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Effect of Asphalt Binder Source on Asphalt Mixture Performance

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16. Abstract
This study aims to identify point and shape rheological parameters that can effectively differentiate between high and low-quality asphalt binders, particularly in their resistance to intermediate-temperature cracking, regardless of binder source or formulation changes. Point parameters assess binder hardness, while shape parameters describe the binder's overall viscoelastic behavior. A total of twenty asphalt binders were tested, comprising seventeen binders from various suppliers and three low-quality binders. Two of the low-quality binders were artificially manufactured, while one was obtained from a supplier. To validate the selected parameters, a Superpave 12.5 mm asphalt mixture was designed using seven of the binders, including the three lower quality ones. The mixtures' susceptibility to intermediate-temperature cracking was evaluated using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) as per ASTM D8225-19. Higher Cracking Tolerance Index (CT_{Index}) values indicate better resistance to cracking. The CT_{Index} results were compared with binder rankings based on the identified point and shape parameters to verify their effectiveness. Glover-Rowe (G-R) at 15°C and 10 rad/s and the phase angle at a specific modulus of 10 MPa (δ_{10MPa}) were found to be effective in distinguishing poor-quality binders. A simplified, rapid test method using a dynamic shear rheometer (DSR) was developed to measure these parameters, showing a strong correlation with traditional master curve analysis. This approach offers a practical tool for routine quality control during production, ensuring consistent binder performance and improved resistance to intermediate-temperature cracking in asphalt mixtures.

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Final Report

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Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Massachusetts Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

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Executive Summary

This study, conducted by the Highway Sustainability Research Center (HSRC) of the University of Massachusetts Dartmouth (UMassD) in collaboration with and funded by the Massachusetts Department of Transportation (MassDOT), addresses a key challenge in asphalt pavement engineering: performance variability in asphalt mixtures caused by changes in asphalt binder source or formulation, even when the binders meet the same Performance Grade (PG) specification. Such variability can cause a Balanced Mix Design (BMD) to become unbalanced during the mix design, production, or placement phases. As MassDOT and other agencies move toward implementing BMD frameworks, there is an urgent need for rheological parameters that can consistently characterize binder quality, particularly in terms of resistance to intermediate-temperature cracking.

The study had two main objectives: (1) to identify rheological parameter(s) capable of reliably distinguishing between high- and low-quality binders based on their susceptibility to intermediate-temperature cracking, and (2) to develop a simplified and rapid testing method for measuring these parameter(s) during mixture design and production.

Two categories of rheological parameters were considered:

- Point Parameters, which reflect binder properties at a specific temperature and loading frequency, offering insight into binder stiffness or hardness under defined conditions.
- Shape Parameters, which describe the overall viscoelastic behavior of the binder across a range of temperatures and loading times, as represented by the shape of the master stiffness curve.

Methodology

Twenty asphalt binders were evaluated, including seventeen obtained from industry suppliers and three known or intentionally engineered to exhibit poor performance. These binders were tested under various aging conditions using the Dynamic Shear Rheometer (DSR) and Bending Beam Rheometer (BBR). Master curves were constructed and a variety of point and shape parameters were extracted. Parameters that consistently identified and ranked the three poor-quality binders as the worst-performing were selected for further validation.

To verify their effectiveness, seven representative binders—including the three poor-quality ones—were used in the design of a 12.5 mm Superpave dense-graded asphalt mixture. The intermediate-temperature cracking resistance of these mixtures was evaluated using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT) in accordance with ASTM D8225. This test yields a Cracking Tolerance Index (CT_{Index}), where higher values indicate better resistance to cracking.

Selected Parameters and Validation

Although many parameters were examined, the study found that no single point or shape parameter alone was sufficient to consistently identify all poor-performing binders. However, when used in combination, two parameters demonstrated strong predictive effectiveness:

1. Glover-Rowe Parameter (G-R) at 15°C and 10 rad/s (*Point Parameter*) – Reflects binder stiffness and consistently identified the poorest-performing binder at all aging levels.
2. Phase Angle at a Complex Modulus of 10 MPa (δ_{10MPa}) (*Shape Parameter*) – Indicates the binder's ability to relax stress at intermediate temperatures and consistently ranked the lab-formulated poor-quality binders among the lowest.

The IDEAL-CT results confirmed the effectiveness of these parameters: mixtures made with the lowest-ranked binders also exhibited the lowest CT_{Index} values. This alignment validates the selected parameters as reliable indicators of intermediate-temperature cracking susceptibility.

Simplified Testing Method

To support practical implementation, a simplified and rapid method was developed to determine the selected parameters using the DSR:

- The G-R parameter can be directly measured at 15°C and 10 rad/s using AASHTO T 315-22.
- The δ_{10MPa} value can be calculated by interpolating DSR measurements collected over a range of intermediate temperatures at a fixed frequency of 10 rad/s. This approach eliminates the need for constructing a full master curve and significantly reduces testing time.

Both parameters determined using the simplified method showed strong correlation with values obtained through master curve analysis, confirming their accuracy and practicality.

Conclusions and Implementation

This study confirms that asphalt binder source and formulation can significantly affect mixture performance—even when binders meet the same PG specification. It also demonstrates that relying on a single rheological parameter is insufficient for capturing such variability. Instead, the combined use of G-R at 15°C and 10 rad/s and δ_{10MPa} offers a robust and validated approach to evaluating binder quality with respect to intermediate-temperature cracking.

Importantly, this research provides a practical solution for MassDOT and other transportation agencies developing or implementing BMD protocols. By incorporating these two parameters into their mix design and quality assurance practices using straightforward, standardized testing procedures, agencies can improve consistency and ensure better long-term pavement performance across a wide range of binder sources and formulations.

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List of Acronyms

Acronym	Expansion
AASHTO	American Association of State Highway Transportation Officials
AR	Asphalt Rubber
BBR	Bending Beam Rheometer
BMD	Balanced Mix Design
CA	Christensen and Anderson (CA) model
DSR	Dynamic Shear Rheometer
FHWA	Federal Highway Administration
FY	Fiscal Year
MassDOT	Massachusetts Department of Transportation
NAPA	National Asphalt Pavement Association
PMA	Polymer Modified Binder
PAV	Pressure Aging Vessel
RTFO	Rolling Thin Film Oven
RAP	Reclaimed Asphalt Pavement
SPR	State Planning and Research

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1.0 Introduction

This study entitled "Effect of Asphalt Binder Source on Asphalt Mixture Performance" was undertaken as part of the Massachusetts Department of Transportation (MassDOT) Research Program. This program is funded with Federal Highway Administration (FHWA) State Planning and Research (SPR) funds. Through this program, applied research is conducted on topics of importance to the Commonwealth of Massachusetts transportation agencies.

State Departments of Transportations (DOTs) in the U.S are increasingly incorporating new constituents into their asphalt mixtures such as non-fossil derived binders and higher contents of sustainable materials like reclaimed asphalt pavement (RAP). Their goal is to design and construct asphalt pavements that are both economical and environmentally friendly (*1*). However, it is crucial they ensure that these new constituents, or the increased use of similar existing constituents, do not negatively impact the performances of asphalt mixtures.

Traditionally, DOTs have required mixtures meet specific volumetric design criterion. However, volumetric designs do not typically account for any new constituents. Therefore, DOTs are increasingly mandating that mixtures must also meet performance criteria for specific tests addressing relevant anticipated pavement distresses. One such mix design method that allows for the incorporation of performance testing is the Balanced Mix Design (BMD) method. The BMD method, as defined by both the National Asphalt Pavement Association (NAPA) and the American Association of State Highway and Transportation Officials (AASHTO), is "Asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress, taking into consideration mix aging, traffic, climate, and location within the pavement structure" (*2,3*).

The challenge facing DOTs is that the performances of asphalt mixtures are heavily dependent on the rheological characteristics of the asphalt binder used. These characteristics influence a mixture's resistance to deformation, cracking, and other distresses, thereby affecting the durability and service life of the pavement. Studies have shown that a BMD can become unbalanced due to changes in the asphalt binder source and formulation even if the same Performance Grade (PG) asphalt binder is used (*4*). Therefore, the specific problem facing asphalt mixture designers is the need for better binder rheological parameters to be incorporated into the BMD method. These rheological parameters should ensure that the quality of the binder remains consistent even if the binder source, and/or formulation, of similarly graded asphalt binder changes during the mix design process, production process, or between the mix design and production. This consistency should ensure that binder source and formulation of a similarly graded asphalt binder (in terms of PG) have no adverse impact on the mixture performance for the specific distresses being addressed by the BMD method.

Clearly there is a need for a rapid test method to measure such rheological parameters, particularly if the binder source and/or formulations change during the production process, where timely data are critical to ensure the best quality mixture is produced. The focus of this study will be to determine rheological parameters that can assess the quality of an asphalt binder in terms of intermediate-temperature cracking and identify or develop a related simple and rapid test to measure them.

2.0 Rheological Properties of Asphalt Binders

The rheological properties of asphalt binders describe their flow and deformation behavior under varying conditions of stress, strain, temperature, and loading time (*5*). The performances of asphalt mixtures are closely linked to these rheological properties because performance characteristics, such as a mixture's resistance to rutting, intermediate-temperature cracking, and low-temperature cracking, are influenced by the asphalt binder's ability to withstand deformation and recover deformations over time.

2.1 Superpave Rheological Parameters

The Superpave PG specifications outlined in AASHTO M 320 (*3*) define critical rheological properties of asphalt binders such as: viscosity, complex modulus (G*), storage modulus (G′), loss modulus (G″), phase angle (δ), creep stiffness (S), and slope (m). These properties are measured using various testing methods, including the rotational viscometer (RV), dynamic shear rheometer (DSR), and bending beam rheometer (BBR). This PG specification was developed for, and validated on, straight-run refinery-produced asphalts for the Strategic Highway Research Program (SHRP).

The AASHTO M320 specification assesses the high-temperature rutting resistance of asphalt binders using the G*/sinδ parameter. This parameter is evaluated in both the original and rolling thin film oven (RTFO)-conditioned states. However, limitations in the Superpave PG system, particularly its inability to accurately predict the performance of modified asphalt binders under heavy traffic loads, led to the development of AASHTO M332 (*6*). This newer specification uses the non-recoverable compliance (Jnr) parameter, obtained from the multiple-stress creep recovery (MSCR) test to grade and evaluate the binder's resistance to high-temperature rutting. The MSCR test is particularly effective in assessing the rutting resistance and elastic recovery of polymer-modified binders. Cracking susceptibility, including fatigue and thermal cracking, is addressed within AASHTO M320 and M332 by testing pressure aging vessel (PAV) conditioned binders. Both AASHTO M320 and M332 evaluate fatigue resistance through the G*sinδ parameter, which corresponds to the binder's loss modulus (G″). To evaluate a binder's resistance to thermal cracking, the BBR test is conducted at low temperatures. This test measures two critical parameters at 60 seconds: the binder's stiffness (S), which reflects its rigidity, and the m-value, which indicates the rate at which the binder can relax stress over time. Together, these two parameters help determine a binder's performance in cold climates.

Due to increased performance demands, economic pressures, and environmental concerns, the use of modified binder grades, reclaimed asphalt pavement (RAP), and various softeners have become more prevalent. However, not all of these materials have demonstrated adequate long-term field performance (*7*). For instance, studies have shown that the current Superpave parameter used to evaluate the intermediate-temperature cracking resistance of asphalt binders, G*sinδ, is inadequate for excluding lower-quality materials from mixtures (*7*). This indicates the need for a new rheological evaluation method to better prevent premature binder aging and pavement cracking at intermediate temperatures.

