Influence of selected test parameters on measured values during the MSCR test

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Abstract. One of today's most commonly used test on a Dynamic Shear Rheometer (DSR) is the Multiple Stress Creep Recovery (MSCR) test. The test is described in the standard EN 16659, which is valid in the Czech Republic since October 2016. The principle of the test is based on repeated loading and recovering of a bitumen sample, according to which it is possible to determine the percentage of elastic recovery (R) and non-recoverable creep compliance (Jnr) of the bituminous binder. This method has been recently promoted as the most suitable test for assessing the resistance of bituminous binders to permanent deformation. The test is performed at higher temperatures and is particularly suitable for modified bituminous binders. The paper deals with the comparison of the different input parameters set on the DSR device - different levels of stress, temperature of test, the geometry of the measuring device and also a comparison of the results for a different number of loading cycles. The research study was focused mainly on modified bituminous binders, but to compare the MSCR test it is performed even with conventional paving grade binders.

1. Introduction
The durability of asphalt mixtures is largely dependent on the quality and performance behavior of the bituminous binder. Basic empirical tests can characterize or classify bituminous binders, but in order to more accurately describe their behavior, functional tests are needed, for example by using Dynamic Shear Rheometer (DSR).

In recent years there has been an increasing demand on road traffic, which lead to the necessity for developing bituminous binders with improved performance behavior relative to conventional paving grade bitumen. This causes the progress and use of a wide range of bitumen modifiers which improve the performance of the basic bitumen and thus the asphalt mixture [1, 2, 3, and 4]. The most widely used technical standards for bituminous binders in the Czech Republic are based on the behavior of neat binders that cannot properly characterize potentials of modified binders.

One of the fundamental failures of asphalt pavements at higher operating temperatures is the formation of ruts. In the past rutting prediction of asphalt mixtures was based on G*/sin δ criteria. This parameter works reliably for conventional speed and moderate traffic volume, but for pavements with slow speed loading and/or high traffic volume it has been shown that it does not correspond enough to permanent deformations [4, 5, and 6]. Values G* and δ are measured in the linear viscoelastic region, but permanent deformations are not a linear viscoelastic phenomenon and therefore the characteristic G*/sin δ does not sufficiently correlate with permanent deformations [7]. From the perspective of
permanent deformation of bituminous binders there is a need to pay attention on the area of nonlinear behavior of bituminous binders, which include $J_{nr}$ parameter obtained during the MSCR test. According to the authors [8, 9] parameter $J_{nr}$ has a significantly better correlation with rutting measurements on asphalt mixtures than conventional oscillatory frequency sweep test.

2. Multiple Stress Creep and Recovery test (MSCR)

Multiple Stress Creep and Recovery test is a test of repeated loading and relaxation/recovery, using a device called Dynamic Shear Rheometer (DSR). The test is used for measuring the accumulated strain in the bitumen within the prescribed stress level. The MSCR test uses a constant stress creep of 1 second duration followed by a zero stress recovery of 9 seconds duration. This cycle is according to present standards in Europe or the U.S. repeated 10 times for each stress level. Figure 1 presents the typical creep and recovery cycle in MSCR test.

![Figure 1. Typical creep and recovery cycle.](image)

Two most important parameters of bituminous binder calculated from the measured strain at individual stress levels are non-recoverable creep compliance ($J_{nr}$) and percent recovery ($R$). $J_{nr}$ is a measure of the amount of residual strain left in the specimen after repeated creep and recovery, relative to the amount of stress applied. Parameter $J_{nr}$ is currently perceived as the best rheological parameter for the assessment of the susceptibility of bituminous binder to resist permanent deformation in asphalt mixture. The lower the $J_{nr}$ is, the greater proportion of the stress the binder is able to absorb and the less susceptible to plastic deformation is. But there are any limiting values neither in the Czech technical standards nor in the European standards. Besides the mentioned characteristics, stress sensitivity parameters $R_{diff}$ and $J_{nr, diff}$ are calculated. Golalipour [10] indicated that determine the stress level is not a simple task and no one level can be clearly defined as most appropriate of what a binder is exposed to in a real mixture. Therefore it seems most reliable to use the sensitivity parameter ($J_{nr, diff}$). The $J_{nr, diff}$ is important mainly when pavement is exposed to unexpected traffic loads or extremely high temperatures. In case the $J_{nr, diff}$ value is greater than 75 %, the bituminous binder is classified as a very stress sensitive material, which is not recommended for use in the construction of a pavement structure, [11].

