THE INFLUENCE OF BINDER RHEOLOGICAL PROPERTIES ON ASPHALT MIXTURE PERMANENT DEFORMATION

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Abstract. The main goal of this paper is to propose the performance parameter for binder which is good for quality prediction of asphalt mixture in frame of resistance to permanent deformation (rutting). Additionally, correlation between, proposed by the authors, repeatable shear creep-recovery test carried out on binder and bituminous mixture rutting test is under evaluation. The results are analysed and correlation between the proposed functional parameter and rut depth is shown. Thanks to that it is possible to claim that expensive rutting test procedure can be assisted with simple test carried out in dynamic shear rheometer at the initial mix design procedure.

Keywords: binder performance parameters, permanent deformation, rutting, dynamic shear rheometer.

1. Introduction

The road structures are currently exposed to the increasing traffic loading, cf. (Žiliūtė, Laurinavičius 2013). For this reason optimization of road structure and road materials is a key issue because of the minimization of building and maintenance costs in context of its resistance to damage. Pavement damage is caused not only by aforementioned factors, but also due to environmental impact, defective project or work quality. In case of semi-rigid pavements, the basic pavement damage mechanism can be divided into three groups such as: rutting, fatigue cracking and low temperature cracking (Bańkowski *et al.* 2013; Coleri *et al.* 2012).

On the basis of research widely presented in the literature connected to rutting phenomena, cf. (Coleri *et al.* 2012; Gagliano *et al.* 2004; Polacco *et al.* 2008), it is easy to name basic factors with direct influence on the rut depth. These factors are interpreted as connected with: aggregate, binder, bituminous mixture, environmental conditions, traffic, structure type and actual road condition (Błażejowski 2007). The purpose of this paper is to analyse the resistance to permanent deformation of modified and unmodified binders as one among the other factors having a large influence onto properties of bituminous mixture (Motamed *et al.* 2012; Słowik 2012).

In majority of the countries the binders are characterized using the standard methods, which allow obtaining basic standard properties, e.g. penetration, softening point, Fraass breaking point in the fixed standard conditions. Such conditions, e.g. temperature, usually do not correspond to the conditions in which binders work in asphalt pavements. As a result, assessment of permanent deformation development using these conventional tests is not sufficient in most cases (D'Angelo *et al.* 2007).

The research methods developed in frame of SHRP program, using such devices as: Bending Beam Rheometer (BBR), Dynamic Shear Rheometer (DSR) or Rotational Viscometer (RV) allow taking into consideration functional parameters based on physical characteristics. Such tests can be carried out not only on original binders but also on binders exposed into aging processes simulated in RTFOT (Rolling Thin Film Oven Test) and PAV (Pressure Aging Vessel).

The high-temperature parameter ($|G^*|/\sin(\delta)$) used in "Superpave" system for performance assessment of binders does not provide a reasonable result in case of polymer modified binders, as it was shown for example in (Polacco *et al.* 2008). In that case the new parameter is needed to assess resistance to permanent deformation for modified and unmodified binders (Merusi, Giuliani 2011; Zoorob *et al.* 2012a, 2012b).

In the USA the new system for performance binder assessment (called "Superpave Plus") was introduced. This system, in comparison with the previous one, was extended by the new requirements for phase angle and material strength in Direct Tension Test (DTT). However it was criticized in the literature. The new and relatively simple test Multiple Stress Creep Recovery Test – (MSCR) seems

to be a milestone for Federal Highway Agency (USA) cf. (D'Angelo *et al.* 2007; Zoorob *et al.* 2012b). The parameter obtained from this test (interpreted as material compliance) describes rheological properties of material.

In general, in order to avoid pavement rutting, the binders for bituminous mixture supposed to have high stiffness with high elastic part of complex modulus (assuming that the rest of the parameters were chosen properly). Quite significant value of complex modulus norm (stiffness level) guarantee small deformations, while high value of elastic part of complex modulus guarantee that after load removing the road pavement will return to its reference configuration. This type of mechanical properties of asphalt binder are determined in DSR (Mezger 2002).