2.2 Rheological Parameters from a Master Curve

Key rheological parameters of an asphalt binder can be determined through the construction of a master curve, which provides a comprehensive graphical representation of the binder's viscoelastic behavior. This curve illustrates the relationship between binder stiffness and reduced frequency across various temperatures and frequencies. To create it, stiffness measurements are taken at multiple temperatures and frequencies, and these data points are then shifted using the principles of time-temperature superposition, also known as the method of reduced variables. The time-temperature superposition principle asserts that the effects of time and temperature on the viscoelastic properties of an asphalt binder are equivalent. Essentially, a change in temperature can be offset by a shift in time (or frequency) to yield the same response from the binder. This allows data collected at different temperatures to be horizontally shifted along the frequency axis, forming a smooth, continuous curve (*5,8,9*).

To construct the master curve, data from the DSR tests are collected across a range of temperatures and frequencies and strain levels in accordance with AASHTO T315, as well as from BBR tests at multiple temperatures in accordance with AASHTO T313. BBR data is then converted into dynamic data to enable an extension of the master curve to cover a larger range of stiffness values (*10*). This enables a more robust analysis over a larger range of stiffness. The interconversion from bending to shear is performed using the methods described by Rowe (*11*). The analysis previously cited showed that a G* of 111 MPa corresponded to the BBR stiffness value of 300 MPa, close to the commonly known relationship of E = 3G, whereas the phase angle of 26.2 degrees is equivalent to a m-value of 0.300.

A reference temperature is selected, and the data at all other temperatures are shifted relative to time until the curves converge into a single, smooth function. The amount of shifting required at each temperature to form the master curve is known as the shift factor, denoted as a(T). The shift factor, a(T), is crucial because plotting it against temperature provides a visual indication of how the viscoelastic properties of materials like asphalt binders change with temperature. This plot, typically presented alongside the master curve, offers a comprehensive characterization of the binder's stress-strain-time-temperature response. The master curve reflects the time dependency of the binder, while the temperature dependency is captured by the temperature shift factors, represented by log a(T). The resulting master curve enables the prediction of binder performance under diverse temperature and loading conditions, providing critical insights into its behavior. The master curves were constructed in this study using the "free-shifting" method, as described in reference (*12*) and implemented in the RHEA™ software (*13*). Unlike alternative methods, the "free-shifting" approach does not rely on a predefined model, such as the Christensen-Anderson (CA) model, to determine the shape of the master curve. This approach allows for more accurate modeling of complex binders, including those with high polymer content. The Christensen and Anderson (CA) model has then been used for interpolation of parameters in the high stiffness area. Rowe et al. (*10*) recommended using a higher limiting stiffness value of 1e6 Pa to enhance the fitting to the CA model for modified binders whereas the original developers suggested a lower limit of 1e5 Pa (*8*). By using CA model, key rheological parameters can be extracted, which are critical for understanding binder behavior across a range of temperatures and loading conditions. These are the cross-over frequency (ω_c) and rheological index (R). The cross-over frequency (ω_c) is the frequency on the master curve where the phase angle equals 45°, indicating that the storage modulus (G′) equals the loss modulus (G″). An increase in ωc suggests a decrease in binder hardness, which is desirable for resisting cracking. The G* at the cross-over frequency is referred to as the cross-over modulus (G_c), while the limiting modulus at very low temperatures, where the phase angle equals 0°, is known as the glassy modulus (G_g). Christensen et al. recommended use of a Gg value of 1 GPa for asphalt binders tested in shear (*8*). The rheological index (R) measures the rheological type of the binder and is calculated as the difference between the log of the glassy modulus (G_g) and the log of the cross-over modulus (G_c) ($R = \log G_g - \log G_c$). A higher R index indicates a flatter master curve, signifying a more gradual transition from elastic to viscous behavior. This gradual transition could be advantageous for resisting rutting at high temperatures but will reduce the binder's responsiveness to stresses at intermediate temperatures, where stress relaxation is needed to resist cracking (*7,10*). Consequently, an asphalt binder with a higher ω_c and lower R is more resistant to cracking, while both ω_c and R are expected to decrease and increase, respectively, with aging. In this study, the glassy modulus was not assumed to be a constant value but rather it was obtained from fitting the CA model to the shifted data, excluding G* stiffness values below 1e6 Pa.

2.3 Other Rheological Parameters

Another parameter derived from master curve data is the Glover-Rowe (G-R) cracking parameter (*14,15*). The G-R parameter was initially calculated at a condition of 15°C and 0.005 rad/s using the formula $G^*(\cos\delta)^2/\sin\delta$. This parameter captures the performance associated with non-load associated cracking susceptibility and assesses the impacts of oxidative aging and asphalt modification on an asphalt binder. The G-R parameter was developed based on the Glover fatigue cracking parameter G'/(η'/G'), which was found to correlate highly with the ductility of the asphalt binder. The Glover parameter was modified by Rowe (*15*) to enable this to be plotted in a Black space plot with a G* and δ. Glover's original threshold values correspond to Glover-Rowe values of 180 kPa for the onset of cracking and 600 kPa for severe damage. More recently NCHRP 9-59 (*16*) suggested that this parameter should be conducted at various temperatures at a frequency of 10 Hz to assess the fatigue resistance of asphalt binders effectively. Rowe et al. (*10*) suggested that a 10 rad/s frequency might be preferable since this relates better to AASHTO T315 and ASTM D7175 methods. Hence, in this study, the G-R parameter was assessed using a frequency of 10 rad/s. The use of the faster frequency results in the G* used in determining the G-R parameter being higher than 1e6 Pa. Generally, it is recognized that cracking of asphalt binders occurs when the complex modulus is greater than 1 MPa (*17,18*).

A study by Anderson et al. (*13*) introduced the parameter Delta T_c (ΔT_c), which measures the loss of relaxation in asphalt binders due to aging and correlates with an increased risk of non-load associated cracking. ΔT_c is determined by testing an asphalt binder using a BBR in accordance with AASHTO T313. This parameter is measured at low temperatures on binders that have been aged using both the RTFO and PAV. By running the BBR test at multiple low temperatures, two critical low temperatures values are identified: one corresponding to a S of 300 MPa and the other to an m-value of 0.300. The difference between these two temperatures, $T_c(S)$ - $T_c(m)$, defines ΔT_c. As ΔT_c becomes a higher negative value, the risk of cracking increases. ΔTc has proven to be a valuable tool for screening out poorly performing binders and represents an improvement over the current M320 specification.

In a separate study, Pavel Kriz proposed using the phase angle (δ_{PK}) at a specific modulus of 8.967 MPa as a criterion for controlling intermediate-temperature cracking in asphalt pavements. This modulus was selected based on extensive analysis of binder behavior and field performance. Kriz and his team found that at this precise modulus, the phase angle (δ_{PK}) demonstrated a strong correlation with the binder's resistance to intermediate-temperature cracking, making δ_{PK} an effective tool for identifying phase-incompatible asphalts, which are particularly sensitive to aging and prone to cracking under intermediate-temperature conditions (*7*). The modulus value of 8.967 MPa is typically considered on a logarithmic (log) scale, where the logarithm of 8.967×106 Pa is approximately 6.953. Based on Kriz's original work, other researchers (19) have suggested rounding this value to 10 MPa for simplicity. On a logarithmic scale, the log of 8.967×106 Pa and the log of 10×106 Pa are very close, being 6.953 and 7.000, respectively. The resulting difference in the calculated phase angle using these rounded values is minimal—less than one degree—where the 10 MPa value yields a slightly lower phase angle (*20*). Therefore, in this study, the phase angle (δ) has been determined at a modulus value of 10 MPa, denoted as δ_{10MPa}. The correlation between δ_{10MPa} and the original phase angle at 8.967 MPa (δ_{PK}) has been evaluated to confirm the practicality and accuracy of using 10 MPa in this context.

3.0 Point and Shape Rheological Parameters

Rheological parameters can be grouped into two categories, point and shape parameters. Shape parameters define the shape or curvature of the master curve whereas point parameters define a rheological property at a particular frequency/loading time and temperature (*10*). Figure 3.1 illustrates a master curve of an asphalt binder and identifies point and shape parameters.

- Point Parameters: These can be considered to capture the hardness of asphalt binders. They include specific values on the master curve, such as the G*, ω_c and the G-R parameter at a reference temperature and frequency (*10*).
- Shape Parameters: These capture the rheological type of asphalt binders (*10*). They describe the overall shape/form of the master curve, reflecting the asphalt binder's response over a wide range of conditions. Governmental agencies are currently evaluating four additional specification parameters to effectively describe the shape of the master curve (*10*): (1) R-value, (2) log G_c, (3) δ_{PK} or δ_{10MPa} and (4) ΔT_c.

To define a material's susceptibility to various forms of distress, such as rutting or cracking, both shape and point parameter must be defined. Since these parameters essentially define the same master curve shape within the high stiffness range (say 1e6 to 1e9 Pa), it is crucial for the industry to identify which parameter best represents this shape, considering factors such as ease of measurement, experimental reproducibility, and repeatability (*10*).

With regard to the point parameter, these could be expressed as a temperature (defined loading time/frequency) where a certain condition exists.

Three of the shape parameters, R-value, log G_c, and δ_{10MPa} are measured using a DSR testing whereas the value of ΔT_c is calculated from a BBR testing from the determination of the critical values associated with the stiffness and m-value in that test. As the value of ΔT_c becomes more negative the slope of the BBR master curve becomes flatter, as shown in Figure 2. In this figure the data for a binder from Anderson et al. study (*13*) shows the value of ΔT_c for that binder computed using the current method ($T_S - T_m$). The numbers 0, 20, 40 and 80 represent PAV aging time. The data is presented using the reference temperature of -18°C for the computation of the stiffness vs. time master curve shown in the Figure 2a. The square symbol identifies the location of the m-value equal to 0.300. The data has then been transposed in Figure 2b to a temperature scale associated with a loading time of 60-seconds. In Figure 3.2 the critical m-value is identified by a square symbol. Hence, the values of ΔT_c are clearly shown to be a shape parameter, with flatter lines tending to significantly negative values.

