A METHOD FOR CHARACTERIZING RECLAIMED ASPHALT PAVEMENT DEGREE OF BINDER ACTIVITY

A Thesis

by

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ABSTRACT

Most transportation agencies in the United States continue to assume reclaimed asphalt pavement (RAP) contributes 100% of its binder to a new asphalt concrete (AC) mixture, which has been proven to be an incorrect assumption, leading to mixtures with insufficient binder and resulting workability and cracking problems. This research assessed the practicality of estimating a realistic reduced amount of RAP binder activity for consideration in AC mixture design, based on indirect tensile (IDT) strength testing of 100% RAP mixtures. The concept and methodology of the Degree of Binder Activity (DoA) was reviewed, modified, and estimated for RAP materials from six states of varying climates in the United States. Pending further validation, the DoA methodology was determined to be practical for inclusion in existing mixture design methods.

DEDICATION

For my parents, to whom I owe everything

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Some data compared in the Results and Analysis section were collected and published in 2019 by Dr. Fawaz Kaseer, formerly of the Texas A&M Transportation Institute, and by Amal Abdelaziz, Graduate Student at Texas A&M University. All other work conducted for this thesis was completed by the student independently.

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INTRODUCTION AND BACKGROUND

Asphalt concrete (AC) pavements are frequently touted as 100% recyclable. While this claim is theoretically true, it is not yet fully understood how the industry can optimize recycling efficiency and rate. At the end of the 2018 construction season, the National Asphalt Pavement Association (NAPA) reported the total estimated amount of reclaimed asphalt pavement (RAP) used in new AC mixtures was 82.2 million tons, and that 110.3 million tons of RAP remained in stockpiles around the country (Williams et al. 2018). Although annual values fluctuate, these data reveal a greater rate of production than usage for RAP, creating a need to encourage the use of higher RAP contents in its various applications. The most common use of RAP – estimated at 81% based on 2018 data (Williams et al. 2018) – is in new AC layers, yet transportation agencies limit the RAP content in new pavements because mixtures with a higher RAP content are known to be stiffer, drier, and more susceptible to cracking due to the aged binder in RAP. Typical limitations are 0 to 30% RAP by total weight of mixture, depending on the AC layer (e.g., leveling versus wearing course) and type of application (e.g., runway versus highway shoulder). For example, the Texas Department of Transportation (TxDOT) allows up to 40% fractionated RAP by mixture weight in a lower base lift, but only allows up to 20% in the surface lift (TxDOT 2019a). These limitations are in place to improve the mixture quality and reliability of the more critical pavement layers.

Increasing the RAP content in new AC mixtures leads to reduced production costs and environmental impacts and is typically seen as a desirable long-term goal of sustainability in the asphalt industry. These reductions primarily result from a smaller amount of raw resource production and use. Asphalt concrete in its most basic form comprises two resources: asphalt binder and aggregate. Asphalt binder is a by-product of the crude oil refining process, and has wider fluctuations in price than other component materials. In 2018 in the United States (U.S.), unmodified asphalt binder cost $468.93 per ton, but only accounts for 5% of an AC mixture by weight. Aggregate production requires higher labor and equipment costs and costs $10.53 per ton while accounting for 95% of an AC mixture by weight (Williams et al. 2018). Based on these prices, the aggregate to make one ton (2,000 pounds) of AC costs $10, while binder costs $23. Both binder and aggregate have high and ever-increasing transportation costs, varying by geographic location. Epps Martin et al. (2020a) conducted an economic analysis and estimated that approximately $10 per ton of AC can be saved if the RAP content in the mixture doubles from the current typical value of 20% to 40%. This cost savings can be most dramatically realized in an asphalt runway reconstruction or overlay, for example, where savings would be in the range of $500,000 to $1,000,000 in material costs. By increasing RAP content, the asphalt industry aims to move toward maximizing sustainability in a future of increasing costs, limited infrastructure funding, and diminishing resources.

Although RAP is now commonly used in most AC applications, many pavement engineers continue to assume the RAP binder is completely active and available for blending with the virgin binder and any additives in the new AC mixture. In a 2019 survey of state Departments of Transportation (DOTs), only four states out of 38 which responded confirmed that their specifications consider a reduced (less than 100%) RAP binder availability factor when designing new AC mixtures (Epps Martin et al. 2020b). This survey revealed that approximately three-quarters of the nation’s DOTs follow the traditional assumption of 100% RAP binder availability. This has been proven an improper assumption through many prior research studies using chemical and rheological properties of binders and mixtures, and advanced imaging and microscopy approaches (Orešković et al. 2020).

This research is part of an international, inter-laboratory investigation organized by The International Union of Laboratories and Experts in Construction Materials, Systems, and Structures (Réunion Internationale des Laboratoires et Experts des Matériaux or RILEM). The umbrella Technical Committee (TC 264) is dedicated to asphalt pavement recycling and was formed in 2015. Within TC 264 are five Task Groups (TG), the fifth of which is focused on Degree of Asphalt Binder Activation. This research was inspired by and is in support of RILEM-TC264-TG5 and also expanded upon a base of knowledge previously acquired at the Texas A&M Transportation Institute (TTI) on the use and characterization of RAP. Results from this round-robin research initiated in 2019 will be compared across multiple laboratories to potentially reinforce the common goal of assessing available RAP binder for use in new AC mixtures. The laboratories participating in this investigation are not funded through the RILEM TG, and research was completed on a volunteer basis.

LITERATURE REVIEW

In this section, binder blending parameters are defined, and the indirect tensile (IDT) test and the effect of the RAP lifecycle are discussed in terms of its relationship with the blending parameters.

Blending Parameters

There are two extremes on the scale of RAP binder availability: 0% and 100% available. Previous research in this field has indicated that the realistic case is some percentage between 0 and 100, or partial availability (Lo Presti et al. 2019). Several efforts have been made to quantify the partial blending, and Lo Presti et al. (2019) summarized and combined those efforts and established the blending parameters of Degree of Activity (DoA), Degree of Availability (DoAv), and Degree of Blending (DoB). This research is focused on establishing the DoA so that DoAv and DoB can be evaluated subsequently.

The DoA is the ratio between the minimum percent of RAP binder that can be considered active - for the formulation of new recycled AC mixtures - to the total RAP binder. The DoA is expressed as a percent, and does not consider the influence of a rejuvenating agent, sometimes referred to as a recycling agent. Equation 1 expresses this ratio in its earliest definition, where $W_{activeRAB}$ is the amount of active RAP binder that depends on the RAP aging condition determined by its type or source, laboratory conditioning time, and conditioning/compaction temperature, and $W_{totalRAB}$ is the total amount of RAP binder, whether active or inactive.

$$DoA = \frac{W_{activeRAB}\left(RAP_{type}, t, T\right)}{W_{totalRAB}} * 100 \qquad \text{(Equation 1)}$$

The DoA is a unique, intrinsic property of each RAP material due to conditions that each pavement section experiences over its service life. Environmental effects such as oxidative aging, ultraviolet ray aging, and the presence of moisture have the greatest impact on the condition of a RAP binder, and a large effect on binder activity. The DoA value is also unique for a specific mixture production process. It might be expected, for example, that mixtures produced at typical hot mix asphalt (HMA) temperatures (150-170°C/302-338°F) would allow for more RAP binder activation than mixtures produced at typical warm mix asphalt (WMA) temperatures (100-140°C/212-284°F). Being highly specific yet flexible based on material history and production method, the DoA value may allow for optimization of the binder blend design for a new AC mixture. Fundamentally, the DoA is a potential starting point in increasing RAP use by quantifying the amount of binder released (activated) from a certain material under specific production conditions (Menegusso Pires et al. 2019).

Earlier research into the estimation of DoA attempted to compare field-aged RAP to an identical, artificially created, laboratory-aged RAP. It was assumed the artificial RAP would provide full blending, or 100% RAP binder activity. Temperature of conditioning/compacting and time of conditioning were varied for the field-aged RAP and for the artificial RAP, and replicates of Marshall-compacted specimens (ASTM D6926) were produced. The indirect tensile (IDT) strength test (ASTM D6931) was performed on each specimen as represented in Figure 1.

Figure 1 - Indirect tensile strength test of 100% RAP, 4" (100 mm) specimen

From the IDT test data, the DoA was then calculated based on several different calculated mixture parameters, including IDT strength peak stress, total energy, pre- and post-peak energy, and the Flexibility Index (FI) (AASHTO TP 124). Equation 2 shows this method, where Y_{RAP} is the resulting parameter for the field-aged RAP prepared at a specific conditioning/compaction temperature X, and $Y_{art,RAP}$ is the corresponding resulting parameter for the artificial RAP at the same temperature X. The researchers compared the calculated DoA results based on each of the parameters. The results revealed that the primary factors affecting DoA were conditioning and compaction temperature and RAP aging condition.

$$DoA = \frac{Y_{RAP}(X)}{Y_{art.RAP}(X)} * 100 \qquad \text{(Equation 2)}$$

After analysis, they recommended a more straightforward method, in which the maximum IDT strength values were used, but only for 100% field-aged RAP mixtures. Based on their results, they assumed the maximum IDT strength results were representative of 100% availability (full blending) and developed Equation 3, where ITS_{RAP} is the peak strength result for a RAP at a specific compaction temperature X, and $maxITS_{RAP}$ is the maximum peak strength result for the

RAP across all compaction temperatures (Menegusso Pires et al. 2019). Equation 3 forms the framework of this research.

$$DoA = \frac{ITS_{RAP}(X)}{maxITS_{RAP}} * 100 \qquad \text{(Equation 3)}$$

While this research is focused on quantifying the DoA, the DoAv and DoB are also discussed in their relationship to and dependence on DoA.

The DoAv is defined by Lo Presti et al. (2019) as the maximum percentage of available RAP binder that can be considered in the design of new AC mixtures. This parameter is meant to be used in new AC mix designs that include rejuvenating agents with RAP binder, with the rejuvenating agent increasing the percentage of available RAP binder depending on the type and dose. Again, DoAv only considers the RAP binder and does not consider the inclusion of virgin binder. In contrast to DoA (activity), which is a minimum percentage, DoAv (availability) is a maximum percentage; but they are similar in that both parameters describe the percentage of useful or effective RAP binder. A graphical interpretation of active binder versus available binder is shown in Figure 2, considering a microscopic scale of a heated RAP particle surface in an AC mixture. Figure 2 also shows the difference between the two scenarios: 1) only RAP, and 2) RAP plus a rejuvenating agent. A key difference is that inclusion of a rejuvenating agent causes more RAP binder to activate, or increase the overall available amount, beyond the limits of only reheating as in the RAP-only scenario. In this research, the DoA of RAP binder was quantified only by reheating, which is considered equivalent to the availability in the RAP-only scenario. This research did not study the effects of rejuvenating agents.

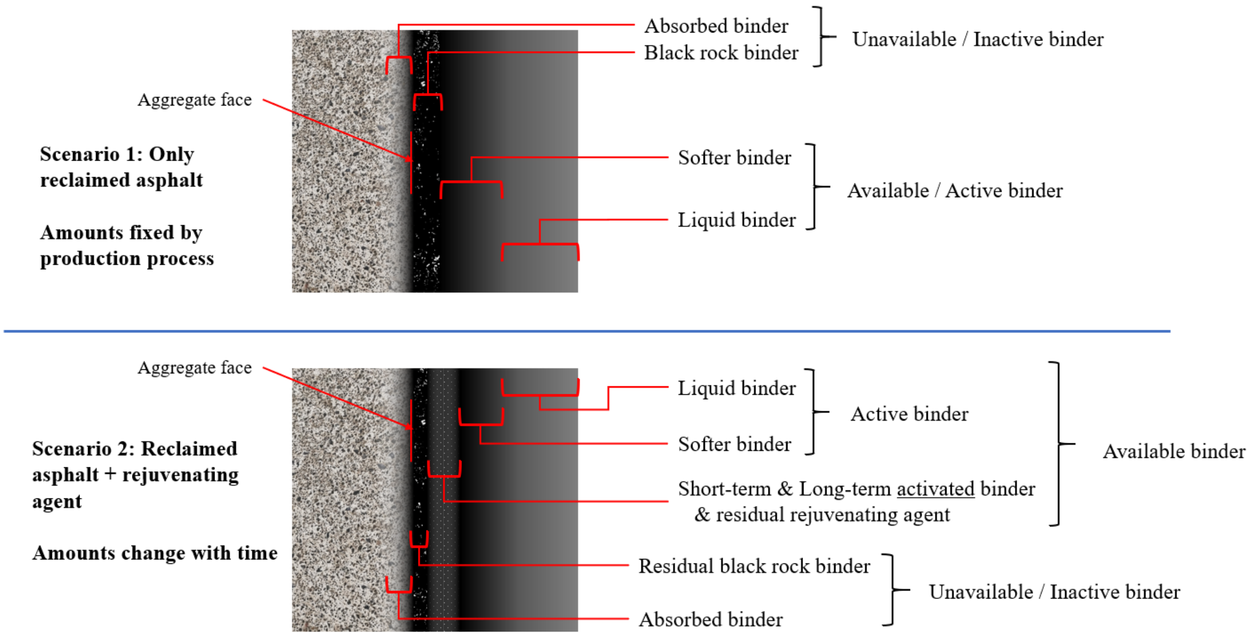


Figure 2 - Two RAP binder scenarios, highlighting differences between available and unavailable RAP binder (Adapted from Lo Presti et al. 2019)

The DoB is an index describing to what extent the aged RAP binder contributes to the final properties of the new AC mixture binder blend, which is composed of virgin binder, RAP binder, and (if included) rejuvenating agent. The DoB is a parameter associated with the new AC mixture and not with the RAP alone. While Lo Presti et al. (2019) did not propose a formula to describe the DoB, several attempts have been made to quantify it, although referred to by other terms such as the Blending Ratio or Binder Availability Factor (BAF). Epps-Martin et al. (2020a) presented the RAP BAF as the percentage of available (effective) RAP binder in the new AC mixture, determined by a linear relationship between 0% and 100% availability. The research presented in the following sections was focused on the DoA based on 100% RAP mixtures, so DoB was not assessed.

As the asphalt industry gained collective experience, common methods were accepted to preserve performance of AC mixtures with a high RAP content. Grade bumping is a common practice in which a softer substitute virgin binder (e.g., Performance Grade (PG) 64-22 substituted for PG 70-22) is included in the mixture when a high RAP content is used (e.g., more than 20%). The American Association of State Highway and Transportation Officials (AASHTO) recommends using binder blending charts when the RAP content is greater than 25% (AASHTO 2017), although these charts incorrectly assume 100% availability and full blending (Asphalt Institute 2014). Including a rejuvenating agent of a specific type and dose is also common practice to mitigate the increased stiffness of the aged RAP binder. These methods do not quantify the blending parameters of the RAP binder (DoA, DoAv, DoB) and thus may not consider the most effective method of designing high RAP content mixtures.

The results presented in the Results and Analysis section strive to help drive the industry towards understanding how to best quantify RAP binder activity (DoA), which is the first step in quantifying all of the blending parameters. The quantification of these parameters should allow for more accurate estimation of the amount of RAP binder to be considered in new AC mix design, precluding the possibility of a dry, brittle, crack-susceptible mixture.

