A LABORATORY STUDY ON THE EFFECT OF HIGH RAP AND HIGH ASPHALT BINDER CONTENT ON THE PERFORMANCE OF ASPHALT CONCRETE

Paul Christian Boriack

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Gerardo Flintsch, Chair
Samer Katicha, Co-Chair
Stacey Diefenderfer

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ABSTRACT

This thesis investigates the effect of added asphalt binder content on the performance and volumetric properties of asphalt concrete mixes containing Reclaimed Asphalt Pavement (RAP). Mixes with three different percentages of RAP (0%, 20%, 40%) obtained from an asphalt producer and three different percentages of asphalt binder (design asphalt content, design +0.5%, and design +1.0%) were evaluated. Additionally, a laboratory produced mix containing 100% RAP with four asphalt binder contents (0.0%, 0.5%, 1.0% and 1.5%) was also evaluated in order to determine the binder level that optimizes mix performance for the extreme case in RAP utilization. Performance of the mixtures was evaluated based on three criteria: stiffness (dynamic modulus), fatigue resistance (flexural beam), and rutting resistance (flow number). Results showed that a 0.5% increase in binder content improved both the fatigue and rutting resistance of the 0% and 20% RAP mixes with only slight decreases in dynamic modulus. However, the addition of various amounts of binder to the 40% RAP mix led to a significant decrease in rutting resistance with little or no improvement to fatigue resistance. Volumetric analysis was performed on all of the mixes to determine how the added binder content affected mix volumetric properties. Results of volumetric testing, specifically asphalt content and Voids in the Total Mix (VTM) at the design compaction effort, N_{design}, revealed that the 40% RAP mix incorporated a significantly higher level of binder during plant production which very likely contributed to the decrease in rutting resistance once additional binder was added in the laboratory. Additionally, the gyratory compaction effort that would result in 4 percent VTM at the optimal binder content over the three performance tests, $N_{4\%}$, was calculated for each mix. Results indicated that the VTM for the optimally performing 20% and 40% RAP mixes were well below current Virginia Department of transportation (VDOT) production standards. In addition, $N_{4\%}$, for the optimally performing 20% and 40% RAP mixes was 50% or less than the current design compaction effort of 65 gyrations.

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CHAPTER I – INTRODUCTION AND OBJECTIVE

INTRODUCTION

Though recycling old asphalt concrete materials into new pavements has been common practice since the 1970s, recently State transportation agencies have focused greater attention on trying to incorporate higher levels of reclaimed asphalt pavement (RAP) in asphalt concrete mixtures due to both the economic and environmental benefits (*1*). Currently, most states only allow between 10 and 20 percent RAP in surface courses that will handle medium or heavy traffic loads (*1*). The main issue preventing states from regularly using higher percentages of RAP is that the interaction between the aged and hardened RAP binder and the new virgin binder is not completely understood, thus making the performance of the composite mixture hard to predict. Current binder selection specifications from AASHTO M 323 state that for RAP percentages below 15%, no change in binder selection is necessary and for RAP percentages between 15 and 25% the virgin binder should be one grade softer than normal. For percentages above 25%, a blending chart procedure is prescribed (*2*). The blending chart process is tedious and time consuming and though many researchers have attempted to develop alternate procedures for determining the binder properties of RAP mixtures, these have not been adopted by Superpave. In addition to binder properties, the mechanical properties of RAP mixtures have also been heavily studied in order to predict the performance of RAP mixes in the field. The consensus among the majority of these studies is that increased percentages of RAP in mixtures results in an increase in rutting resistance and a decrease in fatigue cracking resistance (*3*,*4*).

PROBLEM STATEMENT

Pavement engineers must design asphalt concrete mixes that ensure a proper balance between the pavement performance criteria (durability, rutting, fatigue cracking, etc.) as well as cost and environmental considerations. While the use of RAP in hot mix asphalt (HMA) can provide cost savings and result in lower economic impact, it also has some potential drawbacks in terms of performance. While results are not universally applicable (*5*), in general, increasing the amount of RAP seems to improve rutting resistance but reduce the resistance to cracking (*3-4*, *6*). Related to this issue, Maupin and Diefenderfer (*7*) suggested increasing the asphalt content of underlying layers to produce dense mixtures with improved fatigue and durability characteristics. To prevent mix instability and rutting problems, the authors incorporated RAP into the mixture to help maintain stiffness as an alternative to using a stiffer binder. The authors found that the added increased binder content in the resulting mix improved, or had the potential to improve, durability, permeability, and fatigue characteristics. Ideally, finding the optimal amount of binder in a high RAP mix will result in pavements with superior rutting resistance and improved fatigue cracking resistance which could lead to increased pavement life and thus substantial cost savings.

OBJECTIVE

The overall objective of this thesis was to improve the performance of asphalt concrete mixes containing RAP by evaluating the optimal binder content depending on the percentage of RAP in the mix

There are two sub-objectives:

1) Evaluate the effect of increasing binder content in asphalt concrete mixes containing RAP on mix performance. Performance of the mixes was evaluated based on three criteria: stiffness (dynamic modulus), rutting resistance (flow number) and fatigue resistance (flexural beam).
2) Evaluate the effect of increasing binder content in asphalt concrete mixes containing RAP on volumetric properties at the Superpave design compaction effort and determine the compaction effort which results in 4% air voids.