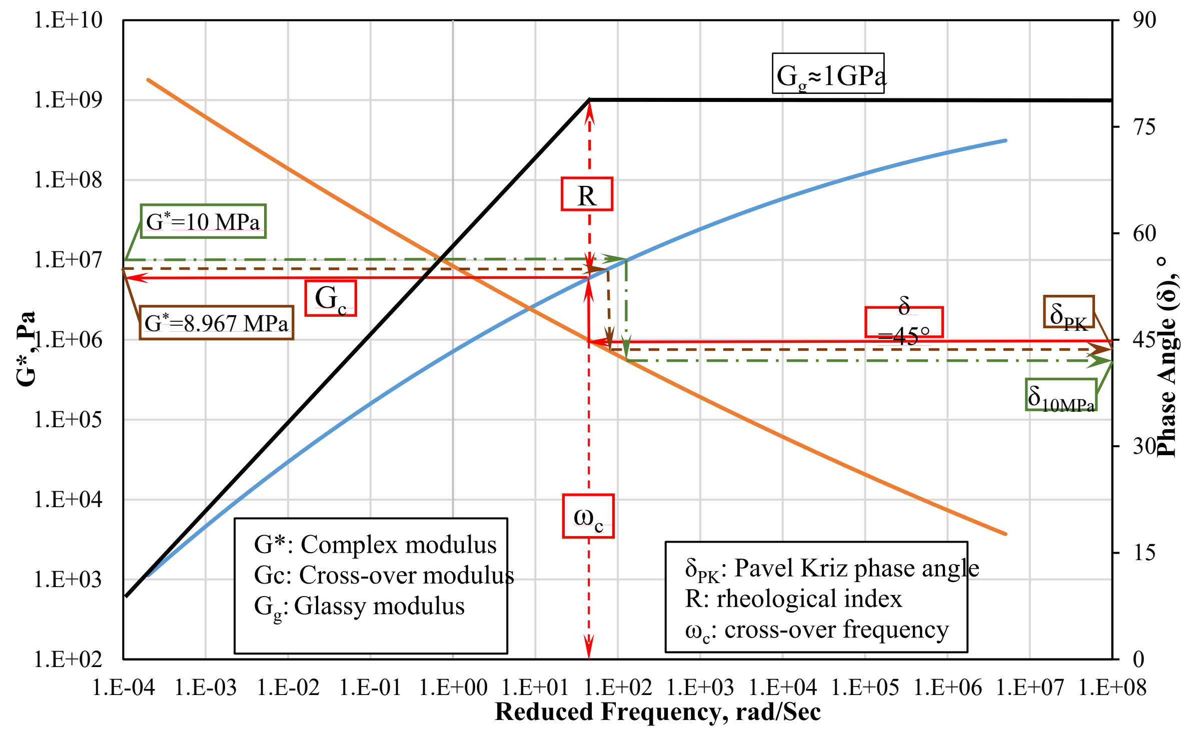
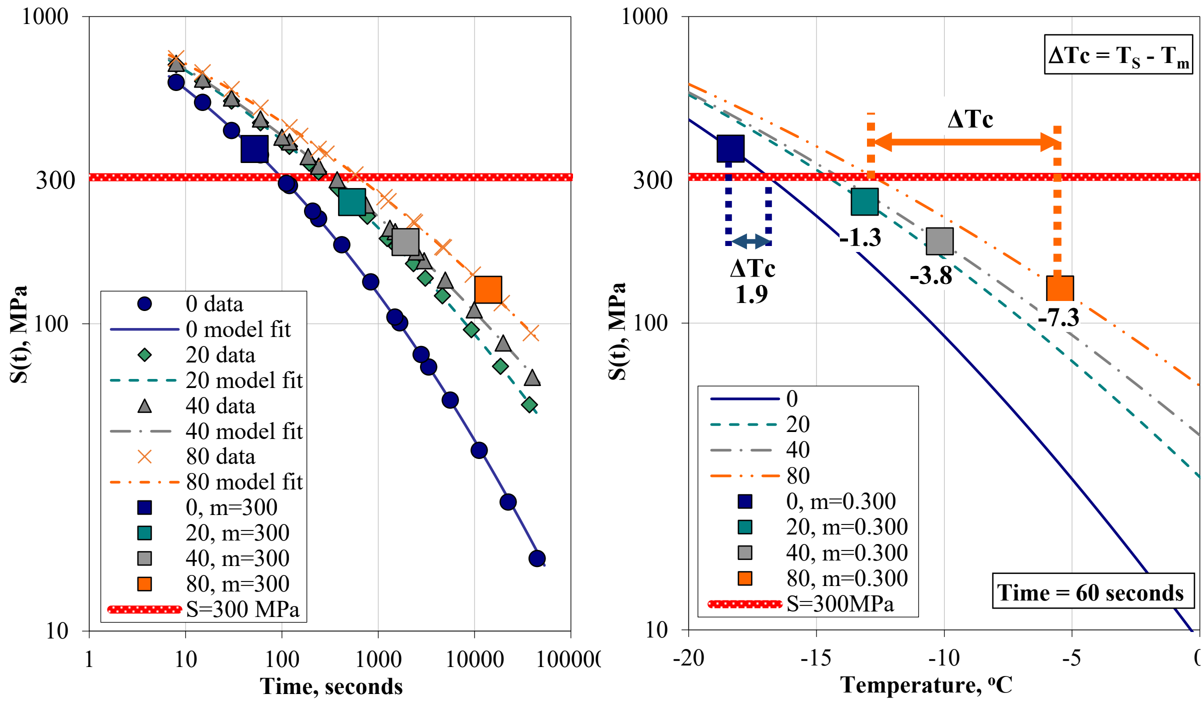


Figure 3.1 - Illustration of point and shape parameters on a master curve.



(a) BBR master curve for a binder at different aging levels illustrating S(60)=300MPa and m-value=0.3

(b) Determination of ΔTc parameter showing the effect on the shape of the master curve

Figure 3.2 - Illustration of ΔTc parameter on the BBR stiffness master curve for a binder at different aging levels. ***Source: Data from Anderson et al, (14). Values of ΔTc taken from Table 12 of that publication***

4.0 Scope of Work

The Massachusetts Department of Transportation (MassDOT) is interested in incorporating rheological parameters in its BMD to ensure its asphalt mixtures remain balanced, specifically in terms of intermediate-temperature cracking, regardless of the binder source or formulation. The scope of this study involves developing and validating rheological parameters—both point and shape—that ensure the quality of an asphalt binder is not compromised with respect to intermediate-temperature cracking, even when the source and/or formulation of asphalt binders (with the same PG) change during the design and production of an asphalt mixture.

The study began by obtaining a total of seventeen asphalt binders from four different suppliers in Massachusetts. These binders included unmodified, polymer-modified, and asphalt rubber types, as well as their corresponding base binders, where applicable. The performance grade (PG) of these binders was PG 64S-28, PG 64E-28, PG 76E-34, and asphalt rubber. Additionally, a binder known for poor intermediate-temperature cracking performance was obtained. Another two binders of poor quality, characterized by poor relaxation properties, were manufactured in the laboratory by incorporating a high dosage of a recycling agent and air-blown asphalt into a PG 64-22 and PG 64-28 base asphalts.

All binders were graded according to AASHTO M 320 and M 332 and tested using the DSR and BBR. Master curves for the binders were constructed, both for binders in their original state and after being aged in the PAV for 0, 20, and 40 hours following short-term aging in the RTFO. These analyses were performed on a total of eighty different binder combinations (20 binders across 4 aging conditions).

The measured rheological data were analyzed using the RHEA™ software, version 2.0 (*13*), which applies an adaptation of the Gordon and Shaw method (*12*) which used free-shifting when generating master curves. From these curves, point and shape parameters were calculated for each binder. The data were further analyzed to identify trends and correlations between these parameters and binder quality, with the goal of identifying parameters that reliably distinguish between high and low-quality binders.

To validate the effectiveness of the identified rheological parameters, a 12.5 mm dense-graded asphalt mixture was designed using seven selected binders, including three of lower quality. The susceptibility of these mixtures to intermediate-temperature cracking was assessed using the Indirect Tensile Cracking Test (IDEAL-CT) to determine their Cracking Tolerance Index (CT_{Index}). The IDEAL-CT results were statistically analyzed to identify mixtures with significantly lower CT_{Index} values, and the rheological parameters of the seven binders were evaluated and ranked numerically. To confirm the reliability of the selected parameters in predicting cracking susceptibility, it was expected that the three mixtures prepared with the lower quality binders would exhibit the lowest CT_{Index} values.

Additionally, a rapid test method using the DSR was developed to measure these parameters during the mix design and production process, ensuring their availability for use in timely and accurate quality control.

4.1 Objectives

This study was conducted to develop and validate rheological parameters to ensure the consistent quality of asphalt binders, particularly regarding their resistance to intermediate-temperature cracking, regardless of changes in binder source or formulation. Specifically, the objectives were:

1. Evaluate the point and shape rheological parameters of various asphalt binders.
2. Identify a point and/or shape parameter that can distinguish between high and low-quality binders.
3. Validate the selected rheological parameters using the IDEAL-CT test.
4. Develop a simple and rapid test method to measure the identified rheological parameters, particularly for use during the production process.

4.2 Experimental Plan

To achieve the objectives of this study an experimental plan was developed as shown in Figure 4.1.

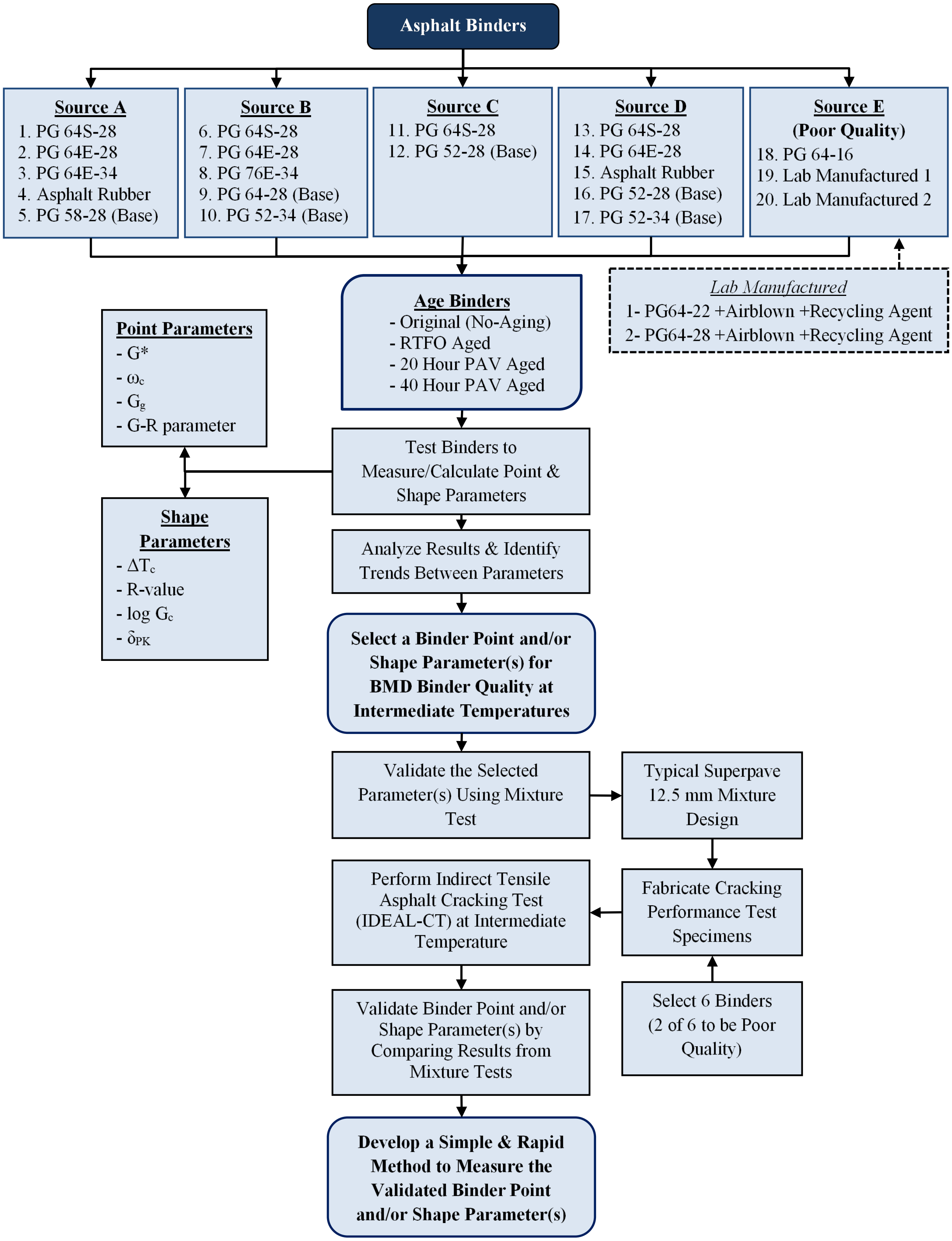


Figure 4.1- Experimental plan.

