Project: WHRP (0092-14-20)

TPF-5 (302)

Modified Binder (PG+) Specifications and Quality Control Criteria

Task Report:

White Paper on:

Analysis of MSCR Parameters as Related to Specification Development and Performance

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Executive Summary

The AASHTO M332, which includes the Multiple Stress Creep and Recovery (MSCR test) has been proposed to replace the AASHTO M320 for the PG grading of binders. In part this proposed replacement is to control the proliferation of the PG+ convention tests, such as the Elastic Recovery, phase angle, ductility and others, which are used today to amend the M320, and better control the use of modified binders. One of the main objectives of this Pooled fund study is to evaluate the existing PG+ tests and propose replacements that can achieve the same objective of controlling quality of modified binders, but are easier to use and can be conducted using the DSR equipment used in the M320 specifications. The MSCR fits well the objective of replacing the PG+ conventional test. However there is a significant debate about the validity and usefulness of the MSCR parameters used in the M332. This white paper is written with the following objectives:

- Briefly summarize the developmental history of the Multiple Stress Creep and Recovery (MSCR) test Percent Recovery (%R) parameter and its *intended usage*;
- Correlate the %R parameter with existing elasticity test methods and comment on the ability of the %R parameter to *detect the presence* of elastomeric modification and potentially provide *indication of the level* of elastomeric modification;
- Comment on existing limits for %R based on available databases, published literature and ongoing research projects (such as the Pooled Fund) *relating %R to performance*;
- Provide recommendations for implementation, if applicable, of the Jnr, % Jnr diff., and %R parameter *based on the needs of the governing agency*.

Data in support of achieving these objectives was provided by the Western States Cooperative Testing Group (WCTG), representing the western United States; the Combined State Binder Group (CSBG), representing the upper Midwest; the State of Kansas DOT; and the State of Ohio DOT. Correlations are made between existing methods to measure elastic response in binders produced in these regions to the MSCR Percent Recovery (%R) parameter at 3.2 kPa. The relationship between %R (as well as Jnr at 3.2 kPa) and performance of mixtures is presented for 13 individual mixtures from different regions in the western United States using the Flow Number test. Based on the data available, the following conclusion and recommendations can be made:

- ***If the objective is to maintain the same modified binder formulations*** as controlled today by the T301/D6084 Elastic Recovery (ER), the %R parameter is a good candidate that can be used to detect the presence of and potentially quality/quantity of elastomeric modification. It is shown to directly correlate with the current T301/D6084 procedures and the phase angle on a state by state basis, but not on a universal basis.
- However, using universal limits for the MSCR %R parameter that are dependent on Jnr values, as stipulated in the M332, is not practical nor useful since current binder formulations are controlled differently by the State Agencies, and more importantly, the % R is not clearly related to rutting or fatigue performance of mixture or pavements.
- ***If the objective is to replace the G*/sin(δ)*** parameter and ensure good contribution of binders to rutting resistance, the Jnr parameter measured at 3.2 kPa is a good candidate, irrespective of the %R. The Jnr values at 3.2 kPa is highly correlated with mixture Flow Number results and literature clearly show it is a better choice than the G*/sin (δ).

- It is important to recognize that the conversion of the grades determined based on the M320 with grade bumping (e.g. PG 70, PG 76, and PG 82) to the traffic grades (PG 58 or PG 64 S,H,V and E) is not simple because the G*/sin(δ) used in the M320 does not correlate well with the Jnr at 3.2kPa. Therefore, if states wish to keep the same binder formulations (or minimize change), but wish to implement the MSCR Jnr parameter, the limits for Jnr at 3.2 kPa will likely be different between regions. However, since the Jnr parameter is well related to rutting performance of mixtures, States should not try to maintain formulations and focus on using universal values of Jnr as related to traffic and climate. This is the part that M332 that is ready for implementation. There is more work to be done to verify that the Jnr values of 4.5, 2, 1.0 and 0.5 1/kPa correctly correspond to the traffic speed and volume designated in the M332.
- The %Jnr Diff. parameter is highly dependent on the binder formulations but lacks a clear relationship to rutting performance. It is claimed in the literature to be an indicator of modification quality, unfortunately no clear evidence is found. In addition since it is measured relative to the Jnr tested at 0.1 kPa, its reliability in terms of variability and in terms of actual condition in typical asphalt mixtures is questionable. If a universal value of 75%, as currently listed in the M332 is used, changes in formulations of binders to meet this limit are expected as shown in the data collected in this study. These changes might not be in favor of better performance or practice.

- The following recommendations are made for each of the MSCR parameters included in the AASHTO M332:
  - **Jnr**: The Jnr parameter measured at 3.2 kPa is a good replacement for the G*/sin (δ) to control binder contributions to rutting resistance. However the conversion of the current PG grades, bumped for traffic, to the H, V, E grades should be calibrated locally.
  - **% R**: A strawman specification for %R based on replacing existing PG + methods aimed to keep same binder formulations, but not necessarily ensure pavement performance, is presented for the existing KDOT and ODOT data with commentary provided on the CSBG limits.
  - **%Jnr Diff**.: The limits for this parameter in the AASHTP M332 could not be validated, and its implementation could force suppliers to change the formulations with uncertain consequences on performance. appears to be highly dependent on binder formulation, particularly for very low Jnr binder, but does not appear to be indicative of performance. It is recommended that if implemented, it should be considered as ‘Report Only’ until more information is gained on this parameter.

Background for MSCR Percent Recovery (%R) Parameter

The MSCR test was developed to better capture the permanent deformation resistance of asphalt binder relative to the Superpave G*/sin(δ) parameter used in the AASHTO M320 grading system. The concept was first introduced in NCHRP report 459 in which it was observed that G*/sin(δ) could not differentiate between polymer modified binders and their contribution to mixture rutting resistance. A significant amount of research followed the NCHRP 459 report and has been devoted to relating the non-recoverable creep compliance parameter, Jnr, measured during this test to laboratory and field measurements of permanent deformation. In general, there is a consensus in the literature that the Jnr parameter does a better job of predicting deformation resistance of polymer modified asphalts; as a result, the FHWA, The Asphalt Institute, and many state agencies have considered adopting the MSCR test for implementation. The grading methodology using the MSCR procedure is standardized as AASHTO M332.

Although many states, particularly in northern climates, do not have significant problems with permanent deformation, an attractive aspect of the MSCR test is the ability to eliminate the need for traditional PG+ elasticity tests through the Percent Recovery (%R) parameter which measures average creep strain recovery. Many state agencies have a version of the AASHTO T301/ASTM D6084 Elastic Recovery test in their specification as a means to ensure modified binders contain elastomeric or partial-elastomeric (hybrid) polymer modification. Although there is no specific research that conclusively relates T301/D6084 Elastic Recovery to performance, it is an easily interpreted test to ensure binders have been modified with elastomeric polymers, which has been at least subjectively linked to better deformation resistance, crack resistance, and durability [1, 2]. From a practical standpoint, it should be noted that the traditional T301/D6084 procedures take several hours to run and require the use of a ductility bath, whereas the MSCR test is DSR-based and takes about 20 minutes to run. Both methods use RTFO residue.

Research suggests that the %R parameter may better capture the quality of modification relative to T301/D6084 since it is run at higher temperatures relative to the traditional elastic recovery test which is run at 25 °C. Literature suggests that at 25 °C the asphalt binder is sufficiently stiff to act as reinforcement to the polymer network, potentially moderating the effects of poor quality modification [1]. An example of this behavior is shown in Figure 1 (data from [2]); two binders modified with the same amount of SBS, but using two different SBS types and modification techniques may provide similar T301 elastic recovery results (73.8% and 83%) , but significantly different MSCR %R results when tested at high temperature (19.2% and 40.3%). In other words, testing at higher temperatures can differentiate more between modified binders with respect to the interaction between the polymer and the base binder.

Comparison of binders with the same base and different polymers and mixing process.					
Continuous Grade	Polymer	Temp °C	J_{nr} 3.2kPa^{-1}	ER	% Recovery 3.2kPa^{-1}
66.7-24.1		64	3.12	5	0
75.7-22.3	4% SBS	70	1.85	73.8	19.2
76.6-25.2	4% SBS	70	1.18	86	40.3

Figure 1. Example of ability of MSCR %R parameter in capturing modification quality [2].

One other positive attribute of the M332 standard that should be considered is the specified testing temperature. The traditional M320 grading procedure uses 'grade bumping' to adjust the high temperature binder grade to account for heavy and/or slow moving traffic; essentially this amounts to testing a particular binder at higher temperatures than it would ever be exposed to in service. It is well established that the integrity of some polymer systems can be highly temperature dependent, meaning that although a certain polymer or polymer concentration may provide adequate performance within a certain climatic zone, it may be eliminated from usage consideration because it is tested at significantly higher temperature than that climatic temperature. The M332 procedure specifies testing only at the high pavement temperature for the climatic zone of the project and adjusting for traffic amount/speed by lowering the maximum limit on Jnr. The result is expected to be a better representation of actual field performance, and correlations of Jnr with field data suggest this to be true.

AASHTO does not provide limits for the %R parameter (or T301 recovery, for that matter), instead a chart is provided in the M332 specification that is intended to provide "an indication of elastic response." The chart is shown in Figure 2. According to the standard, if a binder tested according to AASHTO T350 produces a Jnr and associated %R value that when plotted on the chart falls above the solid line, the binder is said to be "modified with an acceptable elastomeric polymer" and "if the point falls below the line on the graph, the indication is that the asphalt binder is not modified with an elastomeric polymer."

