Research Article

Statistical Evaluation of the Material-Source Effect on the Ductility and Elastic Recovery (ER) of Plant-Mix Extracted Asphalt-Binders

Lubinda F. Walubita,1 Gilberto Martinez-Arguelles2, Harshavardhan R. Chunduri,1 Jose G. Gonzalez Hernandez,2 and Luis Fuentes2

1TI-AN_The Texas A&M University System, College Station, Texas, USA
2Department of Civil & Environmental Engineering, Universidad del Norte (UniNorte), Barranquilla, Colombia

Correspondence should be addressed to Gilberto Martinez-Arguelles; garguelles@uninorte.edu.co

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This study was conducted to quantitatively and statistically evaluate the effects of material source on the ductility of asphalt-binders, measured in terms of the elastic recovery (ER) property. The ER data used in the study were excerpted from the Texas flexible pavements and overlays database, namely, the Texas Data Storage System (DSS), covering plant-mix extracted PG XX-22 asphalt-binders (i.e., rolling thin film oven (RTFO) residues) from 20 different sources and measured using the Ductilometer test at 10°C. The findings of the study indicated that material source has an impact on the ER property of asphalt-binders. Statistically significant differences were observed among some sources and suppliers that reported the same low-temperature asphalt-binder type/grade (i.e., PG XX-22). Overall, the study contributes to enriching the literature on the material-source effects on asphalt-binders’ ER properties, consistency, variability, and data quality. In particular, the study highlights the sensitivity nature of the asphalt-binder ER parameter to material-source effects.

1. Introduction

Among many other influencing factors, the quality consistency and properties of asphalt-binders are dependent on the production process and, subsequently, the corresponding asphalt-binder sources and suppliers [1–3]. Consequently, different asphalt-binders from different sources and suppliers, even those classified with the same type/grade, may thus exhibit different rheological and viscoelastic properties that have an inherent impact on the resultant hot-mix asphalt (HMA) properties and the overall field performance [3–5]. This is further exacerbated by the current asphalt-binder production methods/processes that have changed significantly, among others, due to technical, economic, and environmental evolutions [6, 7]. Thus, studies oriented towards enhancing the chemical, physical, rheological, and viscoelastic properties of asphalt-binders are paramount [6–9] to optimize the HMA durability and mitigate against premature pavement failures such as cracking [7].

Cracking is one of the major distresses that undesirably reduce the durability and long-term performance of HMA pavements [10, 11]. Asphalt-binder, including type/grade and its volumetric content in the HMA mix, significantly influences the cracking resistance properties of HMA mixes and ultimately the cracking performance in the field [12]. Thus, having good-quality asphalt-binders and adequately characterizing their viscoelastic properties such as ductility and elastic recovery (ER) that are related to cracking performance are imperative [13]. However, as mentioned above, asphalt-binders classified with the same types/grades but obtained from different sources and suppliers could exhibit different viscoelastic properties with different performance impacts on both the resultant HMA mixes and pavements in the field [3], hence the need to study the material-source effects on the asphalt-binders’ ductility and ER properties.
The ductility of asphalt-binders, as measured based on the ASTM D113-17 test standard [14], provides a good indicator for the long-term durability performance of asphalt-binders, allowing for the mitigation against cracking [15]. The literature reports that the ductility of asphalt-binders that recovered from HMA pavements correlates with cracking failure [15]. Some field tests have also indicated that ductility measured at low temperatures is a good indicator of the age-related cracking of asphalt-binders [16]. Additionally, ductility is one of the traditionally used test methods to characterize the asphalt-binder viscoelastic response and one of the primary requirements in the penetration grading specification of asphalt-binders [17]. However, some of the literature reviewed have suggested being cautious when selecting the ductility test loading parameters to ensure that the resultant strain levels are representative and simulative of the loading that typically occurs in the HMA pavement during its service life in the field [18, 19]. Similarly, some literature also advise caution when analyzing and interpreting the ductility results as they contend that ductility is an empirical property in terms of its relationship to the fundamental HMA material properties [20, 21]. Nonetheless, the ductility parameter continues to be used in many countries and is still used to provide a quantitative estimation and approximation of the asphalt-binder’s elastic properties, potential to recover after elongation or when subjected to tensile loading, and the resultant HMA’s cracking resistance potential [3, 20].

The Superpave Performance Grading (PG) system introduced the ER test as one of the methods to assess the asphalt-binder property related to HMA cracking (fatigue) performance [22, 23]. This test evaluates and quantifies the elastic properties of asphalt-binders by measuring the amount of recoverable ability of the asphalt-binder after elasticity deformation. The recovery potential of the asphalt-binder is fundamentally seen as a self-recovery ability of the material, during which the distress level decreases and the performance of the asphalt-binder enhances with recovery time [19].

In general, as the asphalt-binder ages, it loses its ductility and self-recovery properties [19]. By and large, the recovery (ER) properties of asphalt-binders are considered as the fundamental properties for correlation with HMA performance, particularly with respect to cracking [18]. However, the ER test is considered as a subjective test because it depends on an eyeball estimate and great care is needed during handling, pouring, and trimming of the asphalt-binder specimen to ensure reliability of the test data [24].