5.0 Materials

5.1 Asphalt Binders

MassDOT typically specifies a PG64S-28 asphalt binder for its Superpave mixtures. Recently there has been a shift towards using a PG64E-28 binder for these mixtures. For high RAP content mixtures, MassDOT now recommends PG64E-34, and for high-performance and gap-graded mixtures, PG76E-34 and asphalt rubber are suggested.

To conduct a comprehensive study, efforts were made to obtain all these PG binders, along with any base binders used in their formulation, from all asphalt binder suppliers serving asphalt producers in Massachusetts. Despite this effort, only one supplier provided PG64E-34, and another supplied PG76E-34. These two binders were included in the study because they are considered high-quality materials, making them suitable for determining and validating point and/or shape parameters that can differentiate between high and low-quality binders with the same PG.

All suppliers attested to the high quality of their binders. To further investigate and identify point and/or shape rheological parameters that could distinguish between good and poor-quality binders, particularly regarding intermediate-temperature cracking performance, two additional binders were artificially produced in the lab. The first binder, PG64-22, was modified with 15% air-blown asphalt and 15.3% Re-refined Engine Oil Bottoms (REOB). The second binder, PG64-28, was produced by adding 12% air-blown asphalt and 6% REOB to a base PG64-28 binder that had previously shown poor performance in intermediate-temperature cracking in an earlier study (*21*). Additionally, a PG64-16 binder, known for its poor relaxation performance, was sourced from a supplier based in the western U.S. Although MassDOT does not specify a PG64-16 binder, it was included in this study solely to assist in identifying and validating the point and/or shape rheological parameters associated with binder quality.

Attempts were also made to trace the origin of the crude oils used to produce these asphalt binders. However, suppliers indicated that this is generally not feasible, as most refineries process a blend of crude oils, and asphalt terminal blending facilities often combine various asphalt streams to produce finished products that meet the required specifications.

All binders were tested and graded according to AASHTO R29, "Standard Practice for Grading or Verifying the Performance Grade (PG) of an Asphalt Binder," and AASHTO M320, "Standard Specification for Performance-Graded Asphalt Binder," to determine their performance grade (PG) (*2*). Additionally, all binders were graded following AASHTO M332, "Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test" (*2*). Table 5.1 presents the PG and continuous grades of the binders.

Table 5.1 - Summary of Asphalt Binder Grading Results for Different Binders.

<table>
<tr><th colspan="2">Binder Source</th><th>Description</th><th>Avg. Binder Continuous Grade High, (Intermediate), Low, °C</th><th>Avg. Binder PG</th><th>MSCR Grade</th></tr>
<tr><td colspan="2" rowspan="5">Source A</td><td>PG58-28 (Base Binder)</td><td>60.3 (15.4) -30.2</td><td>58-28</td><td>58H</td></tr>
<tr><td>PG64S-28</td><td>66.3 (14.3) -31.4</td><td>64-28</td><td>64S</td></tr>
<tr><td>PG64E-28</td><td>73.4 (13.1) -32.9</td><td>70-28</td><td>64E</td></tr>
<tr><td>PG64E-34</td><td>70.1 (8.5) -37.1</td><td>70-34</td><td>64E</td></tr>
<tr><td>AR-20 [Asphalt Rubber]</td><td>87.0 (9.0) -33.3</td><td>82-28</td><td>64E</td></tr>
<tr><td colspan="2" rowspan="5">Source B</td><td>PG52-34 (Base Binder)</td><td>54.6 (13.3) -33.7</td><td>52-28</td><td>52H</td></tr>
<tr><td>PG64-28 (Base Binder)</td><td>64.7 (16.9) -30.7</td><td>64-28</td><td>64S</td></tr>
<tr><td>PG64S-28</td><td>66.4 (14.2) -30.3</td><td>64-28</td><td>64H</td></tr>
<tr><td>PG64E-28</td><td>80.9 (13.7) -31.3</td><td>76-28</td><td>64E</td></tr>
<tr><td>PG76E-34</td><td>81.8 (10.9) -34.5</td><td>76-34</td><td>76E</td></tr>
<tr><td colspan="2" rowspan="2">Source C</td><td>PG58-28 (Base Binder)</td><td>59.6 (14.2) -30.3</td><td>58-28</td><td>58S</td></tr>
<tr><td>PG64-28 Common</td><td>65.9 (13.6) -30.7</td><td>64-28</td><td>64S</td></tr>
<tr><td colspan="2" rowspan="5">Source D</td><td>PG52-34 (Base Binder)</td><td>54.3 (12.6) -33.5</td><td>52-28</td><td>52H</td></tr>
<tr><td>PG58-28 (Base Binder)</td><td>60.4 (16.7) -29.0</td><td>58-28</td><td>58H</td></tr>
<tr><td>PG58-28 AR [Asphalt Rubber]</td><td>86.8 (11.3) -32.0</td><td>82-28</td><td>64E</td></tr>
<tr><td>PG64E-28</td><td>72.1 (16.9) -30.3</td><td>70-28</td><td>64E</td></tr>
<tr><td>PG64-28 PPA</td><td>68.5 (15.5) -31.1</td><td>64-28</td><td>64E</td></tr>
<tr><td rowspan="3">Poor Quality</td><td>Source E</td><td>PG64-16</td><td>67.6 (25.0) -19.4</td><td>64-16</td><td>64S</td></tr>
<tr><td>Formulated Binder 1</td><td>PG64-22</td><td>64.2 (9.3) -23.9</td><td>64-22</td><td>64S</td></tr>
<tr><td>Formulated Binder 2</td><td>PG64-28</td><td>65.4 (12.3) -29.0</td><td>64-28</td><td>64S</td></tr>
</table>

5.2 Aggregates and Reclaimed Asphalt Pavement (RAP)

Granite aggregates were sourced from three different stockpiles, 12.5 mm crushed stone, 9.5 mm crushed stone, and stone sand, along with one Reclaimed Asphalt Pavement (RAP) stockpile containing 5.1% binder content and a RAP binder graded at PG76-22. The aggregates and RAP were collected from a local contractor in Massachusetts and used to design a Superpave 12.5-mm Hot Mix Asphalt (HMA) mixture. Asphalt (HMA) mixture, incorporating a RAP content of 15%, which is typical for the state of Massachusetts. The mixture was used to validate the point and shape parameters that would be selected.

6.0 Asphalt Binders Testing

The asphalt binders listed in Table 5.1 were tested using the DSR and BBR to construct their master curves and determine the corresponding point and shape parameters. As previously mentioned, each binder underwent testing using the DSR and BBR at various aging stages: unaged, RTFO-aged, 20-hour PAV-aged, and 40-hour PAV-aged. Master curves were developed using the RHEA™ software version 2.0 (*13*) following these aging processes. Table 6.1 summarizes the testing conditions used for the rheological testing. To ensure that the specimens remained within the linear viscoelastic region across the selected temperature range when testing in the DSR, a strain range of 0.5% to 2% was used.

Table 6.1 - Test Conditions Used for Testing of Binders.

Test properties/details	**Intermediate and high temperatures**		**Low temperature**
Test device	DSR		BBR
Plate size, mm	8	25	Not applicable
Temperature, °C	5 15 25 35	45 55 65	< 0°C (2 temperatures with 6°C increment)
Strain level, %	0.5 0.5 1.0 1.0	1.0 1.5 2.0	Not applicable
Frequency (ω), rad/sec	0.1, 0.159. 0.251, 0.398, 0.631, 1.0, 1.59, 2.51, 3.98, 6.31, 10	0.1, 0.159. 0.251, 0.398, 0.631, 1.0, 1.59, 2.51, 3.98, 6.31, 10	Not applicable
Time, sec	Not applicable	Not applicable	8, 15, 30, 60, 120, 240

The stiffness, S(t), of each binder, measured at different times using the BBR, was converted to the G* and δ using the methods described by Rowe (*11*).

Based on the work of researchers (*8,22*) analyzing data from the DSR to calculate CA model parameters, data with stiffness values below 1e6 Pa were removed. In the development of the CA model, Christensen and Anderson (*8*) recommended eliminating data with stiffness below 1e5 Pa. Anderson and Rowe (23) also suggested that using a stiffness range between 10e5 Pa and 10e9 Pa when fitting the CA model improves the evaluation of cracking performance by enhancing the model's fit, particularly for δ at low G* values. However, Rowe (*8*) found that for polymer-modified asphalt binders, the CA model fit is improved by raising the lower stiffness limit from 1e5 Pa to 1e6 Pa. This high stiffness region on the binder master curve sufficiently covers the fracture behavior of an asphalt binder and is directly related to its cracking performance. Therefore, in this analysis as noted, data with stiffness values below 1e6 Pa were excluded. From the master curves a total of seven parameters were evaluated, including three point parameters and four shape parameters. The specific point and shape parameters analyzed are detailed in Table 6.2.

Table 6.2 - Point and Shape Parameters (a) Point Parameters (b) Shape Parameters

Point Parameter	Source of Data
G-R at 15°C and 10 rad/s	DSR Measurements and Master Curve
ω_c	Master Curve
G-R at 15°C and 0.005 rad/s	Master Curve

(a)

Shape Parameter	Source of Data
R-value	Master Curve
δ_{10MPa}	Master Curve
Log G_c	Master Curve
ΔT_c	BBR Measurements

(b)

The values of ω_c, G-R at 15°C and 0.005 rad/s, G-R at 15°C and 10 rad/s, R-value, δ_{10MPa}, and log G_c, have been determined by interpolating data from the master curve analysis. The values of the ΔT_c ($T_c(S)$ - $T_c(m)$) have been calculated from the BBR data.

6.1 Point and Shape Parameters Results

Tables 6.3 to 6.6 present the point and shape parameters of the various binders tested at different aging levels. Each result is followed by a numerical ranking in parentheses, ranging from 1 to 20, where 1 represents the best-performing binder and 20 the worst-performing binder for a given parameter. It is important to note that the "worst" result only reflects its position in the numerical ranking. This ranking system was developed to identify one or more parameters, whether point or shape—that would consistently rank the three poor-quality binders as 20.