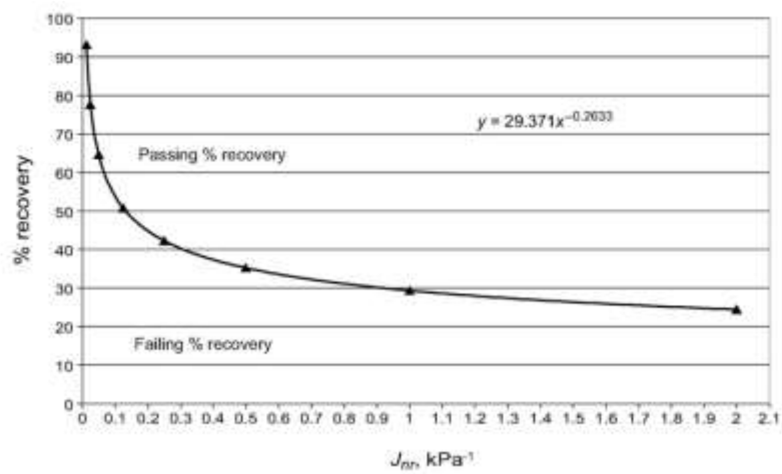


Figure 2. Indication of elastomeric modification, from AASHTO M332-14 [3].

The derivation of the location of the %R line in the plot is described in Anderson et al.(2011); 22 different Canadian asphalt binders with varying levels of modification were tested and based on the correlation between Jnr and %R for each binder, the use of the curve for indicating the presence of a polymer was derived. Several states that have implemented the MSCR grading procedure specify a minimum limit of %R based on this chart directly (i.e. the equation is used with the binder Jnr and if the calculated %R is below the measured %R, the result is acceptable). Others use a 'tiered' approach in which a single minimum %R is used for a given range of Jnr values. The latter is the approach used currently by the Combined State Binder Group (Iowa, Minnesota, North Dakota, South Dakota, Wisconsin, and Nebraska).

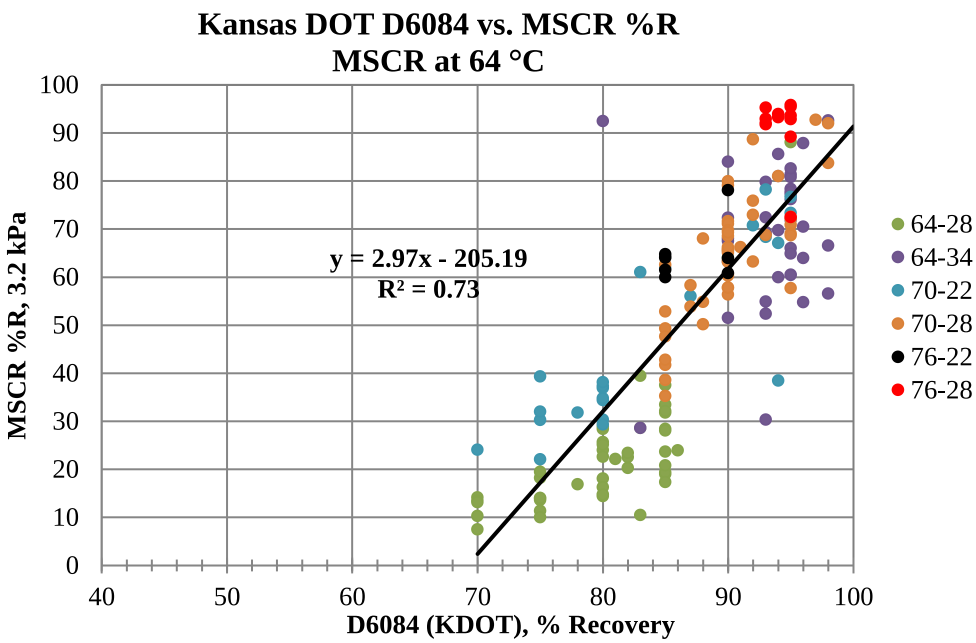
The remainder of this report will evaluate correlations of the %R parameter to existing elasticity tests and/or performance to provide justification for, or commentary on, existing limits.

Correlation of MSCR %R with Existing Measures of Elasticity

Feedback from several pooled fund member states (Kansas, Ohio, and Wisconsin) indicated that *permanent deformation is* *__not__* *a major concern in their respective agencies*, however *replacing the T301/D6084 procedure is a priority*. The same states indicated that, at least in the short term, *they would like to* *__keep formulations of current binders from significantly changing__*. The M332 grading procedure offers several advantages over M320 as described above, so these states are willing to consider the MSCR %R parameter as a replacement to the T301 or phase angle if the binder formulations will not change.

Data from the Pooled Fund Task Report 2 generally indicates that the correlation between the MSCR %R parameter and T301 methods is poor. Data from the Western Cooperative Testing Group (WCTG) generally agrees with this finding, but the general trend is intuitive. However, some of the poor correlations can be attributed to testing the MSCR at the high PG grade temperatures rather than at the climatic temperature. To better understand the value of %R correlations with the T301 and phase angle, values should be analyzed with considering the proper implementation of the MSCR, which includes testing at the climatic temperature.

Two Pooled Fund member states (Ohio and Kansas) have provided databases of MSCR testing conducted at the intended pavement temperature for their given region (predominately 64 °C). Plots of the correlation between elastic recovery (PG+) and MSCR %R for KDOT and ODOT are shown in Figure 3. The plots are intentionally kept separate for three reasons: (1) Kansas and Ohio each run the current PG+ elasticity (both use ASTM D6084) test differently, with Ohio opting for a 5 minute rest after elongation and Kansas not specifying a rest (more commentary will be provided on this topic later); (2) the two states have different limits for the PG+ elasticity tests and have other PG+ tests (phase angle, ductility, etc.) not run by the other state that may influence the type and amount of modification that takes place in the respective state; and (3) ODOT apparently only allows modification with SBR, SB, SBS, or Elvaloy®, whereas Kansas does not directly specify this information. It is important to note that *__specification drives formulation__*, meaning whatever specification a given state or combined state group adopts, regional formulations will adapt to meet that specification. It is therefore expected that comparing binders produced in different regions by different suppliers will not be completely analogous, as evidenced in the correlations drawn in Task Report 2.



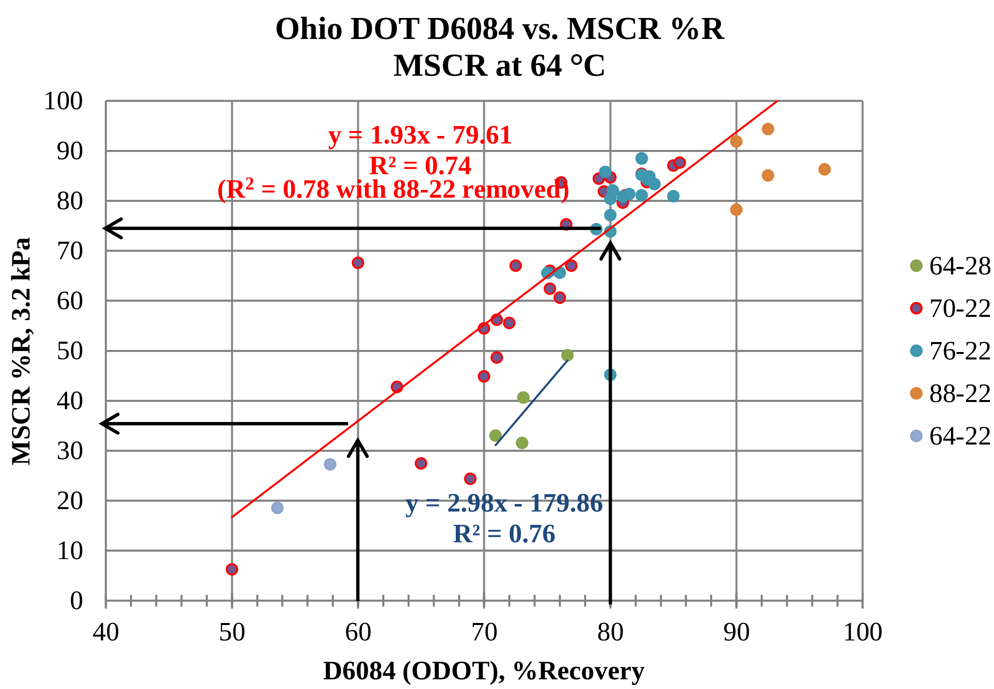


Figure 3. Correlation of elastic recovery to %R for KDOT and ODOT

Several important observations can be made from the plots. First, the explained variance (R^2) when blocking for test method and MSCR test temperature becomes much more reasonable than when combining all data; interestingly, the R^2 values for MSCR tests conducted at 64 °C are approximately equal between the two states. The tests at 58 °C also resulted in a nearly identical R^2 value, although only four data points are included in the 58 °C analysis.

Second, the ranking of %R values appears to be much more logical; one might expect a similar base binder be used in a given region based on refinery availability and modified accordingly to meet specification. For example, a similar 64-22 base was likely used in Kansas to produce 70-22 and 76-22 binders. Since these binders must both pass an elastic recovery spec, a logical way to produce these binders would be to slightly increase the level of modification to achieve the respective grade bump. If an elastomeric modifier is used (based on specification), it stands to reason that the 76-22 should *generally* produce a higher %R than the 70-22, and this appears to be the case. The same can be seen with what could be assumed to be a 58-28 base grade to produce 64-28, 70-28, and 76-28. It should be mentioned that a plausible contributing factor to this ranking could be due to testing a stiffer binder at the same temperature as a less stiff binder.

