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Use of conditional inference trees for evaluating the effect of reclaimed asphalt pavement content and binder grade on the dynamic modulus of asphalt concrete mixtures

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Abstract

Reclaimed asphalt pavement (RAP) has seen increasing use because it significantly reduces the paving cost, conserves energy, and protects the environment. This paper evaluates how RAP content and binder grade affect the dynamic modulus $|E^*|$ of asphalt concrete mixtures. The mix design includes four RAP contents (0%, 15%, 25% and 30%) and three binder grades (PG64-22, PG67-22, PG76-22). Dynamic modulus tests were performed and $|E^*|$ was measured at four levels of temperatures (40, 70, 100, 130 °F) and six loading frequencies (25, 10, 5, 1, 0.5, 0.1 Hz) in accordance with AASHTO T 342. Based on the test results, a conditional inference tree was estimated, which showed a higher level of RAP content or binder grade generally results in a higher $|E^*|$. Across the four levels of RAP contents, a significant increase in $|E^*|$ occurred as RAP increased up to 30%. The hierarchical structure of the estimated conditional inference tree reveals the interplay between the two mix design variables (i.e., RAP content and binder grade) depending on the levels of loading frequency and temperature. In general, the binder grade has a stronger association with $|E^*|$ than the RAP content when the reduced frequency is high while the RAP content has a stronger association with $|E^*|$ than the binder grade when the reduced frequency is low. This implies that a balanced mix design should be sought in selecting proper levels of RAP content and binder grade subject to application contexts in terms of temperature and traffic loading.

Keywords: Asphalt concrete mixture; Reclaimed asphalt pavement (RAP); Binder grade; Dynamic modulus; Reduced frequency; Conditional inference trees

1. Introduction

Due to the rising of oil price as well as a preference of more sustainable pavement construction and rehabilitation, reclaimed asphalt pavement (RAP) has seen increasing use. More than 90% of the roads in the U.S. used RAP [1]. In Georgia, there are approximately 150 approved RAP stockpiles, owned by 26 different contractors across the state. In light of the economic savings and environmental benefits, the Georgia Department of Transportation (GDOT) mix design specifications allow up to 40% RAP for drum plants and 25% RAP for batch plants, while 25–30% RAP is commonly used. Regardless of the expected benefits, some concerns arose due to the increasing use of RAP. One of the main concerns is the potential effect of RAP content on dynamic modulus $|E^*|$, which is a

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key input in Pavement Mechanistic-Empirical (ME) design to evaluate the performance of asphalt pavement. NCHRP Report 752 [3] indicated that RAP content and source significantly affect $|E^*|$ and pavement performance. NCHRP Report 547 [2] developed performance predictive equations based on $|E^*|$ in conjunction with climate and volumetric properties. Azari et al. [17] compared simple performance test $|E^*|$ of accelerated loading facility mixtures and the predicted $|E^*|$ using NCHRP 1-37A and Witczak's new equations. Al-Khateeb et al. [18] developed a new mechanistic empirical model for predicting dynamic modulus of asphalt paving mixtures at a wider range of temperatures and loading frequencies.

Since $|E^*|$ is a direct input for flexible pavement design and performance evaluation, it is important to evaluate the effects of RAP content on $|E^*|$ for reliable new or overlay pavement designs. Additionally, Georgia has historically used Performance Grade (PG) 67-22 asphalt binder for highways having low to intermediate traffic loadings, however this grade has become less available. Recently, the GDOT has allowed the substitution of the more readily available asphalt binder of PG 64-22 in state asphalt mixtures. Since both PG 64-22 and PG 67-22 mixtures are now allowed to contractors, it becomes necessary to investigate the influence of the new binder on resultant pavement. This study is focused on the effects of RAP content and binder grade on $|E^*|$ of resulting asphalt concrete mixtures.

