Cent. Eur. J. Eng. • 3(3) • 2013 • 534-540
DOI: 10.2478/s13531-012-0073-6

VERSITA

Central European Journal of **Engineering**

# Correlation between permanent deformation-related performance parameters of asphalt concrete mixes and binders

**Research Article**

Kálmán Adorjányi[1]*, Péter Füleki[1]

1 *Department of Transport Construction and Municipial Engineering*
*István Széchenyi University, Egyetem tér 1, H-9026 Győr, Hungary*

**Received 05 December 2012; accepted 05 April 2013**

**Abstract:** This paper examines methods to predict the performance of hot asphalt concrete mixes based on performance parameters of binders. Specifically, relationships between binder parameters determined from multiple stress creep and recovery tests were correlated to the creep parameters of hot asphalt concrete mixes obtained from cyclic load compression testing. For the determination of creep parameters, a modified expression of the creep curve is proposed to cover the entire spectrum of permanent deformation; including the tertiary creep phase. Non-recoverable compliance, unrecovered strain, and recoverable strain of binders show good correlation to creep parameters of hot asphalt concrete mixes such as creep rate and high temperature performance ratio. Additionally, unrecovered strain and non-recoverable compliance of binders correlates well with mean rut depth of asphalt concrete mixes. However, no correlation has been detected between the difference in non-recoverable compliance of binders and permanent deformation parameters of asphalt concrete mixes.

**Keywords:** Asphalt concrete mix • Creep rate • Permanent deformation • Binder performance • Non-recoverable compliance• High temperature performance ratio • Rut depth

© *Versita sp. z o.o.*

## 1. Introduction

The resistance to permanent deformation is an important performance requirement in product standards both for binders and asphalt mixes. The validity of the binder performance parameter $G*/sin\varepsilon$ (complex shear modulus/phase angle) in Superpave (Superior Performing Asphalt Pavements) specifications related to permanent deformation has been found unsatisfactory for predicting rutting, especially for modified binders [1, 2] Bahia et al. [1] found poor correlation between $G*/sin\varepsilon$ value and the creep rate of asphalt mixtures determined from repeated-shear, constant-height tests. The value of $G*/sin\varepsilon$ parameter was determined in the linear viscoelastic range at low shear stresses while most of modified binders show nonlinear behaviour. The modified binders also show accumulation of permanent strain at higher stresses beyond the viscoelastic range [1, 2]. Several researchers indicated that $G*/sin\varepsilon$ cannot differentiate between total dissipated energy during cyclic loading and the energy dissipated in viscous deformation [1, 3] In 2007 for determination of binders' performance parameters, the Multiple Stress

*E-mail: adorjany@sze.hu

Creep and Recovery (MSCR) test was developed in the framework of SHRP (Strategic Highway Research Project) and Superpave (Superior Performing Asphalt Pavements) projects. The MSCR test consists of ten repeated shear creep and recovery cycles at different stress levels using a DSR (Dynamic Shear Rheometer). The average values of recoverable and unrecovered deformation parameters from ten creep and recovery cycles were calculated [2]. The stress dependency of binders can be characterized by applying multi-stress creep stages beyond the viscoelastic range. For the determination of the binder performance parameters, the average value of non-recoverable compliance was defined as [2]:

$$J_{nra} = \frac{\gamma_{una}}{\tau} \tag{1}$$

where $J_{nra}$ is the average non-recoverable compliance, [1/kPa]; $\gamma_{una}$ is the average un-recovered strain [mm/mm]; and $\tau$ is the applied creep stress [kPa] [2]. The difference in average non-recoverable compliance at an applied stress of 0.1 and 3.2 kPa as in AASHTO's 2010 designation [4]:

$$\Delta J_{nra}(3.2-0.1) = 100[J_{nra}(3.2) - J_{nra}(0.1)]/J_{nra}(0.1) \tag{2}$$