The ER property of the asphalt-binder is inherently related to its chemical properties such as asphaltenes, resins, and oils that are source-dependent [5, 7, 8, 15, 25]. In this study, a comprehensive statistical analysis was conducted to evaluate and quantify the effects of material source on the ER properties of asphalt-binders. Analysis of Variance (ANOVA) and Tukey’s Honestly Significant Difference (Tukey’s HSD) statistical methods were used to comparatively evaluate up to 20 different sources/suppliers of asphalt-binders covering PG 64-22 and PG 76-22 asphalt-binders, all extracted from plant-mix materials that were directly hauled from field construction sites [26].

In the subsequent sections of the paper, a review of the literature is presented followed by the study matrix plan, test results, statistical analysis, and synthesis of the findings. The paper finally concludes with a summary of key findings and highlights of the research significance along with recommendations for future studies.

2. Literature Review

Many studies have been conducted on the variability and differences in the properties of asphalt-binders and the relation with HMA field performance has been studied by many researchers [2, 4, 5, 27]. However, the literature reviewed is limited with respect to studies on the impacts of different sources and suppliers on the ductility and ER properties of asphalt-binders. Khan et al. [20] used a total of 108 individual ductility tests (AASHTO TS1-09) to measure the ductility properties of 54 asphalt-binders hauled from different construction locations (i.e., sources) in Ontario, Canada. The test results yielded a range of ductility values between 14.3 and 161.3 mm, which evidently represents a large data variability. Reproducibility of the test results showed a coefficient of variation (CoV) of 3.5% and a pooled standard deviation (σp/range) value of 2.9 mm for a single operator test. On the other hand, Alvarez et al. [3] also measured the ductility property of 18 different Pen 60-70 asphalt-binders, all from one refinery supplier in Colombia. Their findings indicated no differences as all the asphalt-binders registered rupture at 148 mm, which was the maximum distance limit of the testing equipment used; thus, the results could not provide any useful information on the variability or reproducibility of the asphalt-binders tested.

Zhang et al. [10, 28] conducted some laboratory studies to measure and characterize the ER properties of plant-mix extracted asphalt-binders relative to the HMA fracture properties as a function of material source. In total, 11 Texas asphalt-binders from different sources and suppliers were comparatively evaluated. The Ductilometer test results at 10°C yielded an ER range of 23% to 49% for PG 64-22 and 59% to 70% for PG 76-22 asphalt-binders, respectively, which clearly presents a huge difference and variability among the different sources, for the asphalt-binders with the same low-temperature grade of –22, i.e., PG XX-22.

2.1. Variability and Asphalt-Binder Source Effects. From the literature reviewed above [1, 3, 10, 28], it can be inferred that asphalt-binders have variability in terms of the rheological and viscoelastic (ER) properties that could be potentially source/supplier related. To further enrich the literature, this study employed statistical methods to evaluate and quantify the material-source effect on the asphalt-binders’ ER property. In particular, the study focused on plant-mix extracted asphalt-binder and the ER parameter measured using the Ductilometer device and covered two commonly used Texas asphalt-binders, namely, PG 64-22 and PG 76-22, from 20 different suppliers. Note that the selected asphalt-
binders in this study presented the same low-temperature grade of −22, i.e., PG XX-22.

2.2. Additives and Plant-Mix Extracted Asphalt-Binders. With asphalt-binders extracted from plant-mix materials as was the case in this study, HMA mix additivities such as recycled asphalt pavement (RAP) and recycled asphalt shingles (RAS) usually tend to stiffen/harden the combined asphalt-binder by increasing the proportion of the aged asphalt-binder in the total asphalt-binder blend [29–31]. This often results in increasing the stiffness of the asphalt-binder blend, which could potentially reduce the ductility (i.e., low ER values) of the asphalt-binder. Thus, in addition to the potential to reduce ductility and ultimately the HMA cracking resistance, these additives also have the potential to impact the consistency and magnitude of the ER parameter of the plant-mix extracted asphalt-binders including the laboratory test ER data variability. Note that the use of RAP/RAS additives in HMA mixes has become a common practice due partly to their economic and environmental benefits [29–31]. However, detailed evaluation of the RAP/RAS effects including chemical and volumetric analysis was outside the scope of this paper as the study’s focus was on the material-source effects.

3. Study Matrix Plan

The study plan is comprised of using the Texas flexible pavements and overlays database, namely, the Texas Data Storage System (DSS), as the primary data source. The DSS, the ductility test, asphalt-binders, and the statistical methods used to analyze the data are discussed subsequently.

3.1. Data Source (the Texas DSS). Maintained in the readily accessible Microsoft Access® platform, the Texas DSS was commissioned in 2010 to serve as an ongoing long-term database for Texas flexible pavements and overlays [26, 32–34]. At the time of writing this paper, the DSS is comprised of 115 in-service highway test sections with comprehensive laboratory and field performance data that includes design, construction, layer material properties (both laboratory and field measured), traffic, climate, existing distresses for overlays, and field performance. The DSS’s extensive material properties include the laboratory measured asphalt-binder ER data from the Ductilometer test, which is the subject of this paper [26, 32].

In addition to the processed and analyzed data (in MS® Access format), the DSS has an accompanying raw data storage system (namely, the Texas RDSS) that contains all the corresponding raw data/files. These raw data, in the RDSS, can be reprocessed and reanalyzed as needed. Full details of the Texas DSS and RDSS can be found in Walubita et al.’s work [26, 32–35].