2. Literature review

The FHWA report [1] summarized the current practices of RAP in asphalt mixture in the U.S. and describes a procedure, detailing the chronology of the tasks, from the RAP source, its storage and handling, collecting and processing to its mix with asphalt through the hot-mix asphalt (HMA) process and along with the description of tests and standards. The Transportation Research Board (TRB) recently published a circular [4] containing papers from a workshop aimed to providing information on current practices of using RAP and RAS. It showed that the last seven years have witnessed a sensible evolution on the use of RAP in asphalt mixtures in the U.S.

For the mix design method and the testing method, the NCHRP Report 752 [3] defines the current guidelines for using RAP in Superpave mixes. The standard of different experiments to meet the requirements of the mix design was described. For the RAP parameters, AASHTO T308 and T164 are the standards, respectively, for the ignition method and the solvent extraction method for the RAP binder removal. AASHTO T85 and T84 are the standards for specific gravities of coarse and fine materials recovered from RAP aggregates. Moreover, the G_{mm} test to determine the bulk specific gravity and the VMA of mixtures follows AASHTO T 209. The virgin binder grade selection was proposed to follow the RAP Binder Ratio (RAPBR) method as a simple way of estimating the total binder needed in the mix based on the RAP content.

Given the increasing use of RAP in the U.S. a number of studies have been undertaken to analyze different parameters and their influences on the resulting asphalt concrete pavement. For example, Zhou et al. [5] highlighted that increasing the RAP content results in a significant increase of OAC (optimum asphalt content) and enhances the moisture resistance. Along the same line, Tomlinson [6] provided evidences that both the dynamic modulus and fatigue life will increase as the amount of RAP increases in asphalt concrete. It was also found that by increasing the amount of binder in mixture, the stiffness of asphalt concrete decreases, but the fatigue life improves. Boriack et al. [16] showed that a 0.5% increase in binder content improved both the fatigue and rutting resistance of the 0% and 20% RAP mixtures with only slight decreases in dynamic modulus. However, the addition of various amounts of binder to the 40% RAP mixture led to a significant decrease in rutting resistance with little or no improvement to fatigue resistance.

McDaniel et al. [7] showed that mixtures with up to 50% RAP could be designed under Superpave, provided the RAP gradation and aggregate quality were sufficient. In some cases, RAP aggregates limited the amount of RAP that could be included in the new mix design to meet the Superpave volumetric and compaction requirements. Mogawer et al. [8] noted that overall the stiffness of the mixtures increased as the percent of RAP increased. The cracking resistance was reduced as the percent of RAP increased. Meanwhile, the rutting and moisture damage resistance improved as the percent of RAP in the mixtures increased. Elseifi et al. [9] had found that polymer-modified asphalt mixtures prepared with low percentages of RAP were good performers against cracking failure.

3. Laboratory test

3.1. Material and specimen preparation

The materials were obtained from the HMA production plants of two GDOT Highway Contractors, Plant A and Plant B. The findings reported in this paper are based on Plant A. The 12.5 mm Nominal Maximum Aggregate Size (NMAS) was selected. Four levels of RAP contents (0%, 15%, 25%, and 30%) and three binder grades (PG 64-22, PG67-22 and PG76-22 were considered. The mixtures were prepared in accordance with the Job Mix Formulas (JMF) approved by GDOT. The sample preparation and compaction were performed in accordance with the AASHTO standard practice for Superpave volumetric design for asphalt mixtures.

The cylindrical specimens were fabricated in accordance with AASHTO PP 6009 [10]. Mixed materials were compacted by Superpave gyratory compactor to the dimension of 150 mm (diameter) by 170 mm (height), which were then cored to a smaller size, i.e., 100 mm (diameter) by 150 mm (height), for the dynamic modulus test. All resulting specimens met an air void target of $4.0 \pm 0.5\%$. Three specimens were prepared for each mix design.