where $\Delta J_{nra}(3.2-0.1)$ is the difference in non-recoverable compliance at 3.2 kPa and 0.1 kPa applied stress, $J_{nra}(3.2)$ and $J_{nra}(0.1)$ are the average values of non-recoverable compliance at applied stress of 3.2 kPa and 0.1 kPa, respectively. This paper aims to establish relationships between the permanent deformation performance parameters of binders at high temperature and asphalt concrete mixes. First, an equation for asphalt concrete creep curve has to be determined. This should generate the best fit to cyclic triaxial compression test data covering all three phases of creep deformation. For binder parameters, properties derived from MSCR tests will be selected. Presented here are the materials tested; basic empirical parameters for different binders and data on the composition of selected hot asphalt concrete mixes. Results from laboratory tests are presented to evaluate the correlations performed in the road laboratory of István Széchenyi University.

The resistance of hot asphalt mixes to permanent deformation can be evaluated by empirical parameters such as the proportional rut depth and the wheel tracking slope; or with fundamental parameters such as creep rate determined by cyclic compression tests. However, little experience is available on the use of fundamental properties of asphalt mixes determined from cyclic load compression tests. The test yields a creep curve showing the development of cumulative permanent axial strain, $\varepsilon(n)$, versus the number of loading cycles, $n$, (Figure 1). Typically the creep curve can be presented in three sections, depending on the testing conditions [11? ]:

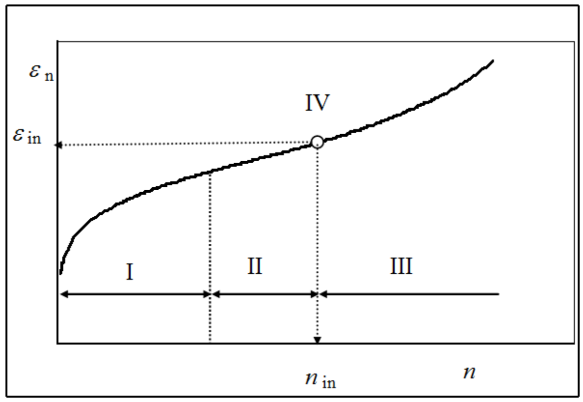


**Figure 1.** Schematic illustration of the creep curve (I, II, III-creep phases, IV- inflection point)

1. primary creep, where the creep rate decreases with the loading cycles (consolidation phase);
2. secondary creep with constant creep rate (steady-state creep), where the increase of permanent deformation is quasi-linear with the loading cycles;
3. tertiary creep with progressive increase of the permanent deformation and the creep rate under which the asphalt mix shows plastic flow. The inflection point (IV) on the creep curve indicates the beginning of the tertiary creep phase.

The creep curve is described by equation (3) given by L. Francken's [5] model, where the cumulative axial strain $\varepsilon(t)$ depends on time t, and curve-fitting parameters A, B, C and D:

$$\varepsilon(t) = At^B + C[exp(Dt) - 1] \tag{3}$$

Another approach for interpretation of the creep curve is given by (4) where the permanent strain $\varepsilon(n)$ is a function of loading cycles, n, and the coefficients $\varepsilon_0$, a, b, c and k can be determined through curve-fitting [6]:

$$\varepsilon(n) = \varepsilon_0 + an^k + b[exp(cn) - 1] \tag{4}$$

Hiersche and Nemesdy [7] determined the relationship between permanent strain $\varepsilon(n)$, [‰] and load cycles n with cubic parabola for uniaxial, unconfined cyclic load compression tests where $a_0, a_1, a_2, a_3$ are the regression constants:

**Table 1.** Empirical parameters of tested binders [13]

| Bitumen type | Sample code | Needle penetration @+25°C [0.1 mm] | Softening point (Ring and Ball)[°C] | Penetration index |
|---|---|---|---|---|
| Chemically stabilized rubber bitumen KSGB[1] | GB04/2012 | 32 | 63.0 | 0.56563 |
| Polymer modified bitumen 10/40-65[2] | PmB2448/09 | 24 | 67.0 | 0.66496 |
| Polymer modified bitumen 45/80-65 | PmB04/2012 | 45 | 80.0 | 4.03229 |
| Polymer modified bitumen 25/55-65 | PmB2842/09 | 48 | 66.2 | 2.0830 |
| Sealoflex®. SfB 5-503[3] | S-01-12-2 | 48 | 98.8 | 6.41308 |
| Paving grade bitumen 35/50[4] | B/4/2012 | 32 | 57.0 | -0.57872 |
| Paving grade bitumen 50/70 | B/E/07 | 49 | 50.3 | -1.16874 |
| Paving grade bitumen 50/70 | B/D/07 | 50 | 52.3 | -0.64064 |
| Paving grade bitumen 50/70 | B/C/1864/09 | 51 | 52.3 | -0.59872 |
| Hard paving grade bitumen 10/20 | B/3/2011 | 11 | 79.3 | 1.05270 |

[1] KSGB is the abbreviation of Chemically Stabilized Rubber Bitumen (in Hungarian)
[2] for polymer modified binders: nominal lower value of the needle penetration/nominal upper value of the needle penetration-nominal value of the Ring and Ball softening point;
[3] Sealoflex® polymer modified bitumen
[4] for paving grade binders and for hard paving grade bitumen: nominal lower value of the needle penetration/nominal upper value of the needle penetration

**Table 2.** Aggregate grading of tested AC 16 asphalt mix [13]

| Sieve opening size, [mm] | Percentage passing [%] |
|---|---|
| 0.063 | 5.9 |
| 0.25 | 9.9 |
| 2 | 27.0 |
| 4 | 45.8 |
| 5.6 | 51.2 |
| 8 | 61.9 |
| 11.2 | 77.8 |
| 16 | 97.5 |
| 22.4 | 100 |

$$e(n) = a_0 + a_1 n + a_2 n^2 + a_3 n^3 \quad (5)$$

Permanent deformation parameters on the quasi-linear part of the creep curve can be determined by two alternative methods, ignoring tertiary creep, as specified in the test standard EN 12697-25 [8]. The quasi-linear part (II creep phase) is described by a linear equation (6), (Method 1), [8]:

$$\varepsilon_n = A_1 + B_1 n \quad (6)$$

where $\varepsilon_n$ [%] is the cumulative axial strain, n is the number of applied loading cycles, $A_1$ and $B_1$ are the regression constants. The creep rate, $f_c$, defined as the slope of the quasi-linear part of the creep curve, given in microstrain per loading cycles [$\mu$m/m/n], is thus

$$f_c = 10^4 B_1 \; [8] \quad (7)$$

Another approach is to analyse the quasi-linear part of the creep curve with a least square power fit (Method 2, EN 12697-25), [8], Witczak et al. [9]:

$$\varepsilon_n = An^B \quad (8)$$

When the creep curve is represented on a log-log scale, the slope of the quasi-linear part equals exponent $B$ in equation (8). Typical parameters derived from the creep curve can be summarized as follows:

- creep rate, $f_c$, (7); the rate of change of permanent axial strain with loading cycles, and a specified performance parameter in the European product standard for hot asphalt concrete mixes [6-8, 9];
- calculated permanent strain after 1000 loading cycles, using equation (8) [8];
- parameter $B$ of the equation (8) [8, 9];
- number of loading cycles at the inflection point corresponding to minimum creep rate, $n_{in}$ [6, 7]; called flow number [9, 11];
- flow time; the time when minimum creep rate occurs during a static creep test (confined or unconfined) [9, 11];