3.2. The Ductility Test: Elastic Recovery (ER). As per the DSS test plan, the ductility test was performed using a Ductilometer device according to the ASTM 6084 [22] specification on plant-mix extracted asphalt-binders. A centrifugal extraction method with a chlorinated solvent was used for extracting the asphalt-binders from the preheated loose HMA (plant-mix) which were hauled directly from the field construction sites and treated as rolling thin film oven (RTFO) residues [26, 32–34]. Three specimens per asphalt-binder type/grade per source were conditioned in a bath at 10°C (50°F) for about 1 hour prior to testing. After 1-hour 10°C water-bath conditioning, the ductility test was then conducted at a specimen elongation rate of 5 cm/min until a 20 cm fixed elongation was obtained and held in this position for 5 min. Thereafter, the specimens were cut at the midpoint into two halves and left undisturbed in the 10°C water bath for about 1 hour to allow recovery. The ductility test configuration and asphalt-binder specimens before and after testing, as conducted during the DSS study, are shown in Figure 1 [26, 28, 33].

After 1 hour, both halves of the asphalt-binder specimen were carefully (manually) adjusted to touch each other to allow for measurement of the total specimen length. The percentage elastic recovery (ER) was then determined using the following equation [22, 26, 28, 32–34]:

\[
ER = \left( \frac{e - x}{e} \right) \%
\]

In equation (1), ER is the recovered elasticity (%), \(e\) represents the original elongation of the specimen (cm), and \(x\) is defined as the elongation of the specimen (cm), at the completion of the specified recovery time (=1 hour), with the severed ends just touching each other [26, 28, 32–34].

3.3. Materials and Asphalt-Binders. As extracted from the DSS [26], 20 asphalt-binder sources/suppliers covering two commonly used Texas PG XX-22 asphalt-binders (namely, PG 64-22 and PG 76-22) were statistically evaluated. The asphalt-binders, with the suppliers donated as “Source01 thru to Source20” for impartial anonymity, are listed in Table 1.

Note that all the asphalt-binders in Table 1 have the same low-temperature grade, namely, −22, i.e., PG XX-22. Furthermore, 90% of the corresponding HMA mixes are comprised of RAP and/or RAS additives. Therefore, a similar reference datum was assumed for the asphalt-binder sources. However, as previously mentioned, detailed evaluation of the RAP/RAS effects including their age and chemical/volumetric analysis was not in the scope of this paper as the study’s focus was on the material-source effects.

3.4. Statistical Methods Used. For evaluating the data consistency, variability, and differences among the different asphalt-binder sources/suppliers, the following statistical methods were employed:

(i) Standard MS® Excel descriptive statistics such as average (Avg) and CoV for assessing the data consistency, variability, and quality
(ii) ANOVA and Tukey’s HSD analysis for assessing the differences among the sources/suppliers
A CoV threshold of 30% (i.e., CoV $\leq$ 30%) was used in this study as a measure of test data consistency and variability with the following subdesignations as suggested in the literature: (a) CoV $\leq$ 10% (excellent), (b) 10% < CoV $\leq$ 20% (good), (c) 20% < CoV $\leq$ 30% (marginal), and (d) CoV > 30% (poor) [26, 36–38]. For ANOVA and Tukey’s HSD, statistical analyses were performed at the typical 95% confidence level (CL) [26, 39, 40].

4. Laboratory Test Results and Analysis

The following section presents an analysis of the results for 20 plant-mix extracted asphalt-binders (PG XX-22), treated as RTFO residue, from 20 different sources and suppliers. As previously mentioned, all the data used in this study were extracted from the DSS [26, 33]. Note, however, that detailed evaluation of the RAP/RAS effects including chemical analysis was not in the scope of this paper.

4.1. ER Test Results. Table 2 provides a list of the asphalt-binder ER test results. The test results represent a mean of three replicate specimens for each asphalt-binder type/grade extracted from plant-mix materials that were hauled directly from field construction sites [26].

From Table 2, the ER ranges from 17.67% (Source04) to 72.00% (Source18), with a CoV range of 0.01% (Source18) to 27.26% (Source15). Source18 (ER $\geq$ 72.00%) presents the best performance in terms of elastic recovery, while Source04 exhibited the worst performance, that is, lowest ER $\geq$ 17.67%. Source12, Source18, and Source19 exhibited ER values $\geq$ 59% which, according to literature reports [16, 28], might infer to better crack resistance potential and longer fatigue life for the corresponding HMA mixes. From Table 2, it is also noted that the top-most highest ER values were recorded for PG 76-22 asphalt-binders, namely, Source18 (72.00%) and Source19 (65.19%), with ER magnitudes that are almost twice the PG 64-22 sources.
Although within the 30% CoV threshold [26], Source15 (PG 64-22) exhibited more test data variability, with a CoV of 27.26%, that is, rated as marginal variability. By contrast, Table 2 shows that Source18 (PG 76-22) exhibited the best test data consistency, with the smallest CoV value of 0.01%. Given that all the asphalt-binders in Table 1 have the same low-temperature grade (i.e., \(-22\)) with most of them having RAP/RAS additives, the results in Table 2 suggest that material source has a significant effect on the asphalt-binder ER properties and data variability.