When blending RAP with virgin mixture, the amount of asphalt in RAP transferrable to virgin aggregate needs to be determined. Huang et al. [11] found about 11% of RAP asphalt transferred to virgin aggregate during the mixing process. GDOT also performed an in-house study of numerous RAP stockpiles in Georgia, where virgin aggregates were heated above normal mixing temperatures and combined with unheated RAP in a pugmill. The goal was to determine how much AC could be transferred to the virgin aggregate in a more real-world scenario. It was noted that only occasional scuffing of the virgin materials without any appreciable mass transfer or coating. To observe the consistency and coating of the RAP aggregate, the samples of stockpiled RAP were oven-heated. The AC was then removed from the samples using an ignition oven. Virgin AC was added back to the RAP aggregate in 0.25% increments until the original consistency and coating was achieved. The difference between the initial and recoated RAP AC percentages was calculated as the effective AC ratio in order to determine how much of the RAP AC was contributing to the effective AC content and AC film thickness. GDOT eventually settled on an average ratio of 75%, meaning that 75% of the AC in RAP was contributing to the effective AC in the mix. This investigation led GDOT to develop the Corrected Optimum Asphalt Content (COAC) for asphalt mix designs.

3.2. Dynamic modulus test

To determine the fundamental material properties of mixtures through dynamic modulus testing it is important to understand the principle of time–temperature superposition (t–TS). Generally speaking, the behavior of a material at high temperatures is the same as that under low loading frequencies, while the material behavior at low temperatures is the same as that under high loading frequencies. Materials that exhibit this type of behavior are called thermorheologically simple. The t-TS of a material can be checked by performing dynamic modulus tests at various temperatures and frequencies. Since the loading frequency and temperature are interchangeable, these two variables can be converted into a one variable, named a reduced frequency. Then, the effect of temperature is converted into a reduced frequency with one representative master curve describing dynamic modulus at any frequency and temperature. The master curve can be described by a sigmoidal function expressed in Eq. (1).

$$log\ |E^*| = a + \frac{b}{1 + \frac{1}{e^{d+g\log(fr)}}} \tag{1}$$

where a, b, d, and g are optimized constants, and f_r is the reduced frequency.

Dynamic modulus tests were performed according to AASHTO T 342-11 [12] and $|E^*|$ was measured at four temperatures (40, 70, 100, 130 °F) with six frequencies (25, 10, 5, 1, 0.5, 0.1 Hz) in accordance with AASHTO T 342. The testing device is Interlaken UniSystem. Specimens were tested from low to high temperature and with the frequency from high to low at each testing temperature. Environmental chamber maintains constant target testing temperature for about four hours for a specimen to reach the target temperature. Two LVDTs were glued to the specimen at 180° directions and the length between LVDT gauge points is 70 mm.

E^* is calculated by Eq. (2), where σ_0 and ε_0 are amplitudes of stress and strain, respectively, obtained by fitting cyclic data in steady state. In order to get data at steady state, last ten cycles at each frequency are used in the analysis.

$$|E^*| = \frac{|\sigma_0|}{|\varepsilon_0|} \tag{2}$$

4. Data analysis

4.1. Data description and coding

The test data were coded for analysis purposes. The variables and their respective coding are presented in Table 1.

4.2. Master curves comparison

For comparison purposes, average $|E^*|$ of three replicates was calculated at each loading frequency and temper-

Table 1
Variables and coding.

Variable	Description	Unit	Value and Coding					
RAP	Percent of reclaimed asphalt pavement content	%	0 R1	15 R2	25 R3	30 R4		
Binder	Binder grade	Grade	PG64-22 Low	PG67-22 Med	PG76-22 High			
Temp	Temperature	°F (°C)	40 (4.4) T1	70 (21.1) T2	100 (37.8) T3	130 (54.4) T4		
Freq	Loading frequency	Hz	0.1 F1	0.5 F2	1 F3	5 F4	10 F5	25 F6
LogFreq	Logarithm of reduced frequency	Range (Hz)	$(-\infty, -15)$ Low	$[-1.5, 2.0]$ Med	$(2.0, +\infty)$ High			

ature. Master curves were constructed based on the average $|E^*|$ with respect to different levels of RAP contents and binder grades. To evaluate how RAP content affects $|E^*|$, the master curves were grouped by binder grade as shown in Fig. 1. As seen, the difference in $|E^*|$ is relatively small for the RAP content up to 25%. However, when RAP content increases to 30%, a jump in $|E^*|$ becomes evident.