MSCR is a test that has received a lot of attention and holds great promise for predicting rutting resistance of asphalt mixtures, but there are still many problems in its implementation, evaluation and interpretation of results. Some of these concerns are related to the number of cycles, the value of stress level or the temperature of testing. Conventional test set is based on the standard EN 16659 [12] and indicates the stress levels (0.1 and 3.2 kPa), number of loading/unloading cycles at each stress level (10) and the geometry of the device (25 mm parallel plate with a 1 mm gap). The test temperature is not exactly defined, which remains still a questionable task for the future.
Some research works showed [8, 13, and 14] that in order to study the behavior of the binder in the nonlinear range, it is necessary to apply a higher stress level than 3.2 kPa, depending on the type of bitumen. Moreover, according to studies [13, 14] the higher stress level is used, the better correlation coefficient for resistance to permanent deformation of mixtures (French rutting test) is received.

3. Testing procedures

This paper compares different groups of bituminous binders due to the widest possible coverage of the different behavior of bituminous binders. Some variants are conventional paving grade bituminous binders, but in most cases modified binders (crumb rubber – labeled CR, polymer modified binders – PMB or low viscosity additives) are tested and analyzed. Attention has been given to assessing the impact on the selection of the applied stress level and temperature of testing. Furthermore, two different testing geometries were used on DSR device and finally calculations were compared using the average of 10 cycles with values calculated from the last 5 cycles.

3.1. Effect of selected temperature and stress level

The attention in this chapter is pay to the use of different test temperatures and stress levels. In the technical standard EN 16659 [12] test temperature is not prescribed, but should be selected suitably in the range 50-80 °C (the temperature corresponding to the normal service temperature of asphalt mixture). The exact prescription of one temperature is even not planned for the revised EN 14023 standard for PMB binders. Different polymer modified binders (PMB) and one neat bitumen were compared. PMB are used in highly loaded pavement structures and for this reason test was measured at normal test temperature (60 °C) and elevated test temperature (70 °C). On the contrary neat bitumen 50/70 was measured at normal test temperature (60 °C) and at a reduced test temperature (50 °C). Another parameter that can be determined during the MSCR test is using different stress levels. The standard EN 16659 prescribes stress level of 0.1 kPa and 3.2 kPa. But as mentioned above, values obtained at higher stress level correlate better with permanent deformations. In addition, the application of a higher stress can cause significant increase of $J_{nr}$. For this reason, the standard stress levels were completed with 8.0 kPa stress.

The following Table 1 presents the calculated values of elastic recovery $R$, non-recoverable creep compliance $J_{nr}$ and stress sensitivity characteristics $R_{diff}$ and $J_{nr,diff}$.

| Binder type | 0.1 kPa | 3.2 kPa | 8.0 kPa | 0.1-3.2 kPa | 3.2-8.0 kPa | 0.1-8.0 kPa |
|-------------|---------|---------|---------|-------------|-------------|-------------|
|             | $R$ [%] | $J_{nr}$ [1/kPa] | $R$ [%] | $J_{nr}$ [1/kPa] | $R$ [%] | $J_{nr}$ [1/kPa] | $R_{diff}$ [%] | $J_{nr,diff}$ [1/kPa] | $R_{diff}$ [%] | $J_{nr,diff}$ [1/kPa] | $R_{diff}$ [%] | $J_{nr,diff}$ [1/kPa] |
| 50/70-50 °C | 2.5 | 1.59 | 1.2 | 1.09 | 0.5 | 1.08 | 53.7 | -31.2 | 60.1 | -0.9 | 81.5 | -31.8 |
| 50/70-60 °C | 0.5 | 4.93 | 0.1 | 4.41 | 0.0 | 4.57 | 87.3 | -10.7 | 60.3 | 3.7 | 95 | -7.4 |
| 45/80-65 °C | 83.1 | 0.12 | 85.5 | 0.09 | 87.2 | 0.07 | -2.9 | -23.3 | -2.0 | -17.1 | -5 | -36.4 |
| 45/80-70 °C | 89.8 | 0.19 | 85.6 | 0.20 | 57.4 | 0.64 | 0.1 | -15.8 | 32.9 | 213.3 | 33 | 163.8 |
| 25/55-60 °C | 69.4 | 0.15 | 66.6 | 0.16 | 66.4 | 0.17 | 4.1 | 3.8 | 0.3 | 5.1 | 4.3 | 9.1 |
| 25/55-70 °C | 70.4 | 0.42 | 58.9 | 0.52 | 52.8 | 0.63 | 16.3 | 25.4 | 10.4 | 20.9 | 25 | 51.7 |
| 25/55-60 °C | 76.8 | 0.13 | 38.5 | 0.49 | 29.7 | 0.57 | 49.9 | 267.0 | 22.9 | 14.7 | 61.4 | 320.8 |
| 25/55-50 °C | 55.1 | 1.06 | 24.7 | 1.85 | 13.5 | 2.38 | 55.2 | 73.6 | 45.3 | 28.8 | 75.5 | 123.6 |