Indirect Tensile Strength

The IDT test has been used extensively in assessing AC mixtures, as it is a simple, practical, and highly repeatable test requiring readily available equipment. The test utilizes a compressive monotonic load along the diameter of a cylindrical specimen, using two arc-shaped rigid platens. The applied vertical compressive stress translates into an induced horizontal tensile stress of approximately one-third the magnitude, which causes the specimen to fracture. Using the known failure plane of the specimen and the measured peak load, the IDT strength, or maximum horizontal tensile stress, of the specimen is calculated with Equation 4 (Vukosavljevic 2006).

$$IDT\ Strength\ (psi) = \frac{2 * P_{peak}}{\pi * D * H} \qquad \text{(Equation 4)}$$

Because of its popularity, a number of studies have identified three key factors of an AC mixture influencing the IDT strength: gradation, binder content, and binder grade. Vasconcelos et al. (2012) tested 12 different AC mixtures with the IDT test and concluded that dense-graded AC mixtures had the highest strength, while gap-graded mixtures such as Stone Matrix Asphalt or Porous Friction Course had the lowest strength. The aggregate skeleton structure created solely by a dense-graded mixture provides some strength to the specimen, as mirrored by the use of the test for soil-only subgrade specimens. Peng and Gao (2020) observed that among dense-graded specimens, a larger nominal maximum aggregate size (NMAS) produced higher IDT strengths. However, the tensile strength in the case of AC mixtures is primarily influenced by binder content and grade. Binder content has a direct relationship with IDT strength, thus RAP binder content and availability has a significant influence on the IDT strength of 100% RAP mixtures (Rao Tangella et al. 1990). In addition, both Vukosavljevic (2006) and Vasconcelos et al. (2012) confirmed that a polymer-modified binder results in greater IDT strength values for corresponding mixtures compared to unmodified binders (e.g., PG 76-22 versus 64-22).

Additionally, other factors affect IDT strength, including RAP content, test temperature, and air voids (AV) content. Kandhal et al. (1995) found that in-service pavements with RAP content around 20% had lower IDT strengths than pavements with only virgin materials (or lower RAP contents). However, several later studies found that higher RAP contents, having stiffer binder, resulted in stiffer and stronger mixtures. For example, Vukosavljevic (2006) found that higher RAP content, up to 30% as studied, resulted in higher IDT strength values. The discrepancy in findings between Kandhal et al. (1995) and other research may be attributable to myriad factors, such as binder contents, RAP properties, or the difference between field- and laboratory-compacted specimens. Test temperature has also been found to have an indirect relationship with IDT strength. Vasconcelos et al. (2012) performed the test at 5, 15, 25, and 35°C and found the highest strengths at the lowest test temperatures, associated with the higher viscosity and lower ductility of the binder. Vasconcelos et al. (2012) also observed differences in failure methods: lower temperatures caused cracks to propagate through aggregate particles, while higher temperatures produced cracks through the binder mastic around the aggregate particles. Finally, a greater AV content in a mixture reduces the IDT strength. Although the complex nature of the amount, distribution, and size of AV in AC mixtures is difficult to capture, it is understood that higher AV contents weaken the fatigue resistance of AC mixtures. More AV in a specimen indicates that there is less interaction between the mastic, with more reliance on stone-to-stone contact, allowing lower stress levels to cause fracture.

Given the simplicity and appropriate influence of binder properties, the IDT test is appropriate for determining the DoA.

Reclaimed Asphalt Pavement Lifecycle

Pavement material undergoes significant modification and processing during its life cycle in order to be useful as a recycled material. Before AC is considered RAP, it experiences a period of service with binder aging. Several mechanisms have been studied to describe the complex processes of aging. Volatilization, primarily experienced during plant production, is the evaporation of lighter molecular weight constituents from binder due to heat. Oxidation, the most prominent mechanism during service, is the chemical reaction between oxygen in the air and binder in the pavement, forming more structured chemical arrangements in the binder. Other aging processes include polymerization, thixotropy, syneresis, and separation, but are not as prevalent as volatilization and oxidation. All of these processes combine in various forms throughout a pavement's service life via the environment to cause binder to age as it is exposed to oxygen, ultraviolet radiation, moisture, and heat (Anderson 2011).

First in the RAP lifecycle, aged pavement is removed by breaking, or most commonly, milling. The high-energy milling drum head causes a significant breakdown of aggregate gradation, and creates fresh aggregate faces not coated by binder. For economic reasons, milling depth is typically no greater than the known depth of surface distresses in a given pavement section. Therefore, the recycled material withstands greater environmental damage (sun, rain, frost) than its lower in-place courses. Plant waste RAP, which is not commonly used as compared to aged pavement RAP, can also be considered (Ross 2015).

Second, RAP is stockpiled in a variety of manners. Best stockpile management practices agree that an ideal RAP stockpile is free of foreign debris, dry and covered, consistent in properties, and single-stacked (less than 20 foot height) to avoid consolidation. A stockpile can either be captive (i.e., from a single project removal), or more commonly, continuous. A continuous stockpile is a general reception point that continuously receives material from multiple pavement sections, and necessitates a RAP quality control (QC) plan due to the inherent variability (Ross 2015). While highly dependent on locality, a RAP aggregate particle may rest in a stockpile up to several years before inclusion in a new AC mixture. From 2018 data collected by NAPA, 94.5% of U.S. producers reported stockpiling RAP, and the reported amount of RAP stockpiled was equivalent to 1.4 years' worth of inventory based on 2018 utilization rates (Williams et al. 2018).

Third, RAP is processed, prepared for future use, and placed in a ready stockpile. Processing is also known as fractionating, where the RAP is passed through a series of crushers and screens in order to achieve a consistent and desirable gradation. Fractionating is desirable as heat transfer becomes more efficient with smaller RAP particles, a key concept in activating RAP binder (Ross 2015). It has been observed that the fractionation process causes a loss of binder content in the coarse fractions, and concentrates the binder in the fine fractions (Asphalt Institute 2014). In the case of in-place recycling techniques, processing and stockpiling are not a concern.

Finally, processed RAP is introduced into new AC mixtures. Continuous drum mixing plants are common in the U.S., which heat the RAP via indirect heat from superheated virgin aggregates. The RAP is injected into the drum beyond the burner combustion zone to avoid smoking and damaging of the RAP binder at typical maximum HMA plant temperatures of 150-170°C (302-338°F). For many drum plants, the injection location and maximum temperature impose a limit on practical RAP content in new AC mixtures. Most conventional drum plants can routinely achieve up to 50% RAP contents, while the double/triple drum plants can reach slightly beyond 50% (Mino et al. 2015). However, some AC mixture producers have achieved high RAP contents previously thought of as unattainable. In New York, the Green Asphalt Company has produced 100% RAP mixtures that perform well. They modified their drum plant to heat the RAP using refractory tubes to fully activate RAP binder without superheated virgin aggregate. They also modified their baghouse to prioritize filtering fumes over dust particles, because of the greater amount of smoke from the RAP binder. The Green Asphalt Company was a pioneer in high-RAP mixtures, but the plant modifications were costly and highly customized (Redohl 2018).

The other option for plant production is the batch plant. Normal batch plants in the U.S. and Europe typically only reach a maximum RAP content of 40% (Mino et al. 2015). Japanese asphalt producers are known to consistently achieve greater than 40% RAP in their new AC mixtures. Primarily, this is due to the commonality of batch plants and the use of parallel heating instead of indirect heating of RAP particles. Additionally, Japanese producers keep their RAP stockpiles dry to reduce energy waste from drying the RAP, and they consistently utilize rejuvenating agents mixed and conditioned directly with RAP. In terms of performance, Japan enforces a lower axle load limit than the U.S., reducing strain levels and reducing fatigue cracking susceptibility (West 2015). While there are myriad methods for achieving greater usage of RAP, understanding and quantifying the RAP binder activity (DoA) may prove itself a stepping stone in widespread increases in RAP utilization.

AC mixtures in pavement sections are typically expected to be in service for at least ten years before any major rehabilitation, but may experience fifteen or more years of aging. The actual ages of each RAP source are difficult to track and are the largest cause for variabilities within a continuous stockpile. Environmental effects, or oxidation and moisture damage, have a greater impact on RAP binder properties than those from traffic-induced stresses. This is tied with the commonality of the preventative maintenance method of wearing course milling and overlaying. Even as perpetual pavement concepts gain popularity, milling and overlaying the wearing surface of AC pavement still remain necessary to retain good functionality and protect the lower structural layers (Pavement Interactive 2020). With a greater in-service age, environmental effects compound and reduce the viability of using a pavement as RAP, primarily from excessive RAP binder stiffness, or low DoA.

Infinitely recyclable asphalt pavement, or consistent use of 100% RAP mixtures, is not currently a focus of the asphalt industry. The efficacy of infinitely recyclable pavement is unknown, but DoA quantification might give insight. If a proper QC testing plan is followed, DoA values of a locality might be expected to decrease over time, assuming a relatively closed loop system of pavement sections and RAP stockpiles. A related unanswered question in the asphalt industry is: how many times can an AC pavement be recycled? This question is more frequently examined in other recyclable material industries such as plastic and metal, but answers vary based on how much the material breaks down between each life cycle. In RAP, the binder undergoes aging as it is heated for mixing and placement, then faces environmental stresses while in service or stockpiled as RAP. The effects of binder aging and rejuvenation are quantified with the Glover-Rowe parameter in the Black Space model with the complex shear modulus ($|G^*|$) and phase angle (δ). Kaseer et al. (2018) used Black Space to conclude that the use of rejuvenating agents can partially restore recycled binder rheology by decreasing $|G^*|$ and increasing δ, but complete rejuvenation to virgin properties is unrealistic. In other words, infinitely recyclable pavements on the basis of RAP binder alone may be infeasible. Aggregate experiences its primary breakdown in gradation under the milling drum, and secondarily during fractionation. The increase in the fine fraction and decrease in coarse fraction over many life cycles can be expected to theoretically create a more single-size particle distribution, which is impractical for most AC pavement applications.

PROBLEM STATEMENT

A higher percentage of RAP in new AC mixtures is desirable, given its environmental and economic benefits. However, a knowledge gap exists in characterizing RAP for increased usage. To achieve increased utilization of RAP, this research provided analysis into how a pavement engineer can evaluate RAP for use in a new AC mixture. First, a RAP material must be characterized by the DoA, which is the topic of this research. Following the DoA estimate, the effects of a potential rejuvenating agent or other additives must be quantified and optimized based on the characterization of the RAP, the virgin binder, and climate and traffic conditions at the pavement location. Finally, a modified AC mixture design methodology considering these new concepts can be presented and validated.

OBJECTIVES

The main objective of this research is to evaluate a proposed practical method to quantify the DoA of a RAP source. The DoA framework was introduced in 2019 and requires validation and refinement before recommendation for use in the asphalt industry. A combination of mechanical mixture testing and rheological binder characterization was used to evaluate the RAP binder contributions to a new AC mixture, allowing pavement engineers to utilize higher RAP contents without sacrificing mixture performance.

The results from this research are reported to and compared with other results in the RILEM effort to label RAP materials on the basis of their DoA (ResearchGate 2020). This research used the IDT strength values of 100% RAP mixtures and compared results between six RAP sources from various states in the U.S. with different environmental conditions.

Finally, the practicality and limitations of the DoA quantification method are presented, with consideration toward adoption by industry and transportation agencies.

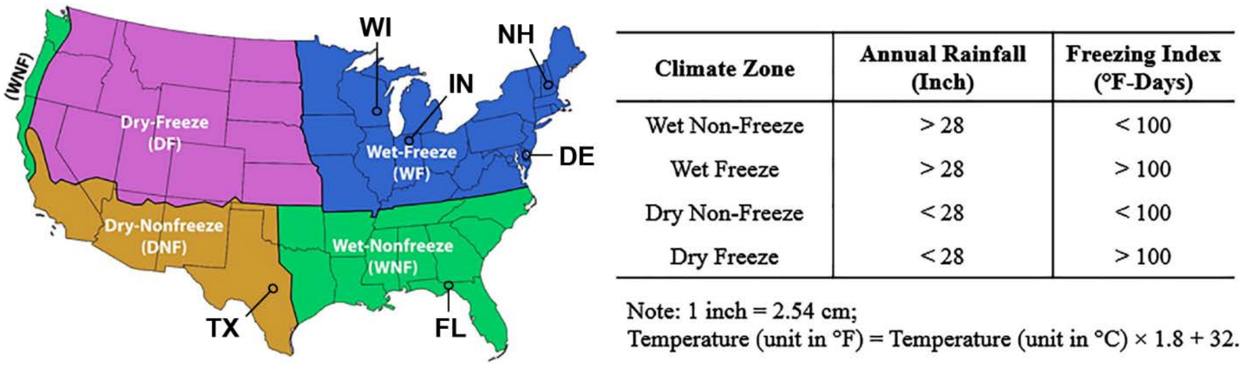
EXPERIMENTAL DESIGN

This section details the specific materials and methods used for this research.

Materials

Materials used in this research were collected from six states: Delaware (DE), Florida (FL), Indiana (IN), New Hampshire (NH), Texas (TX), and Wisconsin (WI). The RAP used was taken from stockpiles of unspecified origin in each state, so the PG and any modifications of the original binder for the RAP is unknown. Additionally, length of time in service and length of time in stockpile are unknown. This research was focused on characterizing RAP regardless of its history, but these unknowns have some impact on binder aging condition that are discussed.

The assortment of the six states used in this research allows for the comparison of primarily climates, and secondarily traffic. Figure 3 shows the four climate zones of the continental U.S., as established by the Federal Highway Administration (FHWA) (FHWA 2016). The six states' RAP materials assessed in this research are labeled and show that four (Wisconsin, Indiana, New Hampshire, and Delaware) are in the wet-freeze zone, one (Florida) is in the wet-non-freeze zone, and one (Texas) is in the dry-non-freeze zone. In the case of Florida and Texas RAP, the specific source stockpile locations are known to be Havana, FL, and Austin, TX, respectively, and the locations are indicated on Figure 3. For the remaining states, the RAP source stockpile locations were unknown, but approximate representative cities have been chosen for the information presented in this section.



Climate Zone	Annual Rainfall (Inch)	Freezing Index (°F-Days)
Wet Non-Freeze	> 28	< 100
Wet Freeze	> 28	> 100
Dry Non-Freeze	< 28	< 100
Dry Freeze	< 28	> 100

Note: 1 inch = 2.54 cm;
Temperature (unit in °F) = Temperature (unit in °C) × 1.8 + 32.

Figure 3 - Climate zones of the continental U.S. (Adapted from FHWA 2016)

These four established climate zones are not adequately descriptive of the environmental conditions experienced by the RAP, especially considering that a continuous RAP stockpile can contain materials from many locations in the region. Additionally, with four states in the same climate zone, more details are needed to better compare them. Climate, or more specifically, temperature range, was a driving factor in the creation of the Performance Graded (PG) Asphalt Binder Specification System in the 1990s. Binder PG is based on the concept that the binder will perform successfully within a range defined by the graded maximum seven-day pavement temperature (e.g., 64°C) and the minimum pavement temperature (e.g., -22°C) throughout its expected service life. The pavement temperature is a function of air temperature, solar radiation, and depth; high temperature is considered at a depth of 0.8 in (20 mm), and low temperature is considered at the pavement surface (Anderson 2011). For example, Texas experiences a wide range of climates and has a corresponding wide range of typical virgin binder PGs: between PG 58-10 and PG 70-28 as depicted in Figure 4 (TxDOT 2019b). Conversely, Wisconsin is simply divided into two climate areas: North (PG 58-34) and South (PG 58-28) (Asphalt Institute 2020).