To assess the effect of binder grade on $|E^*|$, the master curves were grouped by RAP content as shown in Fig. 2. As indicated, $|E^*|$ is generally higher with a higher PG binder. This observation is consistent with findings by [6] (2012). It implies that the stiffer the binder is, the higher the $|E^*|$ would be.

5. Statistical plots

The comparison of master curves was based on the average of $|E^*|$. To gain insight into the variance of $|E^*|$, box-plots were generated with respect to RAP contents and binder grades, shown in Fig. 3.

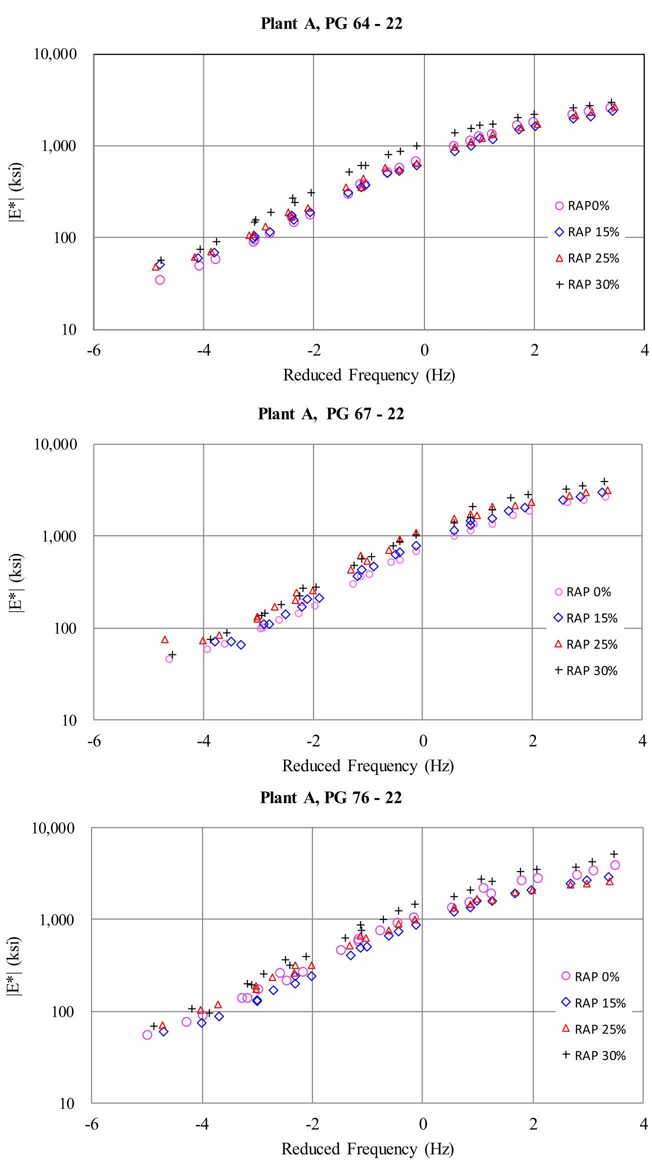

Fig. 1. Master curves – comparison by RAP content.

As seen, PG64-22 specimen distribution showed very little difference in the dynamic modulus (E^*) median value for specimens of 0% RAP (R1), 15% RAP (R2), and 25% RAP (R3). But a sudden increase in mean and variance of $|E^*|$ is observed as the RAP content increases up to 30%. For binder PG67-22, a similar trend was observed. It appears that the higher RAP contents (25% and 30%) result in a higher $|E^*|$ with an increased variance. Binder PG76-22 specimen distribution shows that the higher RAP contents (25% and 30%) result in a higher $|E^*|$ with a considerable increase of the variance when the RAP content increases up to 30%.