Table 6.3 - Point Parameters Ranking (Ranking in Parentheses)

Source	Parameter	Cross-over frequency (ω_c)				G-R (15°C and 0.005 rad/s)			
	Aging Level	**Original**	**RTFO**	**20h PAV**	**40h PAV**	**Original**	**RTFO**	**20h PAV**	**40h PAV**
Source A	**AR-20**	307.2 (19)	85.68 (18)	1.049 (17)	0.081 (11)	17.5 (19)	27.3 (19)	94.3 (10)	255.5 (10)
	PG58-28 (Base Binder)	9303 (6)	1387 (8)	41.49 (5)	0.537 (7)	0.06 (3)	1.4 (4)	29.5 (3)	238.2 (8)
	PG64E-28	6279 (9)	1446 (7)	1.315 (16)	0.024 (14)	3.9 (17)	11.9 (17)	122 (11)	694.6 (14)
	PG64E-34	23940 (3)	4589 (3)	20.81 (8)	0.214 (10)	1.8 (14)	7.1 (10)	48.1 (6)	166.2 (5)
	PG64S-28	4983 (11)	1048 (11)	2.633 (13)	0.015 (20)	1.04 (9)	7 (9)	125.1 (12)	745.5 (16)
Source B	**PG52-34 (Base Binder)**	43430 (1)	9859 (2)	113.1 (2)	6.048 (2)	0.003 (2)	0.14 (2)	15.7 (2)	77.4 (1)
	PG64-28 (Base Binder)	7773 (7)	1359 (9)	3.196 (11)	0.016 (16)	0.34 (6)	4.1 (6)	143.3 (15)	577.3 (13)
	PG64E-28	9866 (5)	405.7 (15)	1.999 (15)	0.017 (15)	1.5 (11)	27.2 (18)	172.3 (18)	728.6 (15)
	PG64H-28	3409 (13)	626.9 (14)	2.252 (14)	0.025 (13)	1.8 (14)	11.3 (16)	133.8 (13)	566.9 (12)
	PG76E-34	18020 (4)	3546 (4)	48.61 (4)	1.306 (5)	3.4 (16)	9.3 (13)	52.6 (7)	148.5 (3)
Source C	**PG58-28 (Base Binder)**	7352 (8)	1137 (10)	20.89 (7)	1.004 (6)	0.11 (4)	1.5 (5)	39.2 (4)	152.9 (4)
	PG64S-28	4019 (12)	873.9 (12)	0.937 (18)	0.039 (12)	1.2 (10)	9.6 (14)	161.3 (16)	454.5 (11)
Source D	**AR**	***239.6 (20)***	***27.56 (20)***	3.761 (10)	0.284 (8)	***27.9 (20)***	***47 (20)***	90.1 (9)	172.6 (6)
	PG52-34 (Base Binder)	40140 (2)	10170 (1)	325.8 (1)	6.194 (1)	0.002 (1)	0.12 (1)	7.2 (1)	78.17 (2)
	PG58-28 (Base Binder)	5861 (10)	1474 (6)	28.4 (6)	1.438 (4)	0.12 (5)	1.3 (3)	39.7 (5)	196.5 (7)
	PG64-28 PPA	2783 (15)	700.7 (13)	2.975 (12)	0.015 (20)	2.3 (15)	10.4 (15)	141.4 (14)	810.9 (18)
	PG64E-28	3013 (14)	2109 (5)	58.68 (3)	1.885 (3)	6.0 (18)	5.9 (7)	53.8 (8)	252.6 (9)
Source E (Poor Quality)	**PG64-16**	1157 (18)	261.2 (17)	5.062 (9)	0.221 (9)	0.52 (7)	6.9 (8)	210.3 (19)	***1034 (20)***
Formulated Binder 1	**PG64-22**	1639 (17)	47.66 (19)	***0.015 (20)***	***0.015 (20)***	0.93 (8)	8.7 (12)	***237.6 (20)***	836 (19)
Formulated Binder 2	**PG64-28**	2355 (16)	298.3 (16)	0.159 (19)	***0.015 (20)***	1.6 (12)	8.1 (11)	166.7 (17)	795.4 (17)

Table 6.4 - Point Parameters Ranking (Ranking in Parentheses)

Source	Parameter	G-R (15°C and 10 rad/s)			
	Aging Level	**Original**	**RTFO**	**20h PAV**	**40h PAV**
Source A	**AR-20**	1558 (18)	2464 (14)	6269 (6)	12640 (6)
	PG58-28 (Base Binder)	595 (6)	2308 (12)	9015 (9)	20380 (11)
	PG64E-28	801.8 (10)	1683 (5)	8017 (7)	20550 (12)
	PG64E-34	238.5 (3)	736.8 (3)	3931 (2)	8510 (1)
	PG64S-28	1008 (12)	2412 (13)	10370 (14)	22770 (17)
Source B	**PG52-34 (Base Binder)**	110.9 (2)	551 (2)	5286 (4)	10410 (5)
	PG64-28 (Base Binder)	646.8 (7)	2084 (7)	12080 (19)	22950 (18)
	PG64E-28	544.2 (5)	2776 (17)	9679 (11)	20860 (14)
	PG64H-28	1336 (16)	2857 (18)	10230 (12)	19560 (9)
	PG76E-34	284.8 (4)	887.8 (4)	4651 (3)	9700 (2)
Source C	**PG58-28 (Base Binder)**	763.3 (9)	2134 (8)	9160 (10)	15350 (7)
	PG64S-28	1120 (15)	2521 (15)	10720 (17)	16640 (8)
Source D	**AR**	2123 (19)	3593 (19)	5848 (5)	10390 (4)
	PG52-34 (Base Binder)	79.1 (1)	480.9 (1)	3326 (1)	10080 (3)
	PG58-28 (Base Binder)	821.5 (11)	2202 (9)	10680 (16)	19890 (10)
	PG64-28 PPA	1398 (17)	2707 (16)	10470 (15)	26330 (19)
	PG64E-28	1097 (14)	1748 (6)	8627 (8)	20840 (13)
Source E (Poor Quality)	**PG64-16**	***3895 (20)***	***10910 (20)***	***41730 (20)***	***70860 (20)***
Formulated Binder 1	**PG64-22**	736 (8)	2231 (10)	11020 (18)	21130 (15)
Formulated Binder 2	**PG64-28**	1039(13)	2247(11)	10260(13)	22300(16)

Table 6.5 - Shape Parameters Ranking (Ranking in Parentheses)

Source	Parameter	Delta Tc (ΔTc)				R-value			
	Aging Level	**Original**	**RTFO**	**20h PAV**	**40h PAV**	**Original**	**RTFO**	**20h PAV**	**40h PAV**
Source A	**AR-20**	-2 (19)	-0.5 (18)	-4.1 (17)	-9 (17)	***2.72 (20)***	3.21 (18)	4.26 (17)	4.21 (12)
	PG58-28 (Base Binder)	3.6 (2)	1.8 (12)	-0.2 (8)	-3.7 (8)	1.62 (5)	1.92 (5)	2.6 (4)	3.58 (7)
	PG64E-28	2.9(6)	3 (3)	-0.1 (7)	-8.4 (15)	2.07 (14)	2.47 (12)	4.33 (19)	4.23 (13)
	PG64E-34	1.1 (17)	2.6 (7)	0.5 (5)	-3.4 (5)	1.72 (8)	2.37 (11)	3.68 (12)	4.52 (17)
	PG64S-28	2.6 (10)	2.9 (5)	0.7 (3)	-3.6 (7)	1.92 (11)	2.36 (10)	3.9 (15)	4.46 (15)
Source B	**PG52-34 (Base Binder)**	2.8 (8)	3.3 (1)	0.8 (2)	-4 (10)	1.42 (2)	1.74 (3)	2.6 (4)	3.09 (3)
	PG64-28 (Base Binder)	3.7 (1)	2.9 (5)	-0.6 (10)	-3.7 (8)	1.79 (9)	2.23 (8)	3.57 (9)	***4.69 (20)***
	PG64E-28	2.8 (8)	1.7 (13)	-1.6 (14)	-8.5 (16)	1.56 (4)	2.78 (16)	3.81 (14)	4.49 (16)
	PG64H-28	1.2 (16)	1.6 (16)	-0.6 (10)	-3.2 (4)	1.95 (12)	2.55 (13)	3.95 (16)	4.62 (18)
	PG76E-34	2.4 (11)	2.2 (10)	-1.6 (14)	-4.1 (11)	1.83 (10)	2.24 (9)	2.96 (7)	3.74 (9)
Source C	**PG58-28 (Base Binder)**	2.9 (6)	1.7 (13)	-0.8 (12)	-2.7 (3)	1.66 (6)	2.09 (7)	2.98 (8)	3.67 (8)
	PG64S-28	2 (13)	2.5 (8)	-0.4 (9)	-2.4 (1)	2.05 (13)	2.57 (14)	4.28 (18)	4.66 (19)
Source D	**AR**	**-3.6 (20)**	-2.5 (19)	-5.8 (18)	-6 (14)	2.62 (18)	3.3 (19)	3.67 (11)	4.17 (11)
	PG52-34 (Base Binder)	3.1 (5)	3.1 (2)	1.5 (1)	-2.6 (2)	1.44 (3)	1.65 (1)	2.49 (2)	3.23 (5)
	PG58-28 (Base Binder)	3.6 (2)	2 (11)	-1.2 (13)	-3.4 (5)	1.67 (7)	1.98 (6)	2.6 (4)	3.26 (6)
	PG64-28 PPA	3.3 (4)	3 (3)	0.2 (6)	-5.7 (13)	2.18 (16)	2.59 (15)	3.79 (13)	4.36 (14)
	PG64E-28	2.1 (12)	2.3 (9)	0.6 (4)	-4.4 (12)	2.08 (15)	1.81 (4)	2.58 (3)	3.02 (2)
Source E (Poor Quality)	**PG64-16**	1.3 (15)	1.3 (17)	-1.7 (16)	-9.3 (18)	1.33 (1)	1.67 (2)	2.17 (1)	2.73 (1)
Formulated Binder 1	**PG64-22**	-0.3 (18)	***-2.9 (20)***	***-15.4 (20)***	***-39.7 (20)***	2.72 (19)	***3.34 (20)***	3.58 (10)	3.21 (4)
Formulated Binder 2	**PG64-28**	2 (13)	1.7(13)	-5.9 (19)	-15.4 (19)	2.45 (17)	2.91 (17)	***4.46 (20)***	3.97 (10)

Table 6.6 - Shape Parameters (Ranking in Parentheses)