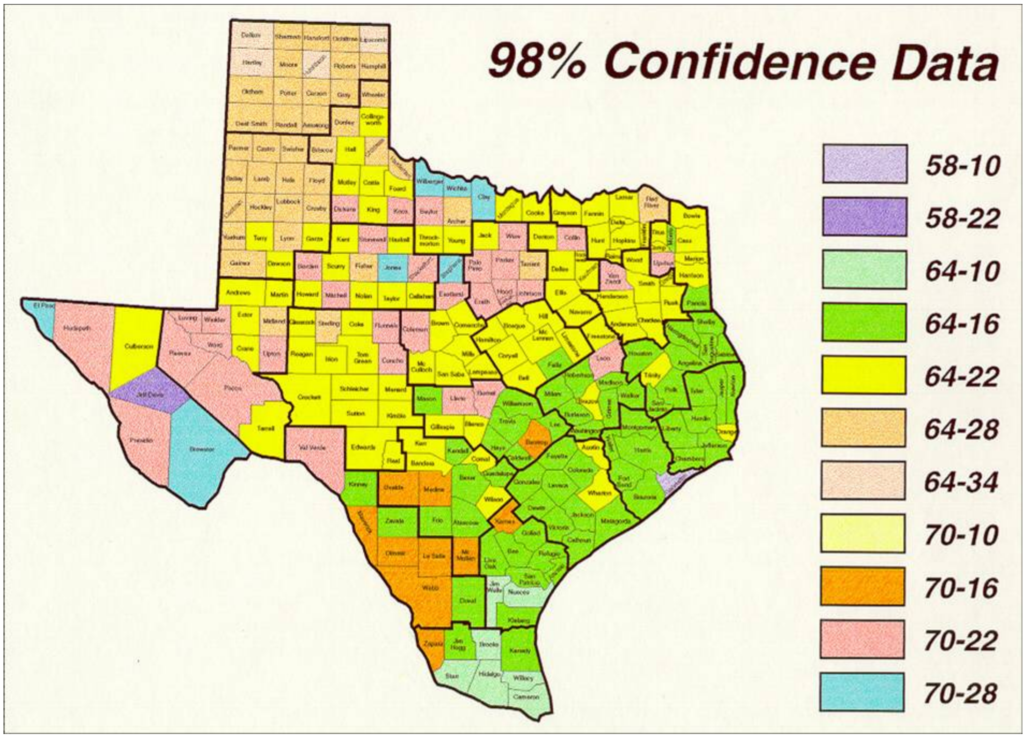


Figure 4 - Typical design binder Performance Grades in Texas (TxDOT 2019b)

The design PG is chosen based on reliability levels (typically 95% or greater) and empirical equations which convert air temperatures to pavement temperatures. Using the LTPPBind v3.1 software, the 50% (mean) reliability pavement temperatures, and the 98% reliability high and low PG values (°C) are listed in Table 1 (FHWA 2020). Based on the LTPPBind data in Table 1, but still as an estimate, the rightmost column summarizes the typical project design PG by actual or assumed locality for the materials used in this research. Florida PG information was estimated based on existing state construction specifications (FDOT 2020).

Table 1 - Estimated design binder PG values (TxDOT 2019a; Asphalt Institute 2020)

	50% reliability pavement temperature (°C)		**98% reliability PG (°C)**		**Estimated design PG (°C)**
Location	**7-day High**	**Low**	**High**	**Low**	
Austin, TX	79.7	-1.5	82	-10	76-10
Milwaukee, WI	64.2	-18.2	70	-28	58-28
Tallahassee, FL	79.2	-2.5	82	-10	67-22
Dover, DE	72.2	-9.9	76	-16	64-22
Indianapolis, IN	70.6	-16.2	76	-28	64-28
Concord, NH	66.2	-20.7	70	-28	64-28

While temperature variations are primarily a concern in the viscoelastic performance properties of AC pavement, temperature can also affect the aging condition of the RAP binder. Higher temperatures over time lead to greater amounts of volatilization and faster rates of oxidation, creating both stiffer and more brittle binders, reducing the potential DoA. Low temperatures are not as overall damaging to the binder, but can cause thermal cracking in AC pavements which can then allow more exposed surfaces for additional water, ice, and air. To compare temperatures likely experienced by the RAP, Table 2 summarizes relevant average weather data from a period of record of 1988 to 2017 (14th Weather Squadron 2020). The hottest state included in this research is Texas, with a median extreme dry-bulb high temperature of 39°C (102°F). Conversely, the coldest state is New Hampshire, with the median extreme high and low temperatures spanning between 35°C and -24°C (95°F and -11°F).

Ultraviolet ray (sunlight) aging of the binder is not as thoroughly researched as thermal or oxidative aging, as it is difficult to reproduce in a laboratory setting. However, it is known that ultraviolet ray exposure progressively breaks down the colloidal structure of the binder, changing it from a colloidal solution (sol) to a stiffer, integrated network (gel) (Yu et al. 2018). To compare ultraviolet exposure levels between the six states, the monthly exposure charts are included in the Appendix. For a simple direct comparison, Table 3 summarizes the approximate annual average sunny days by location, which are defined as days with less than 20% cloud cover (Meteoblue 2020). The dataset covers a period from 1990 to the present. As Wisconsin has the lowest level of ultraviolet exposure amongst those studied, it stands out from the remaining three states in the wet-freeze climate zone and the corresponding RAP binder may have experienced relatively less aging than that in New Hampshire, Indiana, and Delaware.

Table 2 - Representative climate data (14th Weather Squadron 2020)

Location	Extreme high median dry bulb temperature (°C)	Extreme high median dry bulb temperature (°F)	Extreme low median dry bulb temperature (°C)	Extreme low median dry bulb temperature (°F)	Average annual freeze/thaw cycles
Austin, TX	39	102	-6	21	19
Tallahassee, FL	37	99	-7	19	20
Dover, DE	36	97	-12	10	48
Milwaukee, WI	35	95	-21	-5	47
Indianapolis, IN	34	93	-19	-2	53
Concord, NH	35	95	-24	-11	95

Table 3 - Average annual sunny days (Meteoblue 2020)

Location	Average annual sunny days
Austin, TX	129.6
Tallahassee, FL	125.8
Dover, DE	109.5
Indianapolis, IN	97.0
Concord, NH	85.7
Milwaukee, WI	78.2

Beyond temperature, precipitation (moisture) causes distresses in AC pavements. Due to the polarities of aggregates, binder, and water, the water can gain access to the aggregate and reduce the mixture stiffness. In the extreme case, water can peel away the binder coating in a process referred to as stripping, leading to a macro-scale distress called raveling. Extreme low temperatures can cause accelerated stripping and raveling if water infiltrates the aggregate-binder adhesive bond and expands upon freezing. Based on the average annual freeze/thaw cycles in Table 2, the states with a greater risk of freezing are those in the wet-freeze climate zone (New Hampshire, Indiana, Wisconsin, and Delaware). Average annual precipitation amounts are summarized by location in Table 4 with a data period of 2010 to 2019 (National Weather Service 2020). Florida AC pavements have a relatively greater risk for stripping and raveling due to their significantly higher rainfall. New Hampshire has a significantly greater risk of moisture damage than other states in the wet-freeze zone due to 95 average freeze/thaw cycles (Table 2) and 24.6 cm (97.0 in) of precipitation (Table 4) per year. Therefore, with harsher climates, Florida and New Hampshire RAP can be predicted to have lower DoA.

Table 4 - Average annual precipitation (National Weather Service 2020)

Location	Average annual precipitation cm	in
Tallahassee, FL	33.2	130.9
Concord, NH	24.6	97.0
Indianapolis, IN	19.8	77.8
Milwaukee, WI	17.3	68.3
Dover, DE	14.8	58.4
Austin, TX	21.5	34.3

Traffic volume and vehicle weight comparisons may also provide insight into differences between the six states' RAP. It is impossible to estimate how much traffic was supported by the RAP used in this research, but an overall traffic distinction can be made between states. Greater populations generally indicate greater traffic levels and intensities, which lead to faster and greater fatigue cracking. Texas and Florida are the second and third most populous states in the U.S., respectively. By contrast, Delaware is the 46th most populous state, New Hampshire is 42nd, Wisconsin is 20th, and Indiana is 17th (World Population Review 2020). Thus it may be anticipated that Florida and Texas RAP, atop their already more damaging hot climates, experience additional damage from traffic, and due to the stiffer RAP binder, may have lower DoA values. But since the DoA is primarily dependent on the RAP binder age and aging condition, and traffic loads contribute relatively small levels of damage, the traffic levels were not extensively compared. Additional factors that may affect the age and damage of AC pavements include local infrastructure funding levels, availability of high-quality virgin materials, local contractor annual work capacities, and available construction timeframe (typically summers). These factors are highly dependent on locality and are even more difficult to compare than traffic levels.

RAP materials from four of these states (Delaware, Indiana, New Hampshire, and Wisconsin) were also used in the NCHRP 09-58 project, which focused on using recycling agents to facilitate increasing recycled binder ratios (Epps Martin et al. 2020a). As a part of the NCHRP 09-58 project, the Binder Availability Factor (BAF) was measured for these RAPs and was compared with results from this research, as both BAF and DoA are efforts in estimating the realistic reduced availability of RAP binder. In the 09-58 project, the RAP was used as a mixture design component in high-RAP content AC mixtures in varying applications, which were placed in the last five years. While Texas was represented in both NCHRP 09-58 and this research, the specific sources differ between Tyler, TX, and Austin, TX, respectively. Since the different locations in Texas between the two studies are in different climate zones, direct comparison should not be made; Austin, TX is in the dry-non-freeze zone and Tyler, TX is in the wet-non-freeze zone.

The RAP material used was stored in a variety of methods. Some RAP was stored for months outdoors in waterlogged buckets, where stripping, consolidation, and additional aging likely took place. These wet-stored RAPs include a majority of that from New Hampshire, Delaware, and Indiana. Other RAP was stored indoors in nearly dry conditions. Figure 5 gives examples of the difference between wet storage and dry storage of RAP from the same source in New Hampshire. It was clear even before testing that the properties of the two samples were different. These variations in storage conditions might have caused inconsistencies and inaccuracies in the data. Additionally, coloration differences can be seen between two different states (Wisconsin and New Hampshire) in Figure 5 (b).

(a) (b)

Figure 5 - Uncompacted RAP coloration differences: (a) New Hampshire RAP stored inside (left) versus outside (right), and (b) Wisconsin (left) compared to New Hampshire (right) RAP

RAP is typically fractionated and processed by an HMA manufacturer before inclusion in a new AC mixture. The RAP stockpile samples used in this research were fractionated into different sizes prior to shipment, so all RAP was further fractioned to pass the 3/4" sieve in order to achieve consistency across all sources. Notably, the Florida RAP had by far the greatest percentage of clusters and aggregates retained on the 3/4" sieve, shown in Figure 6, potentially indicating that the removal mechanism may have been at a lower energy than that used for other states' materials.

Figure 6 - Uncompacted Florida RAP, passing ¾" on the left, and retained on ¾" on the right

Due to the quick timeline of the research, and its volunteer basis with no direct funding, the RAP used was taken from leftover materials from other projects at the laboratory (i.e., NCHRP 09-58, Florida DOT, Texas DOT). In the case of Florida, the amount of RAP was insufficient by a small amount, only allowing for four replicates instead of the desired five in three of the sample groups. Although seemingly insignificant, the variability and error values may have been slightly impacted.

No virgin materials or rejuvenating agents were included in the experimental design for this research. Characterization of the DoA of each state's RAP was based on RAP alone.

Test Methods and Procedures

The process of laboratory work is outlined in Table 5, accompanied by the appropriate standards. Some standards were dictated by the RILEM organizers to ensure consistent practices in this international research effort (ResearchGate 2020).

Table 5 - Testing procedures

Category	Action	Standard	Note
Raw RAP assessment	RAP drying	RILEM	48 hours in 40°C room
	RAP black gradation analysis	ASTM D6913	
	Maximum Theoretical Specific Gravity	Tex-227-F	
Mixture mechanical testing	Conditioning/Heating	RILEM	70, 100, 140, 170, & 190°C for 4 hrs
	Specimen preparation with the Marshall Apparatus (50 blows per side)	ASTM D6926, RILEM	Mixing for 60 sec by hand; 100 mm diameter, 63.5 ± 1.27 mm height; minimum 5 replicates
	Specimen preparation with the Superpave Gyratory Compactor (N=30)	ASTM D6925, RILEM	
	Bulk Specific Gravity	ASTM D2726	
	Drying/Conditioning	RILEM	24 hrs in 25°C air
	Indirect Tensile (IDT) Strength Test	ASTM D6931	Loading rate set to 50 mm/min
RAP binder testing	Binder extraction with the Asphalt Analyzer	ASTM D8159	Using uncompacted material
	Binder recovery with the rotary evaporator	ASTM D5404	
	RAP white gradation analysis	ASTM D6913	
	Penetration Test	ASTM D5	Original binder
	Rotational Viscosity Test	ASTM D4402	Original binder
	Dynamic Shear Rheometer Test	ASTM D7175	Original, RTFO-aged, and PAV-aged binder
	Bending Beam Rheometer Test	ASTM D6648	PAV-aged binder

Both the Marshall apparatus and the Superpave Gyratory Compactor (SGC), shown in Figure 7, were used due to the Marshall apparatus' commonality in Europe and the SGC's commonality in the U.S. The Marshall compaction apparatus is an older method of laboratory compaction, and relies solely on repetitive vertical compressive impact loads to compact a specimen. It relies on gravity to drop a ten-pound hammer from an 18-inch height (ASTM D6926).

In the U.S., this antiquated method was widely replaced by the SGC as it was recognized that the Marshall apparatus does not properly mimic the actions of roller compactors used in the field and does not produce a similar aggregate structure. The SGC focuses not only on a constant vertical compressive load of 600 kPa (87 psi), but also on a 30-rpm gyration at a 1.25-degree angle, which together more closely model the behavior of an AC mixture under a roller compactor (ASTM D6925).

(a) (b)

Figure 7 - (a) Marshall compaction apparatus and (b) Superpave Gyratory Compactor apparatus

Fifty blows per side (50x2) were used with the Marshall apparatus, as required by ASTM standards (ASTM D6926). As shown in Table 5, the number of gyrations (N) in the SGC was set at 30, so the specimen weight was varied to achieve the target height prescribed in the Marshall compaction (63.50 ± 1.27 mm). This allowed for a better comparison of bulk volumetrics between the two methods. Early discussion among the laboratories in this research resulted in the N=30 determination for two reasons. First, initial results of the DoA method predicted that Marshall-based results would not match SGC-based results. Second, the underlying goal is to establish a procedure, not to compare compaction methods. On the basis of compaction energy, the SGC has a greater capacity for energy input than the Marshall apparatus, allowing for denser specimens with lower AV percentages. Loma and Peña (2013) conducted a comparison between Marshall and SGC compaction of AC mixtures and concluded that finding an equivalent compaction level between the two methods depends on the NMAS, gradation, and binder content and grade. For example, one mixture they studied had an NMAS of 11 mm (7/16 inch) in a stone matrix asphalt, which required 160 gyrations to have an equivalent bulk density of a 50x2 specimen. On the basis of AV, N=30 gyrations is not comparable to 50x2 blows. In early tests, the Marshall specimens consistently had higher AV and problems with segregation that were not seen with SGC specimens, shown in Figure 8. The advantage of the SGC is in its ability to automatically terminate compaction when a desired density or AV content is reached.

Early in the research data collection, it was presumed that a correction factor for AV would be necessary. The significant difference between Wisconsin and the remaining states was thought to be undesirable due to the relatively very low AV contents. The significant influence of AV on IDT strength was initially controlled by normalizing the IDT strength data to 14% AV. This value was selected because it was an average AV content of specimens across the range of conditioning temperatures, but only for the Marshall compaction method, which have significantly higher AV compared to SGC compacted specimens. Additionally, after RAP binder extraction was complete, a correction factor of 4.7% binder content was applied to the IDT strength values. 4.7% was chosen because it was the average value among all six states. However, after all data were collected, it was evident that these normalizations were unwarranted, so the DoA results are presented subsequently based on uncorrected IDT strength data.