As seen in Table 1 it is obvious that the PMBs have high value of elastic recovery and very low non-recoverable creep compliance. As the temperature increases the shear strain increases and that is associated with an increase of $J_{nr}$ value. Increased susceptibility to permanent deformation is logically at higher temperature (higher $J_{nr}$ value). This is connected with the reduction of elastic recovery, but surprisingly, slight increase of $R$ was observed in two PMBs at a stress level of 0.1 kPa. This increase is probably caused due to the variability of the measured values (detailed in section 3.3).
The unmodified binder 50/70 has high stress sensitivity $R_{\text{diff}}$ (Figure 2.), which is caused by very low elastic recovery values (Table 1.). This neat bitumen also experienced the most pronounced reduction in elastic recovery at a higher test temperature. The most significant $J_{\text{nr}}$ change between test temperatures for PMB is in the binder 25/55-60. It could be said that this binder seems no longer to be in the linear viscoelastic range at 70 °C. Figure 2 presents that this binder has a high sensitivity $R_{\text{diff}}$ (at both temperatures) and Figure 3 shows an extremely high sensitivity $J_{\text{nr, diff}}$. This binder is the only one that has failed the US condition $J_{\text{nr, diff}} < 75 \%$ for stresses 0.1 kPa and 3.2 kPa. The same binder has a lower $J_{\text{nr, diff}}$ (0.1-3.2 kPa) at temperature of 70 °C because it has a relatively high $J_{\text{nr}}$ value at stress 0.1 kPa, (the binder is in nonlinear region at higher temperature).

By contrast, the PMB 45/80-65 changed the measured values significantly between stress 3.2 kPa and 8.0 kPa at 70 °C (Figure 2.). And thanks to it, this level can be described as marginal behavior in the nonlinear region for binder 45/80-65. Other binders can be described as very low stress sensitive.

Generally, the increasing temperature increases deformation, reduces elastic recovery and increases non-recoverable creep compliance. Difference is more pronounced with higher stress level.

**Figure 2.** Stress sensitivity parameter $R_{\text{diff}}$.

**Figure 3.** Stress sensitivity parameter $J_{\text{nr, diff}}$.

Higher stress level 8.0 kPa was also conducted for the second group of bituminous binders containing variants with the basic paving grade bitumen 20/30. Bitumen 20/30 was modified by low-viscosity waxes in an amount of 2-4 M% or by combination of crumb rubber CR (15 M%) with low viscosity waxes. Higher stress level was measured only for the selected variants.