**Table 3.** Summary of the permanent deformation parameters of AC 16 asphalt mix and binders

| Code of bitumen sample | Type of bitumen | $J_{nra}$(3.2) [1/kPa] | $\gamma_{reca}$(3.2) [%] | $\gamma_{una}$ (3.2) [%] | $PRD_{AIR}$ [%] | $f_c$ [μm/m/m] | $htpr$ [μm/m/m] |
|---|---|---|---|---|---|---|---|
| PmB2448/09 | Polymer modified bitumen 10/40-65 | 0.0518 | 65.217 | 16.563 | 3.18 | 0.225 | 1.181 |
| GB/04/2012 | Chemically stabilized rubber bitumen KSGB | 0.2436 | 51.532 | 77.957 | 4.63 | 0.692 | 2.529 |
| PmB04/2012 | Polymer modified bitumen 45/80-65 | 0.1019 | 81.572 | 32.609 | 3.78 | 0.702 | 3.380 |
| PmB2842/09 | Polymer modified bitumen 25/55-65 | 0.2460 | 40.330 | 78.717 | 4.15 | 0.542 | 2.181 |
| S-01-12-2- | Sealoflex® SfB 5-50 | 0.0641 | 87.492 | 20.503 | 4.18 | 0.531 | 2.430 |
| B/E/07 | Paving grade bitumen 50/70 | 0.7690 | 7.117 | 246.081 | 6.32 | 3.178 | 19.752 |
| B/D/07 | Paving grade bitumen 50/70 | 1.3291 | 2.490 | 425.320 | 5.84 | 11.610 | 33.732 |
| B4/2012 | Paving grade bitumen 35/50 | 0.4734 | 12.969 | 151.475 | 5.66 | 2.189 | 8.073 |
| B/C/1864/09 | Paving grade bitumen 50/70 | 1.1471 | 7.704 | 367.063 | 5.55 | 7.584 | 26.978 |
| B/3/2011 | Hard paving grade bitumen 10/20 | 0.0035 | 76.704 | 1.110 | 1.20 | 0.084 | 0.390 |

- permanent axial strain at the inflection point of the creep curve, $\varepsilon_{in}$ [6, 7];
- ratio of $n_{in}/\varepsilon_{in}$ [7, 12];
- regression coefficients depending on the equation of the creep curve.

The required values of $n_{in}/\varepsilon_{in}$ derived from uniaxial cyclic load compression tests were also listed in Hungarian technical specifications for hot asphalt mixes [12] The creep parameters for asphalt mixes can be determined by smoothing test data and moving-average techniques without fitting test data to a given mathematical equation. The rate of change of permanent strain depending on flow time or on flow number can be determined with a finite-difference formula (based on 3 points) and the minimum value of rate of change can be determined from the smoothed data (using 5-point moving average) [9, 11]. It was found that the flow number, the creep rate, and the permanent strain are good indicators of resistance to rutting [9].

## 1.1. Materials and tests

### 1.1.1. Testing binders with multiple stress creep recovery test

Data from earlier tests on binders were used to determine correlations to deformation parameters of asphalt concrete mixes [13]. Basic empirical parameters of paving grade binders, hard paving grade bitumen, polymer modified binders (PmB) and chemically stabilized rubber bitumen (KSGB, in Hungarian) are listed in Table 1 [13] These empirical parameters are: needle penetration (in 0.1 mm) determined at +25°C; the Ring and Ball softening point and penetration index. The binder parameters were in a range which corresponds to binders typically applied in Hungary and allowed by technical specifications for hot asphalt concrete mixes [14]. MSCR tests were performed using a DSR according to AASHTO TP 70-10 [2] test specification at 0.1 kPa, 3.2 kPa and 6.4 kPa stress levels. At each stress level, 10 test cycles were applied with 1 s creep phase and 9 s recovery phase. All DSR measurements were performed at a test temperature of +60°C on samples with a diameter of 25 mm and 1 mm gap size.