Figure 8 - Delaware specimens conditioned at 70°C and compacted with the SGC (rear) and Marshall apparatus (front)

To reinforce the results of the DoA analysis of the 100% RAP mixtures, rheological properties of the extracted and recovered RAP binders were compared. The primary comparison was made with the Direct Shear Rheometer (DSR) (ASTM D7175) and Bending Beam Rheometer (BBR) (ASTM D6648) assessment of the $|G^*|$ complex shear modulus, δ phase angle, S stiffness, and m-value which together provided a PG and useful temperature interval (UTI) of the RAP binder according to the Standard Specifications for Performance Graded (PG) Asphalt Binder (ASTM D6373; AASHTO 2017). Additional rheological assessment was made with the rotational viscometer (RV) (ASTM D4402) to directly measure viscosity at production and construction temperatures, and with the penetrometer to estimate stiffness at average pavement temperatures. The PG of RAP binder is currently the key factor in AC mix design with high RAP content, as it is directly considered in blending charts. Furthermore, RAP binder properties have a large influence on IDT strength. Binder rheology results were compared between states, and were compared against binder test results from the NCHRP 09-58 project (Epps Martin et al. 2020a).

For RAP binder extraction, this research used the InfraTest Asphalt Analyzer automated binder extraction unit (ASTM D8159). The equipment uses Trichloroethylene solvent to separate binder from aggregate in a washing drum, and a separate Rotavapor (ASTM D5404) is used to recover the binder from the binder-solvent solution. The NCHRP 09-58 project used centrifugal extraction (ASTM D2172), which may explain some differences in binder results between this research and 09-58. Additionally, the most common binder content test method in the asphalt industry is the ignition method (ASTM D6307), where RAP is placed in a 540°C (1004°F) oven until mass loss rate is low enough to ensure the binder has been fully burned. Subhash et al. (2011) researched the difference in effects between the ignition method and centrifuge method of extraction. They concluded that in regards to binder content in the RAP, the centrifuge method underestimates because the absorbed asphalt is not solubilized, while the ignition method tends to overestimate as some minerals can also burn away. Since the auto-analyzer used in this research is a newer technology (2018), a knowledge base of differences between the centrifuge and auto-analyzer method is less developed. Subhash et al. (2010) concluded that the ignition method can overestimate RAP binder content by approximately one percentage point when compared to the known original mixture's binder content. The difference may include influence from surface treatments such as chip seals. Unless an AC mixture producer and/or laboratory does not account for the potential overestimation of the ignition method, the amount of virgin binder added to an AC mixture containing high RAP contents might be underestimated. This could compound with the improper assumption of 100% RAP binder availability and further contribute to dry, crack-susceptible AC pavements.

RESULTS AND ANALYSIS

Analysis of the results is broken into four parts: IDT strength results, RAP binder rheology, DoA estimates, and DoA method practicality. RAP gradation, RAP binder content, and RAP binder grade are factors affecting IDT strength and thus DoA. These root factors were assessed in terms of their influence on DoA.

While all results are presented, much of the analysis was focused on specimens conditioned at 140°C (284°F) and compacted with the SGC. This group was selected because the temperature and compaction method can be considered the most representative of results that might be used by HMA producers in the U.S. Additionally, direct comparison can be made with the BAF method from the NCHRP 09-58 project, as that research was also conducted at 140°C conditioning temperature (Epps Martin et al. 2020a).

Indirect Tensile Strength

Based on the climate and traffic analysis of the six states, several predictions can be made on the performance of the 100% RAP mixtures. Florida and Texas RAP were predicted to have worse performance due to its greater amounts of environmental and traffic damage. Florida has the second highest amount of ultraviolet radiation, the highest amount of precipitation, and can be expected to carry more traffic, which together can be expected to produce stiffer RAP binder and lower IDT strengths. Wisconsin was predicted to have the best performance due to its softer original binder PG and its lesser amount of damage. Additionally, the BAF results from the NCHRP 09-58 project indicated that Wisconsin would perform best and Florida would perform worst (Epps Martin et al. 2020a).

IDT strength is calculated from the peak vertical compressive load P_{peak} measured from the IDT test, and from the failure plane dependent on the specimen diameter D and height H, as shown in Equation 4. The calculated IDT strength values were averaged over all specimens per sample group, which was at the same conditioning temperature, state RAP source, and compaction method. A best-fit curve was plotted for each state. The results are shown in Figure 9 and are separated by (a) Marshall and (b) SGC compaction. IDT strengths were also indicated by the percentages of air voids (AV) and voids in the mineral aggregates (VMA), shown in Figures 10 and 11. The curves and values seen in the IDT strength plots are generally vertically mirrored by the AV and VMA curves. Typically, VMA is calculated based on the effective binder content, or the volume of binder that is not absorbed by the aggregate. In this research, however, the VMA was calculated on the basis of total binder content, which includes absorbed binder, and thus the values are inflated. For purposes of this relative analysis, this deviation is less important than if the values were considered for project acceptance.

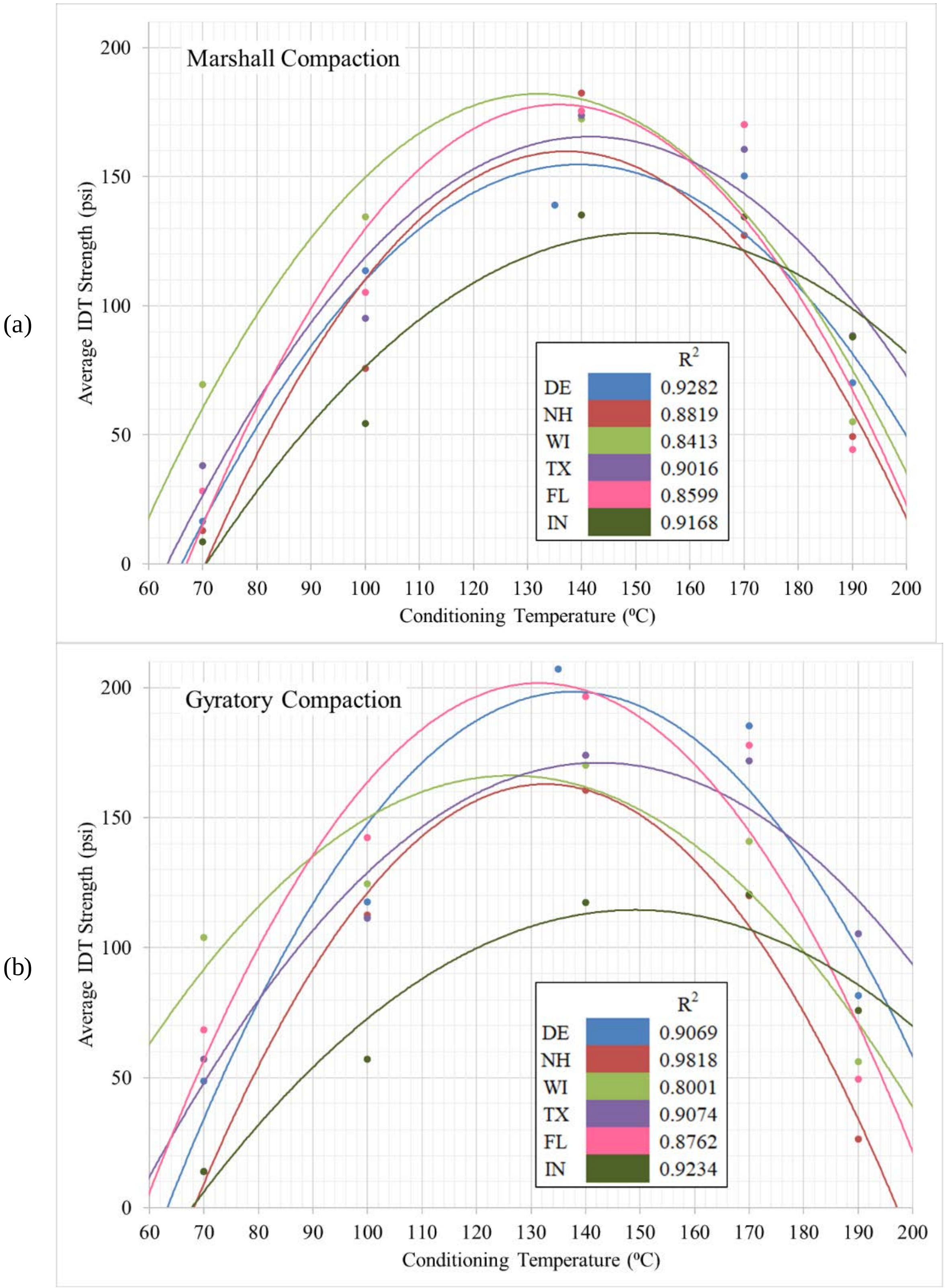
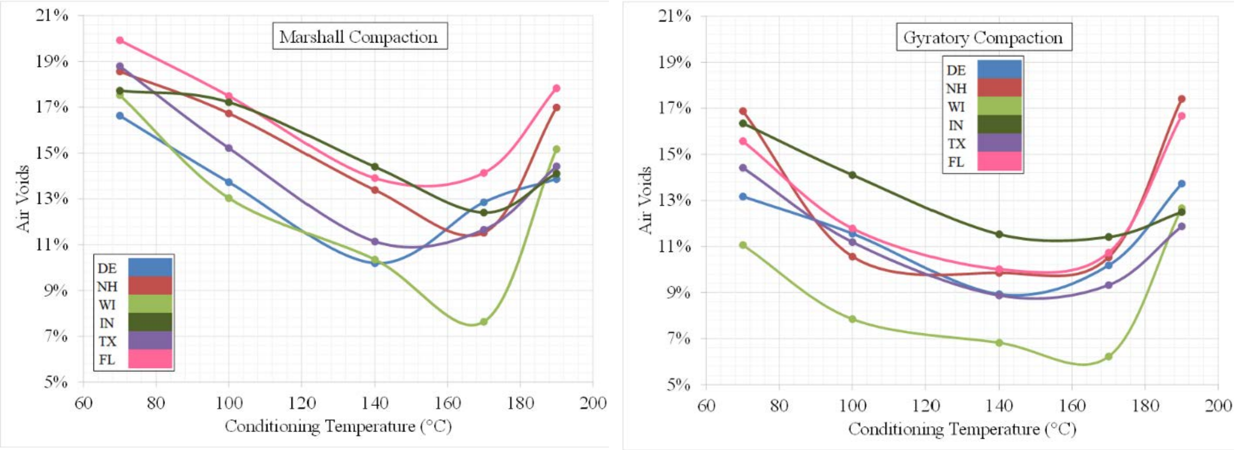
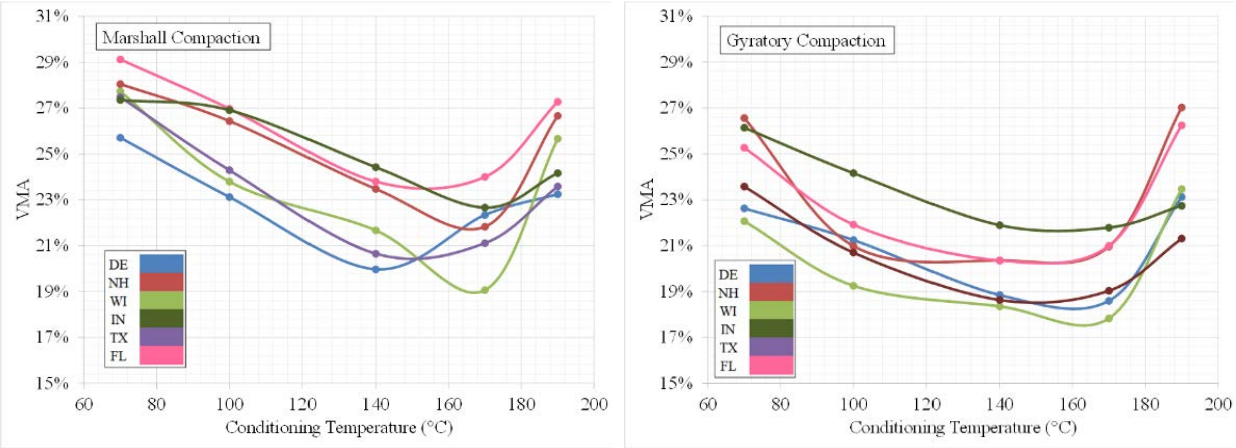


Figure 9 - Indirect tensile strength plots of (a) Marshall compacted specimens and (b) SGC compacted specimens



(a) (b)

Figure 10 - Air void (AV) content by RAP source with (a) Marshall Compaction and (b) SGC compaction



(a) (b)

Figure 11 - Voids in the mineral aggregates (VMA) by RAP source with (a) Marshall compaction and (b) SGC compaction

The strength values produced in this experiment are reinforced by results from prior experiments. Vukosavljevic et al. (2006) also used the IDT test to assess the strength of SGC-compacted AC specimens with varying RAP contents and virgin binder PG. The typical IDT strength values recorded are recreated in Table 6, showing that the 100% RAP mixtures tested here have similar IDT strengths to normal AC mixtures, and that RAP binder provides a similar strength as with virgin binder. In new AC mixtures, for example, TxDOT specifications require an IDT strength between 85 and 200 psi. Strengths below 85 psi indicate a weak mixture susceptible to cracking, while strengths above 200 psi indicate a brittle mixture (TxDOT 2019a). While comparison to normal AC mixtures is useful, this research tests the strength of 100% RAP specimens. Menegusso Pires et al. (2019) tested 100% RAP mixtures in the same manner as this research, assessing the difference between laboratory- and field-aged RAP over several temperatures. The reported IDT strength values and DoA estimates are recreated in Table 7, again mirroring the results from Figure 9. The work completed by Menegusso Pires et al. (2019) was the inspiration for this research, so this positive comparison is significant to note.

Table 6 - IDT test results with varying RAP percentages and binder grades (Vukosavljevic 2006)

	IDT Strength (psi)	
% RAP	**PG 64-22**	**PG 76-22**
0	174	213
10	192	234
20	194	251
30	211	260

Table 7 - IDT test and DoA results with varying temperatures (Menegusso Pires et al. 2019)

	IDT Strength (psi)		
Temperature (°C)	**Field-aged RAP**	**Laboratory-aged RAP**	**DoA (%)**
70	44	93	47
100	110	173	64
140	218	270	81
170	287	283	102

Plant and paving temperature data were collected from field projects in Delaware, Indiana, Texas, and Wisconsin as a part of the NCHRP 09-58 project (Epps Martin et al. 2020a). These average values are shown in Table 8 and compared to the interpolated optimum temperature associated with the maximum IDT strength. These comparisons confirm that typical HMA plant temperatures (150-170°C, 302-338°F) and new pavement mat temperatures (130-140°C, 266-284°F) are already near optimal for maximum activation of RAP binder.

Table 8 - Comparison of plant, paving, and maximum DoA temperatures by state (Epps Martin et al. 2020a)

	Construction report data from NCHRP 09-58 (°C)		**Interpolated optimum temperature (°C) for maximum DoA**	
State	**Average Plant Temperature**	**Average Paving Temperature**	**Marshall**	**Gyratory**
DE	154	136	138	136
IN	151	131	156	150
TX	143	129	141	141
WI	160	132	137	131
FL	-	-	137	132
NH	-	-	138	132

The variation of IDT strength between compaction methods should be noted, although the results have been separated for this research. Table 9 shows the maximum IDT strengths interpolated from the best fit curves, for each state and compaction method. Table 9 also shows the change in magnitude between the two methods.