In this paper the proposition of non-standard method of permanent deformation resistance assessment is presented. The proposed test consists of multiple creep-relaxation tests ending with long relaxation period for specific stress levels. Such tests were carried out in dynamic shear rheometer in case of four binder types: 35/50, 50/70, 30B (PMB 25/55-60) and 80B (PMB 45/80-55).

2. Proposition of assessment method for evaluation of binder resistance to permanent deformation

The proposed test consisting of multiple creep-relaxation tests ending with long relaxation period for specific stress levels is similar to MSCR test with fundamental difference on the stage of resulting parameter evaluation. The proposed test is carried out with stress input function described with the following relationships (Fig. 1):

$$\tau_k(t) = \begin{cases} \tau_0, & t \in \left[(k-1)t_p, kt_p\right] \\ 0, & t \in \left[kt_p, (k+1)t_p\right] \end{cases}, k \to 1, 2, \ldots, 9, \quad (1)$$

for $k = 10$

$$\tau_{10}(t) = \begin{cases} \tau_0, & t \in \left[9t_p, 10t_p\right] \\ 0, & t \in \left[10t_p, 10t_p + t_r\right] \end{cases}, \quad (2)$$

and it will be called as creep under repeated stress load (CURSL).

In relationships (1) and (2) the characteristic times were assumed as follows: $t_p = 50$ s (creep time) and $t_r = 200$ s (relaxation time). It is worth mentioning that at the beginning in the proposed test instead of restriction imposed on t_r the restriction on strain velocity was used. It was assumed that if the strain velocity (with suitable accuracy) is close to zero then the test is stopped. The interpretation of this fact was quite clear – there was full relaxation in material sample. Practically, times needed for full relaxation were significant, so the decision was made to assume *a priori* relaxation time as equal to $t_r = 1200$ s (in MSCR test the creep time was assumed as equal to 1 s and relaxation time in all cycles as equal to 9 s).

Because the criterion proposed will be verified inter-alia through mixtures rutting tests, it was difficult to

choose one stress level on this stage. The same situation is in the case of the value of the temperature at which the test is performed. Thus, it was assumed initially that the test will be conducted at three selected temperatures: $T = 10$ °C, 30 °C, 60 °C.

Having in mind that there is the need for the performance test describing binder properties with conjunction to mixture rutting resistance, a permanent deformation factor in the following form was introduced:

$$w_d = 1 - \frac{\gamma_{zr}}{\gamma_{max}}, \quad (3)$$

where γ_{zr} – stands for permanent strain remaining after relaxation for 1200 s; γ_{max} – for maximal strain after ten cycles of stress (Fig. 2). It is worth noting that $w_d = 1$, when material is purely elastic ($\gamma_{zr} = 0$), and $w_d = 0$, when material is perfectly plastic ($\gamma_{zr} = \gamma_{max}$). In general, deformation factor w_d introduced for the binder is a function of the stress and temperature levels (i.e. $w_d = w_d(\tau_0, T)$). Determination of deformation factor proposed by definition (3) is meaningful only for temperatures well below the softening temperature of asphalt, because when it is exceeded the result for w_d always is close to zero.