# 2. Testing of asphalt concrete mixes

Hot asphalt concrete samples were mixed using AC 16 type (Asphalt Concrete with aggregate upper sieve size of 16 mm, Table 2) aggregate grading and the 10 different binders, shown in Table 1. They were prepared in the laboratory with the same bitumen content of 4.6 m/m% and 0.3 m/m% of cellulose fibres as an additive, as shown in Table 1 [13].

In the course of earlier research wheel tracking tests were performed according to EN 12697-22 [15]test method (procedure B in air) from which mean proportional rut depths ($PRD_{AIR}$%) were taken for the determination of correlations given in Section 3 [13] Test slabs with dimensions of 305 mm x 305 mm x 100 mm were prepared at 5% air voids with roller compactor according to EN 12697-33 [16] test method. Four cores with a diameter of 98 mm were obtained from each slab for cyclic load compression tests. The ends of cylindrical specimens were polished to plan-parallel and dried before testing. Latex membrane and lubricant (graphite powder with silicone grease) systems were applied between the specimen and loading platens. The cyclic load compression test for each mix was performed using a universal hydraulic asphalt testing machine applying haversinusoidal deviator stress of 750 kPa (peak to peak value), at 3 Hz, dead load of 8 kPa, and constant confining pressure of 225 kPa at the test temperature of +60°C.

## 3. Test results and discussion

The creep curves were fitted with equations cited in Section 1 as well as with curve-smoothing techniques such as the finite-difference and moving-average methods. In order to determine the creep parameters, the whole data spectrum was used including data from tertiary creep phase. In order to achieve the best fit, equation (3) was modified as follows:

$$\varepsilon(n) = an^b + c[exp(dn^u) - 1] \qquad (9)$$

The proposed equation (9) will cover all three sections of the creep curve. The parameters *a, b, c, d* and *u* were obtained by applying the least squares method. The creep rate $f_c$ at the inflection point of the creep curve is the minimum value of the first derivative of (9):

$$\frac{\partial \varepsilon}{\partial n} = abn^{b-1} + cdin^{u-1}exp(dn^u) \qquad (10)$$

The inflection point was located at the zero value of the second derivative of (9)

$$\frac{\partial^2 \varepsilon}{\partial n^2} = 0 \qquad (11)$$

The selected performance parameters of binders were the average values of non-recoverable compliance (Equation 1), the difference in non-recoverable compliance (Equation 2), the unrecovered strain, $\gamma_{una}$, and the recoverable strain, $\gamma_{reca}$. The average unrecovered and recoverable strains were determined from MSCR measurements according to AASHTO's 2010 designation [2]. The selected performance parameters for asphalt mixes were the creep rate and the high temperature performance ratio, *htpr*, which is defined as the ratio of permanent strain $\varepsilon_{in}$ $[\mu m/m]$ to the number of loading cycles at the inflection point $n_{in}$:

$$htpr = \frac{\varepsilon_{in}}{n_{in}} \qquad (12)$$

Parameters for binders derived from DSR tests, and results of cyclic load compression tests and wheel tracking tests of asphalt mixes are listed in Table 3. Regression equations obtained from results between performance parameters of asphalt mixes and binders along with their correlation coefficients are given in Table 4. During the cyclic compression tests of asphalt concrete mixes prepared with three different paving grade bitumen 50/70, tertiary creep phase was reached in relatively short test time resulting in low flow numbers and higher variation of permanent strain at the inflection point of the creep curve. In the case of hard paving grade bitumen 10/20, the flow numbers were too large and the test time was impractically too long. The plots of fitted curves and data points are illustrated on Figures 2-7.