Finally, it should be noted that the range in MSCR %R values changes from less than 10% to more than 95% in both state databases, whereas the relative change in PG+ elastic recovery changes from about 50% to nearly 100%, with ODOT values more spread out. The D6084 procedure uses 10 cm elongation, the sample is cut immediately, and a recovery time of 60 minutes is used, whereas KDOT opts to use a total elongation of 10 cm, a hold time of five minutes, and a recovery time of 60 minutes. Based on this information, one might expect elastic recovery values to be higher for given binder tested in the D6084 without a hold time for a given binder there is no stress relaxation period. This appears to be the case when comparing the KDOT and ODOT data (Figure 4). In addition, each state has other PG and PG+ requirements that must be met, and this could influence the elastic recover values as well.

From this analysis it can be concluded that any specification for MSCR %R intended to replace an existing PG+ elasticity specification must: (1) be based on a uniform MSCR test temperature for a given set of binders (most likely the high pavement temperature for a given region), and (2) be correlated to the actual PG+ test used in that region. For agencies interested in keeping similar formulations to what they currently utilize, it appears that implementing a uniform specification for %R across all regions (as in adopting the M332 %R outright) will likely result in formulations changing in a given region, with the magnitude of the change depending on the current specification. For example, the Asphalt Institute recommended to the Southeast Asphalt User Producer Group (document available on the AI website) that an appropriate %R value when moving from T301 to %R at 64 °C is approximately 15% less than the corresponding T301 value. Using the ODOT data, this number is actually closer to a 25% reduction at 60% D6084 and about a 5% reduction at 80% D6084 recovery (shown on Figure 3), suggesting *limits should be based on the binder grade itself rather than a static criterion*. For KDOT on the other hand, since the elastic recovery values are higher, and the slope of the correlation is steeper, the corresponding limits for %R to achieve the same elastic recovery would be lower. For example, 80% elastic recovery correlates to an MSCR %R at 64 °C of only 30%.

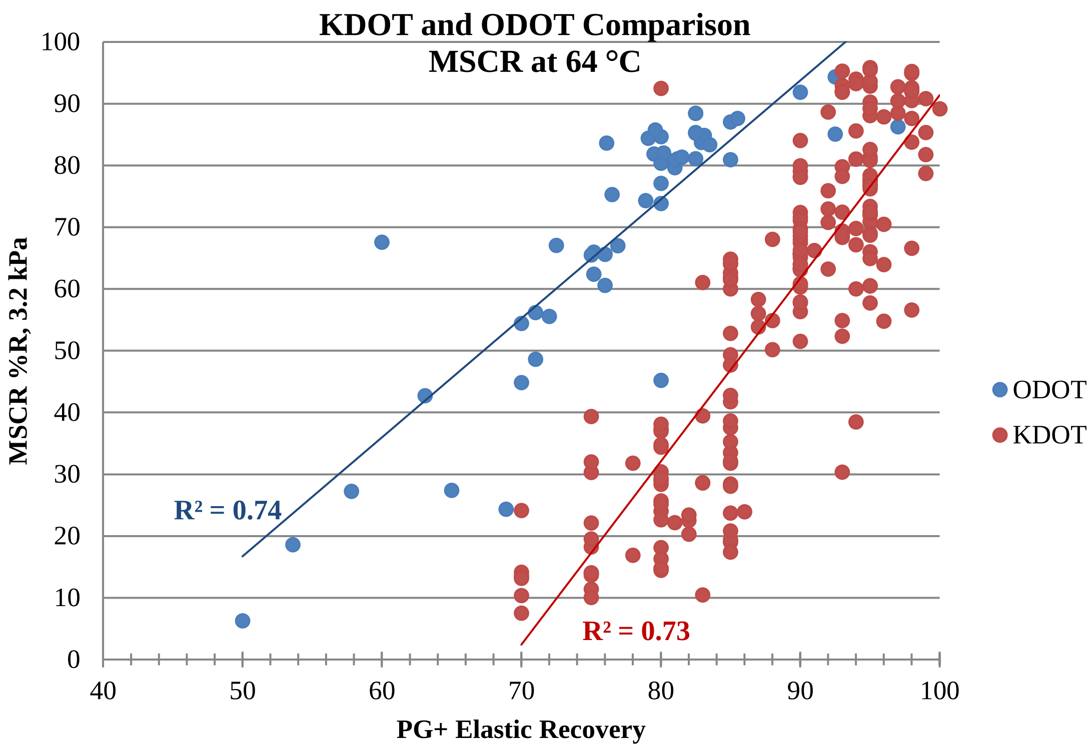
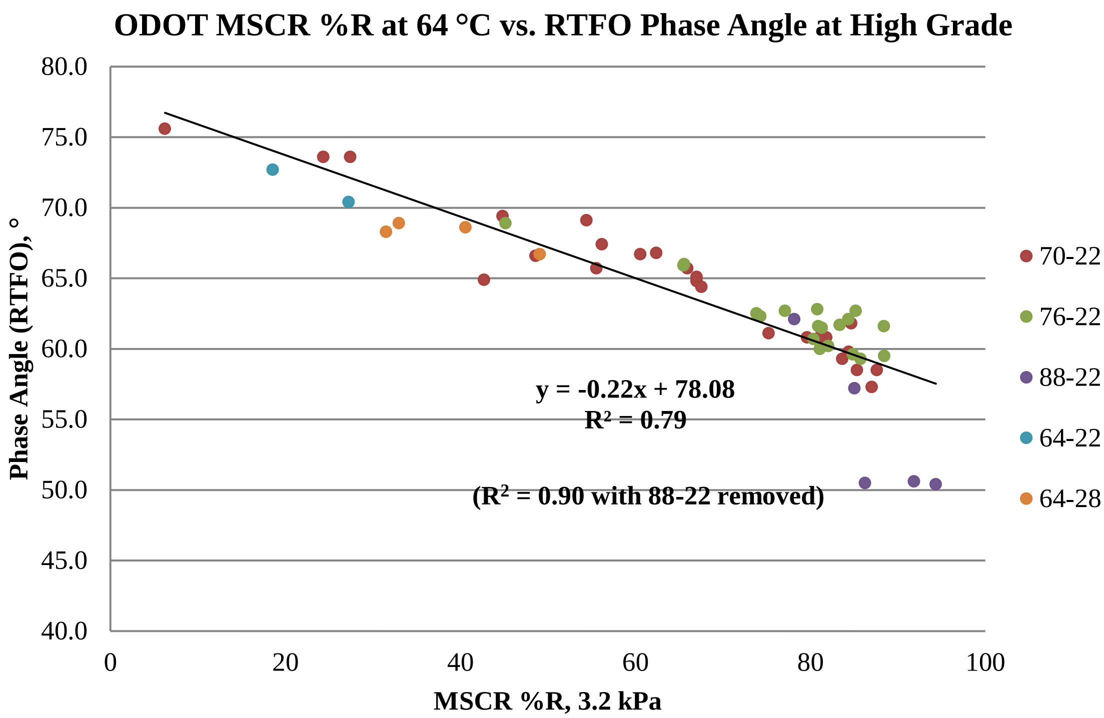


Figure 4. Comparison of KDOT and ODOT data showing effect of PG+ elasticity method.

Phase angle measured at high grade temperature is another PG+ used in conjunction with T301/D6084 to measure elasticity of binders. The perceived benefit of running the phase angle is that it is a quick and repeatable test method, and may be run on original binder (for daily quality control this can cut considerable time). Initial correlations shown in Task Report 2 between MSCR %R and phase angle were poor, with an explained variance of less than 50% for the WCTG database. However, for the reasons presented above, it may not be appropriate to rank binders based on their %R values if different test temperatures are used. The ODOT data included phase angle measurements taken on the original and RTFO residue at the grade temperature of the binder.

Figure 5 shows the correlation for ODOT binders between %R and phase angle (both original binder and RTFO); the correlation is strongly linear for the RTFO aged binders, with an explained variance of nearly 80%. When the 88-22 binders are removed, the correlation increases to 90%. Interestingly, the correlation with the phase angle taken for the original binders is also strong, particularly if the 82-22 binders are removed from consideration. The overall spread in phase angle measurements (i.e. not grouped by binders known to have varying levels of modification), however, suggests the phase angle test may have utility as a quality control point, but is *probably not sufficient to determine amount or quality of modification*. This is the same finding expressed in Task Report 2.



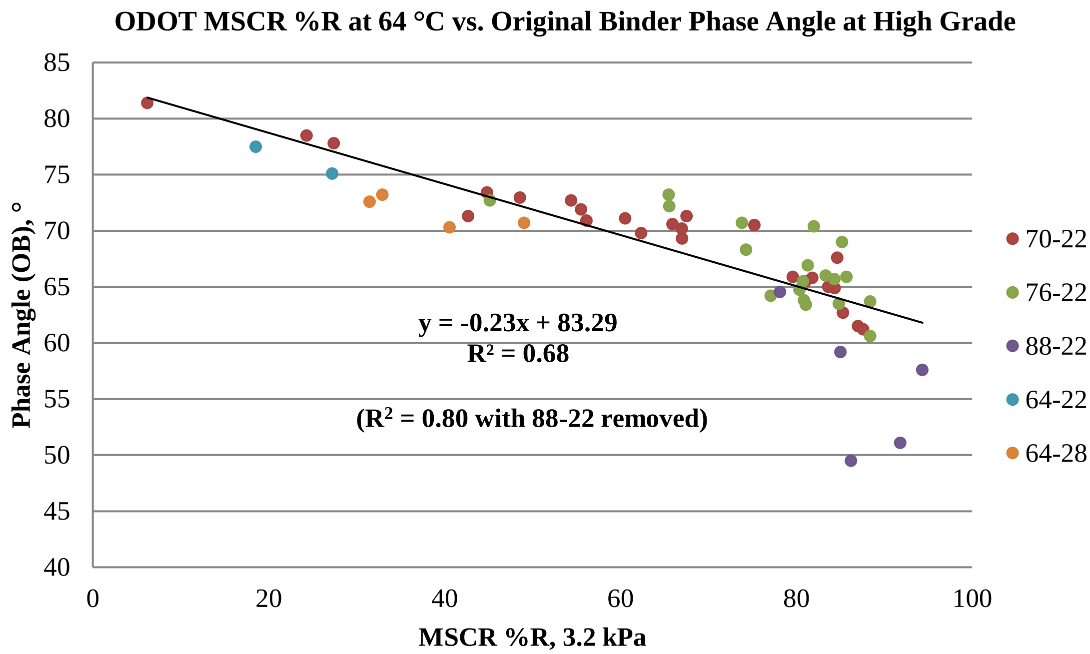


Figure 5. ODOT MSCR %R at 64 C vs. Phase Angle at grade temperature.