SCOPE

Mixes with three different percentages of RAP (0%, 20%, 40%) obtained from an asphalt producer and three different percentages of added binder (design asphalt content, design +0.5%, and design +1.0%) were evaluated. A laboratory mix containing 100% RAP with three asphalt binder contents (0.0%, 0.5%, 1.0% and 1.5%) was also evaluated in order to determine the binder level that optimizes mix performance. Performance of the mixes was evaluated based on three criteria: stiffness (dynamic modulus), rutting resistance (flow number) and fatigue resistance (flexural beam). All samples tested were prepared with an air void content of 7± 0.5%. Additionally, the volumetric properties of the mixes at design asphalt content, design +0.5%, and design +1.0% were determined using the Superpave gyratory compactor at a compaction effort of 65 gyrations which is the stipulated number of gyrations by the Virginia Department of Transportation (VDOT). Compaction data was also used to determine the number of gyrations which results in 4% air voids for all of the mixes.

BACKGROUND

As stated earlier, the majority of research on asphalt concrete mixtures incorporating RAP has focused on the complex interaction between the RAP binder and the virgin binder. However, many researchers have studied the mechanical properties and performance of RAP mixes and the results of some of those studies are summarized below. Additionally, a brief synopsis of the Superpave mix design process including volumetric property requirements and current issues surrounding the Superpave design compaction effort and the effect on design asphalt content and mix durability is also discussed.

Stiffness (Dynamic Modulus)

Many studies have been conducted in order to determine the effect of RAP percentage on the stiffness of asphalt concrete. In a study conducted in 2004 by Li et al. (*8*), researchers tested ten Minnesota asphalt pavement mixes with three percentages of RAP (0%, 20% and 40%) in order to determine the effect of RAP on the dynamic modulus. The results of the study indicated that as the amount of RAP in the mix increased, the dynamic modulus also increased (*8*). The incorporation of RAP in asphalt concrete was also found to increase the dynamic modulus of mixes during a 2007 study by the Oklahoma DOT. While performing dynamic modulus testing on Oklahoma asphalt concrete mixes with the goal of establishing a simpler process for producing dynamic modulus master curves, Cross et al. (*9*) found that mixes incorporating 25% RAP had a higher average stiffness than non-RAP mixes. This increase in stiffness was equated to the stiffness increase produced by increasing the PG binder grade by one level (*9*). Researchers in Illinois also performed dynamic modulus testing on 0%, 20% and 40% RAP mixtures in a 2009 study by Al-Qadi et al (*10*). The overall goal of the study was to determine the degree of blending that takes place between the hardened RAP binder and the virgin aggregate in the mix. Dynamic modulus testing indicated that RAP percentage did affect the dynamic modulus of the mix; however, the results also showed that the dynamic modulus of the 20% RAP specimens did not change significantly from the 0% RAP specimens. The mixture containing 40% RAP did show a significant increase in stiffness as compared to the 0% RAP mix, which researchers felt warranted a double binder bump in PG binder selection (*10*).

Rutting Resistance (Flow Number)

Rutting resistance of Virginia asphalt concrete mixes containing RAP was studied by Apeagyei and Diefenderfer (*11*) in 2011 using the Repeated Load Permanent Deformation (RLPD) test. 18 asphalt concrete mixes commonly used in Virginia containing between 0% and 25% RAP were subjected to a 30 psi haversine load at 130ºF in order to determine the flow number (FN). FNs determined using the Francken model showed that rutting resistance of mixes containing 0% RAP was similar to those containing 25% RAP. Mixes containing percentages of RAP in between those two levels exhibited the highest rutting resistance. Results also showed that 25% RAP mixes produced with PG 64-22 binder had unexpectedly low rutting resistance compared to those using PG 70-22 (*11*). In 2012, Al-Qadi et al. (*12*) studied the effects of RAP percentage and binder bumping on the flow number for asphalt concrete mixes containing 0%, 30%, 40% and 50% RAP. At the base binder level of PG 64-22 there was an obvious increase in FN with increasing RAP. As the binder level was bumped and double bumped to softer grades, there was an obvious decrease in FN for the same RAP percentage (*12*).

Fatigue Resistance

As stated earlier, one of the primary concerns of the use of RAP in asphalt concrete mixes is a reduction in fatigue resistance. Although this would tend to be the obvious conclusion considering the aged, stiff RAP binder in RAP mixes, the results of fatigue studies indicate mixed results. McDaniel et al. (*13*) thoroughly investigated the effects of RAP on asphalt concrete as part of NCHRP 9-12, *Incorporation of Reclaimed Asphalt Pavement in the Superpave System.* In the study, mixes with four different percentages of RAP (0%, 10%, 20% and 40%) and two binder levels (PG 52-34 and PG 64-22) were evaluated for performance, which included fatigue testing using the four-point beam fatigue test. The results of testing showed that fatigue resistance of asphalt concrete mixtures containing higher amounts of RAP significantly decreases unless the binder is bumped to a softer grade. They also found that there was not a statistically significant difference in the fatigue life for mixes containing less than 20% RAP as compared to the virgin mixes (*13*). Contrary to this result, fatigue testing of high RAP mixes performed by Al-Qadi et al. in 2012 (*12*) showed that the incorporation of RAP in mixes actually led to a slight increase in fatigue life. This study also used the four-point beam fatigue test and evaluated fatigue life at six controlled strain levels (1000με, 800με, 700με, 500με, 400με, and 300με). Though results did indicate a slight improvement in fatigue life with the incorporation of RAP, the researchers also stated that single and double bumping of PG binder grade for higher levels of RAP was necessary to achieve those results (*12*). Finally, the results of fatigue testing mixes containing 0%, 10%, 20% and 30% RAP using PG 64-22 binder by Shu et al. (*14*) indicated that the incorporation of RAP increased the fatigue life of mixtures. In this test the failure criterion was considered as a 50% reduction of stiffness under four point loading at 600με controlled strain. However, the study also showed that the mixes incorporating RAP exhibited higher plateau values, or periods during the test where there is a constant ratio of input energy turned into damage, during flexural beam testing, (*15*). The higher plateau values indicated that the RAP mixes experienced significantly more damage and thus a shorter life because for controlled strain conditions, the lower the plateau value, the longer the fatigue life for a specified mix (*15*). The authors concluded that the plateau value criterion appeared better suited for evaluating fatigue resistance of mixes containing RAP (*14*).