4.2. Performance Ranking. The ductility (ER) test is primarily used to evaluate and quantify the recoverability of asphalt-binders after elastic elongation [19]. Theoretically, higher values of the ER (ductility) in asphalt-binders quantitatively represent better cracking resistance potential [10, 28]. With this consideration and based on the ER superiority ranking in Table 2, the best source in terms of potential for cracking resistance is Source18, followed by Source19, both of which are PG 76-22 asphalt-binders. Source04, Source08, and Source09 present the worst performance with the lowest ER values, all of which are PG 64-22 asphalt-binders.

4.3. Data Quality and Consistency. The ER results in Table 2 represent an average of three replicates per source per asphalt-binder type/grade and, thus, permitted the statistical assessment of data variability through CoV analysis, with 30% used as the threshold, i.e., CoV ≤ 30% [26, 38]. The ER results exhibit CoV values lower than 30%, which represents acceptable repeatability and data consistency, partly attributed to good workmanship, proper machine calibration, the use of trained operators, simplicity of the test, etc. [26]. In general, the lower the CoV value, the better the consistency (i.e., lower variability) and data quality. Sources associated with the lowest CoV values are Source18, Source02, and Source05, which represent the best sources in terms of test data consistency and possibly better asphalt-binder quality. In fact, Source18 with PG 76-22, a typically polymer-modified asphalt-binder, ranks top (1st) in terms of consistency and test data quality, i.e., lowest CoV value. On the other hand, Source15, Source03, and Source13 present the highest CoV values but lower than 30% and, thus, acceptable test data consistency and reliability.

According to the ASTM D6084 specification [22], a standard deviation (Stdev) of 0.91% (i.e., Stdev ≤ 0.91%) for a “single-operator precision” and an acceptable range of two test results of 2.6% are recommended for the ER parameter for PG 64-22 asphalt-binders. For PG 76-22, which are often polymer-modified, the thresholds used were Stdev ≤ 0.56 and 1.60% for the acceptability, respectively [22]. Table 3 shows the range of the maximum (Max) and minimum (Min) as well as the corresponding Stdev values.

| Source | Asphalt-binder | ER value (%) | ER ranking | CoV value (%) | CoV ranking |
|--------|----------------|--------------|------------|---------------|-------------|
| Source01 | PG 64-22 | 23.50 | 16 | 2.13 | 5 |
| Source02 | PG 64-22 | 36.67 | 8 | 1.57 | 2 |
| Source03 | PG 64-22 | 27.10 | 12 | 23.78 | 19 |
| Source04 | PG 64-22 | 17.67 | 20 | 14.24 | 16 |
| Source05 | PG 64-22 | 26.79 | 13 | 1.83 | 3 |
| Source06 | PG 64-22 | 27.84 | 11 | 6.27 | 12 |
| Source07 | PG 64-22 | 25.40 | 14 | 2.38 | 7 |
| Source08 | PG 64-22 | 23.01 | 18 | 2.81 | 9 |
| Source09 | PG 64-22 | 21.17 | 19 | 17.32 | 17 |
| Source10 | PG 64-22 | 29.65 | 10 | 7.20 | 13 |
| Source11 | PG 64-22 | 32.04 | 9 | 7.80 | 14 |
| Source12 | PG 64-22 | 59.00 | 3 | 3.39 | 10 |
| Source13 | PG 64-22 | 41.00 | 7 | 18.41 | 18 |
| Source14 | PG 64-22 | 23.49 | 17 | 3.40 | 11 |
| Source15 | PG 64-22 | 24.32 | 15 | 27.26 | 20 |
| Source16 | PG 64-22 | 51.00 | 4 | 1.96 | 4 |
| Source17 | PG 64-22 | 50.00 | 5 | 2.58 | 8 |
| Source18 | PG 76-22 | 72.00 | 1 | 0.01 | 1 |
| Source19 | PG 76-22 | 65.19 | 2 | 2.25 | 6 |
| Source20 | PG 76-22 | 46.14 | 6 | 10.42 | 15 |

CoV: coefficient of variation; ER: elastic recovery; PG: performance-graded; RTFO: rolling thin film oven.
Source19 and Source20. The highest ER range (15.00%) and Stdev (7.55%) recorded are for Source13 (PG 64-22), which ultimately does not meet the ASTM specification [22].

5. Statistical Analysis and Material-Source Effects

Statistical analyses were performed to ascertain if the sources were statistically significantly different (or not) based on the ER parameter. Boxplots, ANOVA analysis, and Tukey’s HSD pairwise comparisons are presented in this section of the paper.

5.1. Boxplots and ER Data. A boxplot is a standardized method of graphically displaying and distinguishing data distribution and detecting outlier presence, for any discrete data set [41]. From Figure 2, it is clearly seen that the true medians differ for all the sources, with ER values between 17% and 72% (on the vertical Y-axis). Source03, Source13, Source15, and Source20 present the greatest variability with wide boxes. Source01, Source02, Source05, and Source18, on the other hand, present the lowest variability with tightly compressed boxes. These observations confirm the CoV results in Table 2. Also, except for Source12, Source18, Source17, Source07, and Source08, most of the sources present an asymmetrical (skewed) distribution of data with large whiskers. Statistically, large whiskers infer to large data dispersion and, consequently, high data variability.