Table 9 - Maximum IDT strengths (psi) by compaction method

State	**Marshall**	**SGC**	**Δ (SGC – Marshall)**
DE	172	273	+101
FL	173	274	+101
IN	133	140	+7
NH	174	232	+59
TX	181	239	+58
WI	286	372	+86

The difference in mechanics and the effectiveness of the SGC over the Marshall apparatus is highlighted by the positive change for all RAP sources. But clearly some states experienced a greater change than others. This might be affected by the differences in aggregate texture and angularity between RAP sources. For example, a highly angular and rough aggregate such as crushed limestone would have a lower compactability than a rounder, smoother aggregate such as river gravel. A recently developed workability and compactability test for AC mixtures that was developed by Dongré and Morari (2013) was used on the same RAP sources studied in this research (except for Texas) (Epps Martin et al. 2020b). The Dongré Workability Test (DWT) uses the SGC in a non-gyratory, 0.05 mm/s compression test. The workability of the RAP was defined as the slope of the non-linear stress versus volumetric strain curve, calculated at 600 kPa (87 psi). Higher DWT values indicated more workable RAP. The researchers found that the factors influencing workability were binder grade (stiffness), aggregate gradation and physical properties, and conditioning temperature (Dongré and Morari 2013). Since these factors are similar to those known to affect IDT strength, it is useful to compare the results. Figure 12 shows that there is some correlation between the values for the states studied. The IDT strengths for both SGC and Marshall specimens conditioned at 140°C are shown, and DWT values are converted to psi. More workable RAP was more compactable and can result in higher IDT strength. Marshall compaction did not compact the specimens to an equivalent strength as the SGC even with an equally workable RAP. IDT strength is absolute, so it can simply be claimed that the SGC generally creates stronger and denser specimens than the Marshall compactor, although it cannot be claimed that the SGC activates more binder than the Marshall compactor. As mentioned previously and seen in prior research, the Marshall apparatus causes greater variability than the SGC (Loma and Peña 2013). This was visually confirmed as shown in Figure 8. These differences between compaction methods indicate the DoA labeling methodology must rely only on data from the same compaction method, and the results are not interchangeable among different compaction methods.

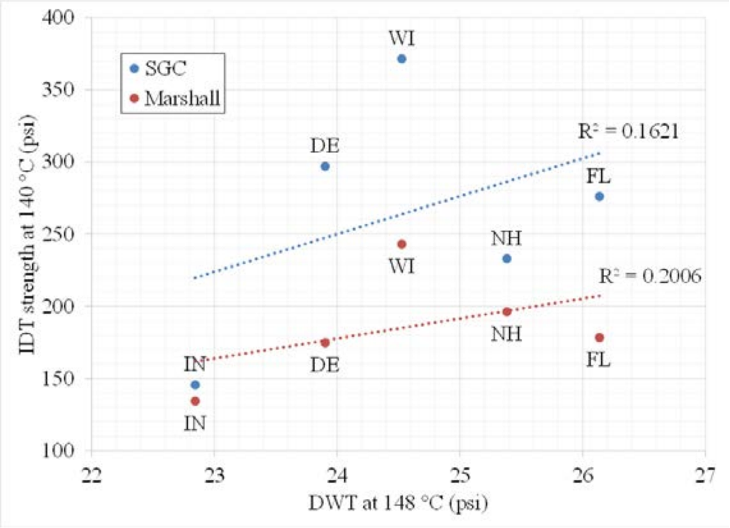
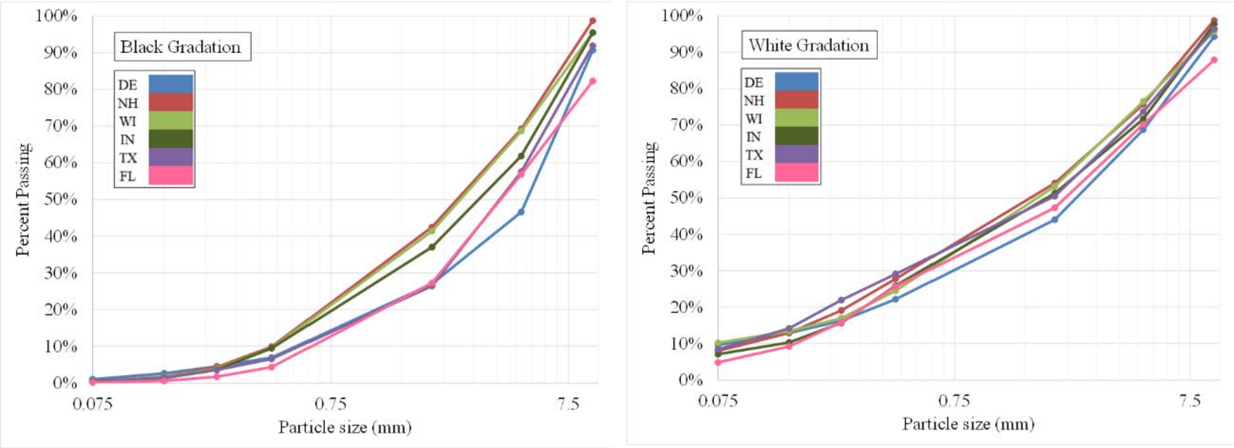


Figure 12 - DWT value versus IDT strength (Epps Martin et al. 2020b)

A linear relationship was predicted to occur between conditioning temperature and IDT strength – with more thermal energy input to the RAP, more binder would be activated; however, a parabolic best-fit curve resulted. The experimental procedures used by Menegusso Pires et al. (2019) were the framework for this research, although they only studied conditioning/mixing/compacting temperatures at 70, 100, 140, and 170°C, not including the 190°C that was studied in this research. The IDT strength results produced a linear trend in this temperature range (70-170°C), leading the researchers to conclude that there is a linear relationship between temperature and DoA. Most prior research did not condition, mix, and compact any AC mixture greater than 170°C, as that is typically the maximum for an HMA plant, so prior knowledge on what happens at this temperature is undeveloped. It is understood that plant gas temperatures greater than 200°C (392°F) can damage the baghouse filters (Mino et al. 2015). However, Bressi et al. (2015) explained the clustering phenomenon of fine RAP particles and assessed high-RAP content (50%) AC mixtures with mixing/compaction temperatures of 140, 160, and 180°C. In Bressi's experiment, the RAP portion was only exposed to the high heat for two hours in contrast to four hours in this experiment. Bressi et al. (2015) found that higher mixing temperatures do not show the clustering phenomenon, and noted that excessively high mixing temperatures can cause RAP binder to lose volatiles and harden, precluding the RAP binder from adhering to other particles. Abed et al. (2018) also studied high-RAP content (50%) mixtures and observed the effect of lower temperatures on the cluster phenomenon, finding that lower temperatures (towards 95°C) caused higher AV contents because clustering did not occur. The finer particle fractions in a gradation have a greater surface area to size ratio, which coincides with a greater ratio of RAP binder to size (Lo Presti et al. 2019). With a greater ratio of RAP binder to size, the finest particle sizes of RAP are the most susceptible to non-clustering regardless of temperature. Based on these prior studies and the parabolic curves of both IDT strength (Figure 9) and AV contents (Figure 10) over the wide range of conditioning temperatures, it can be concluded that RAP binder on the finer particles were not achieving activation at the lowest temperature (70°C), and are potentially experiencing excessive and rapid aging, thus de-activation, at the highest temperature (190°C). In relation to IDT strength, which is tied to the amount and stiffness of the binder in the RAP, the parabolic shape of the curve suggests there is an optimum temperature at which the most RAP binder is activated. Although the parabolic curve was observed with all six state RAP sources in this research, some other laboratories involved in this research did not observe it. The RILEM organizers recently summarized the overall findings and discovered that out of 38 RAPs around the world, nine of them experienced a linear trend, five of them experienced a plateau at the high temperatures, and 24 of them experienced the parabolic trend. These differences are currently under investigation by the RILEM organizers.

Plots of aggregate gradations before RAP binder extraction (black) and after RAP binder extraction (white) are shown in Figure 13. Between the black and white gradations, it immediately can be seen how the fines content was increased from the milling process, and how the RAP experienced the clustering phenomenon as each curve shifts up, equivalent to a greater percent passing each sieve. From the black to white gradation, the percent passing the #200 sieve (0.075 mm) increased from <1% to 9% on average. Florida was the only state to have <5% fines, the typical maximum specification, in the white gradation. Combined with the large clusters (>3/4", 19 mm) observed and struck from the sample before compaction (Figure 6), this could indicate that the Florida RAP was removed from the pavement with a lower energy method than that utilized in the other states. Additionally, in the white gradation, Florida had a NMAS of ½” (12.5 mm), which was one size greater than all other states (3/8”, 9.5 mm). As Peng and Gao (2020) found, a larger NMAS can produce greater IDT strengths.



(a) (b)

Figure 13 - Aggregate gradation by state (a) before binder extraction and (b) after binder extraction

Another assessment of aggregate gradation was performed with the 0.45 power chart, shown in Figure 14. In this chart, the maximum density line (MDL) is based on a maximum aggregate size of 1/2" (12.5 mm), and the aggregate gradation is from after binder extraction (white). As the name implies, an aggregate gradation is theoretically at its greatest density if it matches the MDL. Florida and Delaware were nearest the MDL. Other states were all of a finer gradation and less than optimal, again proving the breakdown experienced by milling and processing.

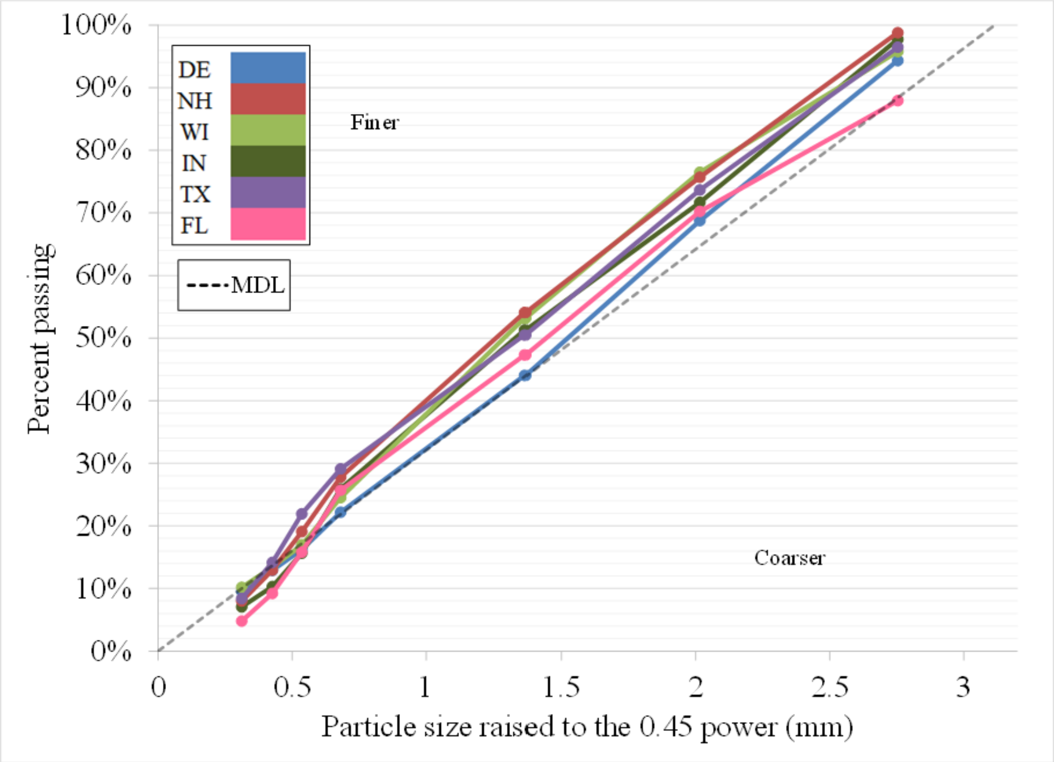


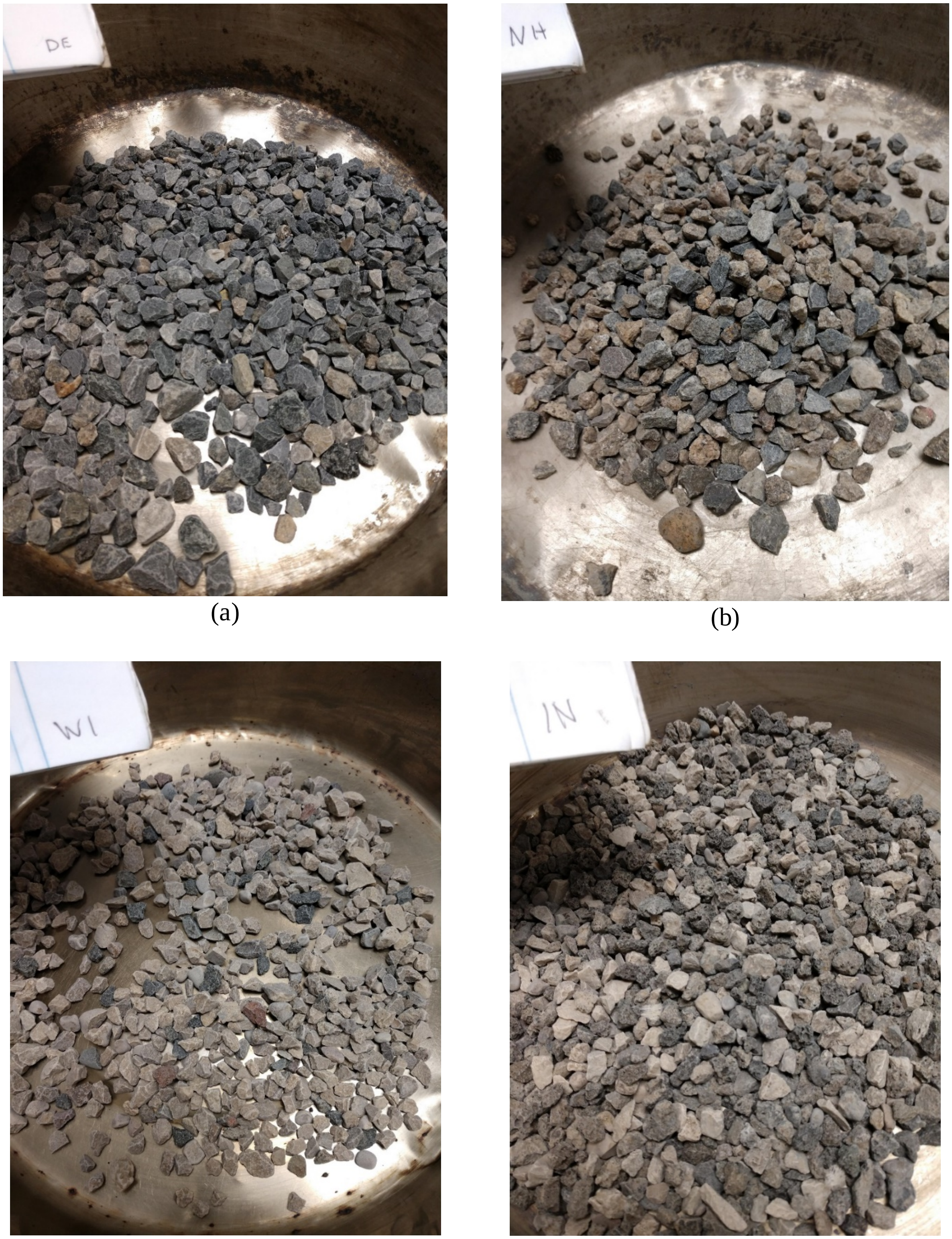
Figure 14 - Aggregate gradation by state on the 0.45 power chart

From Figures 13 and 14 it can be seen that Delaware and Florida had coarser and denser gradations, and Florida had a larger NMAS than other states. Thus, Delaware and Florida received the benefit of optimum gradation when tested with IDT strength. By contrast, Wisconsin had a finer gradation, just as New Hampshire had. These two states had drastically different IDT strengths, indicating that their strengths were more influenced by binder content and grade rather than aggregate gradation. From the comparisons of climates, it should be recalled that New

Hampshire had a more damaging cold climate than Wisconsin. However, the influence of gradation undeniably has an effect on IDT strength and thus DoA. Vasconcelos et al. (2012) also came to this conclusion when comparing dense-graded with gap-graded AC mixtures. The processing and QC of RAP stockpiles to keep a consistent gradation is important for pavement engineers to maintain a consistent and reliable DoA value.