Superpave Volumetric Properties

Superpave, short for Superior Performing Asphalt Pavements, was the result of a 1987 Strategic Highway Research Program (SHRP) initiative to create a new system for designing and evaluating asphalt concrete materials (*16*). In addition to traffic and climate based binder grade selection and aggregate criteria based on traffic loading, Superpave places requirements on the void structure and void requirements of asphalt concrete mixes. These properties are considered the asphalt mixture volumetrics and they include voids in the total mix (VTM) or air voids, voids in the mineral aggregate (VMA) and voids filled with asphalt (VFA). The VTM is the "total volume of the small pockets of air between the coated aggregate particles throughout a compacted paving mixture (*16*)". The durability of asphalt concrete is a function of the VTM as it impacts both permeability and a condition known as flushing. If the VTM is too high, there are too many passageways for the entrance of damaging air and water. If the VTM is too low, excess asphalt will squeeze or flush out of the mix to the surface under traffic loading (*17*). The VMA is the space available in a compacted asphalt concrete mixture to accommodate both air voids and asphalt. The higher the VMA, the more space is available for a film of asphalt to form and provide sufficient durability to the mix (*18*). VFA is the percentage volume of the void space between the aggregate particles, or VMA, that is occupied by the effective asphalt. VFA is also an indicator of relative durability because if VFA is too low, there is not enough asphalt to provide stability and the mix is at risk of overdensification under traffic loading (*19*).

These Superpave volumetric properties along with the defined aggregate properties provide some indication of how mixtures will perform in the field. Asphalt concrete mixes are designed by calculating the volumetric properties of trial blends of aggregate and asphalt compacted to a design gyratory compaction effort, known as N_{design} or N_{des}. The intention of compacting to N_{des} is to produce lab specimens with the void content that would eventually be reached in the field after densification under real traffic. Superpave specifies that the VTM for a mix should be 4% at N_{des} gyrations (*16*). The allowable range of VMA values for a mix is based on the nominal maximum aggregate size of the mix and the minimum VFA level is a function of traffic level. The design asphalt content for a mix is determined by evaluating trial aggregate blends at several asphalt contents and selecting the asphalt content which meets the volumetric requirements (*16*).

Superpave N_{des} Compaction Effort and Asphalt Content

The Virginia Department of Transportation (VDOT) began using Superpave in 1997 and like many other state highway agencies, there was concern that the Superpave design compaction effort was producing mixes with low asphalt content and thus lower durability. In 2003, Maupin (*20*) studied the effects of increasing binder content on Virginia's surface mixes to determine if durability could be increased. In the study it was determined that as much as 0.5 percent asphalt could be added to the nine studied mixes with beneficial results in fatigue life and rutting resistance (*20*). As Superpave mix design specifies that the design asphalt content be determined for a mix with 4% VTM at N_{des} compaction effort, the addition of asphalt binder will lead to a lower VTM. Not long after the adoption of Superpave, VDOT decreased the N_{des} compaction effort from the AASHTO specified level of 75 to 65 gyrations because of the beneficial effects of adding up to 0.5 percent asphalt binder as stated previously.

Several other efforts have been made to calibrate N_{des} including a 1998 study by Brown and Mallick. The Superpave N_{des} compaction effort was established for given mixes at a given traffic levels so that they should ultimately result in the laboratory mix design density (*21*). However, the results of the study indicated that N_{des} values did not correlate with real field densities from actual traffic and that at currently specified levels, the Superpave gyratory compactor (SGC) was over compacting specimens resulting in lower design asphalt contents (*22*). In a subsequent study, Aguiar-Moya et al. (*23*) aimed to optimize the number of design gyrations based on project requirements. The basis for this study was that Superpave mix designs were producing mixes that performed well in rutting, but due to low asphalt binder content they sacrificed fatigue cracking resistance. Three different mixes were produced at the optimal binder content (4% air voids at 100 gyrations) and three additional asphalt binder contents were selected that produced 4% air voids at 50, 75 and 125 gyrations. Specimens were subjected to four-point bending tests as well as Hamburg Wheel tracking device (HWTD) tests and results showed that the number of design gyrations could be reduced significantly to optimize performance (*23*).

A 2010 Federal Highway Administration (FHWA) technical brief tiled "*FHWA-HIF-11-031: Superpave Mix Design and Gyratory Compaction Levels*" recognized concern from many states that the Superpave mix design system was producing asphalt concrete mixes that were too low in asphalt binder. The FHWA Asphalt Mixture and Construction Expert Task Force thoroughly investigated these concerns along with the NCHRP Report 573 "*Superpave Mix Design: Verifying Gyration Levels in the* N_{design} *Table*" which recommended a reduction in gyratory compaction levels and subsequently found that no general recommendation could be made on reductions in design compaction effort (*24*). The FHWA states that the primary concern with reducing design gyratory compaction levels in order to increase binder content is a resultant decrease in rutting resistance. In the brief, it is recommended that if a reduction in gyrations is proposed, rutting performance tests should be performed on the mixes resulting from lower compaction gyrations to determine if reductions cause a large change in rutting performance. Tests recommended by FHWA include the Flow Number test, the Dynamic Modulus test and the Asphalt Pavement Analyzer rut test (*24*).