3. Experimental tests – binders

Binders for tests were chosen in such way to have possibility of comparison of rheological properties of binders
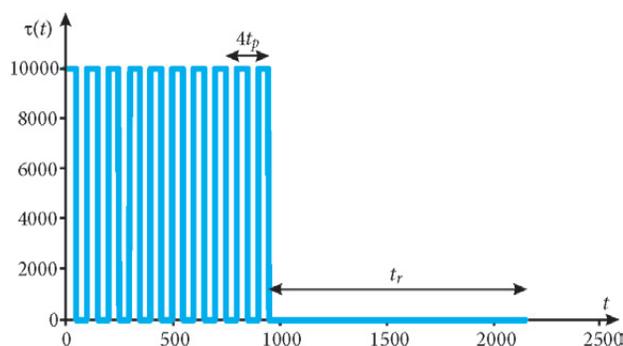
Fig. 1. The stress input function for $\tau_0 = 10$ kPa in proposed creep-relaxation test with multiple loading (Gajewski *et al.* 2009)
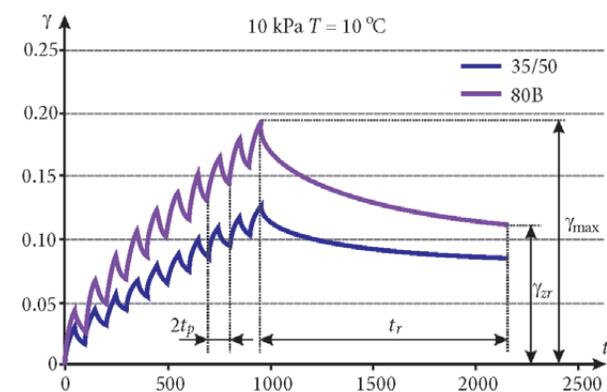
Fig. 2. Shear strain as a time function as a response to a given stress program shown in Fig. 1. Interpretation of the characteristic quantities (Gajewski *et al.* 2009)

commonly used for mix production. Thus, the following binder types, all from Polish refineries, were chosen: 35/50, 50/70, 30B (PMB 25/55-60) and 80B (PMB 45/80-55).

3.1. Basic tests

For some chosen binders the following basic standard tests were carried out: penetration in 25 °C according to *PN-EN 1426:2009 Asfalty i produkty asfaltowe – Oznaczanie penetracji igłą* [Bitumen and Bituminous Binders – Determination of Needle Penetration], softening point R&B according to *PN-EN 1427:2009 Asfalty i produkty asfaltowe. Oznaczenie temperatury mięknienia. Metoda Pierścień i Kula* [Bitumen and Bituminous Binders. Determination of the Softening Point. Ring and Ball method] and Fraass braking point according to *PN-EN 12593:2009 Asfalty i produkty asfaltowe. Oznaczanie temperatury* łamliwości *metodą Fraassa* [Bitumen and Bituminous Binders. Determination of the Fraass Breaking Point].

The obtained results are presented in Table 1. Using two of the parameters, e.g. penetration and softening temperature, it is possible to postulate the ranking of binders having in mind their resistance to the permanent deformation. It seems that the best is binder 30B, since it has the highest softening point and the lowest value of penetration.

3.2. Complex modulus and phase angle

The real and imaginary part of complex shear modulus were tested at temperature $T = 10$ °C with frequency equal to $f = 10$ Hz. These testing conditions are used for stiffness and fatigue tests of bituminous mixtures in Poland and are commonly used in process of flexible pavement design.

On the basis of the information presented in Table 2 it is possible to state, that the highest value of elastic part stands for binder 30B, and the lowest one for binder 50/70. These facts together with information, that the highest

value of phase angle stands for binder 50/70, and the lowest for binder 30B allows to indicate binder 30B as a the best type and binder 50/70 as the worst type. Thus, the ranking of binders resulting from Table 2 is as follows: 30B, 35/50, 80B and 50/70.

3.3. Zero shear viscosity

Zero Shear Viscosity (ZSV) at some established temperature is treated as a functional material parameter, cf. (Sybilski 1996; Morea *et al.* 2011; Zoorob *et al.* 2012a). ZSV is determined using many different rheological tests (Mezger 2002) carried out for example in DSR rheometer (*AASHTO T315-06 Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*):

- in rotational shear test (with stress or strain impulse), as a limit value of $\eta(\dot{\gamma})$ function, for $\dot{\gamma} \to 0$,
- in oscillatory test, carried out for wide range of frequency (or angular frequency), as a limit value of viscosity function $|\eta^*|(\omega)$, for $\omega \to 0$,
- in creep test, as a parameter characterizing stabilized creep phase.

In the first two cases it is obvious that for evaluation of ZSV the constitutive model is needed, because ZSV is a limiting value for $\dot{\gamma} \to 0$ (or $\omega \to 0$) and it cannot be measured in an experiment. Constitutive models for functions $\eta(\omega)$ and $\eta(\dot{\gamma})$ are well developed in literature, cf. (Barnes *et al.* 1989; Sybilski 1996; Ward, Sweeney 2012) and (Delgadillo *et al.* 2012), but in this research model of Carreau and Yasuda was applied.