Alternative Measure of Elasticity-AASHTO TP 123 Method B

As previously stated, the MSCR testing procedure has shown the potential to replace the AASHTO T301 and ASTM D6804 elastic recovery procedures. In addition to the MSCR procedure, the AASHTO TP123 method B standard was introduced as an additional alternative to replace the current elastic recovery procedures used at 25 ºC. *The objective for development of the TP123 testing procedure was to mimic, as closely as possible, how asphalt specimens are loaded according to AASHTO/ASTM T301/D6084 in the DSR* but to solve the problem of changing geometry and necking in the T301 procedure, and the need for another device and time consuming test.

To conduct the ER DSR procedure, 8 mm binder wafers are placed in the DSR and tested after RTFO aging. Elastic recovery is calculated and reported in the same fashion as T301/D6084 in terms of shear *strain recovery* instead of *elongation recovery*. Pooled Fund and WCTG binders were tested using the ER DSR procedure (TP123) and correlated with the elongation elastic recovery procedures (T301-based). WCTG binders were tested using the AASHTO T301 standard. Pooled Fund binders were tested using a mixture of both T301 and D6084 procedures; depending on the corresponding states PG+ specification. Results of testing for each data set were provided in Task Report #2 of this project. With the same set of data, Figure 6 here shows the combined correlation between ER DSR and elongation elastic recovery for both Pooled Fund and WCTG binders. In addition, a recommended ER DSR elastic recovery equation/graph was included in the plot in red font and red dashed line. Where, elastic recovery values above the limitation are passing and below are failing.

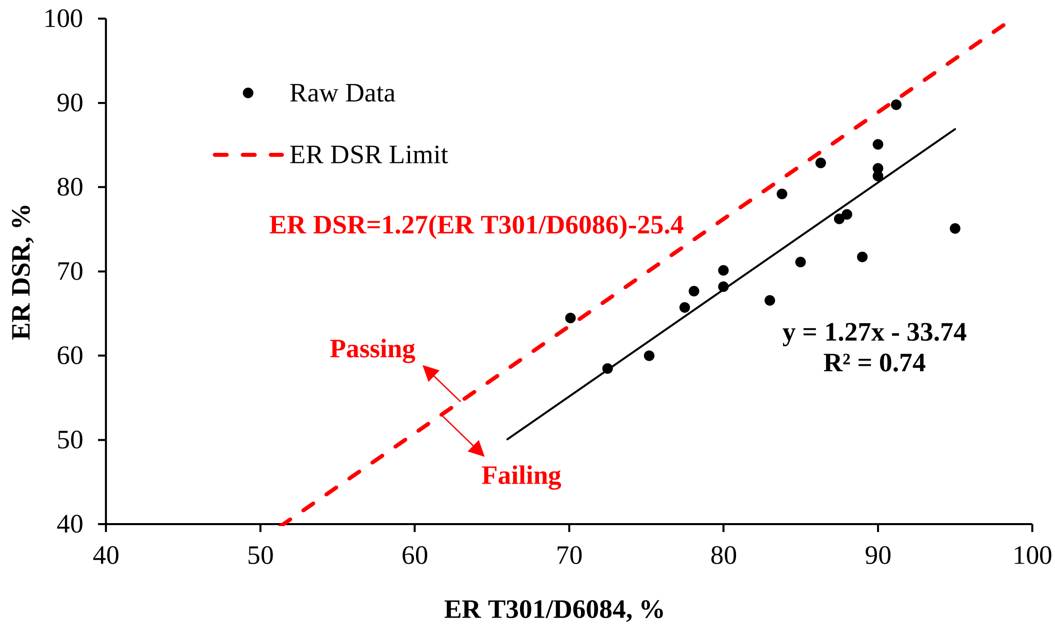


Figure 6. Correlation between ER T301/D6084 and ER DSR (TP123 method B) with recommended limitation for potential ER DSR specification.

As can be surmised from Figure 6, the ER DSR results show an offset from the linear correlation with the T301 results. In order to ensure that *all binders formulated to meet an ER DSR specification would be expected to meet the former elastic recovery specification*, the following equation of ER-DSR as a function of T301 results and an offset value can be used.

ER-DSR=1.27(ER T301/D6086)-25.4

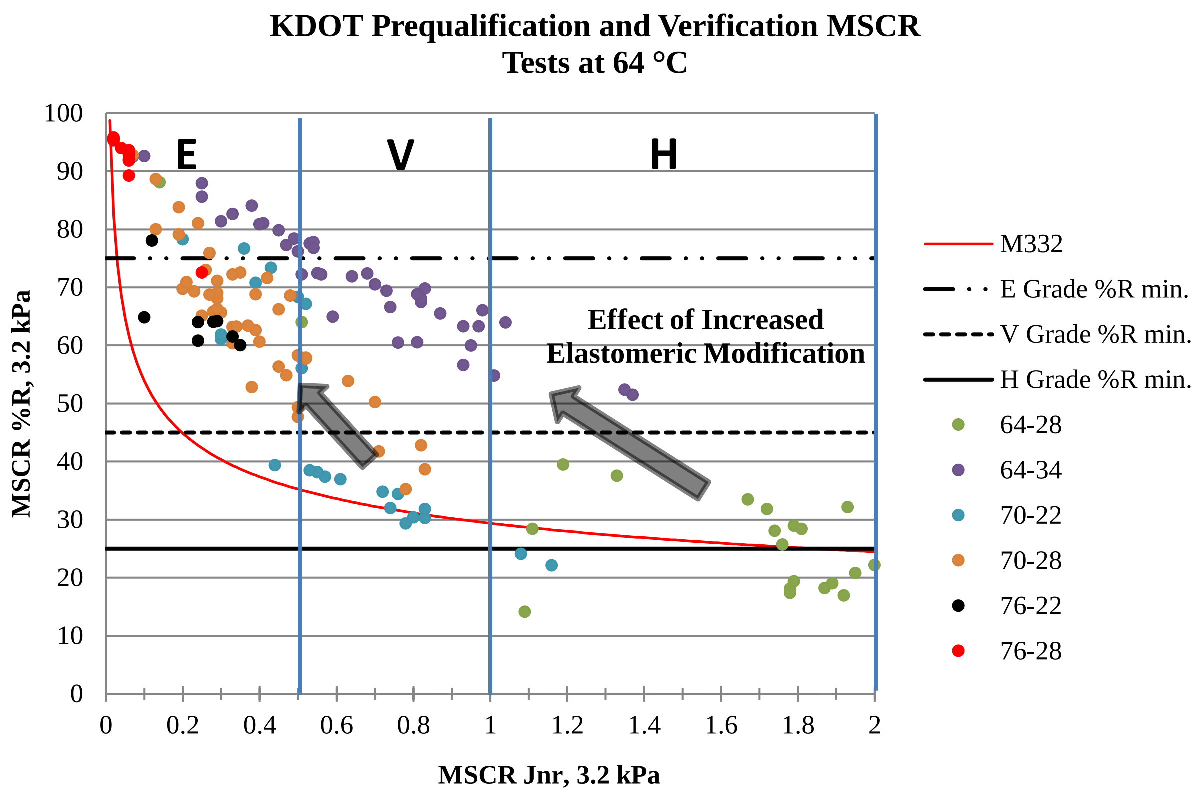
Regardless of the elastic recovery method, T301 or D6084, the ER-DSR procedure offers a reliable alternative for measuring elastic recovery. The advantages for implementing the ER-DSR procedure include:

- *Reduction in sample preparation and testing time.* No additional asphalt binder aging is required to complete testing. Samples identical to the PAV PG testing method are required and less time is required to ensure specimens equilibrate to the target temperature.
- *Modern DSRs are customizable and allow the operator to alter the testing procedure.* In addition to running the ER DSR procedure, recovery time, loading rate, loading time and testing temperature can easily be altered per the user's input.
- *DSRs leave less room for operator error.* T301/D3084 require an operator to cut the asphalt specimen after a specified time. Both of which require the operator's judgement to cut the specimen at the appropriate time and location. The DSR removes this attention requirement.

If DOT agencies are interested in implementation of the ER-DSR procedure, it is recommended that the proposed ER-DSR limits and correlation to T301 results be verified with several of the corresponding DOT's asphalt binders. This will help the agencies refine the ER-DSR limits as needed.

Feasibility of Using M332 to Replace PG+ Methods

The same data from the ODOT and KDOT databases can be plotted on the M332 chart (Figure 7). Delineations for M332 Jnr requirements for H, V, and E grades are shown on the chart along the with %R limits currently in use by the Combined State Binder Group (CSBG) for MSCR tests at 64 °C for reference. Based on the assumptions made earlier about the base asphalts used for modification, the data in Figure 7 seems logical, particularly for KDOT data which likely includes at least two base asphalts tested at the same high temperature. For example, producers would likely need to use more modifier in the 64-34 than the 64-28 since they would likely start with a softer base asphalt (i.e. a higher UTI). The result is a shift to higher %R and lower Jnr values for the 64-34 binders, which is in agreement with the data. The same can be said of the 70-28 vs. 70-22 binders, where the 70-28 binders show a shift in %R higher and a shift in Jnr lower (data moves up and to the left).