THESIS OVERVIEW

This thesis consists of two papers found in chapters 2 and 3.

1. Paper 1: A Laboratory Study on the Effect of High RAP and High Asphalt Binder on the Stiffness, fatigue Resistance and Rutting Resistance of Asphalt Concrete

2. Paper 2: A Laboratory Study on the Effect of High RAP and High Asphalt Binder on the Volumetric Properties of Asphalt Concrete

REFERENCES

1. Copeland, Audrey. *Reclaimed asphalt pavement in asphalt mixtures: state of the practice*. No. FHWA-HRT-11-021. 2011.

2. American Association of State Highway and Transportation Officials. *AASHTO M 323: Standard Specification for Superpave Volumetric Mix Design*, Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 30th Ed.,AASHTO, Washington, DC. 2010

3. Hong, F., D.H. Chen, and M.M. Mikhail, Long-Term Performance Evaluation of Recycled Asphalt Pavement Results from Texas. Transportation Research Record: Journal of the Transportation Research Board, 2010. **2180**(1): p. 58-66

4. Li, X., M.O. Marasteanu, R.C. Williams, and T.R. Clyne, Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures. Transportation Research Record: Journal of the Transportation Research Board, 2008. 2051(1): p. 90-97.

5. Maupin Jr, G., S.D. Diefenderfer, and J.S. Gillespie, *Evaluation of Using Higher Percentages of Recycled Asphalt Pavement in Asphalt Mixes in Virginia.* VTRC Report VTRC08-R22, Charlottesville, Virginia. 2008.

6. West, R., A. Kvasnak, N. Tran, B. Powell, and P. Turner, Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixes. Transportation Research Record: Journal of the Transportation Research Board, 2009. 2126(1): p. 100-108

7. Maupin, G.W., and Diefenderfer, B., *Design of high-binder high-modulus asphalt mixture*. VTRC Report VTRC07-R15, Charlottesville, Virginia. 2006

8. Li, Xinjun, Timothy R. Clyne, and Mihai O. Marasteanu. *Recycled asphalt pavement (RAP) effects on binder and mixture quality*. No. MN/RC-2005-02. 2004.

9. Cross, Stephen A., Yatish Jakatimath, and Sumesh KC. *Determination of dynamic modulus master curves for Oklahoma HMA mixtures*. No. FHWA-OK-07-05. 2007.

10. Al-Qadi, Imad L., S.H. Carpenter, G.L. Roberts, H. Ozer, Q. Aurangzeb, M.A. Elseifi, and J. Trepanier. *Determination of Usable Residual Asphalt Binder in RAP*. No. FHWA-ICT-09-031. 2009.

11. Apeagyei, Alex K., Brian K. Diefenderfer, and Stacey D. Diefenderfer. "Rutting Resistance of Asphalt Concrete Mixtures That Contain Recycled Asphalt Pavement."

Transportation Research Record: Journal of the Transportation Research Board 2208.1 (2011): 9-16.

12. Al-Qadi, Imad L.,Q. Aurangzeb, S.H. Carpenter, W.J. Pine, and J. Trepanier. *Impact of High RAP Contents on Structural and Performance Properties of Asphalt Mixtures*. No. FHWA-ICT-12-002. 2012.

13. McDaniel, Rebecca S., et al. "Recommended use of reclaimed asphalt pavement in the Superpave mix design method." *NCHRP Web Document* 30 (2000).

14. Shu, Xiang, Baoshan Huang, and Dragon Vukosavljevic. "Laboratory evaluation of fatigue characteristics of recycled asphalt mixture." Construction and Building Materials 22.7 (2008)

15. Carpenter, Samuel H., Khalid A. Ghuzlan, and Shihui Shen. "Fatigue endurance limit for highway and airport pavements." *Transportation Research Record: Journal of the Transportation Research Board* 1832.1 (2003): 131-138.

16. Design, Superpave Mix. "Superpave Series No. 2 (SP-2)." *Asphalt Institute, Lexington, KY* (1996).

17. Christensen Jr, Donald W., and Ramon F. Bonaquist. *Volumetric Requirements for Superpave Mix Design*. No. Project 9-25/9-31. 2006.

18. Kandhal, Prithvi S., Kee Y. Foo, and Rajib B. Mallick. "Critical review of voids in mineral aggregate requirements in Superpave." *Transportation Research Record: Journal of the Transportation Research Board* 1609.1 (1998): 21-27.

19. Cominsky, Ronald J., et al. *The Superpave mix design manual for new construction and overlays*. No. SHRP-A-407. Washington, DC: Strategic Highway Research Program, 1994.

20. Maupin, G.W., *Additional asphalt to increase the durability of Virginia's superpave mixes*. VTRC Report VTRC03-R15, Charlottesville, Virginia. 2003

21. Prowell, Brian D., and E. Brown. *Superpave Mix Design: Verifying Gyration Levels in the Ndesign Table*. No. Project 9-9 (1). 2007.

22. Brown, E. R., and R. B. Mallick. An Initial Evaluation of N-design Superpave Gyratory Compactor. Proceedings of the Association of Asphalt Paving Technologists, Vol. 67, 1998, pp. 101–116.