**Table 4.** Summary of the correlation equations between the performance parameters of different binders and AC 16 asphalt mix

| Parameter of asphalt mixes, y | Parameter of binders, x | Correlation equation | Correlation coefficient $R^2$ |
|---|---|---|---|
| $f_c$ | $J_{nra}(3.2)$ | y = 0.2777 exp(3.0029 x) | 0.8726 |
| $f_c$ | $\gamma_{reca}(3.2)$ | y = 36.929 x | 0.8180 |
| *htpr* | $J_{nra}(3.2)$ | y = 25.054 x - 1.0348 | 0.9722 |
| *htpr* | $\gamma_{reca}(3.2)$ | y = 39.315 - 8.999 ln (x) | 0.8838 |
| $PRD_{AIR}$% | $\gamma_{una}(3.2)$ | y = 1.1463 + 0.813 ln (x) | 0.9925 |
| $PRD_{AIR}$% | $J_{nra}(3.2)$ | y = 5.836 + 0.813 ln (x) | 0.9925 |

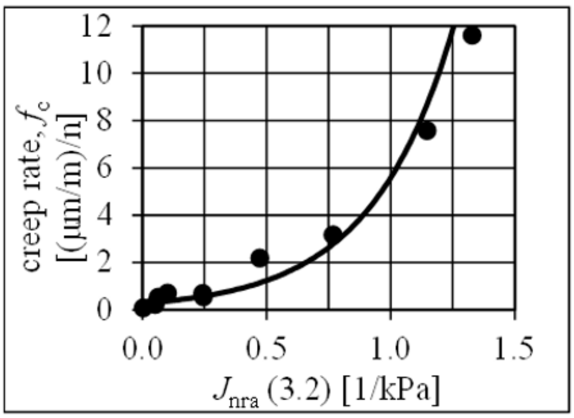


**Figure 2.** Correlation between creep rate of AC 16 asphalt mixes and average non-recoverable compliance of different binders

## 4. Conclusions

Good correlations have been found between binders' performance parameters obtained with MSCR tests and AC 16 asphalt concrete mixes permanent deformation parameters obtained from cyclic compression tests and wheel

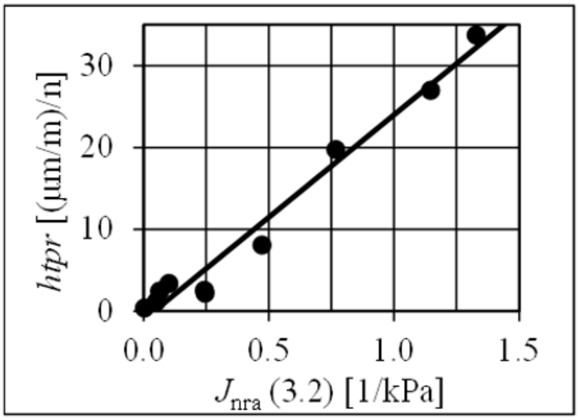


**Figure 3.** Correlation between high temperature performance ratio of AC 16 asphalt mixes and average non-recoverable compliance of different binders

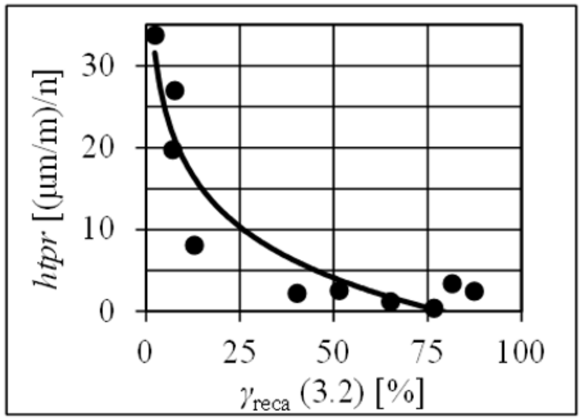


**Figure 5.** Relationship between high temperature performance ratio of AC 16 asphalt mixes and average recoverable strain of different binders