Source	Parameter	Log cross-over modulus (G_c)				Phase angle at 10 MPa (δ_{10MPa})			
	Aging Level	**Original**	**RTFO**	**20h PAV**	**40h PAV**	**Original**	**RTFO**	**20h PAV**	**40h PAV**
Source A	**AR-20**	***6.603 (20)***	6.427 (18)	5.789 (18)	5.576 (12)	***39.9 (20)***	38.6 (18)	34.9 (18)	32.9 (15)
	PG58-28 (Base Binder)	7.518 (4)	7.247 (6)	6.757 (5)	6.122 (6)	53.5 (5)	48.5 (5)	41.8 (5)	36.7 (6)
	PG64E-28	7.312 (12)	7.08 (12)	5.922 (17)	5.553 (13)	49.6 (12)	46.1 (11)	36.5 (15)	31.9 (18)
	PG64E-34	7.374 (9)	7.127 (11)	6.284 (10)	5.622 (10)	51.2 (9)	46.8 (9)	38.3 (9)	34.4 (10)
	PG64S-28	7.36 (11)	7.132 (10)	6.196 (12)	5.513 (17)	50.2 (11)	46.6 (10)	37.9 (11)	32.1 (17)
Source B	**PG52-34 (Base Binder)**	7.614 (1)	7.457 (2)	6.818 (4)	6.402 (3)	56.4 (2)	52.4 (2)	42.6 (4)	38.5 (2)
	PG64-28 (Base Binder)	7.442 (6)	7.206 (7)	6.302 (9)	5.55 (14)	52.3 (7)	47.8 (7)	38.2 (10)	34.2 (11)
	PG64E-28	7.532 (3)	6.902 (16)	6.132 (13)	5.501 (19)	54.1 (4)	44.2 (16)	37.6 (12)	32.6 (16)
	PG64H-28	7.288 (13)	7 (15)	6.123 (14)	5.524 (16)	48.5 (15)	44.7 (14)	37.2 (14)	33.1 (14)
	PG76E-34	7.364 (10)	7.181 (8)	6.575 (7)	6.033 (8)	51.1 (10)	47.1 (8)	40.7 (7)	36.5 (7)
Source C	**PG58-28 (Base Binder)**	7.437 (7)	7.141 (9)	6.555 (8)	6.109 (7)	52.3 (7)	46.1 (11)	40.1 (8)	36.5 (7)
	PG64S-28	7.272 (14)	7.024 (14)	5.946 (16)	5.542 (15)	48.6 (14)	44.7 (14)	36.2 (16)	33.6 (12)
Source D	**AR**	6.615 (19)	6.286 (19)	5.996 (15)	5.74 (9)	40.1 (19)	37.8 (19)	35.1 (17)	34.7 (9)
	PG52-34 (Base Binder)	7.594 (2)	7.48 (1)	6.937 (1)	6.381 (4)	56.8 (1)	53.7 (1)	44.2 (1)	38.5 (2)
	PG58-28 (Base Binder)	7.432 (8)	7.25 (5)	6.717 (6)	6.324 (5)	52.4 (6)	48.5 (5)	41.3 (6)	37.8 (5)
	PG64-28 PPA	7.27 (15)	7.05 (13)	6.216 (11)	5.582 (11)	48.7 (13)	45.5 (13)	37.4 (13)	33.2 (13)
	PG64E-28	7.212 (16)	7.338 (3)	6.844 (3)	6.42 (2)	47.7 (16)	50.2 (4)	42.8 (3)	39.4 (1)
Source E (Poor Quality)	**PG64-16**	7.496 (5)	7.333 (4)	6.872 (2)	6.453 (1)	54.9 (3)	50.5 (3)	43.4 (2)	38.4 (4)
Formulated Binder 1	**PG64-22**	6.775 (18)	***6.24 (20)***	***5.54 (20)***	5.508 (18)	42.4 (18)	***37.2 (20)***	***29.7 (20)***	***26.9 (20)***
Formulated Binder 2	**PG64-28**	7.027 (17)	6.701 (17)	5.604 (19)	***5.494 (20)***	45.2 (17)	41.1 (17)	34.0 (19)	29.9 (19)

6.2 Selection of a Shape and/or Point Parameters

Based on the rankings shown in Tables 4 and 5, no single point or shape parameter consistently ranked all three poor-quality binders as the worst (ranked 20) across all aging conditions. However, the point parameter G-R at 15°C and 10 rad/s consistently identified the poor-quality binder from source E as the worst at every aging level. Among the shape parameters, δ_{10MPa} effectively ranked the lab-formulated poor-quality binder, PG64-22, as the worst relative to the other binders after aging in the RTFO, 20-hour PAV, and 40-hour PAV, and near the bottom (ranked 18) in the unaged condition. It also placed the other formulated poor-quality binder, PG64-28, close to the bottom at every aging condition—unaged, RTFO, 20-hour PAV, and 40-hour PAV—with rankings of 17, 17, 19, and 19, respectively. Another shape parameter, log G_c, similarly ranked both lab-formulated poor-quality binders near the bottom across all conditions. Another shape parameter, ΔT_c, closely followed by ranking the other two poor-quality binders—formulated in the lab—as the worst in two or three out of the four aging levels.

These observations indicate that neither a single point rheological parameter nor a shape rheological parameter alone is sufficient to evaluate the relative quality of asphalt binders regarding their susceptibility to cracking at intermediate temperatures. While G-R at 15°C and 10 rad/s consistently identified the poor binder from source E as the worst across all aging levels, δ_{10MPa} and log G_c, effectively ranked the formulated poor-quality binders as the worst in most aging levels. This underscores the importance of using both point and shape rheological parameters to assess asphalt binder quality concerning intermediate-temperature cracking.

Based on these findings, G-R at 15°C and 10 rad/s along with δ_{10MPa} or log G_c are recommended as the point and shape parameters, respectively, for evaluating asphalt binder quality. It is suggested to age the binders using the 20-hour PAV procedure, as neither δ_{10MPa} nor log G_c ranked the formulated poor quality PG64-28 binder as the worst under the unaged or RTFO-aged conditions. Given the objective of developing simple and rapid tests to measure these rheological parameters, the shortest aging process that successfully identified the poor-quality binders using both parameters was selected. This approach ensures efficiency while maintaining the accuracy needed to assess binder quality. The next step in this study is to validate these recommendations through mixture testing.

7.0 Validation of the Selected Parameters

To validate the effectiveness of the selected point parameter, G-R at 15°C and 10 rad/s and the two best shape parameters (phase angle at a specific modulus of 10 MPa (δ_{10MPa}) and log G_c), a Superpave asphalt mixture was designed using seven of the twenty tested asphalt binders. The binders chosen were PG64-28 Base, PG64E-28, PG52-34 Base, and PG76E-34 from source B, along with the three lower-quality binders: PG64-16 from source E, and the lab-formulated PG64-22 and PG64-28. These binders were selected to represent a range of performance levels.

- Two binders ranked in the top ten by the three parameters after RTFO and 20 hours of PAV aging (PG52-34 Base and PG76E-34)
- One binder ranked differently by the three parameters after 20 hours of PAV aging (PG64-28 Base)
- One binder ranked similarly by the three parameters after RTFO and 20 hours of PAV aging (PG64E-28)
- Three binders ranked poorly by one or more parameters (PG64-16, PG64-22, and PG64-28).

Table 7.1 lists the ranking of the selected binders according to the G-R at 15°C and 10 rad/s and the corresponding ranking according to the phase angle at a modulus of 10 MPa (δ_{10MPa}) and log G_c after RTFO and PAV.

Table 7.1 - Numerical Ranking of the Selected Binders.

Selected Binder	G-R at 15°C and 10 rad/s		Phase angle at 10 MPa (δ_{10MPa})		Log cross-over modulus (log G_c)	
	RTFO	*20 Hour PAV*	*RTFO*	*20 Hour PAV*	*RTFO*	*20 Hour PAV*
PG52-34	2	4	2	4	2	4
PG76-34	4	3	8	7	8	7
PG64-28 Base	7	19	7	10	7	9
PG64E-28	17	11	16	12	16	13
PG64-16	20	20	3	2	4	2
PG64-22 Lab Formulated	10	17	20	20	20	20
PG64-28 Lab Formulated	11	13	17	19	17	19

The susceptibility of these seven mixtures to intermediate-temperature cracking was assessed using the Indirect Tensile Asphalt Cracking Test (IDEAL-CT), following ASTM D8225-19, "Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at Intermediate Temperature" (*24*). Since higher Cracking Tolerance Index (CT_{Index}) values typically indicate better resistance to intermediate-temperature cracking, aligning the CT_{Index} rankings of the mixtures with the binder rankings based on the G-R parameter, δ_{10MPa}, and log G_c would confirm the efficacy of the selected rheological parameters. Specifically, if the mixtures containing poor-quality binders show the lowest CT_{Index} values, it would validate these parameters as reliable predictors of cracking susceptibility.

7.1 Asphalt Mixture Design

To validate the rheological parameters, a typical Superpave dense-graded asphalt mixture, commonly produced and placed in Massachusetts with a Nominal Maximum Aggregate Size (NMAS) of 12.5 mm, was designed using the seven selected binders. As a result, seven mixtures were prepared. The design compaction effort (N_{des}) for each mixture was set at 75 gyrations, corresponding to a traffic range of 0.3 to 3 million Equivalent Single Axle Loads (ESALs). Each mixture utilized virgin aggregates, a selected binder, and 15% Reclaimed Asphalt Pavement (RAP), which is the maximum allowable in surface mixtures per MassDOT's specifications (*25*). The aggregate gradation for the control mixture is shown in Figure 7.1.

The mixture design adhered to Superpave guidelines as specified in AASHTO M323, *Superpave Volumetric Mix Design*, and AASHTO R35, *Superpave Volumetric Design for Hot Mix Asphalt*. The optimum binder content, determined based on volumetric analysis, was 5.3%. To achieve the target combined gradation, virgin aggregates were sieved and batched by individual size fractions to ensure precise control. All seven mixtures met the volumetric requirements for a Superpave 12.5 mm mixture according to AASHTO R35.

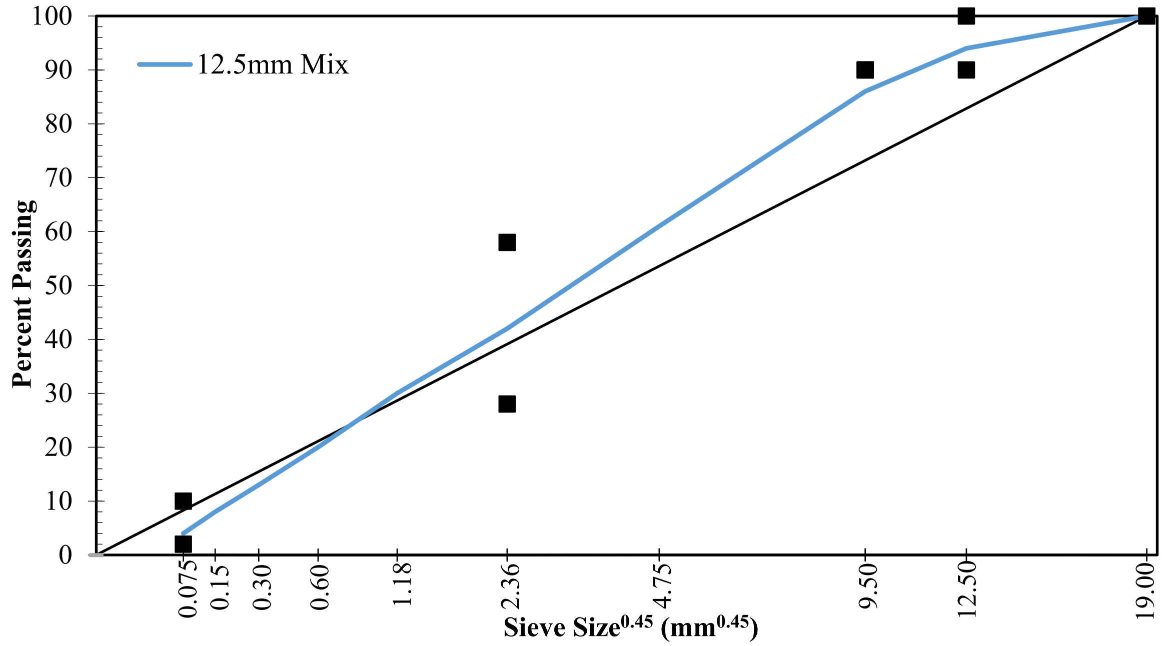


Figure 7.1 - Control mixture aggregate gradation.