23. Aguiar-Moya, José P., Jorge A. Prozzi, and Maghsoud Tahmoressi. "Optimum Number of Superpave Gyrations Based on Project Requirements." Transportation Research Record: Journal of the Transportation Research Board 2001.1 (2007): 84-92.

24. “TechBrief: Superpave mix design and gyratory compaction levels”, FHWA TechBrief No. FHWA-HIF-11-031, 2010.

CHAPTER II – PAPER 1: A LABORATORY STUDY ON THE EFFECT OF HIGH RAP AND HIGH ASPHALT BINDER ON THE STIFFNESS, FATIGUE RESISTANCE AND RUTTING RESISTANCE OF ASPHALT CONCRETE[1]

ABSTRACT

The objective of this study is to improve the performance of asphalt concrete mixes containing Reclaimed Asphalt Pavement (RAP) by evaluating the optimal binder content depending on the percentage of RAP in the mix. Mixes with three different percentages of RAP (0%, 20%, 40%) obtained from an asphalt producer and three different percentages of asphalt binder (design asphalt content, design +0.5%, and design +1.0%) were evaluated. Additionally, a laboratory mix containing 100% RAP with four asphalt binder contents (0.0%, 0.5%, 1.0% and 1.5%) was also evaluated in order to determine the binder level that optimizes mix performance. Performance of the mixtures was evaluated based on three criteria: stiffness (dynamic modulus), fatigue resistance, and rutting resistance (flow number). It is well established that aged RAP binder in high RAP mixes aids stiffness and rutting resistance but poses problems to fatigue resistance. The results showed that a 0.5% increase in binder content improved both fatigue and rutting resistance of the 0% and 20% RAP mixes with only slight decreases in dynamic modulus. The addition of various amounts of binder to the 40% RAP mix led to a decrease in both rutting and fatigue resistance, suggesting that the plant produced mix already incorporated the optimum asphalt content in the original design. The mixes containing 100% RAP exhibited extremely high dynamic modulus and rutting resistance at all binder levels tested and fatigue resistance comparable to the 20% RAP mix was achieved for the mix with the addition of 1.5% binder.

[1] This paper was co-authored by Samer Katicha and Gerardo Flintsch and is scheduled for presentation on January 12, 2014 at the 93rd annual meeting of the Transportation Research Board and has also been recommended for publication in the 2014 Journal of the Transportation Research Board.

INTRODUCTION

It has been well established that predicting the performance of high Reclaimed Asphalt Pavement (RAP) asphalt concrete mixes is very difficult given the complex interaction between the aged RAP binder and fresh asphalt binder in the composite mix (*1*, *2*). Currently the percentage of RAP permitted for use in asphalt concrete mixes by state DOTs is generally limited to 25%. RAP percentages above the 25% threshold are considered "high RAP" mixes which require more testing and the use of blending charts to aid in binder selection (*3*). This differs from binder selection for mixes with lower percentages of RAP where there is either no change in binder selection when the percentage of RAP is below 15% or a binder "bump" of 1 Performance Grade (PG) lower for RAP percentages between 15 and 25%. "Softer" binders are used when the percentage of RAP increases in order to mitigate the effects that the stiff aged RAP binder has on the composite mix. Mixes that incorporate RAP improve the dynamic modulus and rutting resistance of mixtures (*4*), and reduce the use of virgin aggregates and asphalt binder which has a positive environmental and economic impacts (*5*, *6*). On the other hand, one of the disadvantages of high RAP mixes is the potential decrease of the mixture fatigue cracking resistance (*7*). Related to this issue, Maupin and Diefenderfer (*8*) suggested increasing the asphalt content of underlying layers to produce dense mixtures with improved fatigue and durability characteristics. To prevent mix instability and rutting problems, the authors incorporated RAP into the mixture to help maintain stiffness as an alternative to using a stiffer binder. The authors found that the added increased binder content in the resulting mix improved, or had the potential to improve, durability, permeability, and fatigue characteristics. This study will build on the results of Maupin and Diefenderfer (*8*) to design a high RAP mix by increasing the asphalt binder content to an optimal value that will result in desirable mix characteristics.

OBJECTIVE

The objective of this study is to investigate the effect of asphalt binder content on the performance of mixtures containing RAP. Mixes with three different percentages of RAP (0%, 20%, 40%) and three different percentages of asphalt binder (design, design +0.5%, and design +1.0%) were evaluated. Additionally, the performance of a mix containing 100% RAP, an extreme case for RAP in asphalt mixtures, was evaluated at three additional virgin asphalt binder contents in order to determine the added binder content that optimizes mix performance.

RESEARCH PLAN, MATERIALS AND TESTS

The scope of this work consists of obtaining a virgin asphalt mix, two asphalt mixes with RAP, stockpiled RAP and asphalt binders used in the Commonwealth of Virginia; making virgin and recycled mixes of increased virgin binder content; testing the samples for dynamic modulus, fatigue cracking resistance using the third point bending beam test, and rutting resistance (flow number); and analyzing the results. A flow chart of this process is shown in Figure 1.