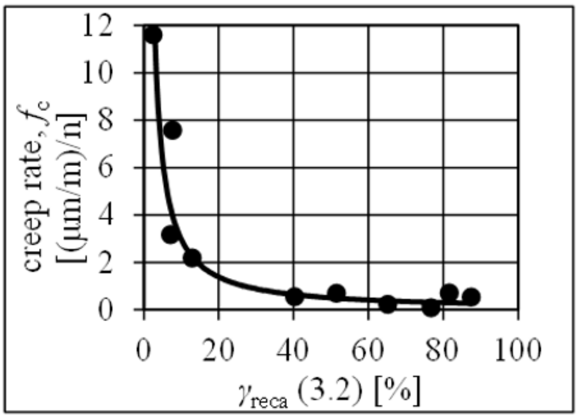


**Figure 4.** Relationship between creep rate of AC 16 asphalt mixes and averagere recoverable strain of different binders

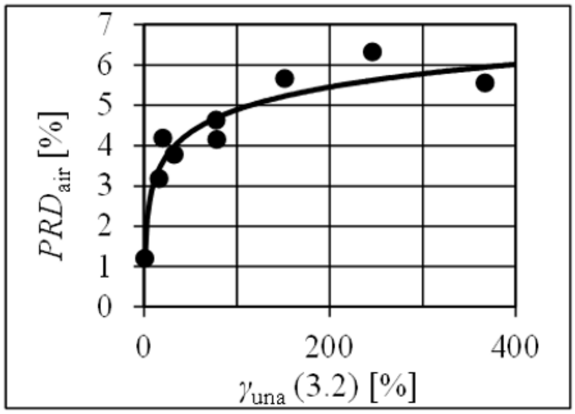


**Figure 6.** Proportional mean rut depth of AC 16 asphalt mixes versus unrecovered strain of different binders

tracking tests. Correlation coefficients are 0.8726 and 0.9722 for non-recoverable compliance and 0.9225 for unrecovered strain and are 0.8180 and 0.8838 for recoverable strain. Very good linear correlation has been found between non-recoverable compliance of binders and high temperature performance ratio of asphalt concrete mixes ($R^2$=0.9722). The coherence between unrecovered strain as well as non-recoverable compliance of binders and resistance to permanent deformation of asphalt mixes determined with wheel tracking tests also manifested with good correlation ($R^2$=0.9225) for proportional mean rut depth. No correlation has been detected between difference in non-recoverable compliance of binders and creep parameters of AC 16 asphalt concrete mixes. Parameters derived from the creep curve equation (9) determined with regression analysis provided better correlation coefficients than those obtained with equations mentioned in Section 1 as well as with finite-difference and moving average methods. From data analysis it was revealed that with increasing bitumen penetration the creep parameters of asphalt concrete mix show larger variation. For hard paving bitumen the test stress level should be increased to obtain appropriate and comparable creep parameters.

## 5. Acknowledgements

The laboratory tests of asphalt concrete mixtures presented in this paper were performed within the frame of research project TÁMOP 4.2./B-10/2010-0010, supported by National Development Agency, at the István Széchenyi University, Hungary.

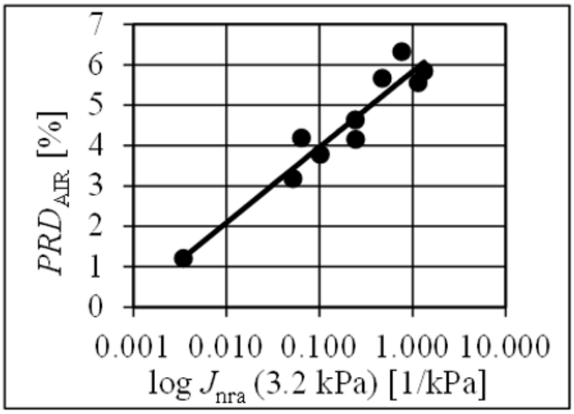


**Figure 7.** Proportional mean rut depth of AC 16 asphalt mixes versus non-recoverable compliance of different binders

## References


[1] Bahia H.U., Hanson D.I., Zeng M., Zhai H., et al. Characterization of Modified Asphalt Binders in Superpave Mix Design. NCHRP Report 459, TRB, National Academy Press, Washington D.C., 2001, 1-93.