In general, the boxplots in Figure 2 display two statistical representations and interpretations of the data [41, 42]. If the boxes overlap in the vertical orientation, it means that the sources are statistically indistinguishable and vice versa. For instance, Source16 and Source17 are indistinguishable but are statistically different from Source01 and Source18. Narrow boxes and shorter whiskers infer to high data consistency and low variability, and vice versa [41, 42]. Thus, Source01 exhibits better data consistency than Source13. Similarly, while Source01 and Source18 are both associated with high data consistency and quality, they are statistically significantly different in terms of the ER magnitude.

5.2. ANOVA and Tukey’s HSD. ANOVA was performed using an open-source statistical software R [43] at 95% CL (i.e., \( \alpha = 0.05 \) for 95% CL) in terms of the \( p \) values. Interpretively, if \( p \) value is less than \( \alpha \), that is, \( p \) value < 0.05, then there might be some potential statistical differences among the sources/suppliers with respect to that particular parameter and vice versa [39]. Similarly, if the \( F \) value is greater than the critical \( F \), then there is a significant statistical difference among the sources. The results of ANOVA analysis are summarized in Table 4.

From Table 4, the statistical \( F \) value of 72.0668 is significantly higher than the critical \( F \) of 1.8529, hence confirming that there are statistically significant differences among the sources [39]. Table 4 also shows a probability value (\( p \) value) of 5.139\( \times 10^{-25} \), which is considerably lower than the 0.05 significance level, meaning that, at 95% CL, there is at least one source among the 20 sources that could be statistically different from the others.

Although the ANOVA analysis provides a first insight into the statistical differences on a whole population among the asphalt-binder sources, it cannot provide exactly where

| Source | Asphalt-binder | Min ER | Max ER | Range | Standard deviation (stdev) |
|--------|----------------|-------|--------|-------|---------------------------|
| Source01 | PG 64-22 | 23.00% | 24.00% | 1.00% | 0.50% |
| Source02 | PG 64-22 | 36.00% | 37.00% | 1.00% | 0.50% |
| Source03 | PG 64-22 | 20.00% | 21.50% | 1.50% | 0.75% |
| Source04 | PG 64-22 | 15.00% | 20.00% | 5.00% | 2.52% |
| Source05 | PG 64-22 | 26.36% | 27.33% | 0.97% | 0.49% |
| Source06 | PG 64-22 | 26.04% | 29.53% | 3.49% | 1.75% |
| Source07 | PG 64-22 | 24.80% | 26.01% | 1.21% | 0.61% |
| Source08 | PG 64-22 | 22.34% | 23.63% | 1.29% | 0.65% |
| Source09 | PG 64-22 | 19.05% | 25.40% | 6.35% | 3.67% |
| Source10 | PG 64-22 | 27.19% | 31.02% | 3.83% | 2.14% |
| Source11 | PG 64-22 | 29.15% | 33.48% | 4.33% | 2.50% |
| Source12 | PG 64-22 | 57.00% | 61.00% | 4.00% | 2.00% |
| Source13 | PG 64-22 | 34.00% | 49.00% | 15.00% | 7.55% |
| Source14 | PG 64-22 | 22.91% | 24.40% | 1.49% | 0.80% |
| Source15 | PG 64-22 | 19.00% | 31.75% | 12.75% | 6.63% |
| Source16 | PG 64-22 | 50.00% | 52.00% | 2.00% | 1.00% |
| Source17 | PG 64-22 | 48.71% | 51.29% | 2.58% | 1.29% |
| Source18 | PG 76-22 | 72.00% | 72.00% | 0.00% | 0.00% |
| Source19 | PG 76-22 | 63.50% | 66.04% | 2.54% | 1.47% |
| Source20 | PG 76-22 | 40.64% | 49.53% | 8.89% | 4.81% |

Threshold [22] =

| Test temperature = 10°C, elongation rate = 5 cm/min |
|--------------------------------------------------|
| RTFO residue | Min ER | Max ER | Range | Standard deviation (stdev) |
|----------------|-------|--------|-------|---------------------------|
| PG 64-22 ≤ 2.60% | Source01 | 23.00% | 24.00% | 1.00% | 0.50% |
| PG 76-22 ≤ 1.60% | Source03 | 20.00% | 21.50% | 1.50% | 0.75% |
| PG 64-22 ≤ 0.91% | Source04 | 15.00% | 20.00% | 5.00% | 2.52% |
| PG 76-22 ≤ 0.56% | Source05 | 26.36% | 27.33% | 0.97% | 0.49% |

PG: performance-graded; ER: elastic recovery; CoV: coefficient of variation; Max: maximum; Min: minimum; numbers in red text: did not meet ASTM D6084 specification [17].

PG: performance-graded; ER: elastic recovery; CoV: coefficient of variation; Max: maximum; Min: minimum; numbers in red text: did not meet ASTM D6084 specification [17].
the differences are. Hence, a Tukey Post Hoc Test (HSD) was also conducted to check which specific sources are different. This test is a statistical tool used to determine if the relationship between two sets of data is statistically significant by building confidence intervals with an α level of significance for all possible pairwise comparisons based on the following hypotheses [27]:

\[ H_0: \mu_i = \mu_j, \text{ versus } H_1: \mu_i \neq \mu_j, \tag{2} \]

where \( H_0 \) is the null hypothesis and \( H_1 \) is the alternative hypothesis. A “True-False” methodology was proposed to denote that the differences in the ER results between each pair of the asphalt-binder source were high enough to be considered statistically different at a 95% CL. These True-False results are listed in Table 5, where “True” means that the paired sources are statistically significantly different and vice versa for “False,” that is, similar.