**Table 2.** Values of elastic recovery, non-recoverable creep compliance and sensitivity parameters.

| Binder type | 0.1 kPa  | 3.2 kPa | 8.0 kPa | 0.1-3.2 kPa | 3.2-8.0 kPa | 0.1-8.0 kPa |
|-------------|---------|---------|---------|-------------|-------------|-------------|
|             | $R$ [%] | $J_n$ [1/kPa] | $R$ [%] | $J_n$ [1/kPa] | $R_{\text{diff}}$ [%] | $J_{\text{nr, diff}}$ [%] | $R_{\text{diff}}$ [%] | $J_{\text{nr, diff}}$ [%] | $R_{\text{diff}}$ [%] | $J_{\text{nr, diff}}$ [%] |
| 20/30       | 9.4     | 0.425   | 6.7     | 0.402       | -           | -           | -           | -           | -           | -           |
| 2% CM       | 15.4    | 0.209   | 8.9     | 0.296       | 4.0         | 0.385       | 42.6        | 41.7        | 55.4        | 29.9        | 74.4        | 84.0        |
| 3% CM       | 18.1    | 0.222   | 14.1    | 0.236       | -           | -           | 22.0        | 6.4         | -           | -           | -           | -           |
| 3% BM       | 11.1    | 0.656   | 5.4     | 0.644       | -           | -           | 51.2        | -1.7        | -           | -           | -           | -           |
| 4% BM       | 14.6    | 0.462   | 7.3     | 0.495       | 2.3         | 0.590       | 50.0        | 7.0         | 68.4        | 19.2        | 84.2        | 27.5        |
| 15% CR      | 73.5    | 0.015   | 67.9    | 0.018       | -           | -           | 7.6         | 20.9        | -           | -           | -           | -           |
| 15% CR+2% CM| 81.7    | 0.006   | 74.6    | 0.008       | 73.3        | 0.009       | 8.7         | 31.8        | 1.8         | 6.3         | 10.3        | 40.2        |
| 15% CR+2% BM| 78.6    | 0.007   | 75.7    | 0.008       | 73.3        | 0.009       | 3.7         | 12.5        | 3.2         | 11.4        | 6.8         | 25.3        |
| 15% CR+2% E10| 72.7   | 0.011   | 70.6    | 0.012       | 67.6        | 0.013       | 2.9         | 1.8         | 4.2         | 9.1         | 7.0         | 11.1        |

Table 2 shows the fundamental values calculated from MSCR test. Crumb rubber modification resulted in a significant increase in the percent recovery and decrease in $J_{\text{nr}}$ in comparison with
bitumen 20/30. High $J_{nr}$ values are expected to mean low resistance to permanent deformation. Application of low-viscosity additives does not significantly influence $R$ or $J_{nr}$ values. $R$ values are very low and vice versa $J_{nr}$ relatively high, when low-viscosity waxes are used with the bitumen 20/30, which leads logically to higher stress sensitivity characteristics $R_{\text{diff}}$ (Figure 4.). On contrary, CR binders have high percent recovery, which helps to have low $R_{\text{diff}}$ (below 10 %) for all stress levels. This indicates good elastic properties even at a stress 8.0 kPa. When comparing the stress sensitivity parameter $J_{nr,\text{diff}}$, it is obvious that the US limit for stress level 0.1 kPa and 3.2 kPa ($J_{nr,\text{diff}} < 75 \%$) would be fulfilled by all tested binders. But it is clear that a binder that has 2% CM is the most stress sensitive and especially $J_{nr,\text{diff}}$ is in this case high comparing the lowest (0.1 kPa) and the highest (8.0 kPa) stress level.

![Figure 4. Stress sensitivity parameter $R_{\text{diff}}$.](image1)

![Figure 5. Stress sensitivity parameter $J_{nr,\text{diff}}$.](image2)

3.2. Effect of selected testing geometry used for Dynamic Shear Rheometer

In general, for more than two decades two testing geometries are used with the DSR for bitumen testing, namely 8 mm diameter plate-plate with a 2 mm gap between the lower and upper plate (labelled PP08) or 25 mm diameter plate-plate and 1 mm gap (PP25). Selecting geometry of the testing device is based on the operating conditions. Geometry PP08 is generally used at low and medium temperatures (-5-30 °C) or for aged binders (frequency sweep test). Geometry PP25 is normally selected for measurements at high temperatures (30-90 °C) and is therefore selected as a base for performing MSCR test. Different geometries were compared for PMBs and neat 50/70 after ageing, and in addition for the binder with a crumb rubber (CR).

