Rheological properties of RAP binder extracted from RAP aggregates of different sizes

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ABSTRACT: Reclaimed Asphalt Pavement (RAP) obtained from milling bituminous layers consists of aggregate and aged binder. Fractionating RAP into different fractions facilitates better control over the binder content, rheological properties of RAP binder and aggregate gradation. Existing research shows that the binder content varies across fractions with coarser fractions having lower binder content and the finer fractions containing higher binder content. However, a detailed understanding on the extent of variation in rheological properties across such fractions is necessary. In this study, RAP was separated into three fractions namely: coarse, medium and fine. The binder was extracted and recovered from each fraction. All the recovered binders were subjected to a systematic rheological characterization. The results indicate the manner in which the binder ages and how its subsequent rheological properties vary for individual fractions of RAP. In most cases, the RAP binder from coarse fraction was found to exhibit higher stiffness when compared to the other fractions. Also, the temperature susceptibility of the binder fractions is observed to be different with the Medium RAP binder exhibiting a higher temperature sensitivity.

1 INTRODUCTION

Reclaimed Asphalt Pavement (RAP) is the material obtained from milling existing pavement layers, comprising aggregates and aged binder. It serves as an essential component in sustainable pavement construction due to its environmental and economic advantages. Using RAP helps reduce emissions and minimizes the reliance on raw materials. To ensure homogeneity of RAP feedstock, Mangiafico et al. (2016) suggested classifying RAP into different sizes. Fractioning RAP stockpiles into coarse and fine fractions has been shown to provide better control of the aggregate gradation and binder content (West at al. 2015). Such separation is also expected to improve the consistency of the recycled mix, as fractionation enhances the ability to achieve the desired gradation (Stroup Gardiner et al. 1999, West et al. 2013).

Studies suggest that the RAP binder content in different RAP fractions is not uniform (Stroup-Gardiner et al. 1999, Kaseer et al. 2019). Stroup-Gardiner et al. (1999), showed that the RAP binder content was typically lower in the coarse fractions (1.2 mm above) compared to the entire stockpile. This is expected as coarser aggregate particles have a smaller surface area per unit weight, leading to a reduced binder coating. Conversely, finer fractions contain more binder due to their larger surface area. Thus, the binder content present in different fractions of RAP is expected to be different and reduces with increase in the surface area of the aggregates.

In addition to the quantity of binder, the properties of the binder are also expected to vary in the different RAP fractions (Kaseer et al. 2019). Typically, binder extracted from fine RAP is observed to exhibit a higher PG value when compared to that extracted from a coarse RAP. These differences are reported to be of the order of 2°C to 6°C for different types of RAP (West et al. 2013). The same study has reported that, for certain cases, the binder extracted from coarse RAP exhibited a higher PG value. The differences can be attributed to the type of mix and extent of aging. Most of the current studies have evaluated the specification-based parameters such as PG values for different fractions of RAP. Evaluation of their rheological properties is expected to provide further insights facilitating an understanding of why such differences are possibly observed. This paper aims to evaluate the rheological response of binders extracted and recovered from different RAP fractions against that obtained from full RAP.

A RAP stockpile was identified and the RAP was processed. The processed RAP was separated into coarse, medium and fine fractions. The binder was

extracted and recovered from separated RAP fractions and the full RAP. The softening point was measured for the four binders. Additionally, continuous high and intermediate temperature PG values were measured and a frequency sweep test was performed to estimate its rheological response.