RAP binder content of a mixture influences the IDT strength as the binder behaves like a viscous glue. In an AC mixture, the effective binder content is the portion of binder that actually contributes to strength. In this research, unfortunately, the effective binder content was not measured, so values presented are the total binder content from solvent extraction. However, as discussed previously, it should be considered that solvent extraction methods may not solubilize all of the binder. As with VMA, the relative comparison of binder contents within these six states is more important than the specific value. The differences between total and effective binder content becomes greater with increasing aggregate porosity and absorption. Again, aggregate porosity and absorption were not measured in this research, but some empirical estimates can be made.

As seen in Figures 9 and 10, Indiana has the greatest AV content and lowest IDT strength. Indiana has a relatively mild climate, compared especially to Florida and Texas. A supposedly less-aged RAP binder would equate to higher IDT strength, but in the case of Indiana, it is likely due to lower effective binder content. Figure 15 (d) shows the Indiana aggregate after binder extraction. With approximately half of the coarse fraction consisting of highly porous igneous rock, the effective binder content was likely reduced, resulting in a lower IDT strength. Figure 15 also shows the relatively consistent aggregate types of the remaining states.



(a) (b)

(c) (d)

Figure 15 - “White” aggregate after binder extraction by state

(e) (f)

Figure 15 (continued) - “White” aggregate after binder extraction by state

The Florida RAP was the only material in which the source aggregate was known from prior research. The stockpile sampled consisted of granite and limestone aggregates, which are known to have greater absorption capacities (Arámbula Mercado et al. 2018), thus lower effective binder. Considering these unmeasured potential differences, the total binder contents are listed in Table 10. Wisconsin had the greatest binder content at 5.0%, which contributes to its superior strength seen in Figure 9 and low AV content in Figure 10. The lowest binder contents were in the RAP from Texas and Delaware at 4.3%, yet Delaware still had low AV and relatively high IDT strength, which may be explained by its high dust proportion.

The dust proportion (DP) is the ratio of percent passing the #200 (0.075 mm) sieve and percent effective binder content, and can highlight the effect of fines and binder content on IDT strength. DP should be calculated based on effective binder, but was calculated based on total binder in this research since data were not available. Just as with VMA, the exact value is less important than the relationship to the other states. The binder contents, fines content (% P_{200}), and resulting dust proportion are listed in Table 10. For new AC mixtures, the typical desired values range between 0.6 and 1.2, in line with a desire for a fines content less than 5%. Higher DP values in new AC mixtures typically mean the mixture has an inadequate amount of binder and will experience early cracking (Asphalt Institute 2014). However, in this case, where RAP aggregates are broken down by the milling and fractionating processes, the fines content is skewed much higher than intended for the DP value. Therefore, the key comparison in Table 10 is the dust content: Wisconsin and Delaware had the highest dust contents and this may have contributed to more clustering, lower AV, and better strength development than other states.

Table 10 - RAP binder contents and dust proportions by state

State	**P_{200}, %**	**% binder**	**DP**
FL	4.8	4.7	1.02
IN	7.1	4.8	1.49
NH	8.0	4.8	1.68
TX	8.4	4.3	1.94
WI	10.2	5.0	2.04
DE	9.6	4.3	2.21

Although the fines contents were directly related to IDT strengths, the DP values were generally inversely related to the IDT strengths of SGC specimens at 140°C, with Florida as an exception. The Florida DP is mostly affected by its relatively low fines content, but also by its aggregate absorption capacity and reduced effective binder. Because the Florida RAP still had high IDT strength despite a low fines content, the influence of a dense, coarse gradation with a larger NMAS is again highlighted. However, even though states with a high fines content had low AV and high strength (Delaware and Wisconsin), this factor should not motivate pavement milling operations to create as much fines as possible. A higher fines content in the RAP will require greater QC efforts due to the remaining 5% fines limit in new AC mixtures, and it will require more energy expenditures in the milling and fractionating processes. A best practice in milling operations still holds that the least energy necessary should be used, such as a slower milling drum speed (Ross 2015).

The correlation between RAP binder content and DoA is shown in Figure 16. The wide spread of values is most likely due to the issues of effective versus total binder, plus the DP as discussed. If effective binder content was measured, it can be predicted that the correlation would be more direct because the Florida and Indiana data would shift to the left.

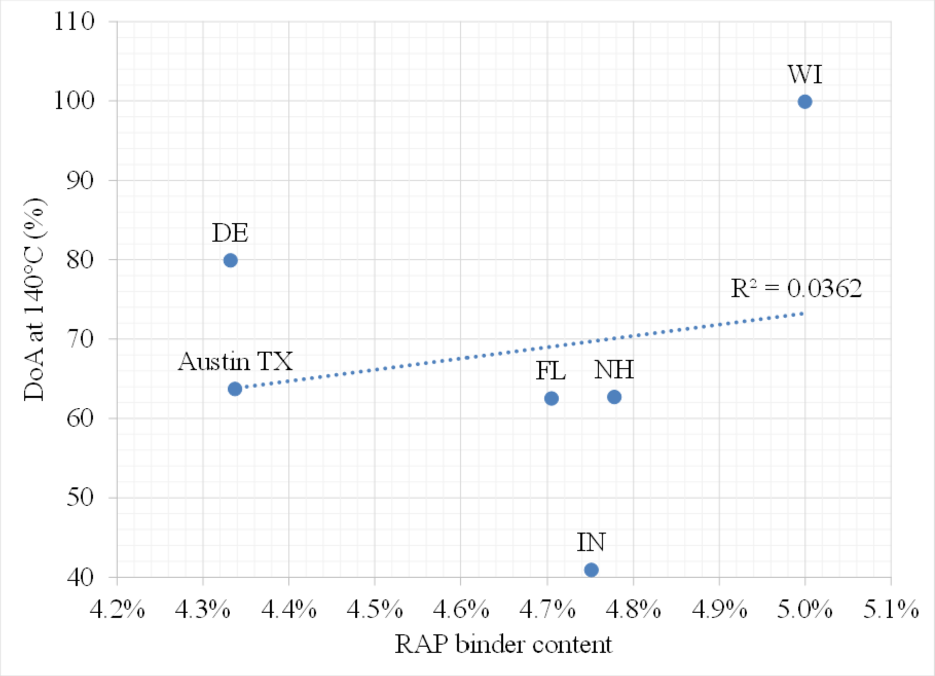


Figure 16 - RAP binder content correlation with DoA

Binder Rheology

Binder grade is the third main influence on IDT strength and DoA. A softer binder (i.e., less viscous, less stiff) should be expected to be more active than a more aged, stiffer binder.

The rotational viscometer was used to measure each state's RAP binder viscosity at several high temperatures: 135, 140, 170, and 190°C (275, 284, 338, and 374°F). Lower temperatures of 100°C and 70°C (212°F and 158°F) were not measurable with the rotational viscometer due to the high viscosity of the binder at those temperatures. The viscosity in Pascal-seconds versus temperature is shown in Figure 17 with specific values tabulated at the end of this section. The unrealistic Delaware results may have been impacted by a mistake in data collection techniques and are likely outliers. Wisconsin RAP binder was significantly less viscous than that from all other RAP sources, likely due to it being the softest original binder PG and a less damaging climate. For virgin binders, certain viscosity values are targeted for typical mixing and compaction temperatures of 155°C and 140°C (311°F and 290°F), respectively.

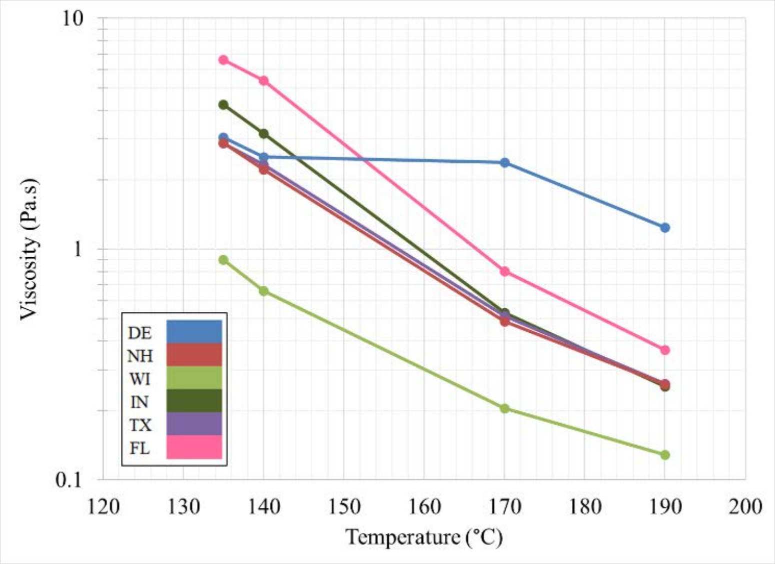


Figure 17 - Viscosity data measured with the Rotational Viscometer

Although the penetrometer is uncommon in the U.S., the test was requested by RILEM as part of the round robin research due to its commonality in Europe. Penetration values in decimillimeters (dmm) for each state are shown in Figure 18 and Table 11. As with the rotational viscometer, the Wisconsin RAP binder was significantly softer than that from other states. However, all binder penetration results were too low to be graded in the Penetration-Graded specification system, which requires a minimum penetration of 40 dmm (ASTM D946).

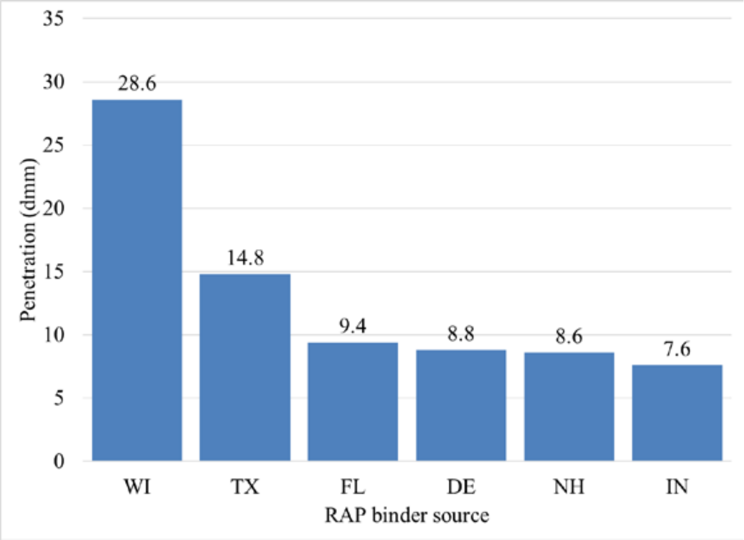


Figure 18 - Penetration data measured with the Penetrometer

The viscosity and penetration data are useful in older binder grading systems more common in Europe, but the PG system requires the use of more advanced rheology equipment, including the Dynamic Shear Rheometer (DSR) and the Bending Beam Rheometer (BBR).

The DSR was used to test the high and intermediate temperature behavior of three aging states: originally extracted/recovered RAP binder (OB), Rolling Thin-Film Oven aged RAP binder (RTFO), and 20-hour Pressure Aging Vessel aged RAP binder (PAV). Although RAP binder has already experienced at least one life-cycle of aging, the RTFO and PAV were used in this research to simulate the further aging that the RAP binder would experience during and after inclusion in a new AC mixture. The high-temperature testing of RTFO-aged binder is a key result from DSR testing, as it is used to report the high PG temperature (PGH). Kaseer et al. (2019), as a part of the NCHRP 09-58 project, found a significant negative correlation between PGH and BAF; lower RAP binder PGH produced a greater BAF, otherwise stated that softer binder is more available. These results are shown in comparison to the results measured in this research in Figure 19. The greater PGH values in this research were likely due to two main reasons: (a) the NCHRP 09-58 data were measured approximately two years before the DoA research data, and (b) the binder extraction methods differed as discussed previously. Figure 19 confirms that a higher PGH, linked to more damaging climates, correlates with a reduced DoA.

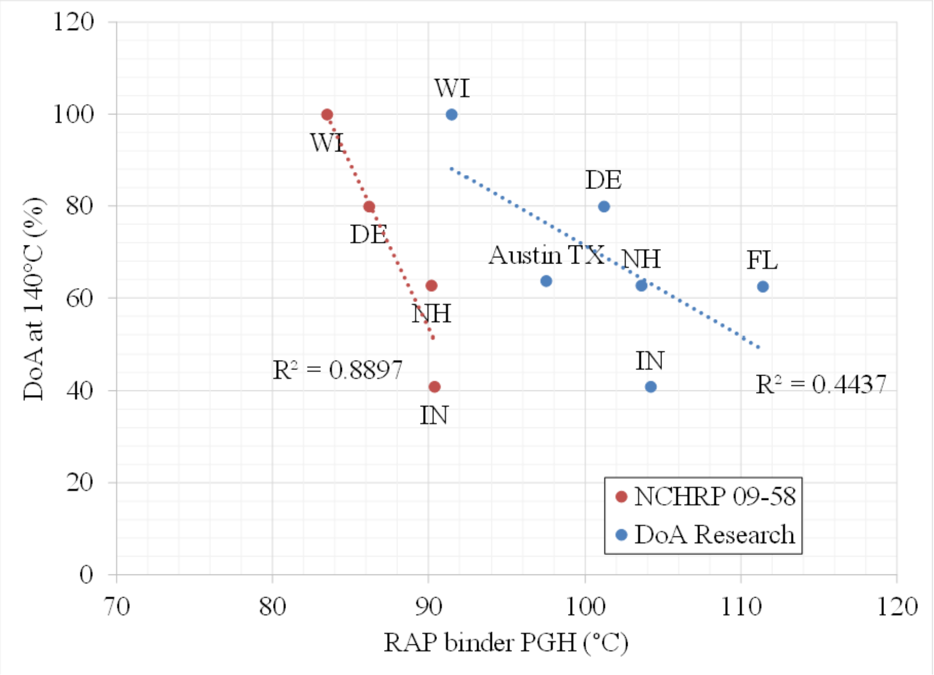


Figure 19 - Correlation between RAP high temperature PG and DoA (Epps Martin et al. 2020a)

The PGH results, part of the continuous PG, from this research are compared against results from the BAF study performed as a part of the NCHRP 09-58 project in Table 11.

Low temperature PGs (PGL) were measured with the BBR, and ΔT_c values were calculated from the differences between the stiffness-based PGL and the relaxation-based (m-value) PGL. Positive ΔT_c values are realized by binders that are controlled by the stiffness at low temperatures, while negative ΔT_c values are determined for binders that are controlled by their relaxation ability at low temperatures. A greater magnitude of a negative ΔT_c value means that the asphalt binder has less ability to relax the buildup of tensile stresses due to restrained thermal contraction. Previous research into the ΔT_c parameter concluded that binders with values lower than -5°C or -6°C (23 or 21°F) are at significant risk of thermal cracking in pavements. Additionally, it has been observed that low (more negative) ΔT_c values have a reduced fatigue life, based on flexural fatigue beam tests (Asphalt Institute 2019). Both thermal and fatigue cracking are common issues in high-RAP content AC mixtures, so a low-magnitude ΔT_c value is desirable when considering these results. Values of ΔT_c from this research, as well as from NCHRP 09-58, are included in Table 11. The results between the two methods are closely related.

As the ΔT_c parameter is a relatively new concept for describing binder properties, there is currently no research connecting ΔT_c to binder availability or other blending parameters. As shown in Figure 20, neither BAF nor DoA has a significant correlation with ΔT_c. ΔT_c values were all negative, indicating the PGL of all RAP sources studied were governed by its relaxation rate (m-value) instead of its stiffness, as expected. The magnitudes of all ΔT_c values except for New Hampshire confirm that these RAP binders are at a high risk for premature cracking in pavements. If the desired effect of increased usage of RAP is realized, pavement engineers should consider the effects of high-magnitude ΔT_c values of RAP binders.