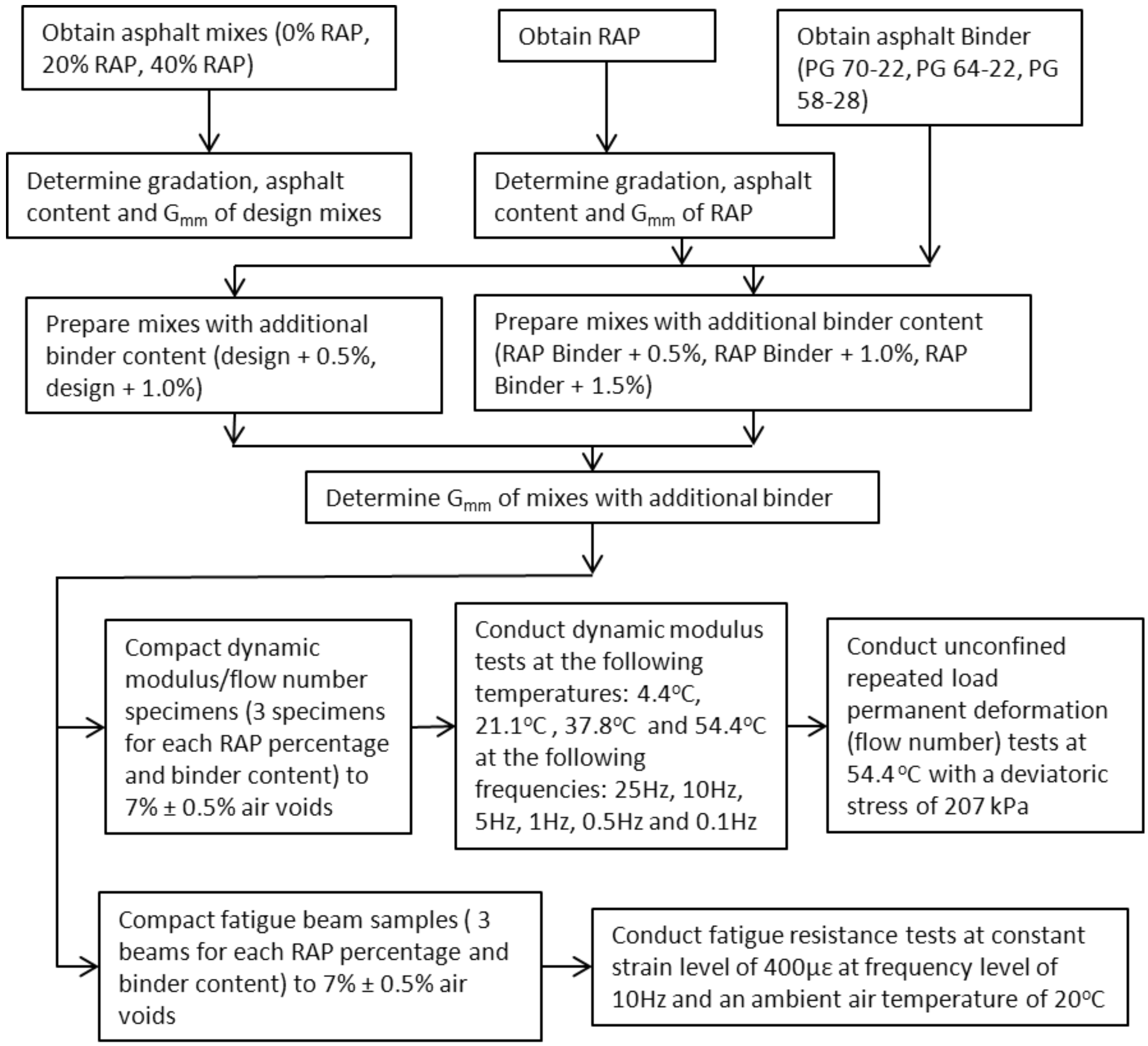


FIGURE 1 Test plan employed in study

Three SM-9.5 asphalt concrete surface mixes typically used in Virginia were obtained from asphalt concrete producers in Northern Virginia. A control mix, SM-9.5D, containing 0% RAP (PG 70-22) was obtained from one supplier. A SM-9.5D mix containing 20% RAP (PG 70-22) and an SM-9.5A mix containing 40% RAP (PG 64-22) were obtained from another supplier. The 0% and 20% RAP mixes were both Virginia Department of Transportation (VDOT) approved mixes with the original or design binder content determined by the producer in accordance with VDOT specifications. The 40% RAP mix, a RAP percentage not approved by VDOT at the time of this project, was obtained from a private project as this study served as initial investigation into the use of high RAP mixes. Additionally, 100% stockpiled RAP used in those asphalt mixes was also obtained from the producer. The theoretical maximum specific gravity (G_{mm}) of each of the three mixes was determined using the Rice method following AASHTO T 209. The ignition oven was used to determine the asphalt content (AC) of the plant mix material. The process followed was adapted from the Virginia Test Method 102. When material was heated and separated to conduct the G_{mm} testing, three samples exceeding 1500g (3.3 lbs) were taken for use in the ignition oven, to determine the AC. An ignition oven correction factor was unable to be developed due to a lack of material. Sieve analysis following AASHTO T 27 was then performed on two of the burned samples after asphalt content testing. Gradation curves were produced based on the average of the two sieve analysis for each mix and the stockpiled RAP material. A summary of the properties of the three mixes and the RAP material as well as volumetric data for the 20% and 40% RAP mixes provided by the asphalt concrete producer is shown in Table 1.