For the 190 possible source-pairs, 50% (95 source-pairs) were statistically different (i.e., “True” response in Table 5). Source18 presents the major statistical differences from other sources, with 18 “True” responses and just one “False” response, followed by Source12, Source17, and Source19, with statistical differences between 16 and 17 sources (i.e., 16 and 17 “True” responses). On the other hand, Source03 and Source 05 show the least “True” responses, with statistical differences for seven sources (i.e., seven “True” responses) and 12 “False” responses, which means a statistical indifference with 12 sources.

Overall, Table 5 illustrates the variability of the ER test data among the different sources. Ultimately, this indicates the sensitivity nature of the ER parameter to material-source effects for plant-mix extracted asphalt-binders, that is, RTFO residues.

### 6. Synthesis and Discussion of the Results

Figure 3 shows the graphical spreads associated with the asphalt-binder sources in terms of the ER parameter and data variability (CoV). The figure comprises a mean value for each source and the overall average (Avg) incorporating all the 20 asphalt-binder sources.

From Figure 3(a), the ER values range from about 17% to 75%, with only three sources (i.e., Source12, Source18, and Source19) meeting the ER ≥ 59.00% threshold for cracking resistance potential of the corresponding HMA mix [10, 28]. The overall average ER is 36.15%. Twelve out of 20 sources fall below the average value. In terms of the asphalt-binder comparisons, Source18 and Source19, which are all PG 76-22 asphalt-binders, exhibited the highest values, as theoretically expected. The lowest ER value at 17.67% was recorded for PG 64-22 from Source04. Apparently, all the HMA mixes associated with PG 64-22 asphalt-binders were comprised of RAP and RAS additives; see Table 1. Therefore, it is possible that these additives contributed to the low ER values of some PG 64-22 asphalt-binders such as Source04, which may not have been the case for Source12, Source16, and Source17 that exhibit ER values around 50% and ranked in the 3th, 4rd, and 5th positions in terms of performance superiority (Table 2).

Among the 20 asphalt-binder sources evaluated in this study, only Source08 (PG 64-22), Source18 (PG 76-22), and Source20 (PG 76-22) had no RAP additive. However, Source08 had 3% RAS, while Source18 and Source20 both had 1% of lime. Based on the results presented in Sections 4 and 5 of this paper, it was verified that asphalt-binders classified as PG 76-22 provided the overall highest ER values, ranging between 46.14% and 72%, respectively. In the case of Source20, it should be highlighted that it presented the lowest ER value among the PG 76-22 asphalt-binders tested and also yielded the highest CoV (10.42%) value, that is, had the highest variability. This could have been probably due to the presence of cellulose fibers that may have chemically interacted with the chlorinated solvent during the extraction process, thus impacting the ER results, in terms of both the ER magnitude and data variability [44, 45].

In analyzing the PG 64-22 asphalt-binders, an average of 31.74% ER value was obtained, which represents almost half the average ER value (61.11%) of the PG 76-22 asphalt-binders. This may be explained from a rheological point of view. PG 64-22 is two high-temperature grades below PG 76-22 in terms of rutting performance but at the same low-temperature grade of ~22. This means that both asphalt-binders are theoretically expected to have the same response behavior in terms of controlling low-temperature cracking at
Table 5: Tukey HSD results (True-False) @ 95%CL.