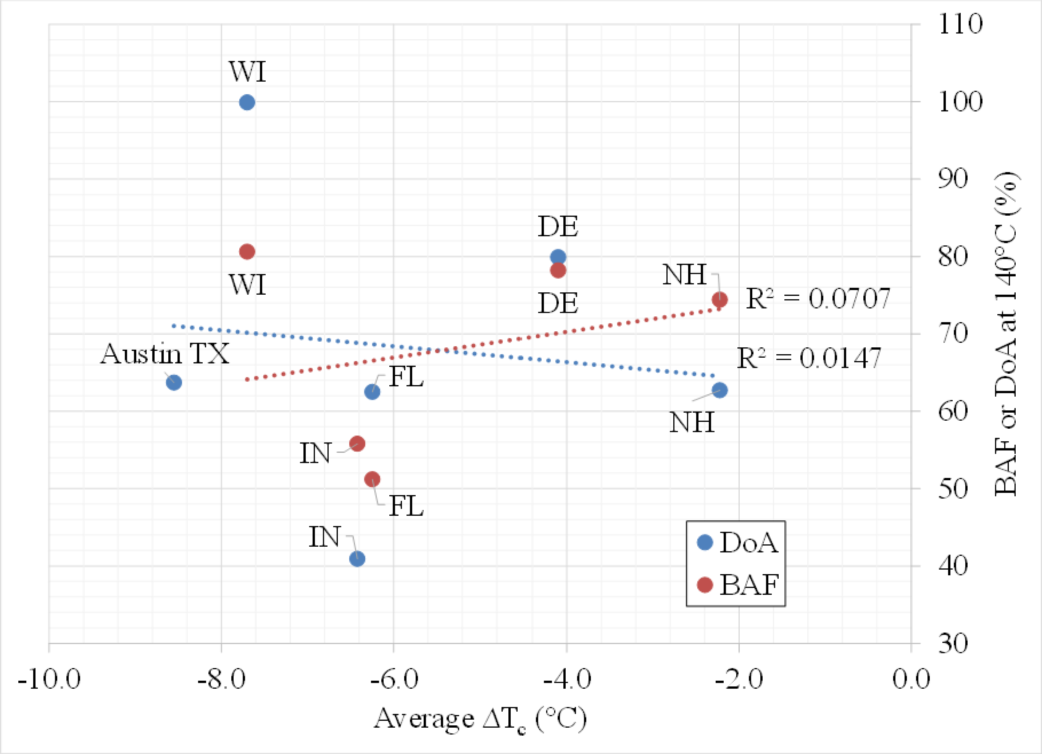


Figure 20 - Correlation between ΔT_c and RAP BAF or DoA (Epps Martin et al. 2020a)

Differences in binder rheology results between NCHRP 09-58 data and this research might be explained primarily from the difference in binder extraction methods as previously discussed, the additional storage/aging time of the RAP, or within laboratory variability.

Table 11 - RAP binder tests summary (Epps Martin et al. 2020a)

RAP Source	**Binder content (%)**	**Penetration (dmm)**	**Viscosity @135°C (Pa.s)**	**BAF @140°C (%)**	**DoA @140°C, SGC (%)**
DE	4.3	8.8	3.06	78.2	79.9
NH	4.8	8.6	2.90	74.4	62.7
WI	5.0	28.6	0.90	80.6	99.9
IN	4.8	7.6	4.23	55.8	40.9
FL	4.7	9.4	6.63	51.2	62.5
Austin, TX	4.3	14.8	2.88	-	63.7

Table 11 (continued) - RAP binder tests summary

RAP Source	Continuous PG (09-58)	Continuous PG	PGH (RFTO)	Inter. PG (PAV)	PGL (S)	PGL (m)	ΔT_c (09-58)	ΔT_c
DE	86-14	101-11	101.2	41.1	-14.2	-10.7	-4.4	-3.8
NH	90-21	104-8	103.6	45.8	-10.2	-7.8	-2.1	-2.3
WI	83-11	92-11	91.5	36.7	-17.9	-11.2	-7.3	-8.1
IN	90-14	104-6	104.2	42.1	-14.0	-5.8	-6.2	-6.6
FL	-	111-5	111.4	46.4	-11.6	-4.7	-	-6.2
Austin, TX	-	97-8	97.5	37.7	-24.0	-7.9	-	-8.6

Considering the multitude of factors that affect IDT strength, a summary comparison is useful before the analysis of the DoA results. The DoA results rely solely on IDT strength data, which have been found to have several influencing factors with varying levels of control, as shown in Table 12. In addition to the factors analyzed in this research, Lo Presti et al. (2019) summarized several other influential factors on IDT strength of 100% RAP specimens, including conditioning temperature, conditioning time, and mixing time. When considering the degree of blending within a high-RAP content AC mixture, the list expands to include RAP content, virgin binder and aggregate properties, and rejuvenator type and dose.

Table 12 - Summary of influential factors on IDT strength

Factor	**Optimum density**	**NMAS**	**Coarseness**	**Aggregate Porosity**	**Workability (DWT)**	**Effective binder content**	**Fines Content**	**PGH**	**Compactive effort**
Effect on IDT strength	+	+	+	-	+	+	+	-	+
Controlling?	Yes					Yes		Yes	

Note: + : positive relationship; e.g., a larger NMAS causes a higher IDT strength
- : negative relationship; e.g., a higher PGH causes a lower IDT strength

Degree of Reclaimed Asphalt Pavement Binder Activity (DoA)

The DoA of RAP is calculated from the IDT strength using Equation 3. The numerator in the ratio is the IDT strength of the specified temperature and source, and the denominator is the interpolated maximum IDT strength of all sources across all conditioning temperatures. In this research, the maximum interpolated values were for Wisconsin at 285.8 psi (1.97 MPa) for Marshall compacted specimens and 371.8 psi (2.563 MPa) for SGC specimens. Table 9 includes all RAP IDT strengths compared at 140°C. It is important to remember that this DoA estimation solely considers IDT strength, and no other parameter.

The denominator was chosen to be the global maximum from all six RAP sources (while still separating by compaction method), instead of a unique maximum value for each source. This reduces the unnatural cases of some source/temperature combinations of having a DoA greater than 100%, and it allows for better comparison between RAP aging conditions (climates). If a unique denominator was used, the DoAs for all states would be at or near 100% at 140°C, which was considered unrealistic and not useful, so relative DoA values were used. A DoA value equal to or greater than 100% is unrealistic because there will always be some RAP binder that is absorbed by the RAP aggregate, which will not be available for blending. In these data, one instance of DoA >100% occurred: Wisconsin at 170°C conditioning with Marshall compaction (117.5%). This case occurred because of the significantly higher average IDT strength at 170°C for Wisconsin. In this situation, the DoA value would be corrected (reduced) to a more realistic value less than 100%, but the result will remain uncorrected for this analysis.

The calculated DoA results are presented in Figure 21. The error bars are determined from one standard deviation of the IDT strength data. The wide spreads of the error bars were a result of (a) the inherent variability of RAP, and (b) small specimen size (100 mm x 63.5 mm), which still experienced segregation of the mixture. The DoA plots naturally followed the IDT strength plots as evidenced by a peak in DoA values between 140°C and 170°C, and the lowest values at the extreme temperatures of 70°C and 190°C. Visual evidence of this parabolic gradient can be seen in Figure 22, which highlights the coloration differences between conditioning temperatures, as well as increased AV at extreme temperatures. The lower strength and DoA at 70°C and 190°C are associated with higher AV content (Figure 10) due to the inactivity of the RAP binder on the finest particles. Additionally, RAP sources with the lowest IDT strength have the least DoA, as seen with Indiana.

(a)

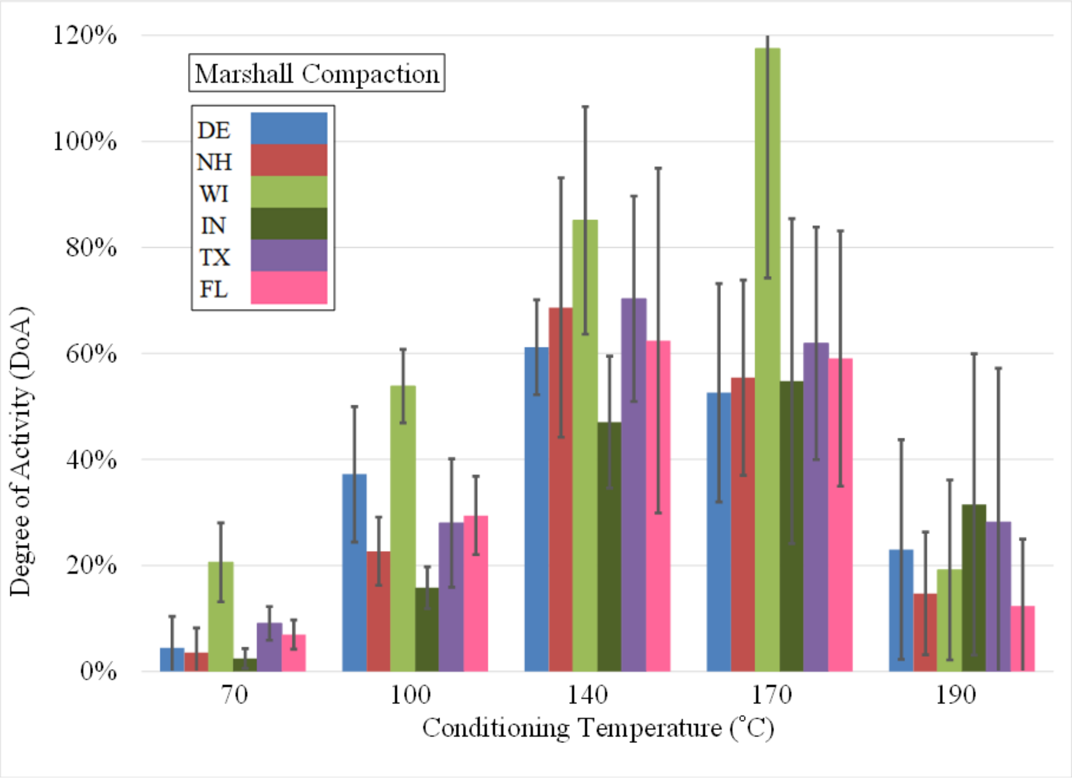


Figure 21 - DoA results of (a) Marshall compacted specimens and (b) SGC compacted specimens

(b)

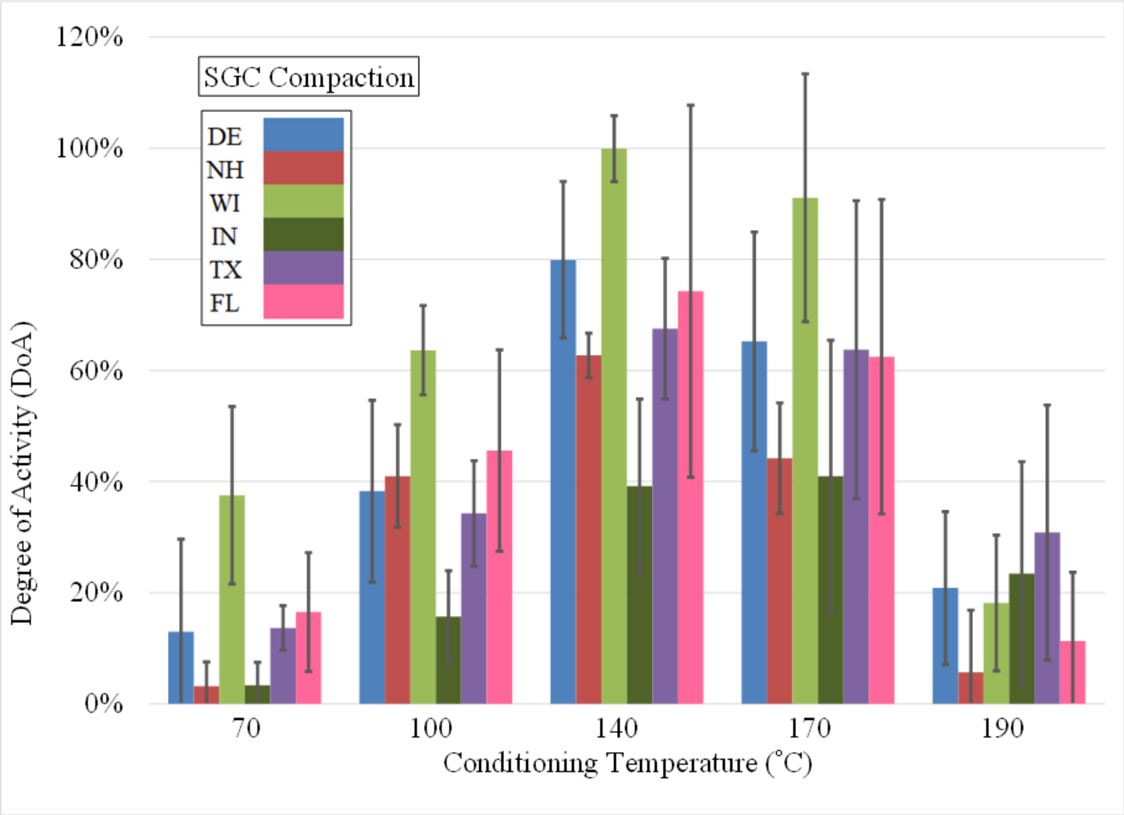


Figure 21 (continued) - DoA results of (a) Marshall compacted specimens and (b) SGC compacted specimens

Figure 22 - Texas RAP conditioned at all temperatures and separated by Marshall compaction (rear) and SGC compaction (front)

It is impossible to truly know if these DoA values are accurate, just like all other methods, because empirical methods are the only methods in practice. However, useful comparisons can be made between the DoA estimated here and the Binder Availability Factor (BAF) (Epps Martin et al. 2020a). The BAF research was based only on mixing, conditioning, and extracting, and carefully controlled the gradations of the mixtures studied, so aggregate gradation could not be studied for influence. This DoA research was based on IDT strength, which is naturally influenced by aggregate gradation. The values of BAF and DoA at 140°C are compared in Figure 23 and show good correlation between the methods. Both Marshall and SGC compaction methods are shown.

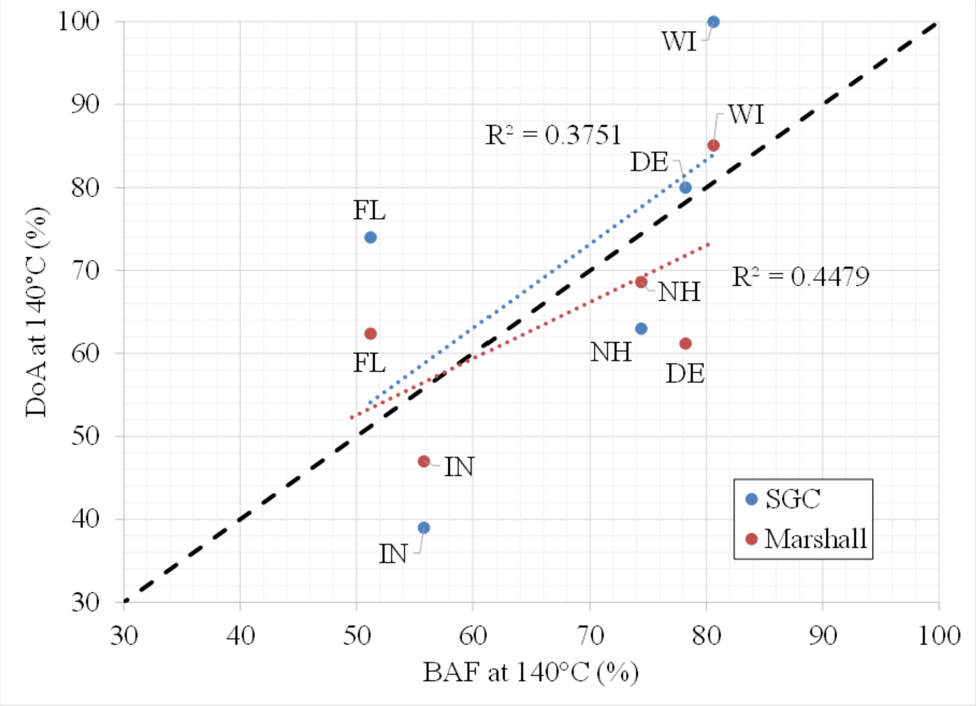


Figure 23 - Correlation between RAP BAF and DoA (Epps Martin et al. 2020a)

The BAF method had certain differences from the DoA method that may affect the comparison between values. First, the BAF method only used RAP of intermediate size (between #4 and 3/8" sieve (4.75 - 9.5 mm)); as previously discussed, the finer fraction (passing #4 (4.75 mm)) has shown to have a greater ratio of binder to particle size and thicker binder film, which have the greatest effect on clustering and AV content (Epps Martin et al. 2020a; Lo Presti et al. 2019). Second, the BAF method only mixed and conditioned the mixture, and did not compact specimens. When considering the basis of energy, the DoA method uses a greater amount of mechanical energy in addition to thermal energy, instead of relying primarily on thermal energy as in the BAF method. Additionally, because the DoA method uses compaction, it considers the actual production of AC pavements and not just laboratory conditions. Finally, the DoA method has the advantage of using 100% RAP samples, while the BAF method mixes RAP with virgin materials. This distinction is key for establishing the DoA as a practical labeling method for RAP.