TABLE 1 Properties of asphalt mixes and stockpiled RAP

	0% RAP	20% RAP	40% RAP	100% RAP
Average Property				
Binder Grade	PG 70-22	PG 70-22	PG 64-22	unk
[a]Asphalt Content (%)	5.629	5.539	5.994	5.770
G_{mm}	2.686	2.614	2.603	2.623
Volumetric Data provided by Asphalt Concrete Producer				
V_b	--	5.18	5.42	--
V_a	--	3.1	1.9	--
VMA	--	15.2	14.7	--
VFA	--	79.6	87.1	--
F/A Ratio	--	1.2	1.2	--
Gradation (percent passing)				
19 mm (3/4-inch)	100.0	100.0	100.0	100.0
12.5 mm (1/2-inch)	100.0	99.3	98.7	99.3
9.5 mm (3/8-inch	92.1	89.2	90.3	94.1
4.75 mm (No. 4)	65.2	57.6	58.5	68.0
2.36 mm (No. 8)	45.6	41.8	42.0	49.6
1.18 mm (No. 16)	31.8	31.8	32.1	37.5
0.6 mm (No. 30)	21.9	22.9	23.1	28.4
0.3 mm (No. 50)	12.9	14.4	14.5	20.3
0.15 mm (No. 100)	7.7	9.4	9.4	14.5
0.075 mm (No. 200)	5.0	6.1	6.3	10.2

[a]Asphalt Content (%) measured using ignition oven at VTTI (no correction factor)
V_b = binder content (%), V_a = air voids (%), VMA = voids in mineral aggregate
VFA = voids filled with asphalt, F/A ratio = fines to asphalt ratio

Sample Preparation

The three asphalt concrete mixes, as well as the 100% RAP, were then modified by adding increased amounts of asphalt binder. Two levels of increased binder content were evaluated for the 0% RAP, 20% RAP and 40% RAP mixes: design, design + 0.50% and design + 1.00%. The original binder content was determined by the producer in accordance with VDOT specification. The original + 1.00% level was used, as it was suggested by Maupin and Diefenderfer (*8*), that it might be the additional asphalt content needed to see appreciable improvement in fatigue cracking resistance. Four levels of binder content were evaluated for the mix containing 100% RAP; RAP with no added binder, RAP binder + 0.5%, RAP binder + 1.0% and RAP binder + 1.5%. PG 70-22 binder was added to both the 0% RAP and 20% RAP mixes and PG 64-22 binder was added to the 40% RAP mix, the same binder grades used in initial production. PG 58-28 binder was used for the 100% RAP mix and was chosen because it has been argued that the softer binder would blend and mix with the aged RAP binder to decrease the stiffness of the overall mix (*7*).

All mixing of additional asphalt binder samples followed the following procedure. The 0% RAP, 20% RAP 40% RAP mixes as well as the 100% RAP material were placed in ovens preheated to 152^{o}C (305^{o}F). The PG 70-22, PG 64-22 and PG 58-28 binders were placed in a separate oven and preheated to 148^{o}C (298^{o}F). Once the mixing temperatures were reached, the material was removed from the oven, placed in a preheated mixing bucket and weighed. The heated binder was then added to the material as a percentage based on the amount of material in the bucket. The materials were then mixed for approximately five minutes using a preheated mixing arm on an electric mixer, until the aggregates were sufficiently coated with the virgin binder. The G_{mm} of the mixes with added binder was also determined using the Rice method after mixing was complete.

The scope of this study included producing one set of cylindrical specimens for dynamic modulus and flow number testing as well as one set of beam specimens for fatigue testing. The same samples that were used for dynamic modulus were also used for the flow number testing once dynamic modulus testing was complete. The dynamic modulus specimens were compacted using the Superpave gyratory compactor at a temperature of 143^{o}C (290^{o}F). All specimens were compacted to a height 178mm (7 inches) in a 152mm (6 inch) diameter mold. Since the goal was to achieve a target air void level of 7.0% ± 0.5%, the number of gyrations varied based on the targeted air voids of 7% for all of the mixes as shown in Figure 2. Visual inspection of figure 2 shows that as the binder content of the mixes increased, the number of gyrations necessary to achieve the target air void level decreased. It also must be noted that the design asphalt content for the 0%, 20% and 40% RAP mixes used in this study was determined by the asphalt producer as the binder content required in order to achieve 4% air voids at 65 gyrations. Once sufficiently cooled, the specimens were then cut and cored to a length of 152mm (6 inches) and a diameter of 102mm (4 inches). The bulk specific gravity (G_{mb}) of the cut and cored specimens was then determined using AASHTO T 166. The results of testing the specimens for bulk specific gravity, G_{mb}, and air voids, AV, are shown in the following Table 2.