2 EXPERIMENTAL INVESTIGATION

2.1 *Materials*

A RAP stockpile obtained from a National Highway in India was selected for this study. The stockpile corresponds to RAP milled from the surface layer of the existing pavement which is a Bituminous Concrete, grade II mix, as per Indian guidelines (MoRTH, 2013). Since the nominal maximum aggregate size as per this gradation is 13.2 mm, particles larger than 19 mm were considered as agglomerated aggregate particles. The RAP was sieved using a 26.5 mm IS sieve to remove such agglomerated particles. It was then processed in a twin shaft pug mill at 100 rpm for 20 minutes to de-bond the particles. The processed RAP was then separated into three fractions. Materials passing 19 mm and retained on 4.75 mm sieve were considered as Coarse; materials passing 4.75 mm and retained on 1.18 mm sieve were considered as Medium; materials passing 1.18 mm were considered as Fine. It is to be noted that there is no specific guideline on the sieve sizes to be adopted for such gradations and hence the sieve sizes demarcating individual fractions were chosen independently in this study.

2.2 *Binder extraction and recovery*

After separating the three fractions, the RAP binder was extracted and recovered from the three fractions and the full mix. The extraction process was carried out using a centrifuge extractor following the guidelines of ASTM D2172 (2024). N-Propyl bromide was used as the solvent for the extraction process. The bitumen-solvent extract was then filtered and recovered following the guidelines of ASTM D5404 (2021). The recovered binders were subjected to short-term aging using rolling thin film oven based on the procedure mentioned in ASTM D2872 (2022). This step was performed to remove traces of solvent, if any, based on the guidelines provided in Asphalt Institute-MS2 (AI MS2, 2014).

To characterize the rheological properties of recovered RAP binders, the following tests were performed on the four binders: Softening point test, High temperature and intermediate temperature performance grading and frequency sweep test.

2.3 *Binder content*

The binder content of the full RAP and three distinct RAP fractions were determined using the Ignition oven method following the guidelines of ASTM D6307 (2019). Softening point test was carried out on these four binders as per ASTM D36 (2006). The results are shown in Table 1.

Table 1. Basic Properties of RAP fractions

Binder	Binder content %	Softening Point °C
Full RAP	4.49	82.7
Coarse RAP	2.85	85.6
Medium RAP	3.86	81
Fine RAP	6.81	78.8

From Table 1 it can be observed that the binder content exhibits a similar pattern as mentioned by Stroup Gardiner et al. (1999). The binder content reduces with increase in size of RAP aggregates. The binder content in Full RAP falls between that of the medium and Fine RAP with the values closer to that of Medium RAP. Table 1 shows that the Coarse RAP binder exhibits the highest softening point and the Fine RAP binder exhibits the least softening point. The softening point values of Full and Medium RAP binders are comparable with a marginally higher value for Full RAP binder.

2.4 *Performance Grading*

The high temperature PG grade is determined based on the values of $|G^*|/Sin\ \delta$, set at 1.0 kPa for unaged binders and 2.2 kPa for binders subjected to short-term aging. The recovered RAP binders were tested for continuous high temperature PG for RTFO aged condition. It is the temperature at which $|G^*|/Sin\ \delta$ is 2.2 kPa as per the specifications given in ASTM D6373 (2023) when tested based on the test procedure specified in ASTM D7175 (2023). For the intermediate temperature PG, the fatigue parameter, $|G^*| \times Sin\ \delta$ is used to assess the binder performance. The continuous intermediate temperature PG of the four binders was also determined as per the specifications given in ASTM D6373 (2023) for the RTFO aged binders.

2.5 *Frequency sweep test*

To evaluate the frequency dependency of RAP binders, a frequency sweep test was conducted within the linear viscoelastic (LVE) region. In order to find the LVE limit, amplitude sweep test was conducted at highest frequency and lowest temperature. In this study, amplitude sweep was performed at 50 Hz and

40°C. The LVE limit was found to be 0.3% as per the procedure specified in ASTM D7175 (2023). Hence 0.1% strain was considered for the frequency test. The frequency sweep test was conducted at temperatures from 40°C to 80°C in intervals of 10°C. The frequency was varied from 50 Hz to 0.1 Hz. In this frequency range, 23 different frequencies were chosen for the test with data collected for every 5 seconds.