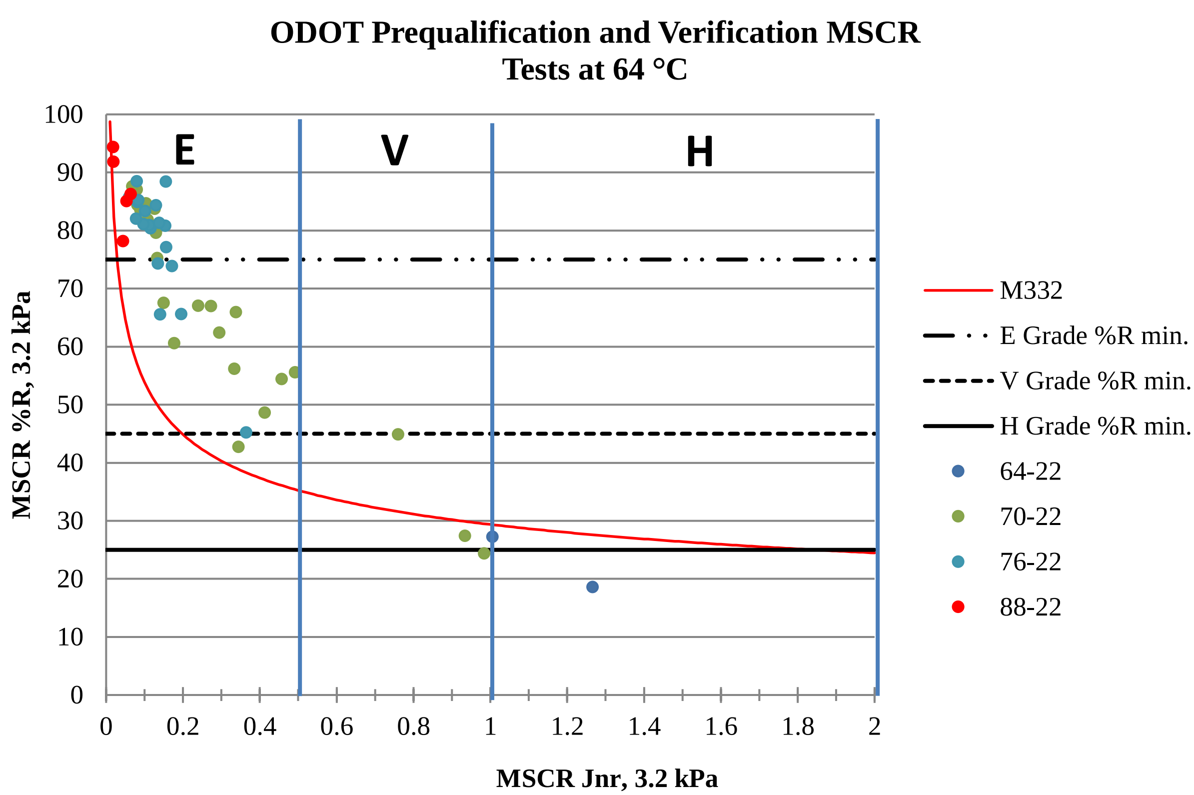


Figure 7. KDOT and ODOT MSCR data on M332 chart

If only the %R parameter is desirable to partner states, and not considering any relationship of %R to performance, it is clear from the plots that a minimum limit on %R could be applied to the dataset that includes most of the test data provided and should not result in a significant change in formulations. For states attempting solely to replace their current elastic recovery procedures with MSCR %R, they could follow standard M320 grading procedures as usual, test the binder in the MSCR at the pavement temperature and report only the %R value. This would likely save time as one of the M320 test temperatures could be used to run the MSCR test. This is expanded upon further in the 'Recommendations for Implementation' section.

If these states wish to implement M332 as a grading procedure, the data in Figure 7 suggests that at least for some base binders, *changes in formulation will likely occur over time*. Using the Kansas data as an example (and assuming no other changes to the specification), if a region requires a 64-22 for climatic reliability, a M320 grade bumped PG 70-22 would be approximately equivalent to a M332 64H-22. However, the 70-22 binders actually fall in the 'V' and 'E' region, likely because of the higher level of modification used to achieve the requirements of the M320. Since the V and E grades require higher minimum %R values than H grade, suppliers producing 70-22 can actually drop the concentration of elastomer, adjust reaction/cross-linking times, or utilize a hybrid modification system to produce a binder that is actually softer with a lower elastic response and pass specification for the H grade. In other words formulations of modified binders are likely to change if the M332 is used to replace the M320.

Similar conclusions can be made when looking at a subset of Combined State Binder Group (CSBG) data. Qualification and quality control samples from projects specifying polymer modified asphalt were collected into a central database to develop (or validate) limits on %R. An example of this data is shown in Figure 8; each point represents a quality control or verification sample taken for a given project, not necessarily an individual binder. Several members of the CSBG (Wisconsin, for example) have made the decision to 'phase in' the M332 grading procedure over the course of two to three years. Originally Wisconsin utilized the T301 elastic recovery and phase angle requirements for all polymer modified asphalts, with the MSCR %R as a 'report only' parameter. The T301 recovery was dropped (phase angle remained), and the MSCR %R minimum requirement was implemented (the binder was still 'graded' by M320, but the MSCR test was run at 58 or 64 °C). Beginning in 2016, the M332 procedure will take full effect, where all binders will be tested at their climatic pavement temperature.

In Wisconsin, two base asphalts are used: 58-28 and 58-34. A 64-28 and 70-28 would therefore be approximately equivalent to a 58H-28 and 58V-28, respectively. A 58-34 and 64-34 would be approximately equivalent to a 58H-34 and 58V-34, respectively. Examining Figure 8, one can see that these equivalencies do not necessarily hold true, and in fact for all but the 58-34 binders, the Jnr classifications are one traffic grade higher than expected (Jnr is lower).

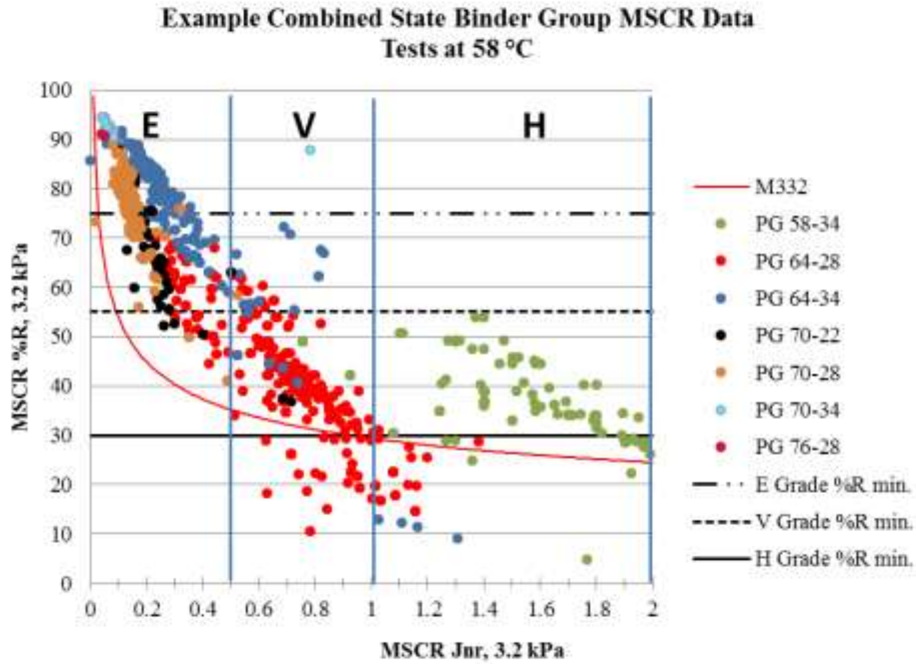


Figure 8. Combined State Binder Group example data (adapted from [4]).

Table 1 shows a breakdown of statistics for the binders shown in Figure 8 [4]. It is clear that the majority of currently produced binders pass the proposed specification, many by a wide margin, particularly in Jnr values. Binders that pass specification by a wide margin are likely overdesigned for the M332 specification, meaning they *cost more up front to the agency*, and are significantly stiffer than intended. From the data shown, it can be reasonably expected that current formulations will likely change over time to more closely meet the M332 specification, and associated costs will likely drop accordingly.

Table 1. M332 Grading Information for Example CSBG Data

Binder	PG 58-34*	PG 64-28	PG 64-34	PG 70-22	PG 70-28	PG 70-34	PG 76-28
MSCR %R Limit @ 58 C	30%	30%	55%	55%	55%	75%	75%
No. Tests	109	374	274	52	176	31	2
No. Passing	92	290	259	47	173	31	2
% Passing	84.4%	77.5%	94.5%	90.4%	98.3%	100.0%	100.0%

Binder	PG 58-34*	PG 64-28	PG 64-34	PG 70-22	PG 70-28	PG 70-34	PG 76-28
MSCR Grade Des.	H	H	V	V	V	E	E
Jnr @ 3.2 kPa Limit (kPa)	2.0	2.0	1.0	1.0	1.0	0.5	0.5
No. Tests	109	374	274	52	176	31	2
No. Passing	107	373	270	52	176	30	2
% Passing	98.2%	99.7%	98.5%	100.0%	100.0%	96.8%	100.0%

Relationship of MSCR Specification to Performance

From a pavement engineering viewpoint, elastic materials are desirable since they show complete strain recovery after deformation (rut resistance), however they could be a problem for thermal carking since they cannot relax stresses by viscous flow. The direct relationship between elastic behavior and performance is therefore not clear and could be highly dependent on climate, loading and type of distress. In addition, the conventional ways used to measure 'elasticity' in asphalt binders may not be representative of field conditions or loading, and are not actually measuring a true material property, per se. For example, the T301 elastic recovery test strains the binder significantly more than would be expected in the field, potentially damaging the polymer structure. Nevertheless, these tests continue to be used as a means to measure 'elasticity'. This section attempts to justify the use of MSCR %R (or T301/D6084 for that matter) based on relationship to performance.