In Fig. 3 the summary results of zero shear viscosity for different binders as a function of temperature are presented. As expected, all functions are decreasing, i.e. zero shear viscosity decreases with increasing temperature.

With assumption that ZSV value is a good criterion for performance grading, it is easy to observe that in full

Table 1. Standard binder properties – tests results

Binder property	Binder type			
	35/50	50/70	30B	80B
Penetration in temp. 25 °C, 0.1 mm	43	67	33	62
Softening temperature R&B, °C	54.2	48	71.4	56.4
Fraass breaking point, °C	−19	−22	−23	−18

Table 2. The values of real part, imaginary part and norm of complex modulus together with phase angle in temperature $T = 10$ ºC and frequency $f = 10$ Hz

Parameter	Binder type			
	35/50	50/70	30B	80B
$|G^*|$, MPa	35.11	22.55	36.60	26.92
$Re(G^*)$, MPa	28.75	17.27	30.76	21.08
$Im(G^*)$, MPa	20.16	15.26	19.86	16.75
δ, degree	35.05	41.53	32.86	38.48

Note: the values in the table are averages from 16 measurements (because of that, the well-known relationships: $Re(G^*) = |G^*|\cos(\delta)$, $Im(G^*) = |G^*|\sin(\delta)$ are not compliant in the Table 2.

temperature range the best is bitumen 30B. Results for binders 35/50 and 80B are very close to each other, with the fact that for higher temperatures (range between 60–70 °C) binder 80B seems to be slightly better. Almost in whole range the worst is binder 50/70, and only for temperature equal to 70 °C binder 50/70 is better than binder 35/50.

3.4. CURSL – creep under repeated stress load

In the case of chosen binders the analysis of the deformation parameter w_d (Section 2) was performed for three selected temperatures: $T = 10$ °C, 30 °C and 60 °C and six levels of shear stress: $\tau_0 = 0.1, 0.5, 1.0, 10.0, 20.0, 30.0$ kPa. All obtained results are presented in (Gajewski *et al.* 2009). For example, in Fig. 4 there are provided the permanent deformation parameters w_d as a function of shear stress τ_0 obtained at a temperature $T = 10$ °C. At a temperature $T = 30$ °C there is a clear decrease in the w_d parameter for unmodified binders in the whole range of stresses. Modified binders tend to be much more resistant to permanent deformation affected by the temperature, but only in a certain range of stress, i.e. from 0.1 to 1 kPa (Figs 4 and 5).

It is also noted that at higher temperatures for moderate levels of stress deformation coefficients w_d take higher values for the binder 80B, than for the binder 30B. In the case of unmodified bitumen at a temperature $T = 60$ °C the deformation parameters w_d in the whole range of stresses are close to zero. However, this fact is consistent with predictions made on the basis of the softening point temperature determined in the standard test, which for the binder 35/50 is 54.4 °C, and for the binder 50/70 only 49 °C. This means that in these two cases, the test was performed on a substance with properties similar to fluids and not to a viscoelastic solid.

Modified binders at high temperatures also exhibit higher values of the w_d parameter, but only for moderate stress. After the crossing of about 10 kPa the internal structure which is stabilized by a modifier is disintegrated and then the w_d parameter is close to zero.

On the basis of the results presented in (Gajewski *et al.* 2009) and in Figs 4 and 5, it is clear that bitumen function $w_d(T, \tau_0)$ has its max at $T = 10$ °C and $\tau_0 = 1.0$ kPa. Consequently, it is assumed that $T = 10$ °C and stress $\tau_0 = 1.0$ kPa are the most appropriate conditions for most binders in CURSL test.