3 RESULTS AND DISCUSSION

3.1 *PG Values*

The continuous high temperature PG value for the four binders is shown in Table 2 and it is seen that this value is lower for Fine RAP binder when compared to the other binders. The values for Coarse and Medium RAP binders are closer. With 5% variability, all the continuous high temperature PG values are considered to be similar but if the individual PG grades are considered, the high temperature grade of Medium RAP binder could be a higher grade when compared to the other three RAP binders.

Table 2. PG values of binders

Binder	Continuous high temperature PG (°C)	Continuous intermediate temperature PG (°C)
Full RAP	104.5	32.7
Coarse RAP	105.2	29.5
Medium RAP	106.1	28.9
Fine RAP	101.2	31

The continuous intermediate temperature PG values are also shown in Table 2. Here, the Full and Fine RAP binder are observed to have similar values, whereas the values for Coarse and Medium RAP binders are similar. It is interesting to note that the Medium RAP binder exhibits the highest continuous high temperature and lowest continuous intermediate temperature PG values. However, the binder extracted from Fine RAP exhibits the reverse trend with lower "stiffness" at high temperature and higher "stiffness" at low temperature. This highlights the difference in aging characteristics of binders present in different RAP fractions. Also, it is observed that the continuous intermediate and high temperature PG of the Full RAP binder is dictated by the PG of Fine RAP binder and Coarse RAP binder respectively (Table 2).

3.2 *Frequency sweep*

The variation of absolute shear modulus with frequency, for tests performed at 40 and 80 °C are shown in Figures 1 and 2. At all temperatures, the absolute shear modulus of the Full RAP binder is relatively lower when compared to the binder extracted from other RAP fractions. Among the three fractions, Coarse RAP binder exhibits marginally higher modulus at all temperatures. The lower 'stiffness' of Fine RAP binder observed here was also evident from the continuous high temperature PG values shown in Table 2. However, the difference among the other fractions is not clear from this parameter. The differences are further evident when the phase angle is considered.