Although this Pooled Fund study does not include high temperature performance testing, Lyngdal used the WCTG binder database to attempt to correlate MSCR test parameters and flow number results [5]. Mixtures were collected that were intended for use with a specific binder; each mixture had potentially different aggregate sources, design considerations, and design traffic levels. The findings (as shown in Figure 9) indicate that if the MSCR is run at the mixture performance test temperature, a logical trend exists between flow number and Jnr at 3.2 kPa, with a reasonably high explained variance considering the variation in mixtures tested. A power law was used since Jnr cannot fall below zero, yet flow number can continue to increase unbounded; this presents an important observation: there is a diminishing return on very low Jnr values (i.e. agencies are paying more for a limited and unpredictable amount of improvement to performance).

Another important observation is that in terms of similar levels of performance, binders can show large changes in the Jnr value (note the Jnr is on a logarithmic scale). Clearly this indicates that while a general trend exists, and it appears a lower Jnr improves rut resistance, the other components/design factors in the mixture have a large impact on performance.

In terms of the %R parameter, although the power fit is similar, the general scatter in the data suggests that the %R is much less important for high temperature performance. For changes in recovery of less than 5%, nearly two orders of magnitude difference in flow number exists for the data. For softer binders (which by association would allow more deformation for each load pulse) it is plausible that %R has a larger impact since more recovery could take place during each cycle. %R is not normalized to the load as is Jnr, so it is a parameter derived from the deformation that takes place during each cycle. Therefore, if a binder had a very large %R and a relatively high Jnr, the %R parameter might impact performance more. This is the converse of how the M332 spec is written, however, in that high Jnr values require lower minimum %R values.

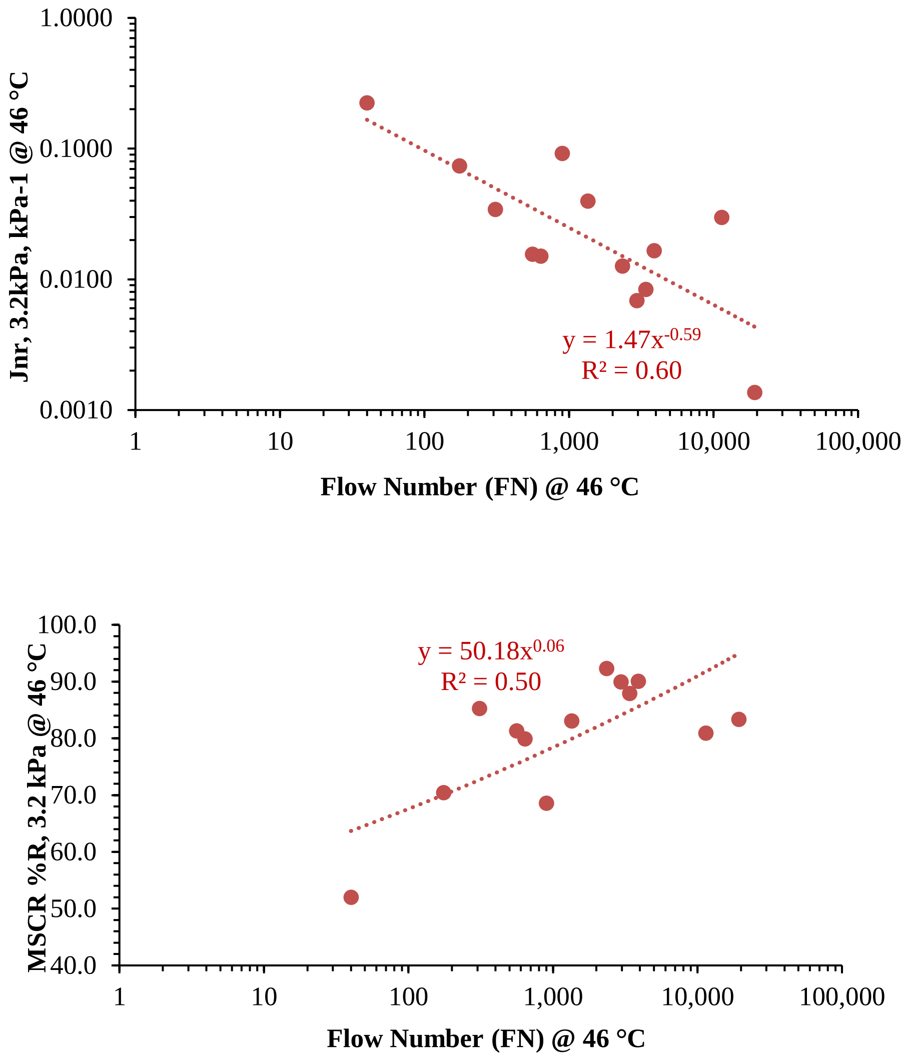


Figure 9. Flow Number testing relative to MSCR data on WCTG mixtures (From [5]).

From the data presented above, it can be concluded that the Jnr shows merit in predicting high temperature performance of mixtures, but the binder properties alone cannot be used to fully predict mixture performance. For lower Jnr values, the %R value does not appear to easily discriminate mixture performance. Since the M332 spec is written to allow lower %R limits for higher Jnr values, the impact of %R on performance is not expected to be strong for any level of Jnr. Therefore, if states wish to implement a performance based specification, it appears the Jnr value is the most important, and the %R is included to force the use of elastomeric modification (which may or may not directly benefit performance).

Percent Jnr Diff. and Stress Dependence of Modified Binders

In the MSCR procedure, the 0.1 kPa and 3.2 kPa stress levels are used to estimate the %Jnr Diff. parameter. Since almost all asphalt binders are stress-softening, the 3.2 kPa Jnr should always be equal to or larger than the 0.1 kPa Jnr value. Depending on the base asphalt and modification type, the %Jnr Diff. can range widely for different asphalt binders. To ensure that asphalt binders do not exhibit a high stress sensitivity, a maximum %Jnr Diff. of 75% is placed on the Jnr when stress is increased from 0.1 kPa to 3.2 kPa in AASHTO M 332. To understand how this requirement applies to the binders provided by Pooled Fund members, binders were tested at three stress levels: 0.1, 3.2 and 10 kPa. The %Jnr Diff. was calculated between each subsequent stress level (i.e. %Jnr difference between 0.1 and 3.2 kPa and %Jnr difference between 3.2 and 10 kPa). Each Pooled Fund binder % Jnr Diff. values are compared in Figure 10. Each binder was labeled with the first letter of the respective partner state and the PG grade for identification; this testing was completed at the grade temperature of the binder.

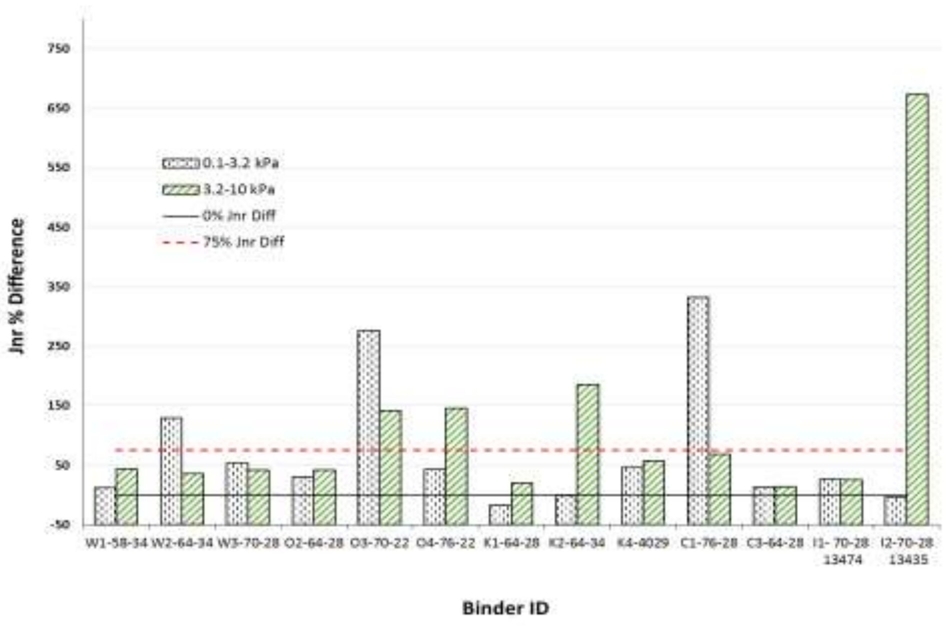
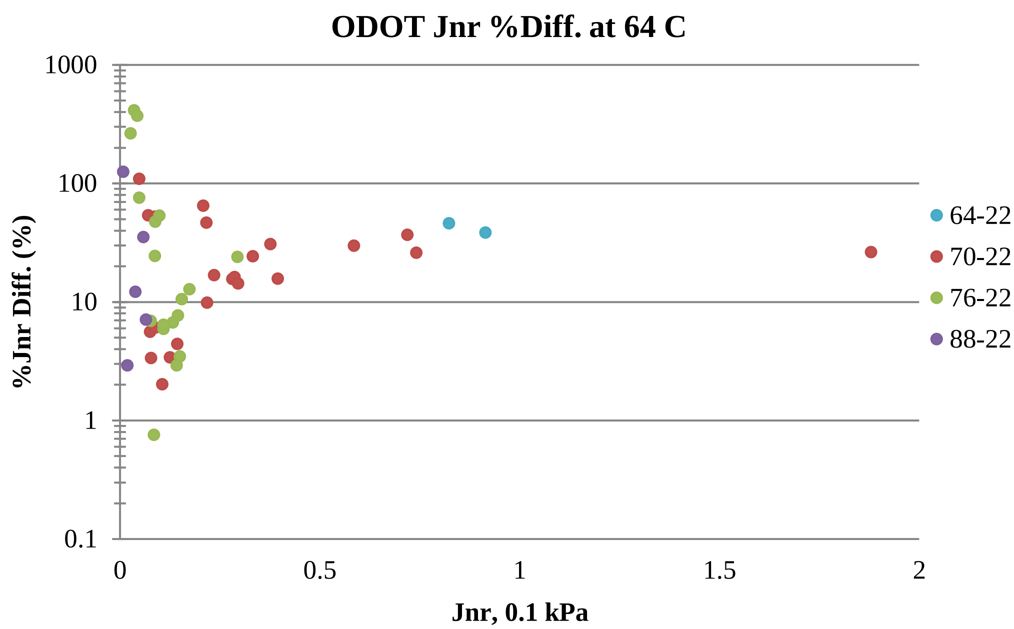