6. Conditional inference trees

Recursive partitioning is a fundamental tool in data mining. It helps explore the structure of data, while developing easy-to-visualize decision rules for predicting a categorical (classification tree) or continuous (regression tree) outcome. The conditional distribution of statistics measuring the association between responses and covariates is the basis for unbiased selection among covariates measured at different scales [13]. Specifically, a generic algorithm that recursively partitions a sample is formulated using non-negative integer valued case weights. The algorithm involves two steps: (1) variable selection, and (2) splitting. In step 1, the covariate of strongest association with the response is selected for splitting. In step 2, a permutation test framework [15] is used to find the optimal binary split for the selected covariate in step 1. The two steps are repeated recursively until the global null hypothesis of independence between the response and any of the covariates cannot be rejected at a pre-specified level, say 0.05. In this case, the Bonferroni-adjusted p-value was used. Details on using ctree was described by Hothorn et al. [13]. For this study, R program [14] and conditional inference trees (ctree) in the R party package [13] were used.

Since the loading frequency and temperature are interchangeable, the reduced frequency was used for conditional inference tree analysis. For this purpose, a new categorical variable (LogFreq in Table 1 was created based on the range of the log reduced frequency. This new variable, together with RAP content and binder grade, were used in estimating a conditional inference tree as shown in Fig. 4.

In interpreting the conditional inference tree estimated in Fig. 4, each rectangular box represents a leaf. The number of "n" in each box indicates the sample size. The value of "y" in each box indicates the mean value of $|E^*|$ based on the data sample. The splitting variables are indicated by the oval nodes at various levels. The variables appearing at the higher levels (close to the root) have stronger association with $|E^*|$ than those at the lower levels (close to the leaves). As shown in Fig. 4, the reduced frequency (LogFreq) was the splitting variable at the root, indicating it has strongest association with $|E^*|$, which is expected. Following the left

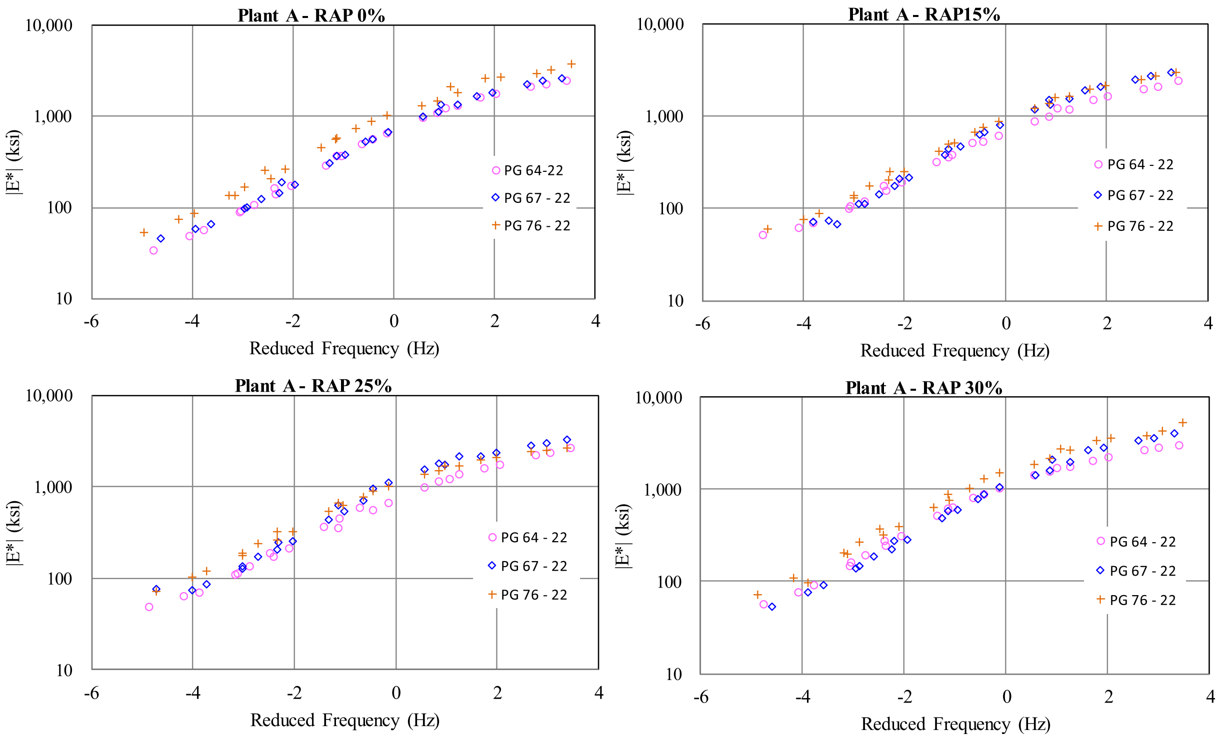

Fig. 2. Master curves – comparison by binder grade.