| S-P | T-F | S-P | T-F | S-P | T-F | S-P | T-F | S-P | T-F |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| S10| #S11| False | S13| #S11| False | S20| #S13| False | S19| #S16| True | S8| #S19| True |
| S11| #S11| False | S14| #S11| False | S20| #S13| False | S20| #S16| False | S20| #S2| False |
| S12| #S11| True | S15| #S11| False | S3| #S13| True | S20| #S16| False | S20| #S2| False |
| S1| #S11| True | S16| #S11| True | S4| #S13| True | S3| #S16| True | S3| #S2| False |
| S14| #S11| False | S17| #S11| True | S5| #S13| True | S4| #S16| True | S4| #S2| False |
| S15| #S11| False | S18| #S11| True | S6| #S13| True | S5| #S16| True | S5| #S2| False |
| S16| #S11| True | S19| #S11| True | S7| #S13| True | S6| #S16| True | S6| #S2| False |
| S17| #S11| True | S2| #S11| False | S8| #S13| True | S7| #S16| True | S7| #S2| True |
| S18| #S11| True | S20| #S11| True | S9| #S13| True | S8| #S16| True | S8| #S2| True |
| S19| #S11| True | S3| #S11| False | S15| #S14| False | S9| #S16| True | S9| #S2| True |
| S2| #S11| False | S4| #S11| False | S16| #S14| True | S18| #S17| True | S3| #S20| True |
| S20| #S11| True | S5| #S11| False | S17| #S14| True | S19| #S17| True | S4| #S20| True |
| S3| #S11| False | S6| #S11| False | S18| #S14| True | S3| #S17| True | S5| #S20| True |
| S4| #S11| False | S7| #S11| False | S19| #S14| True | S20| #S17| False | S6| #S20| True |
| S5| #S11| False | S8| #S11| False | S2| #S14| False | S3| #S17| True | S3| #S20| True |
| S7| #S11| False | S9| #S11| True | S20| #S14| True | S4| #S17| True | S8| #S20| True |
| S8| #S11| False | S14| #S12| True | S4| #S14| False | S6| #S17| True | S4| #S3| False |
| S9| #S11| False | S15| #S12| True | S5| #S14| False | S7| #S17| True | S5| #S3| False |
| S11| #S10| False | S16| #S12| False | S6| #S14| False | S8| #S17| True | S6| #S3| False |
| S12| #S10| True | S17| #S12| False | S7| #S14| False | S9| #S17| True | S7| #S3| False |
| S13| #S10| True | S18| #S12| True | S8| #S14| False | S19| #S18| True | S8| #S3| False |
| S14| #S10| False | S19| #S12| False | S9| #S14| False | S20| #S18| True | S9| #S3| False |
| S15| #S10| False | S2| #S12| True | S16| #S15| True | S20| #S18| True | S5| #S4| False |
| S16| #S10| True | S20| #S12| True | S17| #S15| True | S3| #S18| True | S6| #S4| True |
| S17| #S10| True | S3| #S12| True | S18| #S15| True | S4| #S18| True | S7| #S4| False |
| S18| #S10| True | S4| #S12| True | S19| #S15| True | S5| #S18| True | S8| #S4| False |
| S19| #S10| True | S5| #S12| True | S2| #S15| True | S6| #S18| True | S9| #S4| False |
| S2| #S10| False | S6| #S12| True | S20| #S15| True | S7| #S18| True | S6| #S5| False |
| S20| #S10| True | S7| #S12| True | S3| #S15| False | S6| #S18| True | S7| #S5| False |
| S3| #S10| False | S8| #S12| True | S4| #S15| False | S9| #S18| True | S8| #S5| False |
| S4| #S10| False | S9| #S12| True | S5| #S15| False | S2| #S19| True | S9| #S5| False |
| S5| #S10| False | S14| #S13| True | S6| #S15| False | S20| #S19| True | S5| #S6| False |
| S6| #S10| False | S15| #S13| True | S7| #S15| False | S3| #S19| True | S8| #S6| False |
| S7| #S10| False | S16| #S13| True | S8| #S15| False | S4| #S19| True | S9| #S6| False |
| S8| #S10| False | S17| #S13| False | S9| #S15| False | S5| #S19| True | S8| #S7| False |
| S9| #S10| False | S18| #S13| True | S17| #S16| False | S6| #S19| True | S9| #S7| False |
| S12| #S11| True | S19| #S13| True | S18| #S16| True | S7| #S19| True | S9| #S8| False |

S-P: source-pair; T-F: True-False; S4#S1: Source04 is not similar to Source01; True: the paired sources are statistically significantly different; False: the paired sources are statistically indifferent (i.e., similar).

Figure 3: ER-CoV graphical plots.

(a) ER (%) vs No. of data points (sources)
(b) CoV (%) vs No. of data points (sources)
−22°C no matter the high-temperature asphalt-binder grade. However, their ER response behavior, as evident in Table 2 and Figure 3, was different in terms of their quantitative magnitudes. This could be partially explained by the fact that PG grades higher than 70°C typically incorporate some type of modifiers, that is, modified. In fact, PG asphalt-binders that differ in the high- and low-temperature specification by 90°C or more generally require some sort of modification [46].

On the other hand, among the 17 PG 64-22 asphalt-binder sources evaluated, only three sources (namely, Source12, Source16, and Source17) had ER values exceeding 50%. Similarly, three other sources (namely, Source02, Source11, and Source13) had their ER values ranging between 30% and 50%, respectively. The possible reasons for these variations include the following assumptions: (i) in spite of 16 out of 17 PG 64-22 sources containing RAP and/or RAS with an almost similar content, the RAP and RAS came from different sources; (ii) the asphalt-binders from RAP/RAS mixes may have had different levels of aging and residual asphalt-binder concentration; and (iii) depending on the asphalt-binder source (chemical composition) and RAP/RAS type, there might have been different degrees of blending during the HMA production process, aspects which could have impacted the ER data variability. To verify these assumptions, further physical and chemical testing including SARA (i.e., Saturate, Aromatic, Resin, and Asphaltene) fractional analyses and RAP/RAS evaluations are recommended [47, 48]. However, as previously mentioned, detailed evaluation of the RAP/RAS effects nor the SARA fractional analysis was not in the scope of this paper.

In terms of the ER data variability, Figure 3(b) showed a range of CoV values between 0.00% and 30.00%, indicating an excellent to marginal data consistency with none exceeding the 30% threshold [26, 33]. An average CoV value of 7.85% was obtained and 14 out of 20 sources present excellent data consistency below this average [47]. Four sources present good data consistency (i.e., 10% < CoV ≤ 20%) and only two sources exhibited marginal data consistency (i.e., 20% < CoV ≤ 30%) [20, 26, 28, 33].

7. Conclusions and Recommendations

This study was conducted to evaluate and statistically quantify the effects of the material sources on the ER property of short-term aged asphalt-binders (treated as RTFO residue) that were extracted from plant-mix materials. The ER data were excerpted from the Texas DSS based on Ductilometer measurements for PG XX-22 asphalt-binders (namely, PG 64-22 and PG 76-22) from 20 different sources/suppliers. The study findings and recommendations are summarized as follows:

(i) The ER test was able to detect variability in the asphalt-binders classified with the same low-temperature grade of −22, that is, PG XX-22.