Figure 10. Values of % Jnr Diff values for each Pooled Fund binder. Where 0.1-3.2 kPa data represents the % Jnr Diff between stress levels of 0.1 and 3.2 and 3.2-10 kPa data represents the % Jnr Diff between stress levels of 3.2 and 10 kPa.

As shown in Figure 10, there is a wide range of potential outcomes depending on the binder type. Three of the 0.1-3.2 kPa %Jnr Diff. values fail the %Jnr Diff. parameter and have a 0.1-3.2 kPa %Jnr Diff. that is significantly greater than the 3.2-10 kPa %Jnr Diff. For each of these binders, one was graded to withstand very heavy traffic and two were graded for extremely heavy traffic according to AASHTO M 332. Therefore, the asphalt binders meet the Jnr requirements for large volumes of traffic, but fail the specification due to high stress sensitivity.

These results are not logical, given that the same three binders have 0.1-3.2 kPa %Jnr Diff. values greater than the corresponding 3.2-10 kPa %Jnr Diff. values. As previously stated, as the stress level increases, the Jnr is also expected to increase. Therefore, the 0.1-3.2 kPa %Jnr Diff. would be expected to be lower than the 3.2-10 kPa % Jnr Diff. A potential cause of the stress sensitivity failures can be found in the test procedure itself. For “E” and “V” binders, the Jnr values at 0.1 kPa are extremely small, even approaching the resolution limits of the DSR, so when the % Jnr Diff is calculated, a very large number usually results.

To supplement the Pooled Fund data, the Ohio binder database was also used to determine if a trend exists between the Jnr parameter and the %Jnr Diff. The %Jnr Diff. as reported in the Ohio database was compared against the measured Jnr values at 0.1 kPa and 3.2 kPa. All testing was conducted at 64 °C. This data is shown in Figure 11.



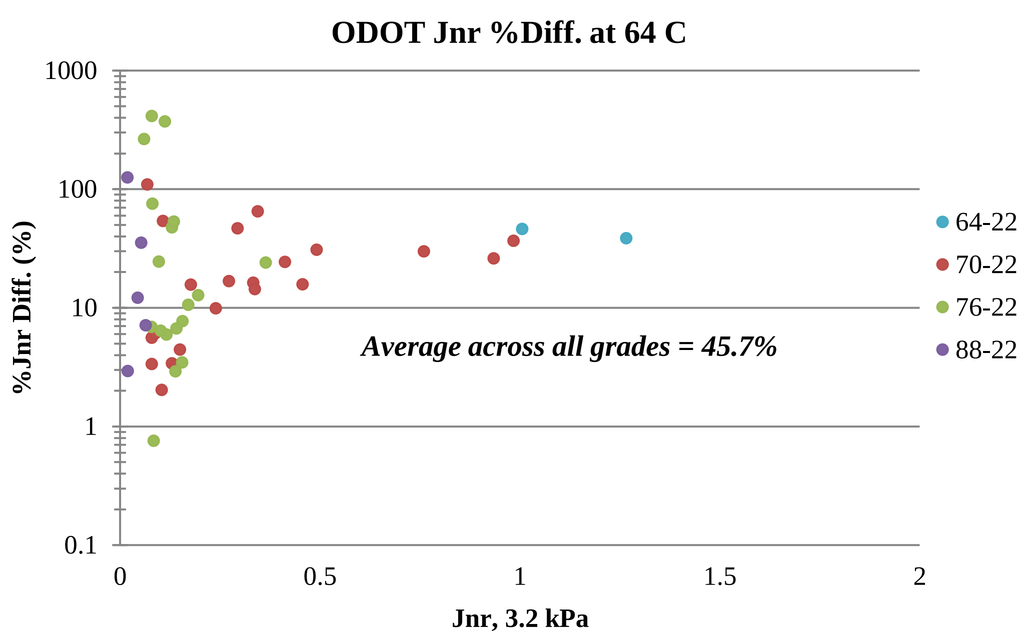


Figure 11. ODOT MSCR %Jnr Diff. vs. Jnr at two stress levels.

Figure 11 clearly shows that there is no direct correlation between the measured Jnr value at either stress level and %Jnr Diff., however as the Jnr becomes increasingly small, the %Jnr Diff. parameter appears to show much higher variation for a given Jnr value (but not necessarily a high value). It is shown that binders that fail the maximum limit of 75% are mostly of the PG 88-22 and the PG 72-22, which are currently used for only the very heavy traffic conditions. In addition, none of the binders that would effectively grade as H of V by Jnr limits of 0.5 and 1.0 fail the specification for this data set. This could be due to several factors; it may be a result of the test procedure itself, as alluded to when describing the findings in Figure 10. It may also be due to the concentration of polymer since to achieve an E grade from the same base binder, more polymer would inherently be needed. The polymer concentrations and formulation processes for the PG 76 and PG 88 binders are unknown, however the trend indicates that using the Jnr Diff limit of 75% could lead to change in formulations of such grades to meet the requirement.

Clearly the analysis of the combined data indicates that more work is needed to better understand this parameter, particularly for high performing binders, before States should consider implementing it in their specifications. Consideration should be made to list the parameter 'Report Only' until a clearer understanding of the parameter is achieved. This is recommended since there is no clear evidence that the parameter is related to performance in the lab or in the field, or that the limit is selected to reduce risk of premature rutting.

Summary of Findings

The MSCR test and AASHTO M332 includes new parameters that are better indicators of binders' contribution to rutting resistance of mixtures. The parameters include the Jnr, the %R, and the % Jnr difference. Based on the data presented in this report and the feedback from partner states, the implementation of the MSCR can target more than one objective. The research team can make the following recommendations regarding the targeted objective and the feasibility of using one or more of the MSCR parameters.

- *If the objective is to maintain the same modified binder formulations as controlled today by the T301/D6084 Elastic Recovery (ER), the %R parameter is a good candidate that can be used to detect the presence of and potentially quality/quantity of elastomeric modification. It is shown to directly correlate with the current T301/D6084 procedures and the phase angle on a state by state basis, but not on a universal basis.*
- *Recommending universal limits for the MSCR %R parameter, as stipulated in the M332, that are dependent on Jnr value is not practical nor useful from pavement performance point of view, since % R is not clearly related to rutting performance.*
- If the objective is to replace the G*/sin(d) parameter and ensure good contribution of binders to rutting resistance, the Jnr parameter measured at 3.2 kPa is a good candidate, irrespective of the %R. Rutting resistance is highly correlated with mixture Flow Number results and literature clearly show it is a better choice than the G*/sin (d).
- The conversion of the grades determined based on the M320 with grade bumping (e.g. PG 70, PG 76, and PG 82) to the traffic grades (PG 58 or PG 64 S,H,V and E) is not simple because the G*/sin(d) used in the M320 does not correlate well with the Jnr at 3.2kPa. Therefore, if states wish to keep the same binder formulations (or minimize change), but wish to implement the MSCR Jnr parameter, the limits for Jnr at 3.2 kPa will likely be different between regions. However, since the Jnr parameter is well related to rutting performance of mixtures, States should not try to maintain formulations and focus on using universal values of Jnr as related to traffic and climate. This is the

part that M332 that is ready for implementation. There is more work to be done to verify that the Jnr values of 4.5, 2, 1.0 and 0.5 1/kPa correctly correspond to the traffic speed and volume designated in the M332.

- The %Jnr Diff. parameter is highly dependent on the binder formulations but lacks a clear relationship to rutting performance. It is claimed in the literature to be an indicator of modification quality, unfortunately no clear evidence is provided. In addition since it is measured relative to the Jnr tested at 0.1 kPa, its reliability in terms of variability and in terms of actual condition in typical asphalt mixtures is questionable. If a universal value of 75%, as currently listed in the M332 is used, changes in formulations of binders to meet this limit are expected as shown in the data collected in this study.

Grade Bumping and Equivalent MSCR Grading

The primary function of the Jnr parameter in the MSCR grading system is to rank and tier asphalt binders in terms of rutting resistance. Where, binders with a lower Jnr have a higher rutting resistance. In AASHTO M332, there are four different Jnr performance levels based on the predicted traffic level; a higher traffic level pavement design requires a lower Jnr. Table 2 provides a summary of the current M332 specification.

Table 2. Jnr traffic grading system in the AASHTO M332 standard.