| Table 3. Values of elastic recovery, non-recoverable creep compliance and sensitivity parameters. |
|---------------------------------|----------------|----------------|----------------|----------------|----------------|
| Binder type                    | 0.1 kPa | 3.2 kPa | 0.1 kPa | 3.2 kPa |
| PP25                           | PP08    | PP25    | PP08    |
| 50/70+10% CR                   | 35.5    | 0.50    | 7.8     | 0.81     | 33.7           | 0.42       | 7.5     | 0.70     |
| 50/70_R                        | 5.6     | 1.59    | 1.1     | 1.57     | 8.1           | 0.54     | 5.1     | 0.58     |
| 25/55-60_R                     | 73.9    | 0.16    | 73.2    | 0.15     | 73.9          | 0.07     | 74.8    | 0.06     |
| 40/100-65_R                    | 84.8    | 0.09    | 88.9    | 0.04     | 84.8          | 0.03     | 89.2    | 0.02     |
| 50/70_R+P                      | 17.0    | 0.28    | 14.0    | 0.23     | 25.2          | 0.06     | 23.9    | 0.06     |
| 25/55-60_R+P                   | 64.5    | 0.07    | 64.2    | 0.06     | 69.0          | 0.02     | 65.1    | 0.03     |
| 40/100-65_R+P                  | 88.6    | 0.02    | 88.2    | 0.02     | 91.7          | 0.01     | 90.1    | 0.01     |
| 50/70_3R                       | 16.9    | 0.32    | 13.0    | 0.28     | 21.5          | 0.11     | 22.2    | 0.08     |
| 25/55-60_3R                    | 70.0    | 0.07    | 65.6    | 0.09     | 67.0          | 0.05     | 66.9    | 0.04     |
| 40/100-65_3R                   | 92.1    | 0.02    | 91.8    | 0.02     | 82.7          | 0.02     | 90.4    | 0.01     |

Table 3 presents a relatively low difference of the percent recovery between the two geometries. The percentage difference is up to 10 % with the exception of all variants 50/70, which have very low
values of R and for this reason the percentage change is significant. The percentage difference between the two geometries of \(J_{nr}\) value is shown in Figure 6. The \(J_{nr}\) value is always lower in the case of PP08 and even more than about half in most variants (with the exception of variant with CR). Overall, this implies that the selected testing geometry has a major influence on the \(J_{nr}\) values.

![Figure 6. Percentage difference between two geometries.](image)

### 3.3. Effect of number of cycles for calculating characteristics of the MSCR test

Taking the average of the 10 cycles to calculate characteristics, as required in the MSCR standard procedure, could be misleading because the response is significantly changing with number of cycles. The following figures show the percentage difference for the calculation from the last 5 cycles compared to the calculation from all 10 cycles for each group described in the previous chapters.

![Figure 7. Percent change between two methods of calculating R.](image)

![Figure 8. Percent change between two methods of calculating \(J_{nr}\).](image)

Figure 7 presents the percent change of percent recovery between the values calculated from all 10 cycles, and only the last 5 cycles. The calculated differences are not significantly high at all stress levels (less than 7 %). Figure 8 shows the percentage difference of \(J_{nr}\) between two methods of calculating. The maximum difference is about 20 % at stress level of 0.1 kPa, which is quite significant change that may be a source of variability of the results. This change is lower at higher stress and it is about 5 % when the stress level is 8.0 kPa, which can be considered negligible. Higher difference of \(J_{nr}\) is evident for binders with CR.
Figures 9-12 show that applying higher stress level leads to reduction of result variability in the test. The dotted lines in the figures show the average values calculated from all 10 cycles. Individual values have larger fluctuations at a low stress level, while a higher stress level contributes to a better reproducibility of results. Modification with low-viscosity waxes (Figure 9 and 10) have only a first calculated value significantly different from other values at the stress level 0.1 kPa. Conversely in case of modification with CR (Figure 11 and 12), there is not only the first value significantly different for all stress levels. For these binders (modified by CR with max. 15 M% content) would be therefore certainly appropriate to increase the number of cycles to obtain steady values (especially at lower stress level). This might by as hypothesis valid only for CRmB binders where the content of used crumb rubber would not exceed 15 M% and the maximum particle size would not exceed 1.0 mm.