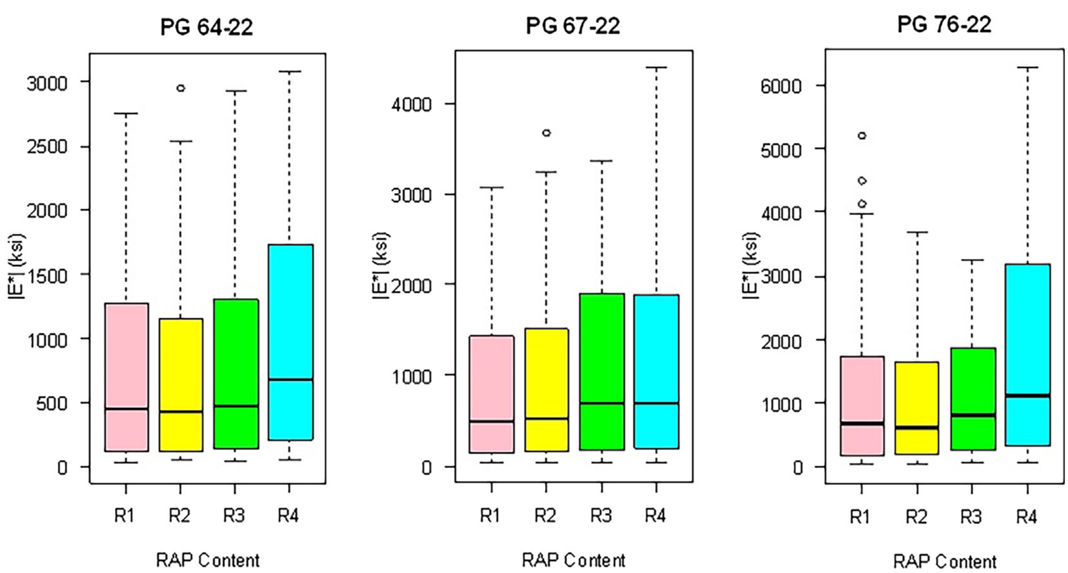

Fig. 3. Boxplots of $|E^*|$.

branch of the tree, when LogFreq is high, binder grade (at the second level of the tree from the root) is more significant than RAP content. The low binder grade results in a lower $|E^*|$ as compared to high and medium binder grades. Moving down the left branch, the low binder grade (Binder = Low) results in a lower $|E^*|$ (2267.070) as compared to the medium and high binder grades. Continuing down on the left branch, when the binder grade is high or medium, a lower RAP content (R1, R2, or R3) results in a lower $|E^*|$ (2804.242) as compared to the highest RAP content (R4). Moving further down the branch under R4, the binder grade became the splitting variable again and the medium binder grade results in a lower $|E^*|$ as compared to the high binder grade (3617.544 versus 4760.541).

Similarly, following the right branch of the tree, under the medium level of the reduced frequency (LogFreq = Med), binder grade is the splitting variable, indicating binder grade has a stronger association with $|E^*|$ than RAP content at the medium levels of load frequencies. Following the right branch of the tree, under the low level of the