7.2 Asphalt Mixtures Resistance to Intermediate Temperature Cracking – IDEAL-CT

For each mixture, four specimens, 62 mm in height and 150 mm in diameter, were compacted using a Superpave Gyratory Compactor (SGC) to achieve final air voids of 7 ± 0.5%. The specimens were tested at 25°C with a constant loading rate of 50 mm/min according to ASTM D8225. During testing, a load was applied along the vertical diametral axis of the cylindrical specimen, while both the load and Load Line Displacement (LLD) were continuously measured. These measurements were used to calculate the Cracking Tolerance Index (CT_{Index}), a metric that evaluates the mixture's resistance to cracking, following the procedure outlined in ASTM D8225. The mixtures in this study were subjected to long-term aging (LTA), which involved placing loose mixtures in a forced-draft oven for four hours at 135°C to induce short-term aging (STA), followed by 20 hours at 110 °C. This aging protocol was developed in a separate study (*26*).

The results of the IDEAL-CT testing are presented in Figure 7.2. Generally, higher CT_{Index} values indicate better resistance to intermediate temperature cracking. The error bars in Figure 5 represent the standard deviation of the results for each mixture, and mixtures with overlapping error bars are considered to have no significant difference in resistance to intermediate temperature cracking. The three poor-quality binders—PG64-16 and the formulated PG64-22 and PG64-28—exhibited significantly lower CT_{Index} values compared to the other four mixtures.

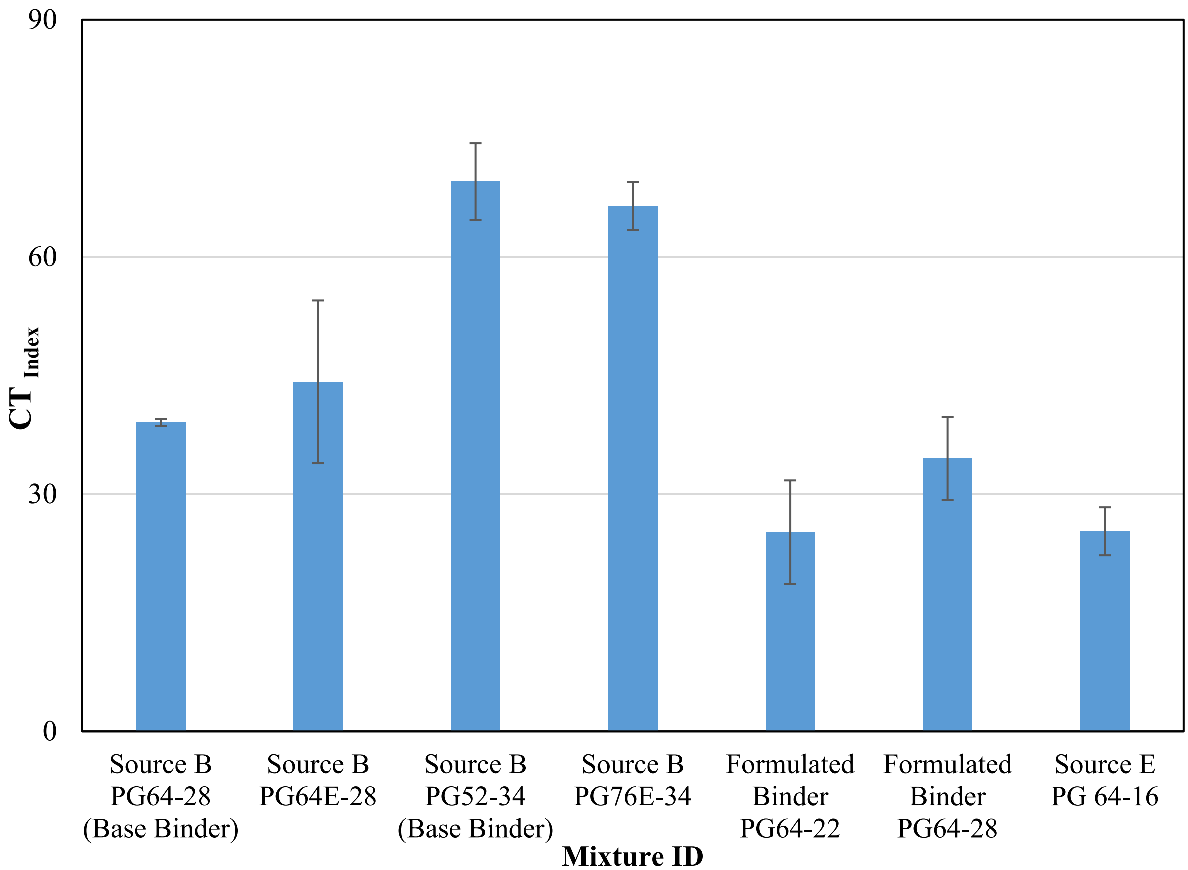


Figure 7.2 - IDEAL-CT results of the seven selected asphalt mixtures.

This outcome validates the selection of G-R at 15°C and 10 rad/s, along with either phase angle at a modulus of 10 MPa (δ_{10MPa}) or log G_c as the key point and shape rheological parameters for identifying poor-quality asphalt binders in terms of their resistance to intermediate temperature cracking. Notably, these combined parameters accurately ranked the poor-performing binders relative to the others. Furthermore, they identified PG52-34 and PG76E-34 as the two best-performing binders among the seven tested, aligning with the IDEAL-CT results and further supporting the validity of these parameters.

8.0 Developing a Simple and Rapid Test to Measure the Selected Point and Shape Parameters

The selected rheological parameters, G-R at 15°C and 10 rad/s, and either the phase angle at a specific modulus of 10 MPa (δ_{10MPa}) or log G_c, were identified to ensure that the quality of the asphalt binder, particularly regarding intermediate-temperature cracking susceptibility, remains consistent even if the binder source changes for the same PG asphalt binder. The two parameters, point and shape, when used together, effectively identified the three poor-quality binders among the twenty binders tested. However, for these rheological parameters to be efficiently determined and widely adopted, a simple and rapid testing method is essential. "Simple" refers to the possibility of using existing AASHTO and ASTM standard tests, and "rapid" refers to the ability to perform the test in a time frame comparable to running a Dynamic Shear Rheometer (DSR) test for grading an asphalt binder.

8.1 Measurement of the Point Paramter G-R at 15°C and 10 rad/s

The G-R parameter, a point measurement, is directly obtained by performing the AASHTO T 315-22 test, "Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)," using an 8-mm disk at 15°C and 10 rad/s. In this test, the complex shear modulus (G*) and phase angle (δ) are measured, and G-R is calculated using the formula: $G^*(\cos\delta)^2/\sin\delta$. This parameter successfully identified one of the poor-quality binders, PG64-16, at every aging level.

8.2 Measurement of the Shape Paramters δ_{10MPa} and log G_c

The values of phase angle at a specific modulus of 10 MPa (δ_{10MP}) and log G_c were obtained by interpolating data from the master curve analysis. Constructing a master curve typically requires testing in both the DSR and BBR, which can be time-consuming. Alternatively, these parameters can be directly determined by testing the asphalt binder according to the AASHTO T 315-22 standard test method (*10*).

To determine δ_{10MPa}, the complex modulus (G*) and phase angle (δ) are measured at multiple intermediate temperatures and a frequency of 10 rad/s. A polynomial function is then fitted to the log G* versus δ data, and the corresponding phase angle at the specific modulus of 10 MPa (δ_{10MPa}) is calculated using the fitted equation. It is crucial to use the logarithmic value of |G*| for accurate calculation of δ_{10MPa} (*7*). Similarly, using the polynomial function, log G_c can be determined as the modulus corresponding to a δ of 45 degrees. This method offers a rapid and straightforward approach for determining δ_{10MPa} and log G_c, making it practical for routine quality control.
Figure 8.1 illustrates the testing scheme used in this study for one of the twenty asphalt binders evaluated. A polynomial fit was applied to interpolate the values of log |G*| and δ, measured

at temperatures ranging from 22°C to 7°C, with 3°C increments and a frequency of 10 rad/s, to determine δ at the specific modulus of 10 MPa (δ_{10MPa}) and log G_c at a δ of 45 degrees. It should be noted that, to avoid extrapolation beyond the measured range of G*, the binder may need to be tested across a wide temperature range to ensure that a G* value greater than 10 MPa is obtained.

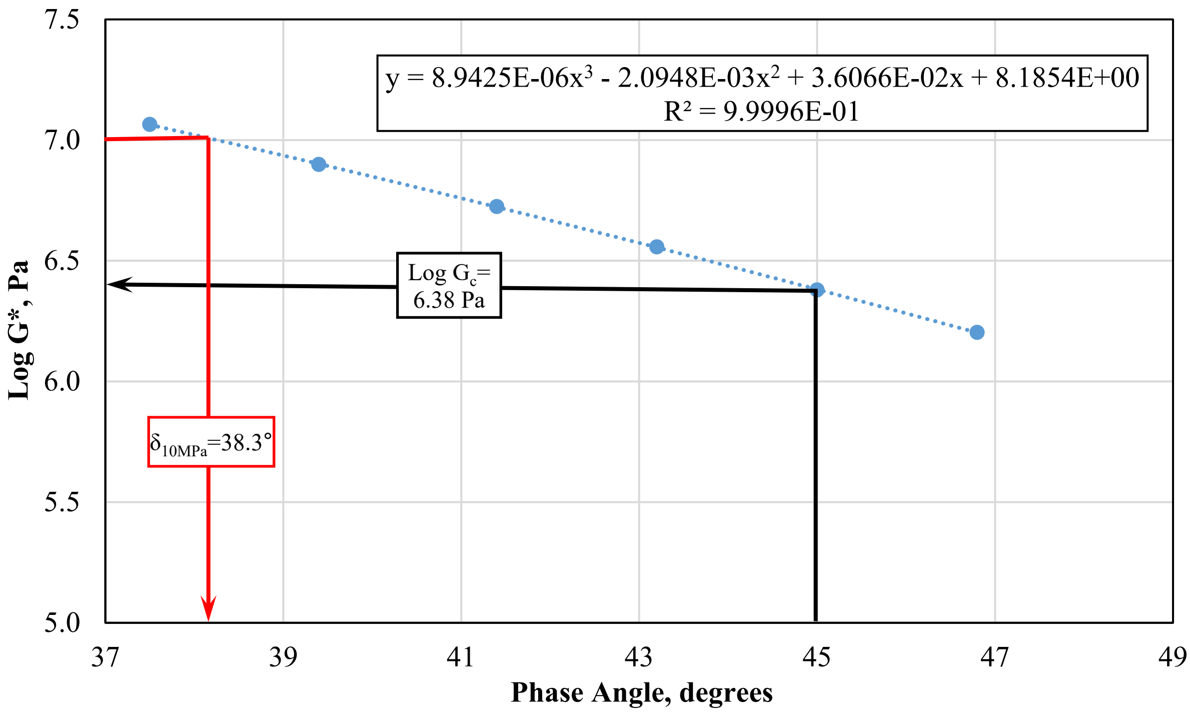


Figure 8.1 - Testing scheme to determine the δ_{10MPa} using a polynomial fit for interpolation.

8.3 Validation of the Simple and Rapid Test

To validate the accuracy and practicality of this simplified and rapid testing scheme, a strong correlation between the δ_{10MPa} values obtained from the simplified procedure and those derived through master curve interpolation for the twenty binders is expected. Similarly, a strong correlation is anticipated between the log G_c values derived from master curve interpolation and those obtained using the simplified method. Figure 8.2 demonstrates this correlation for δ_{10MPa}, showing a high level of agreement between the values calculated by both methods. Figure 8.3 similarly illustrates a strong correlation for log G_c values, indicating consistency across the two approaches.