Figures 13 and 14 present the difference of the values calculated as the average of all 10 cycles in comparison with the average of last 5 cycles. The difference in percent recovery ranges up to 12 %, but for certain binders are differences in the calculation of Jnr considerably higher. All PMB binders
have similar trend which is seen in Figure 16 and 17, wherein the R values in the first 3-4 cycles gradually grew up ($J_{\text{nr}}$ values decrease) and in the following cycles are stabilized. This pattern is evident among stress levels 0.1 kPa and 3.2 kPa. Increase of percentage change looks like a very low because of the relatively high values of R. Conversely, the variants that have very low $J_{\text{nr}}$ have percent change significant between values calculated of 10 cycles and 5 cycles. Important change occurred in PMB 45/80-65 at 70 °C (Figure 18), $J_{\text{nr}}$ value is increasing in each cycle at stress 8.0 kPa, which is the opposite trend than at other stress levels. This likely indicates the fatigue of the material which occurs in the nonlinear viscoelastic region. The closest values of all cycles are evident for neat binders (represented by Figure 15), only for the lowest stress level 0.1 kPa are apparent differences, but very low.

Figure 15. R values at each cycle.  
Figure 16. $J_{\text{nr}}$ values at each cycle.  
Figure 17. R values at each cycle.  
Figure 18. $J_{\text{nr}}$ values at each cycle.  
Figure 19. Percent change between two methods of calculating $J_{\text{nr}}$ at stress level 3.2 kPa.

Figure 19 shows the last group of bituminous binders with different geometry of the test device. Variants with geometry PP08 are labeled (2). While the change in the calculation of R, considering the last 5 cycles, is less than 10 % for all variants of this group (excluding 50/70 + 10% CR variant, which
has a 15 % difference), the change of $J_{nr}$ value is around 30 % for most PMBs, which generally corresponds to the previous group with PMB binders. Unmodified binders have the smallest difference of $J_{nr}$, but this is again mainly related to high $J_{nr}$ value thanks to which, the percentage difference is very small between the $J_{nr}$ value calculated from all 10 cycles and the last 5 cycles.

4. Conclusions
Currently, the MSCR test is promoted as the most appropriate method for assessing the resistance of bituminous binders to permanent deformation. The advantage of MSCR test compared to Frequency Sweep test is applying a larger load and deformation which reflects better the real situation in the pavement. Parameter $G^*/\sin \delta$ characterizes bituminous binder in its linear region (lower stress/strain) but permanent deformation occurs in nonlinear region and therefore it is necessary to describe the characteristics in nonlinear field with different parameter, e.g. $J_{nr}$.

This paper analyzes the results of MSCR test comparing the influence of temperature, stress level, type of geometry on measuring device and number of cycles for calculation individual values.

Performed measurements indicate that the method of averaging the response for 10 cycles at each stress level can lead to misleading values due to the changes during the cycles. Since the greatest differences are during the initial cycles, it would be appropriate to calculate non-recoverable creep compliance and percent recovery from the second half of the cycles at each stress level.

Furthermore research shows that it would be preferable (especially for PMB) to increase the number of cycles since the 10 cycles for most of PMBs is according to our findings not sufficient to achieve a stable secondary creep. An alternative option is to select a higher stress level, which leads to faster stabilization of test results.

In case the strain is very small (on the border of the measuring device range) it is not possible to calculate sufficiently the accuracy of determined values. This problem occurs especially at lower test temperatures or at low stress level (0.1 kPa) when the divergence between cycles is high. Additionally, correlation with asphalt mixtures (resistance to permanent deformation) is lower when the stress level is 0.1 kPa [15]. For these reasons, it is preferable to use a higher stress level, e.g. 8.0 kPa.

Selected testing geometry used for Dynamic Shear Rheometer primarily affects the $J_{nr}$ value. Classical geometry PP25 is simpler for handling in DSR, as well as sample preparation (pouring) is easier. But in case of modification by crumb rubber with particle size of 1 mm or larger, it is necessary to use different geometry with a larger gap (PP08) or to analyze the possibility to use the standard geometry PP25 with a larger gap. The results show that the use of different geometry produce varying results and therefore it is always necessary to specify the type of used measured geometry.

Performing the test at a higher temperature leads to a higher strain, thereby reducing the risk of inaccurate measurements due to the extent of the device. Temperature 60 °C would be an appropriate temperature conducting the MSCR test assuming that the test resistance to permanent deformation for asphalt mixtures would be performed at the same temperature of 60 °C (currently, the test is carried out at 50 °C), in order to better compare the measured values.

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