4. Experimental tests – mixtures

Determination of resistance of asphalt mixes to permanent deformation was performed by means of the so-called large device (LD, LCPC device) and small device (SD) (both methods according to *PN-EN 12697-22+A1:2008 Mieszanki mineralno – asfaltowe – Metody badań mieszanek mineralno – asfaltowych na gorąco – Część 22: Koleinowanie* [Bituminous Mixtures – Test Methods for Hot Mix Asphalt Part 22: Wheel Tracking]. A compacted bituminous plate in the test is exposed to repeated load transferred through standard rubber wheel, in the standard conditions of temperature, pressure and number of loads repetitions. After completion of the test rut (rut depth) created by the wheel

in an asphalt sample is measured. SMA11 mixture was designed according to Polish requirements (*WT-2 Nawierzchnie asfaltowe na drogach publicznych* [Asphalt Pavements on Public Roads], *IBDiM, Warsaw, Poland 2008*) as a wearing course for a medium and heavy traffic category, cf. (Błażejowski 2007).

The SMA11 mixture is made of the following material components: bitumen (35/50, 50/70, 30B, 80B), limestone filler, granite fraction 0/2 mm, basalt fraction 2/5, 5/8, 8/11 mm, Wetfix adhesive additive and the stabilizing additive ARBOCEL. All mixtures SMA11 are prepared with the same mineral composition, with the same content of the binder, but with different binder type (35/50, 50/70, 30B, 80B). As an example the test results obtained with a large device are shown in Fig. 6, and more detailed results are presented in (Gajewski *et al.* 2009).
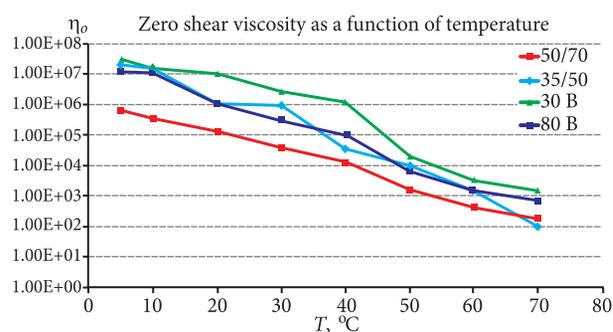
Fig. 3. Zero shear viscosity (in Pas), for the chosen binders as a function of temperature
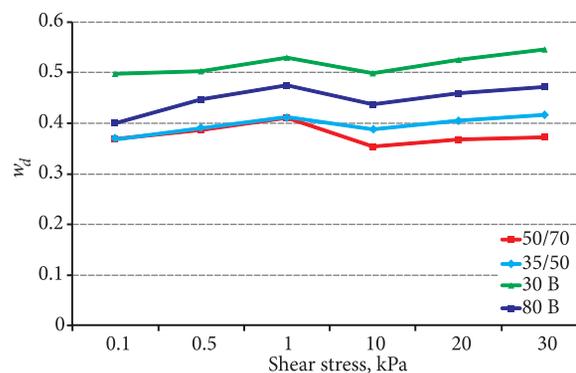
Fig. 4. The permanent deformation parameter as a function of shear stress τ_0 obtained at temperature $T = 10$ °C
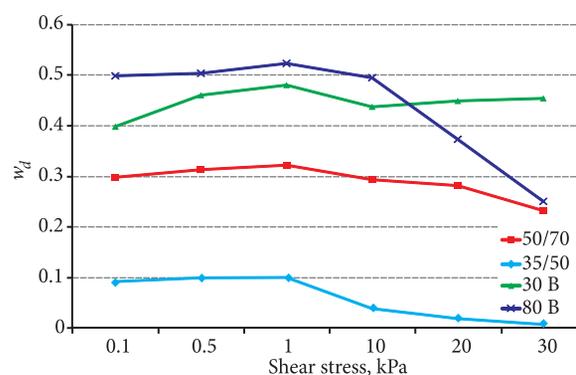
Fig. 5. The permanent deformation parameter as a function of shear stress τ_0 obtained at temperature $T = 30$ °C

Based on the graphs provided in Fig. 6 the mixture ranking in terms of their resistance to rutting in large device is as follows: 30B, 35/50 and 50/70 (from best to worst). In the case of the mixture with a binder 80B its position in the ranking varies with the number of cycles. After exceeding 20 000 cycles rut depth of a mixture with binder 80B is the highest.