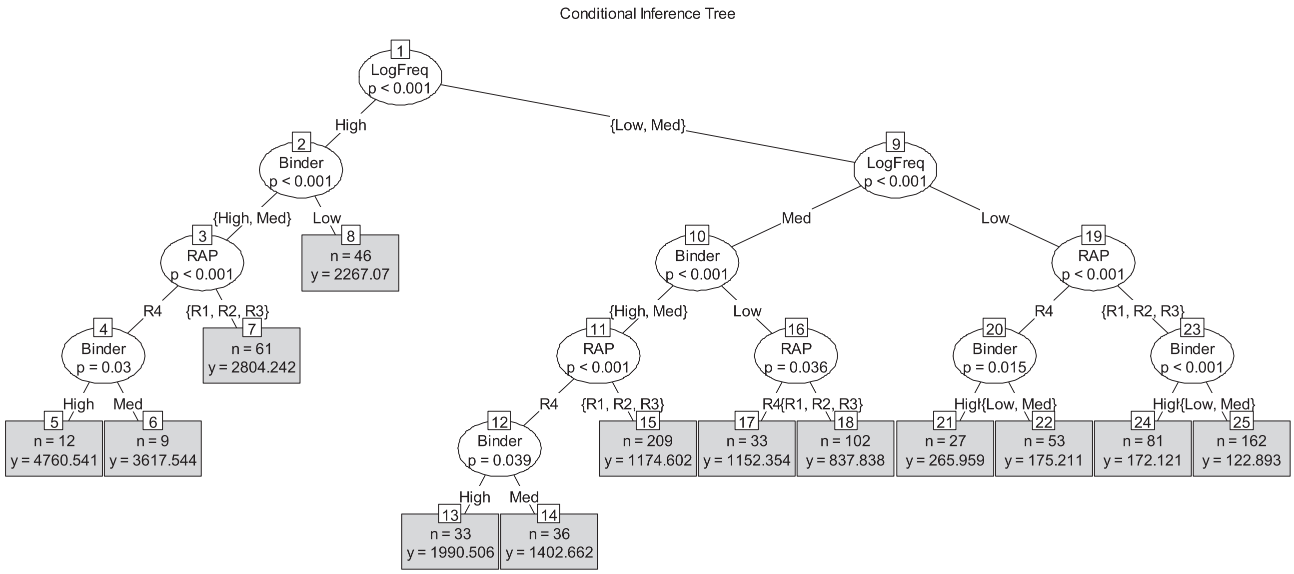

Fig. 4. Conditional inference tree of $|E^*|$.

reduced frequency (LogFreq = Low), RAP content is the splitting variable, which indicates that RAP content has a stronger association with $|E^*|$ than binder grade at the low levels of loading frequencies.

Based on the splitting variables and hierarchies presented in the tree, a general observation is that a higher RAP content or binder grade results in a higher $|E^*|$. The highest $|E^*|$ (4760.541 in the left most leaf of the tree) was found in the mixtures of the highest binder grade (Binder = High) and the highest RAP content (RAP = R4), subjected to the highest reduced frequency (LogFreq = High). As implied by the structure of the tree, interactions exist between the binder grade and the RAP content. Binder grade has a stronger association with $|E^*|$ than RAP content when the load frequencies are at the high or medium levels while RAP content has a stronger association with $|E^*|$ than binder grade when the load frequency is low.

7. Conclusion

This paper demonstrated that conditional inference tree is an effective technique for evaluating complex factorial effects. In general, the results are in agreement with previous studies in that $|E^*|$ increases as RAP content increases and a higher PG grade results in a higher $|E^*|$, which is likely due to stiffer mixtures. By a closer examination of the hierarchical structure of the estimated conditional inference tree, the binder grade has stronger association with $|E^*|$ than RAP content when the load frequencies are at the high and medium levels while the RAP content has stronger association with $|E^*|$ when the load frequency is low. This indicates that a balanced mix design should be sought in selecting proper levels of RAP content and binder grade subject to the application contexts in terms of temperature and traffic loading. As such, further studies are required to examine the sensitivity of interplay between the two mix design variables. Another interesting finding is that the tree splitting level for RAP content occurred between R4 and R1-R3, revealing a significantly higher $|E^*|$ when the RAP content increases up to 30%. This implies that the behavior of asphalt concrete mixtures changes dramatically as the RAP content increases to a certain level. This may adversely affect other performance criteria, such as fatigue resistance, which should be carefully assessed to ensure the constructed pavement meet desirable performance criteria for the intended service life.

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