Traffic Rating	Maximum Jnr (kPa^{-1})*	Traffic Guidelines (ESALS and Traffic)
S Standard	4.5	<10 mil ESALs and standard traffic loading
H Heavy	2.0	10-30 mil ESALs or slow moving traffic.
V Very Heavy	1.0	>30 mil ESALs or standing traffic.
E Extreme	0.5	>30 mil ESALs and standing traffic.

Prior to the AASHTO M332 specification, grade "bumping" was used to account for increased traffic levels. For example, if a pavement requires a binder grade of PG64-22 based on the climatic temperature, but traffic is expected to be greater than 30 million ESALs, a grade "bump" from a PG64-22 to a PG76-22 is specified. In general, binder modification is required to achieve this grade "bump" and reduce Jnr. However, the extent of binder modification required for PG "bump" vs. level of decrease in the Jnr value is not well understood. In the PG "bumping" system, the PG grade is increased by ensuring that the G*/sinδ parameter is greater than 1.0 kPa at an elevated temperature in six degree increments. For the M332 system, all testing is done at the same climactic temperature but the required Jnr value targeted are reduced. In other words the target increase in temperature to achieve the limit of 1.0 kPa for the G*/sinδ is replaced with targeting decrease in Jnr value at the same testing temperature. To better understand the relationship between PG "bumping" and Jnr decrease, the continuous PG grade (true Grade) and Jnr values were plotted as shown in Figure 12. Two M332 Jnr climatic grades (58 and 64 °C) were included from both the Pooled Fund and WCTG binder databases.

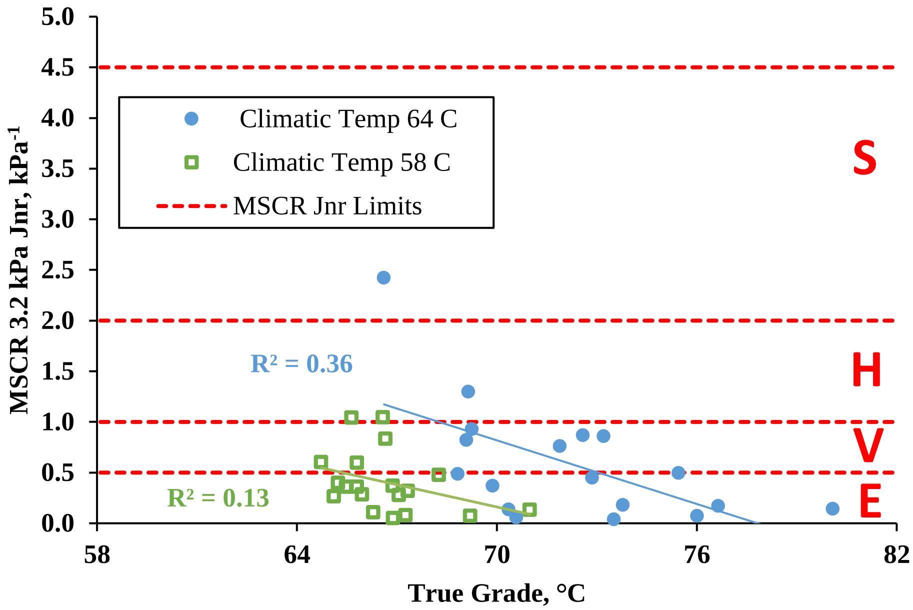


Figure 12. Relationship between asphalt binder continuous grade and Jnr at 3.2 kPa.

From Figure 12, there are two significant takeaways: 1) for a given continuous grade, there can be a wide range of Jnr values; and 2) Jnr values are relatively low for all binders tested at 58 and 64 C including many binders graded at PG 64, PG 70 and PG 76. For example, for a continuous grade of 65 -67, five binders ranged from a Jnr of 0.1 to 1.0 kPa^{-1}; spanning from an "H" to an "E" grade. The same trend was observed for other true grades as well. This suggests that the Jnr and PG "bumping" systems are providing different information with respect to a binder's resistance to rutting. However, as the binder grade increases, the Jnr tends to decrease which indicates that there is logical relationship between the two parameters, but there is no good correlation.

The majority of binders in Figure 12 were intended to the PG grade bump from either a climatic grade of PG58 to PG64 or a climactic grade of PG64 to PG70. When a binder was "bumped" the resulting Jnr value is very low. For each PG grade bump, Table 3 summarizes the average Jnr and one standard deviation above and below the average for all binders that were graded to have one six-degree PG "bump" at a climactic temperatures of 58 and 64°C.

Table 3. Average Jnr values compared against PG "bumped" binders.

Climactic Grade, °C	58	64
Continuous Bumped Grade, °C	64-69	70-75
Average Jnr, kPa^{-1}	0.418	0.440
Average Jnr +1 Standard Deviation, kPa^{-1}	0.722	0.780
Average Jnr -1 Standard Deviation, kPa^{-1}	0.113	0.101

Table 3 shows that one PG grade "bump" is approximately equivalent to changing a M332 "S" graded binder to an "E" graded binder with 50% reliability. These findings suggest that current binders produced with PG "bumps" will be graded to accommodate greater than 30 million ESALs or high traffic roadways in the M332 system. If DOT agencies would like to ensure, with 84.1% reliability, that asphalt binders graded with the MSCR have same formulations as binders graded with PG "bumping" system, a target Jnr of 0.1 kPa^{-1} is recommended. This indicates that Jnr limits included in the M332 are not well calibrated to the PG grade bumping and new limits should be imposed to maintain same formulation.

Recommendation for Implementation

Based on the above listed findings, the implementation of the MSCR test can be done for 2 main goals, as follows:

1. If the goal is to replace the T301/D6084 while minimizing changes to binder formulations the following alternatives can be considered:
    a. Initial 'strawman' specifications for Kansas and Ohio binders can be proposed using the linear relationships plotted in Figures 3 and 6. Assuming a high pavement design temperature of 64 °C, the strawman specification is shown below for each respective state in Table 4. The states would continue to 'grade' binders using M320 and use the %R at 64 °C as a replacement to existing PG+ elastic recovery criterion. Interestingly, these limits fall very near the minimum limits already proposed for other states in the CSBG, which are intended to replace the phase angle. Unlike the M332, there are 3 levels of minimum required % R measured at 3.2 kPa: 25 %, 50%, and 75%. Note that for a given binder grade (PG 70-22, for example), the limit for minimum %R is different between the two states. The reasoning for this was explained throughout the document, but stresses the importance of local calibration of test methods.

Table 4. Example Specification for MSCR %R at 64 °C for Partner States Wishing to Replace T301/D6084

Kansas		Ohio	
Binder	**Min. %R at 64 °C**	**Binder**	**Min. %R at 64 °C**
Base	-	Base	-
64-28	25%	64-28*	25%
70-22	25%	64-22	25%
64-34	50%	70-22	50%
70-28	50%	76-22	75%
76-22	50%	88-22	75%
76-28	75%		

*Tested at 58 °C if intended for PG 58 region

    b. Use the combined Pooled Fund and WCTG ER-DSR – T301/D6084 correlation plot and equation in Figure 6 to set new ER-DSR specifications. The only purpose of the ER DSR is to mimic the current elastic recovery procedures and does not provide additional information such as high temperature rutting resistance. Table 5 includes proposed specification limit for the ER DSR using the equation shown in Figure 6.

Table 5. Proposed ER DSR Limitations for ER DSR (AASHTO TP123) test method.

Elastic Recovery, % (T301/D6084)	ER DSR, % (AASHTO TP123)	State
45	32	KS
50	38	CO/ID
60	51	WI
65	57	OH
75	70	-

Based on the data collected to date, it appears that the limits listed for %R will not result in a significant change in the amount or quality of elastomeric polymer used. However, since most binders are significantly over-designed in terms of Jnr, there is the possibility that reformulation will result in different modification processes being used with unknown performance history.

2. If the goal is to use the Jnr at 3.2 kPa to determine the traffic grades (S, H, V, and E) and replace the M320 with M332, the following steps should be taken:
    a. Jnr limits are to be calibrated such that the binder formulations used currently do not change significantly. Based on the data collected in this study, a Jnr value of 0.10 1/kPa is needed for a given grade bump. However, a transition period to collect necessary information and consideration of correlation to mixture and field is highly recommended. Limits for Jnr values have been discussed widely in the literature and were not the focus of this study. The lack of 'soft' binders in this study should be noted.
    b. It appears that specifying a low Jnr and high %R value is redundant in terms of performance, and could result in significant changes in binder formulations that are not necessarily in favor of better performance. As shown in Table 1, the CSBG has empirically selected % R limits that will require blends with more polymer just to meet the artificially selected values, particularly for V and E grades. Therefore Interim/transitional specifications should focus on Jnr at 3.2 kPa with % R as report only until the needed limits could be derived.
    c. The %Jnr Diff. parameter should also be "report only" at this time until more data is collected to define the need for this parameter that is highly influenced by the Jnr at 0.1 kPa and is not clearly related to performance.

References

[1] "The Multiple Stress Creep Recovery (MSCR) Procedure," FHWA Office of Pavement Technology, Washington, D.C., 2011.

[2] J. D'Angelo, "New High Temperature Binder Specification Using Multistress Creep and Recovery," *Trasnportation E-Circular: Development in Asphalt Binder Specifications* , pp. 1-13, 2010.

[3] A. Hanz, *MSCR Implementation and Impacts on Asphalt Binder Grading*, Minneapolis, Minnesota, 2015.

[4] AASHTO, "Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test," *STANDARD SPECIFICATIONS for TRANSPORTATION MATERIALS and METHODS OF SAMPLING AND TESTING,* 2014.

[5] E. Lyngdal, "CRITICAL ANALYSIS OF PG AND PG+ ASPHALT BINDER TEST METHODS," University of Wisconsin Madison, Madison, 2015.