5. Analysis of obtained results for establishing link between CURSL and rutting tests

The main goal of this paper is to identify the parameter characterizing the binder which is suitable enough to predict the ranking of mineral asphalt mixtures made with that binder in terms of their resistance to permanent deformation. An additional goal is to find a correlation between the results of the proposed test of creep under repeated stress load (CURSL) performed on the asphalt binder and rutting tests carried out on plate samples made of bituminous mixtures. At this stage of the analysis, the rutting tests has been performed in a large device (LCPC) and a small device, respectively at 60 °C in the LCPC-type device and 45 °C and 60 °C in a small device.

The analysis of the correlation between results of the CURSL test, and results of the rutting test carried out in LCPC device shows that it is possible to find a linear relationship between the parameter w_d (τ_0 = 0.1, 0.5, 1.0 kPa, T = 10 °C) and the rut depth after 10 000 load cycles carried out in temperature equal to 60 °C, see Table 3. Determination coefficient is then in the best case equal to 0.941 (Fig. 7).

Similar results for higher stress levels in CURSL test are observed (Fig. 8). Nevertheless, at higher temperatures
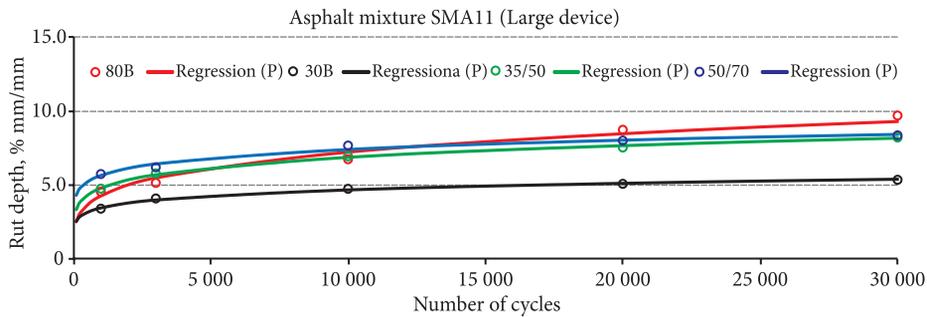
Fig. 6. The rut depth as a function on cycle number in case of SMA11 mixture with 35/50, 50/70, 30B and 80B binders – tests in the temperature 60 °C carried out in large device
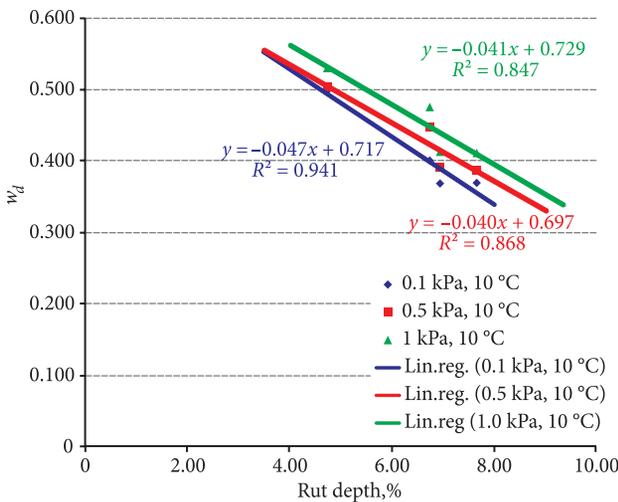
Fig. 7. Correlation of parameter w_d (τ_0 = 0.1, 0.5, 1.0 kPa, T = 10 °C) with rut depth after 10 000 cycles in LCPC device at temperature 60 °C
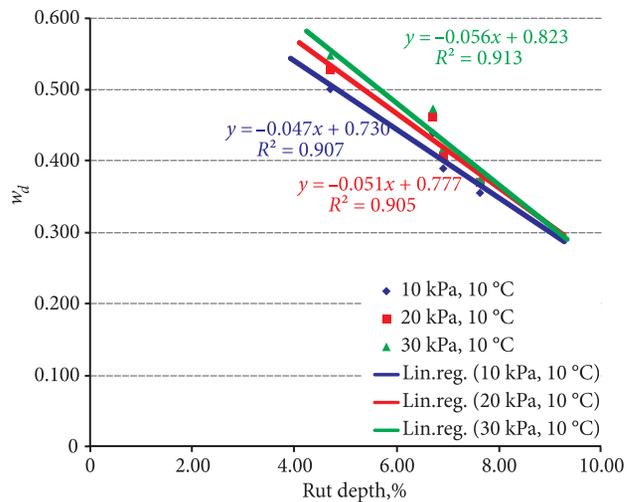
Fig. 8. Correlation of parameter w_d (τ_0 = 10, 20, 30 kPa, T = 10 °C) with rut depth after 10 000 cycles in LCPC device at temperature equal to 60 °C