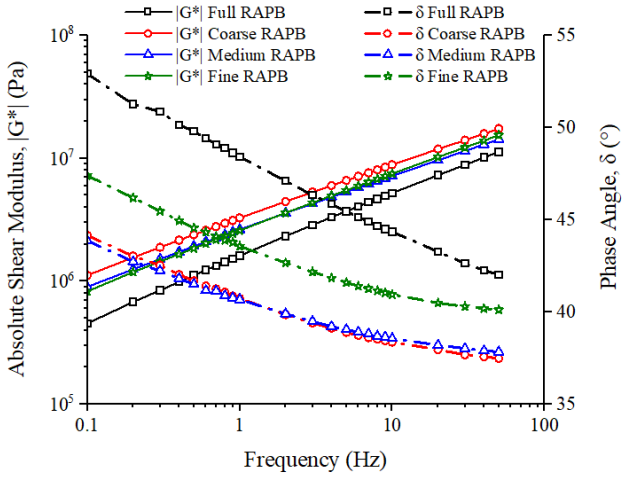

Figure 1. Variation of |G*| and δ with frequency at 40 °C

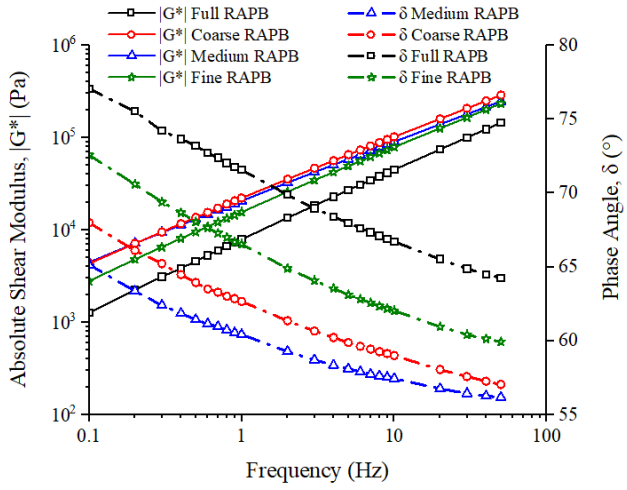

Figure 2. Variation of |G*| and $\boldsymbol{\delta}$ with frequency at 80 °C

Figure 1 shows that the phase angle is the highest for Full RAP binder and the least for Coarse and Medium RAP binder at 40°C. At 80°C (Figure 2), however, distinct differences are observed between the four binders. Here also, the Full RAP binder exhibits the highest phase angle. The difference between Coarse, Medium and Fine RAP binders could be observed here.

At this juncture, it is understood that the binder coating the coarse aggregates ages more and that coating the fine aggregate ages less. Many factors including the mix type, aggregate surface area, binder content

and resulting binder film thickness play a major role here. Data have to be collected addressing all these factors to comment on variation in stiffness of binders extracted from different RAP fractions.

3.3 *Master Curve*

In order to find the rheological behaviour of binder extracted from RAP fractions at different temperatures and over a wide range of frequencies, frequency sweep test data from 40 to 80 °C was analyzed and a master curve was constructed. A reference temperature of 60°C was used here and the master curve is shown in Figure 3.

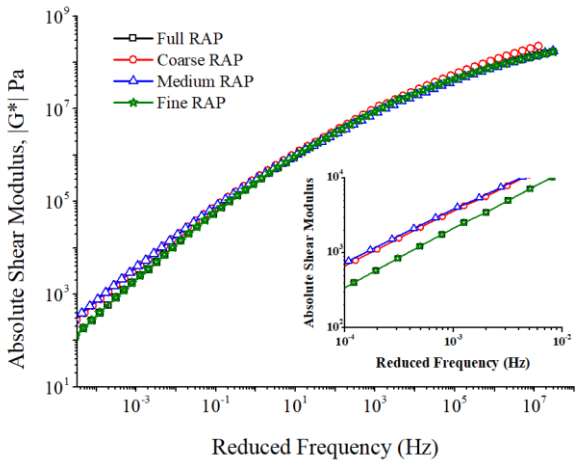

Figure 3. Master curve at 60 °C

From the master curve it can be seen that the response of Full RAP and Fine RAP binder is similar with a lower modulus across all frequencies. The coarse RAP binder exhibits a higher modulus across all frequencies. The Medium RAP binder exhibits a higher stiffness at low frequencies and a comparatively lower value at higher frequencies. This behaviour is also observed from the continuous high and intermediate PG values reported in Table 2.

4 IMPLICATIONS

Fractionation of RAP into individual stockpiles is necessary to achieve the desired gradation and binder content. Different parameters such as softening point, continuous high and intermediate temperature PG values, absolute shear modulus and phase angle indicate that the rheological properties of the binder extracted from Full RAP and that of the three individual fractions are different. The temperature susceptibility of the binder fractions is observed to be different with the Medium RAP binder exhibiting a higher temperature sensitivity.

Current industry practices for determining the RAP binder replacement ratio rely on blending charts, whose limits are well documented in the literature. This study within the context of RAP management, provides preliminary data emphasizing the importance of separating RAP into various fractions, characterizing the rheological properties of the binder in each fraction and utilizing appropriate stockpiles for blending calculations. The differences are although small for the RAP source considered in this study. Multiple RAP sources have to be analyzed to validate this response among different RAP fractions.

Currently in India, 30% RAP is utilized. For low proportions of RAP and when the Full RAP is used, the differences among fractions are averaged out in the mix. However, these differences might be more pronounced if specific fraction of RAP is utilised in the recycled mix design or if a higher proportion of RAP is used. Using preliminary data, this study highlights the need for a comprehensive investigation of RAP and virgin binder blends before selecting a specific RAP binder proportion.

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