points which is more clustered near the axis origin compared to the previous Test case.



TEST CASE 3	
β_1	-0.0756
β_2	-1.1903
β_3	-10.9344
β_4	5.7066
β_5	12.3746
β_6	-0.0006
ϑ_0	15.3469
ϑ_1	-0.3272
ϑ_2	-0.0452
ϑ_3	0.0225
ϑ_4	-4.2495
ϑ_5	-0.0006

FIGURE 7 Test case 3 measured and calculated ε_N; multipliers.

Figure 7 reports the data points distribution and the new parameters calculated. A further improvement in terms of *R–squared* than Test case 2 was observed: R^2 is 0.87 at 100 seconds, 0.86 at 1000 seconds, 0.83 at 10000 seconds.



TEST CASE 4	
β_1	-0.1630
β_2	-0.6130
β_3	-8.0746
β_4	-0.5499
β_5	6.8926
β_6	0.0015
β_7	1.1463
ϑ_0	11.8591
ϑ_1	-0.2370
ϑ_2	-0.0310
ϑ_3	0.0489
ϑ_4	-2.8850
ϑ_5	-0.0014
ϑ_6	-0.1680

FIGURE 8 Test case 4 measured and calculated ε_N; multipliers.

In Figure 8 the comparison between measured and calculated data and the parameters are reported. Test case 4 gives the best result in terms of *R–squared*: 0.91 at 100 seconds, 0.89 at 1000 seconds and 0.86 at 10000 seconds.

CONCLUSIONS

New formalistic models are proposed for a-priori determination of the indirect tensile strength and the permanent strain of AC mixtures on the basis of the mix composition characteristics. Two different Asphalt Concrete mixes that fulfill the CEN standards and that were produced with different production methods were used for calibration. The predictions of the new equations match well with the test result. Differences were observed in the compositional characteristics of the three mix production methods. These reflected on the values of the calculated multipliers of the various physical mix composition parameters developed for mix performance prediction and characterization. Analyses of more of the NL-LAB data are currently underway to improve and to validate the models.

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REFERENCES

1. Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures, Final Report, Part 3, Design Analysis, Chapter 3 Design of New and Reconstructed Flexible Pavements, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, Project 1-37A, March 2004

2. Comité Européen de Normalisation. European Standard EN 12697-23, Bituminous mixtures–Test methods for hot mix asphalt–Part 23: Determination of the indirect tensile strength of bituminous specimens. 2003.

3. Comité Européen de Normalisation. European Standard EN 12697-25, Bituminous mixtures–Test methods for hot mix asphalt–Part 25: Cyclic compression test. 2005.

4. Numerical Recipes in Fortran 77, The Art of Scientific Computing, Second Edition, William H. Press, Saul A. Teukolsky, William T. Vetterling, Brian P. Flannery. Cambridge University Press, New York, 1992.