Table 3. The values of R^2, depending on rutting conditions and device type (CURSL at 10 °C)

Rutting device and temperature	R^2 for small stress levels			R^2 for high stress levels		
	0.1 kPa	0.5 kPa	1.0 kPa	10.0 kPa	20.0 kPa	30.0 kPa
SD 45 °C	0.45	0.65	0.65	0.81	0.82	0.83
SD 60 °C	0.52	0.73	0.73	0.87	0.87	0.88
LD(LCPC) 60 °C	0.94	0.87	0.85	0.91	0.91	0.91

there is no linear correlation of w_d with the rutting results what is consistent with limitations stated above. All determination coefficients depending on rutting conditions and device type are presented in Table 3.

It is worth noting that the generalization of conclusions based on the above graphs for the existence of a linear correlation between the $w_d(T, \tau_0)$ parameter (at a given temperature and stress level) and rutting results (obtained in two different devices and at two different temperatures) formulated for SMA11 onto other types of bituminous mixtures at this stage of research are unjustified.

Obtained correlations are true under certain requirements concerning other important parameters (such as air voids content, binder content, etc.) strongly influencing the mixture rutting. The thesis that it is possible to point out a good relationship for all mixture types, must at this stage of research be rejected. Obtaining the ranking of mixtures due to their resistance to rutting under the proposed CURSL test, which was the primary objective of this work, is as far as possible, provided that the design of asphalt is made in accordance with all rules and technical requirements.

6. Conclusions

1. The study presented in this paper proved that there is a correlation between the parameter w_d of the binder and the rut depth for the bituminous mix designed as optimal. The parameter w_d is the result of creep tests performed under load repeated at different temperature and shear stress levels. Rutting tests were conducted in two types of device: large and small, respectively at temperature 45 °C and 60 °C. Very good correlations were obtained for the w_d parameter identified at 10 °C and rutting results after 10 000 cycles in large device ($R^2 = 0.9$) for both small (0.1–1.0) kPa and high stress levels (10.0–0.0) kPa. It is possible to formulate similar opinion for the rutting results obtained in small device at 60 °C, for low stress levels ($R^2 = 0.7$) and high stress levels ($R^2 = 0.9$). Fairly good correlation of w_d parameter at 10 °C with rutting in a small device at 45 °C (determination factor $R^2 = 0.8$) was obtained for high stress levels (10.0–30.0) kPa and ($R^2 = 0.65$) for small stress levels (0.1–1.0) kPa. There was no evidence of correlation between w_d parameter and rutting test results at temperature 30 °C.

2. Better determination coefficients for w_d parameter and rutting results were obtained when binders were tested in dynamic shear rheometers at higher stress levels. The type of device used in the rutting test had little effect on determination factors obtained in the same conditions. Lower values for determination coefficients were obtained for tests carried out in a small rutting device.

3. Summarizing the experimental tests results, it is possible to formulate the thesis that in the case of the mixtures analysed in this work there is potential to assist rutting test at the initial design with proposed relatively simple test on binder carried out in dynamic shear rheometer. It is possible to extend this conclusion for application of the proposed test onto other mixtures after the previous experimental calibration.

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