The alignment of results from these methods suggests that the simplified testing procedure provides reliable and comparable outcomes to the more time-consuming master curve analysis. This strong correlation validates the simplified approach, making it a practical tool for routine quality control of asphalt binders. By eliminating the need for extensive DSR and BBR testing typically required to construct a master curve, the proposed method offers a more efficient and less labor-intensive alternative without compromising accuracy. This makes it particularly advantageous in field or laboratory settings where quick and accurate assessments of binder quality are essential.

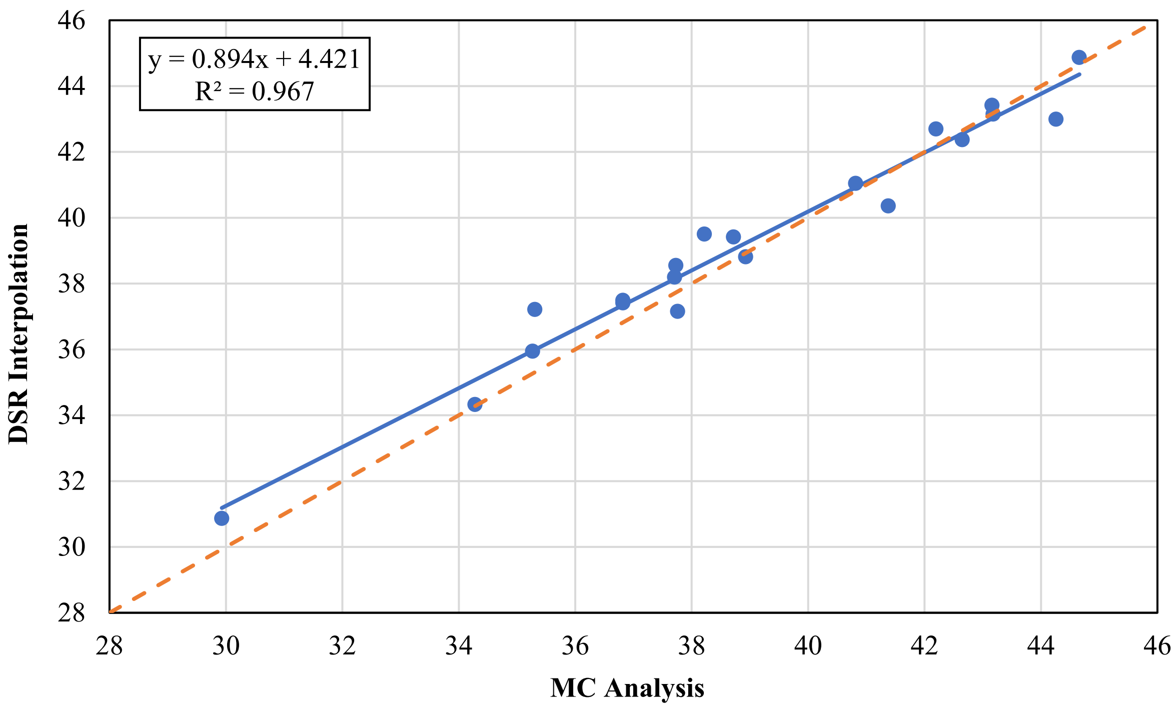


Figure 8.2 - Relationship between δ_{10MPa} determined by interpolating data from the master curve analysis and from direct measurements using the DSR.

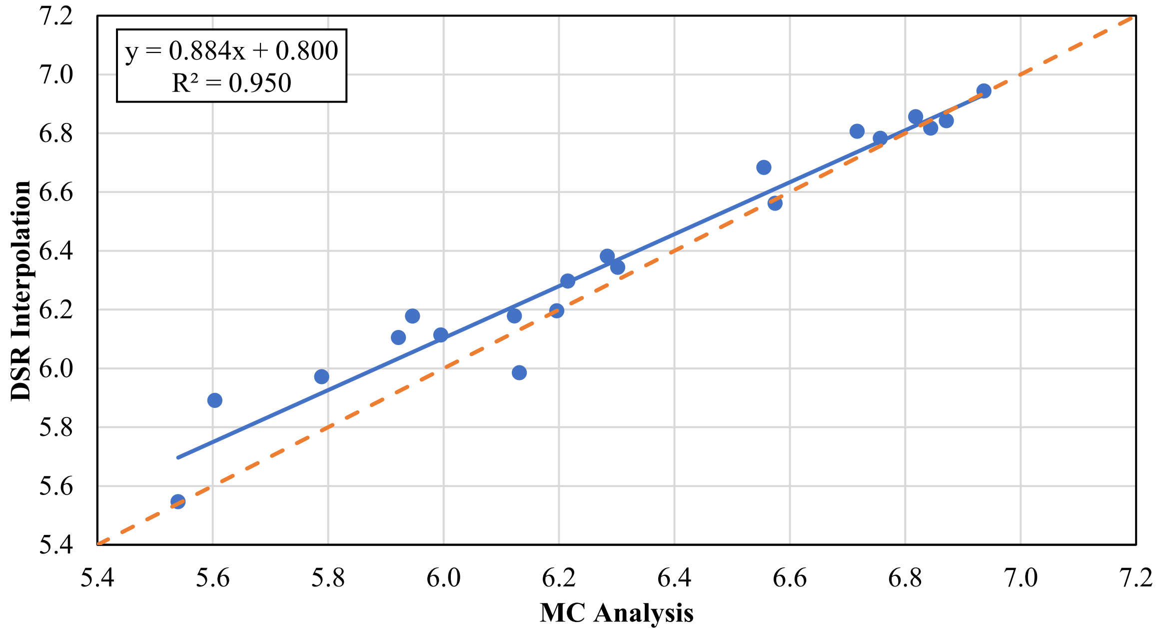


Figure 8.3 - Relationship between log G_c determined by interpolating data from the master curve analysis and from direct measurements using the DSR.

8.3.1 Correlation between δ_{PK} and δ_{10MPa}

As mentioned earlier, the correlation between the phase angle at 10 MPa (δ_{10MPa}) and the original phase angle at 8.967 MPa (δ_{PK}) was assessed to validate the use of 10 MPa as a substitute for 8.967 MPa. Figure 8.4 illustrates the relationship between δ_{PK} and δ_{10MPa}. The results demonstrate that the phase angles at both modulus values are nearly identical, confirming that using 10 MPa provides a practical and accurate representation of the material's behavior.

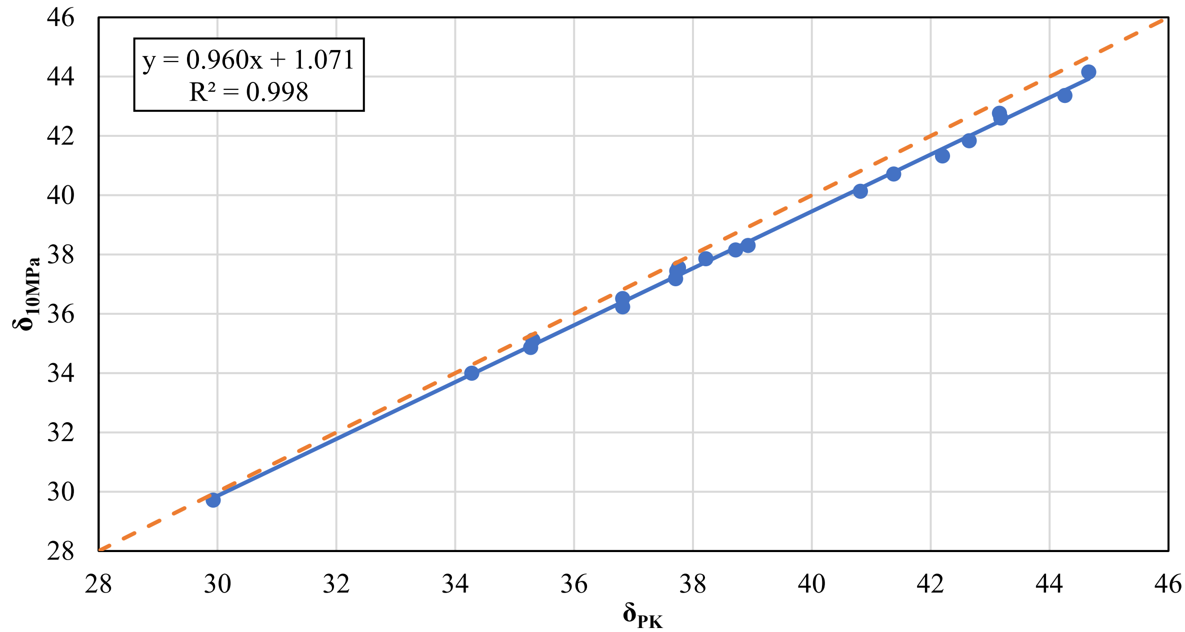


Figure 8.4 - Relationship between phase angle at a modulus of 8.967 MPa (δ_{PK}) and 10MPa (δ_{10MPa}) determined by interpolating data from the master curve analysis of the twenty binders.

8.3.2 Discusion on two shape parameters

Work presented by Rowe (*20*) showed that for complex binders, the value of log G_c value can fall significantly below 6 (1MPa) and thus would not be representative of cracking performance, whereas regardless of modification level the value δ_{10MPa} always produced reasonable values. Thus, based on this work and the fact that the industry is moving to more complex materials it is considered preferable to use δ_{10MPa} rather than the log G_c in a specification approach.

9.0 Conclusions

Baed on this reserch study, the following concuslion were made:

1. AASHTO (2010). Identification of Point and Shape Parameters: The study successfully identified point and shape rheological parameters specifically, Glover-Rowe (G-R) at 15°C and 10 rad/s and the phase angle at a modulus of 10 MPa (δ_{10MPa}) as effective indicators for evaluating asphalt binder quality. These parameters reliably differentiated between low-quality binders (such as PG64-16 and formulated PG64-22 and PG64-28) and high-quality binders (such as PG52-34 and PG76E-34), even when the binder source or formulation changed within the same performance grade. As mentioned above, based on Rowe (*20*), δ_{10MPa} is recommended over log G_c due to its consistency in assessing the quality of complex binders.

2. Validation Using IDEAL-CT Test: The effectiveness of the selected rheological parameters was validated through the Indirect Tensile Asphalt Cracking Test (IDEAL-CT). The CT_{Index} values of the asphalt mixtures correlated well with the binder rankings derived from G-R at 15°C and 10 rad/s and δ_{10MPa}. Hence, based on the IDEAL-CT test results these parameters are reliable predictors of asphalt binder quality in terms of their susceptibility to intermediate-temperature cracking.

3. Development of a Rapid Testing Method: A simplified and rapid method was developed using the dynamic shear rheometer (DSR) to measure G-R at 15°C and 10 rad/s and δ_{10MPa}, bypassing the need for extensive master curve analysis. This approach, utilizing polynomial interpolation of DSR data, demonstrated strong agreement with traditional master curve results. The new method provides an efficient and accurate tool for routine quality control during production, ensuring consistent binder performance and enhanced resistance to intermediate-temperature cracking.

Overall, the combination of G-R and δ_{10MPa} parameters, along with the development of a simplified testing method, offers a practical and efficient framework for evaluating asphalt binder performance in terms of their resistance to intermediate-temperature cracking.

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