[2] D'Angelo J., Kluttz R., Dongre R., Stephens K., et al. Revision of the Superpave High Temperature Binder Specification: The Multiple Stress Creep Recovery Test. Journal of the Association of Asphalt Paving Technologists, Volume 76, 2007, 123-162.

[3] Merusi F., Giuliani F. Intrinsic resistance to non-reversible deformation in modified asphalt binders and its relation with specification criteria. Construction and Building Materials, 2011, 25, 3356-3366.

[4] American Association of State Highway and Transportation Officials (AASHTO) Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR), AASHTO Designation: TP 70-10, 2010.

[5] Francken, L. Deformations permanentes observées en laboratoire et sur routes experimentales. Internationales Kolloquium über die plastische Verformbarkeit von Asphaltmischungen, (29-30th September, 1997, Zürich, Switzerland) ETH Zürich, Mitteilung Nr. 37, 1977, 112-137.

[6] Einaxialer Druckschwellversuch-Bestimmung des Verformungsverhaltens von Walz-asphalten bei Wärme, Technische Prüfvorschriften für Asphalt im StraSSenbau TPA-StB, 756/3, Arbeitsgruppe AsphaltstraSSen, FGSV, e.V. Köln, Ausgabe 1999, 5-12.

[7] Hiersche, E-U., Nemesdy E. Development of dynamic asphalt tests-Comparative dynamic creep tests, In Fritz H.W., Eustacchio E. (Ed.), Mechanical Tests for Bituminous Mixes, Proceedings of 4th International RILEM Symposium, ISBN 0-412-39260-7, (23-25th October,1990 Budapest Hungary), Chapman and Hall, 1990, 469-482.

[8] EN 12697-25:2005 Bituminous mixtures-Test methods for hot mix asphalt-Part 25: Cyclic compression test, CEN, Brussels, 2005, 1-29.

[9] Witczak, M.W., Kaloush K., Pellinen T., El-Basyouny, et al. Simple Performance Test for Superpave Mix Design, NCHRP Report 465, TRB, National Academy Press, Washington, D.C. 2002, 1-114.

[10] EN 13108-1:2006 Bituminous mixtures-Material specifications. Part 1: Asphalt Concrete, CEN, Brussels, 2006, 1-29.

[11] Bonaquist R.F., Christensen D.W., Stump W. Simple Performance Tester for Superpave Mix Design, NCHRP Report 513, TRB, National Academy Press, Washington, D.C. 2003 1-169

[12] Bituminous bases and pavements for road construction. Technical Specifications for Roads, ÚT 2-3.301:1995, Ministry of Transport, Telecommunication and Water Management-Hungarian Road Society, Budapest, 1995, 1-19. (in Hungarian)

[13] Bituminous Mixtures for Road Construction-Asphalt Concrete. Technical Specifications for Roads, ÚT 2-3.301-1:2010, Ministry of Transport, Telecommunication and Energy- Hungarian Road Society, Budapest, 2010, 1-19. (in Hungarian)

[14] Adorjányi K., Füleki P. Investigation of relationships between rheological parameters of bitumen binders and rutting resistance of asphalt concrete. Proceedings 14th International Scientific Conference Q-2012, Construction, funding and administration of the roads and highways, (September 13-14, 2012 Őilina, Slovakia), University of Őilina, 2012, 81-87.

[15] EN 12697-22:2003+A1:2008 Bituminous mixtures-Test methods for hot mix asphalt-Part 22: Wheel tracking, CEN, Brussels, 2003, 1-29.

[16] EN 12697-33:2003+A1:2008 Bituminous mixtures-Test methods for hot mix asphalt-Part 33: Specimen prepared by roller compactor, CEN, Brussels, 2003, 1-18