(ii) The ER values for the PG XX-22 asphalt-binders ranged from 17.67% to 72.00%. PG 76-22 asphalt-binders presented the highest ER values with quantitative differences that were almost twice PG 64-22. These higher ER values for PG 76-22 also suggest that the ER parameter has the potential to identify the presence of polymer modifiers. However, only three of the sources evaluated exhibited ER values ≥ 59%, which infers to better crack resistance potential and longer fatigue life for the corresponding HMA mixes.

(iii) Source18 (PG 76-22) was top ranked with the highest ER value and best potential for cracking resistance, followed by Source19 (also PG 76-22). Source04, Source08, and Source09 (all PG 64-22) presented the lowest performance ranking. Material improvements including quality for ER improvements are recommended for these lowly ranked sources such as Source04.

(iv) A CoV range of 0.01% to 27.26% was obtained, representing excellent to marginal ER data consistency (i.e., CoV ≤ 30%). Source15 (PG 64-22 with RAP/RAS additives) presented more test data variability (i.e., CoV = 27.26%), while Source18 (PG 76-22 without RAP/RAS additives) exhibited the best test data consistency with a CoV of 0.01%. Material quality and consistency improvements are recommended for Source15 and Source03.

(v) material quality and ER test data variability, Source18, Source02, and Source05 were the best sources in terms of test data consistency and possibly asphalt-binder quality with the lowest CoV values. Source15, Source03, and Source13 presented the highest values of CoV but lower than 30% and, thus, acceptable test data consistency and reliability.

(vi) The boxplots showed that the true medians differed for all the sources with values between 17% and 72%. Source03, Source13, and Source15 (all PG 64-22) presented the greatest data variability with wide boxes and longer whiskers. Source18, Source02, and Source05, on the other hand, presented the lowest variability with tightly compressed boxes and shorter whiskers. In general, most of the sources presented an asymmetrical ER data distribution with large whiskers but no outliers.

(vii) ANOVA analysis indicated some statistical differences among the sources, while Tukey’s HSD indicated a large variability between some specific sources. Source18 (PG 76-22), which yielded the highest ER value and best data consistency (lowest CoV value), presented the greatest statistical difference from the other sources. Thus, Source18 would be the preferred choice for having superior and quality materials and vice versa for Source03, Source04, and Source15. Recommendations would be to improve both the material superiority and
quality through, among others, enhancing their production and quality-control processes for these sources.

Overall, the study highlighted the sensitivity nature of the ER parameter with respect to evaluating the effects of material sources and suppliers on the plant-mix extracted asphalt-binders’ ER properties based on Ductilometer measurements. The test results and findings confirmed that material source has an impact on the ER property of asphalt-binders. From the study findings, it can also be concluded that one has to be cautious of the material-source effect on the rheological properties, grading, and, ultimately, the performance of the asphalt-binders. The study also suggests that, in as much as performance superiority (and costs of course) is a very crucial issue in deciding the asphalt-binder source and supplier, consistency and quality aspects cannot be ignored. That is, in addition to cost considerations, material-source effect should be holistically viewed and assessed from both performance (rheological properties) and quality (consistence) perspectives.

8. Research Significance and Future Studies

This study has yielded technically informative data related to asphalt-binders extracted from plant-mix materials (i.e., RTFO residue) as a function of material-source effects. More studies of this nature are recommended to further supplement and substantiate the results and findings reported herein. These types of studies are fundamental in trying to understand the field performance of asphalt-binders and the resultant HMA mixes considering the material-source effects. Quite often asphalt-binders of the same type/grade may behave differently, displaying markedly different aging characteristics, water or stripping susceptibilities, fatigue resistance, low-temperature strength, flexibility, etc. That is, although asphalt-binders from different sources and suppliers may register the same type/grade classification, it should not always be assumed that they would automatically exhibit exactly the same response behavior and performance. Depending on the source and supplier, some performance differences may exist even though it is the same asphalt-binder type/grade classification. Thus, studies of this nature are imperative to distinctively and quantitatively characterize the ductility and ER response behavior of asphalt-binders from different sources and suppliers, even though they may be having the same low-temperature grade.

Overall, the study contributes to enriching the literature on the material-source effects on asphalt-binders’ ER properties, consistency, variability, and data quality. In particular, the study highlights the sensitivity nature of the asphalt-binder ER parameter to material-source effects. However, the population size was limited to 20 different Texas asphalt-binder sources and suppliers for PG 64-22 and PG 76-22 asphalt-binders. Therefore, future follow-up studies should cover more sources/suppliers and asphalt-binder types/grades. In addition, the study approach could include a detailed evaluation of the RAP/RAS effects including chemical and volumetric analysis which were not in the scope of this paper. Laboratory tests covering physical, rheological, and chemical tests such as viscosity, penetration, ring and ball, fatigue performance, the multiple stress creep-recovery (MSCR), and SARA (Saturate, Aromatic, Resin, and Asphaltene) fractions could also be conducted to supplement these findings. Other aspects for future studies could also include a comparative documentation of the production processes and quality-control practices engaged by at the different asphalt-binder sources and suppliers evaluated in this study.

Data Availability

All data used to support the findings of this study are available from the corresponding author upon request.

Disclosure

The contents of this paper, which do not constitute a standard, reflect the views of the authors who are solely responsible for the facts and accuracy of the data presented herein and do not necessarily reflect the official views or policies of any agency or institute.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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