The black 1:1 line in Figure 23 and the DoA trendlines indicate that the DoA method with SGC specimens estimated more binder was activated than the BAF method. DoA values from Marshall specimens had a similar trend but tend to underestimate binder activity both compared to the BAF method, and the values from SGC specimens. The clear explanation of differences between both compaction methods and the BAF method is that the influence of aggregate gradation is included in the DoA method but not the BAF method. A RAP with a coarse and dense gradation, a high fines content, large NMAS, and low-porosity aggregate will have higher IDT strength and a greater DoA, as summarized in Table 12 and evidenced by the results of Delaware and Florida RAP. However, because the DoA label is intended to characterize only the RAP binder behavior, and not the aggregate properties, a correction factor may be necessary to include in the DoA method. Correcting the DoA values for aggregate properties would lower the DoA estimates to even lower values than those produced in this research, but can aid in the proper design of new AC mixtures to include adequate levels of virgin binder and/or rejuvenator. Gradation is linked to AV content, which is linked to density of the specimen, which is affected by compactive effort. So a focus on compactive effort for estimating and correcting the influence of gradation can be accomplished through one of two ways: (a) if the SGC is used, a termination value of a certain relative density can be used to reduce the effect of AV on DoA; (b) with the Marshall apparatus or SGC, use a fixed compaction repetition (i.e., 50x2 or N=30), then apply a correction factor to IDT strength based on the measured AV results. Another focus for gradation correction can simply be through empirical and experiential reduction factors as a pavement engineer tests more and more RAP for DoA. For example, using the RAP gradation data already gathered through standard mix design practices, a pavement engineer could apply a reduction factor based on its proximity to the MDL (Figure 14). Further research into the influence of aggregate properties and gradation is recommended to develop the DoA labeling method into a more accurate estimate.

In general, the predictions made based on climate and estimated original binder PG were confirmed with the DoA data. Binder content and grade are the main factors affecting IDT strength and thus DoA, as shown with Wisconsin. Gradation and aggregate properties also influence IDT strength and DoA, as seen with Florida, Delaware, and Indiana. The parabolic trends seen in AV contents, IDT strengths, and DoA were confirmed visually as the compacted RAP specimens showed a gradient of color and porosity (Figure 22), and were explained with the clustering phenomenon of the finest fraction of the RAP. With the assumption that the prior research on the same RAP materials is accurate, the DoA values calculated were a realistic estimate of reduced RAP binder availability, with few exceptions. The 99.9% DoA result of Wisconsin SGC specimens at 140°C conditioning, and the 117% DoA result of Wisconsin Marshall specimens at 170°C conditioning are both unrealistic. These values would likely decrease to realistic values either through common-sense correction factors or as the DoA knowledge base develops with more diverse RAP sources.

Degree of Activity Labeling Method

The DoA labeling method used here is a practical method to give pavement engineers a more realistic estimate of the amount of RAP binder that contributes to a new AC mixture. The process only requires two pieces of equipment – a compactor and an IDT test frame – which are simple and commonly available in asphalt laboratories around the globe. The DoA testing procedure can be completed within one day or less and should not add excessive burden to the engineer or technician. Additionally, as more IDT strength tests are completed on a wider variety of stockpiles, the DoA values become more reliable. Proper testing frequency has the potential to reveal major shifts in RAP quality. For example, if the DoA value suddenly drops, it may initiate a discussion between agency, AC producer, and contractor in efforts to improve QC.

The DoA process can be integrated within the typical existing mixture design process. The normal minimum procedures a pavement engineer or technician must perform on RAP include determining the binder content and gradation of the RAP. A more complete test regimen for RAP might also include determining the continuous PG, the ΔT_c parameter, or other binder properties. The DoA procedure will first require multiple tests at varying temperatures to interpolate the maximum IDT strength of 100% RAP mixtures. For typical HMA applications, a temperature range of 150°C to 170°C (302°F to 338°F) would be appropriate. This first step establishes the denominator of the DoA ratio. Second, the RAP must be tested at its expected plant mixing temperature, typically 160°C (320°F). This value establishes the numerator of the ratio and finally provides an estimate of the DoA to be considered in mixture design. As concluded previously, a correction factor for aggregate gradation may be necessary before finalizing the estimated DoA value. Additionally, some consideration should be given to the amount of time the RAP will spend at high production temperatures, such as while in a storage silo. It has been found that longer conditioning periods are more beneficial for RAP binder activation (Lo Presti et al. 2019). With the binder content, gradation, and DoA of the RAP; a pavement engineer can then continue with normal mix design procedures outlined by their state DOT specifications or by industry standards such as the Asphalt Institute MS-2 manual (Asphalt Institute 2014). If the pavement engineer decides to add rejuvenating agent to a new AC mixture containing RAP, then the increase in available binder must be considered with the DoAv as explained by Lo Presti et al. (2019). Overall, a DoA value of 60-90% would be expected for typical HMA plant production. For WMA, 10-60% DoA is more applicable, but RAP binder may not be reliable at the lowest temperatures (70°C), except from the coldest climates with a soft original PG binder such as Wisconsin. These general estimates were also seen in the results from Menegusso et al. (2019), recreated in Table 7. As seen in Table 8, typical HMA plant temperatures range between 150°C and 170°C (302°F and 338°F), although the production temperature depends on the viscosity of the virgin binder used in the mixture. WMA production temperatures are typically in the range of 90°C to 110°C (194°F to 230°F). In-place recycling methods, while not creating RAP stockpiles, may be able to utilize the DoA estimate when optimizing the proportions of virgin binder and/or rejuvenating agent in the rapidly mixed and replaced pavement. This method would require the effective sampling of the existing pavement to be recycled via cores to the design milling depth. Greater reliabilities could be achieved in this technique, assuming the existing pavement section was constructed to acceptable consistencies. DoA could also be used in the design of a bitumen-stabilized base course, provided RAP is used in the mixture. The high IDT strengths produced in this research indicate that the DoA methodology could allow for better optimized base courses.

As with any laboratory procedure, there are some limitations. The DoA relies solely on the IDT strength of the specimens, which is empirical and may be affected by other factors inherent to the variability of RAP, such as the presence of modifiers, additives, or foreign debris. The simplicity of the estimate, while also a benefit, can cause an improper estimate of actual activated RAP binder; theoretically there will be a single stockpile that is labeled 100% available, though that is impossible in reality as some amount of virgin binder is always absorbed into the aggregate, rendering it ineffective/unavailable. Any testing of RAP stockpiles depends on the variability within the stockpile. For example, a series of questions to consider include: How many and what type of pavement sections are represented in this stockpile? What was the pavement removal technique used (i.e., milling versus breaking)? What stockpile storage methods were used (e.g., single-stack, uncovered versus covered)? Were the RAP stockpiles maintained properly by blending? Greater confidence in the availability of RAP binder can be achieved with extensive sampling and laboratory testing, but the drawback is in the cost, time, and difficulty in performing those advanced analyses. This proposed DoA method is designed to be practical and fast enough while providing adequate estimates of RAP binder availability.

If DoA labeling were to be implemented, a feasible option would be to have state agencies manage a database of RAP stockpiles at a certain testing frequency. This could allow for realistic data management and support a regional or nationwide database. The size and variability within the state must be considered when developing a RAP stockpile label such as DoA. For example, in Texas alone, there are two major climate zones, with wide temperature and precipitation variations, causing different aging conditions in RAP sources across the state. Testing frequency should be at least the same rate as existing practices for RAP gradation and binder content, particularly since DoA is influenced by gradation and binder content. The results and analysis indicate that there is an effect of gradation on DoA that causes a potential overestimation of the actual binder activity. If this overestimation is confirmed with further research, it is recommended that a correction factor be used.

CONCLUSIONS

This research assessed the practicality of a RAP labeling method based on IDT strength testing of 100% RAP mixtures to estimate a realistic reduced amount of RAP binder activity for use in AC mix design. Several conclusions can be drawn:

1. RAP binder on the finer particles is not activating at the lowest temperature (70°C, 158°F), and is potentially experiencing excessive and rapid aging, and thus de-activating at the highest temperature (190°C, 374°F) considered.

2. Typical HMA plant temperatures (150-170°C, 302-338°F) and new pavement mat temperatures (130-140°C, 266-284°F) are already near optimal for maximum activation of RAP binder. DoA is optimized between 140 and 170°C (284 and 338°F).

3. The differences between compaction methods (Marshall and SGC) indicate the DoA labeling methodology must rely only on data from the same compaction method, and the results are not interchangeable. Marshall compaction creates issues with segregation within specimens that may affect DoA values.

4. RAP binder content and grade has the greatest effect on DoA, but aggregate gradation and physical properties can skew the DoA to unrealistic levels. A correction factor to account for the impact of gradation and aggregate properties should be applied after further research.

5. Effective binder content should be measured when researching DoA. Using only the total binder content does not account for absorbed binder which will not become activated.

6. The DoA denominator should be a global maximum instead of unique to the stockpile tested. A shared database of stockpile DoA labels would be beneficial, and data quality and DoA estimates would improve over time.

7. A DoA value of 60-90% would be expected for typical HMA production. For WMA, 10-60% DoA is more applicable, but RAP binder may not be reliable at the lowest temperatures (70°C, 158°F) unless additional binder activation techniques are used.

8. The DoA labeling method is practical, simple, and can be incorporated into existing mixture design methods to allow pavement engineers to estimate a reduced (less than 100%) RAP binder availability.

9. The DoA label is limited because it is related to itself, empirical in nature, and can be affected by many inherent factors of variability.

Because the DoA method is newly introduced as of 2019 but shows promise in its efficacy and practicality, further research is recommended in this area. Specifically, the influence of aggregate gradation must be addressed and corrected, and the relationship of effective binder content to DoA must be understood. The performance of new AC mixtures utilizing RAP at varying contents with the DoA methodology must be studied in order to validate this method. Additional studies with RAP from more varying sources should be performed to further bolster the DoA knowledge base. Finally, studies of the effects of certain variations of RAP on the DoA should be conducted, such as understanding the effects of RAP with modifiers, additives, or other recycled products.

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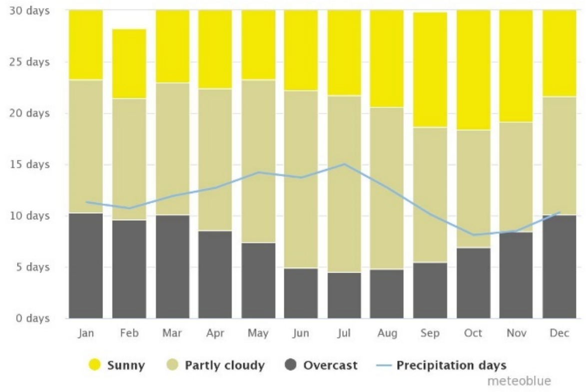
APPENDIX – Solar exposure by location [29]



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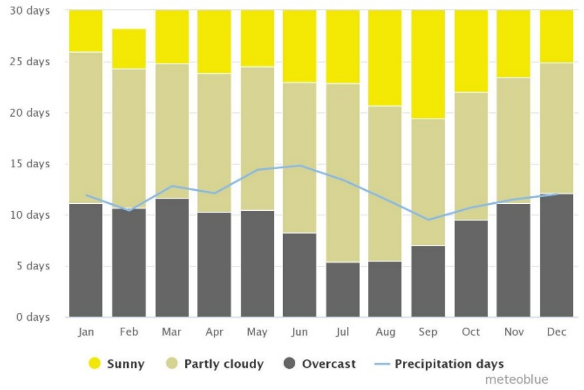

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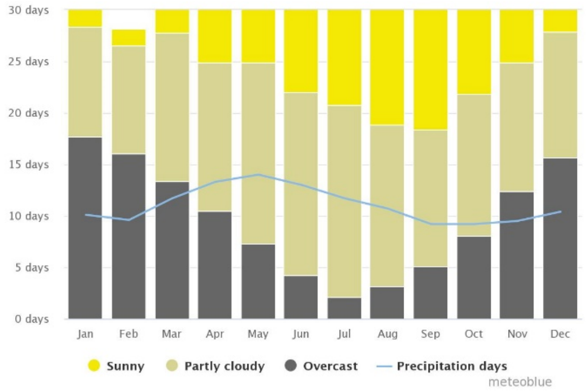

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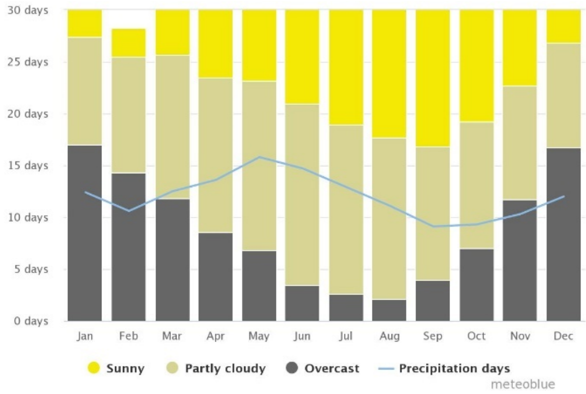

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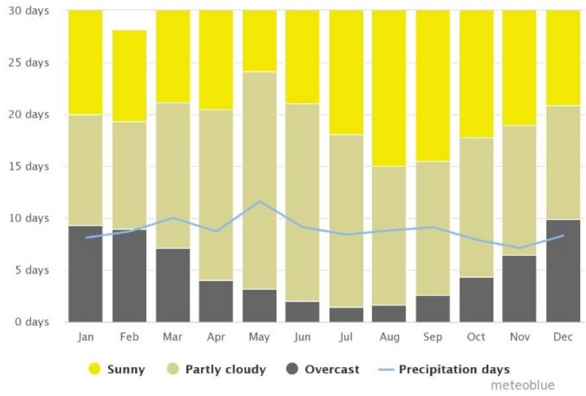

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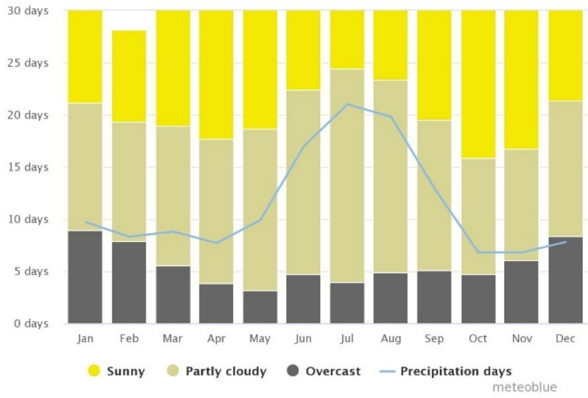

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