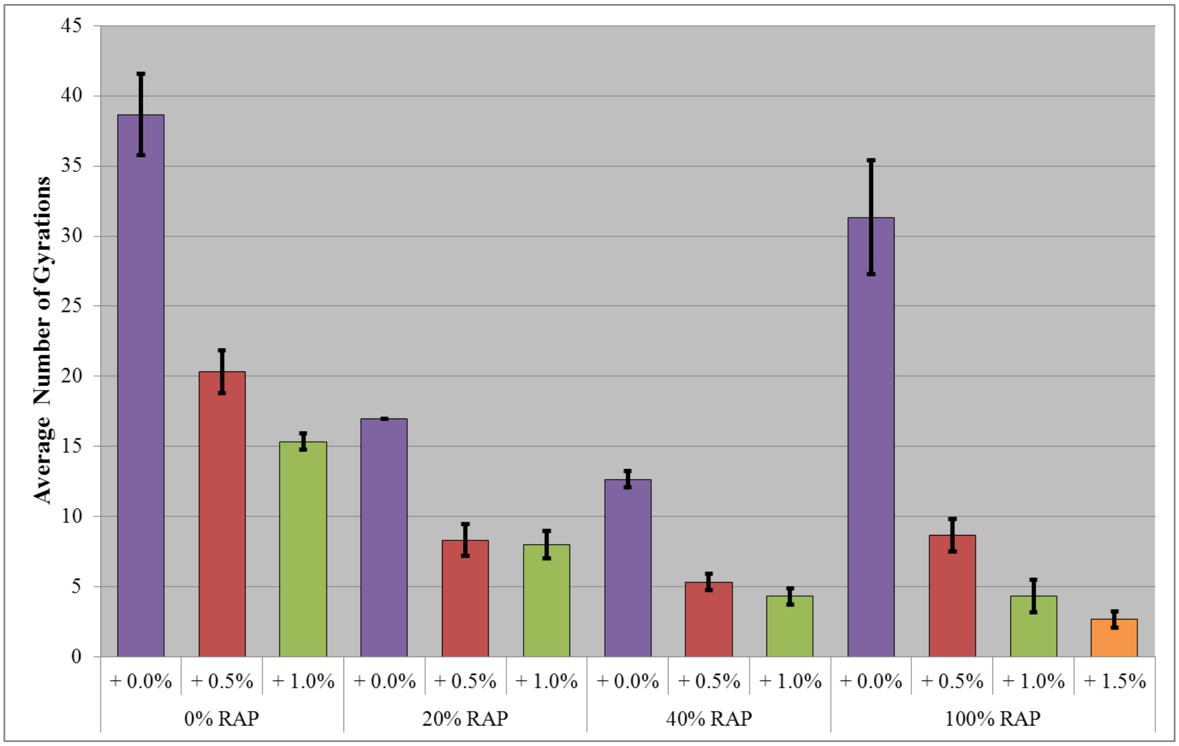


FIGURE 2 Average gyrations for dynamic modulus and FN specimen compaction

TABLE 2 Volumetric Mix Design Data for Different Mixtures

	G_{mm}[a]	G_{mb}[b]	Air Voids (%)[b]
0% RAP + 0.0% Binder	2.686	2.503	6.8
0% RAP + 0.5% Binder	2.668	2.488	6.7
0% RAP + 1.0% Binder	2.648	2.468	6.8
20% RAP + 0.0% Binder	2.614	2.431	7.0
20% RAP + 0.5% Binder	2.595	2.410	7.1
20% RAP + 1.0% Binder	2.576	2.393	7.1
40% RAP + 0.0% Binder	2.603	2.424	6.9
40% RAP + 0.5% Binder	2.584	2.399	7.1
40% RAP + 1.0% Binder	2.565	2.382	7.1
100% RAP + 0.0% Binder	2.626	2.438	7.1
100% RAP + 0.5% Binder	2.623	2.442	6.9
100% RAP + 1.0% Binder	2.598	2.427	6.6
100% RAP + 1.50% Binder	2.586	2.411	6.8

[a]G_{mm} = maximum specific gravity as average of 3 Rice specific gravity tests

[b]G_{mb} and Air Voids as that was the average of the three specimens tested

Beam fatigue specimens 51mm (2 inches) high, 64mm (2.5 inches) wide, and 381mm (15 inches) long, were prepared using the asphalt vibratory compactor (AVC). Three specimens were produced for each RAP and binder content. A maximum compaction time of 35 seconds was used for all specimens as it was determined sufficient to achieve the target 7.0% air voids.

Dynamic modulus

Dynamic modulus testing was conducted according to the testing procedure prescribed in AASHTO TP 62-03 “Standard Method of Test for Determining Dynamic Modulus of Hot-Mix Asphalt Concrete Mixtures”. Tests were performed at 4.4, 21.1, 37.8, and 54.4°C (40, 70, 100, and 130°F) and at frequencies of 25, 10, 5, 1.0, 0.5, and 0.1 Hz at each temperature using an Interlaken Technology Corporation (ITC) servohydraulic machine. Table 3 displays the specifics of the dynamic modulus test temperatures and conditioning times, frequencies, cycles and pressures. Load levels were chosen such that maximum strain limits for the test would not be exceeded and the same loads were used for all specimens. Three sets of linear variable differential transducers (LVDTs) with a gauge length of 100mm (four inches), placed 120 degrees apart, were mounted on aluminum studs to measure displacements in the asphalt specimens under dynamic loading.

TABLE 3 Dynamic modulus testing specifics

Test Temperature, °C (°F) (conditioning time, hrs from room temperature at 25 °C)	Frequency, Hz	Pressure, kPa (psi)	Cycles
4.4 (40) (overnight)	25	621 (90)	200
	10	621 (90)	200
	5	552 (80)	100
	1	552 (80)	20
	0.5	483 (70)	15
	0.1	483 (70)	15
21.1 (70) (1 hr)	25	483 (70)	200
	10	483 (70)	200
	5	379 (55)	100
	1	379 (55)	20
	0.5	276 (40)	15
	0.1	276 (40)	15
37.8 (100) (4 hrs)	25	276 (40)	200
	10	276 (40)	200
	5	172 (25)	100
	1	172 (25)	20
	0.5	103 (15)	15
	0.1	103 (15)	15
54.4 (130) (4 hrs)	25	103 (15)	200
	10	103 (15)	200
	5	69 (10)	100
	1	69 (10)	20
	0.5	34 (5)	15
	0.1	34 (5)	15

The dynamic modulus curve was constructed at a reference temperature of 21.1°C (70°F) using the Witczak sigmoidal model (*9*).

Flow Number (FN) test for Rutting Resistance

The unconfined repeated load permanent deformation (RLPD) test was used in order to determine permanent deformation characteristics, i.e., rutting characteristics of the mixes in this study (*10*). The flow number (FN) for each the specimens is obtained using the results of the RLPD and is defined as the loading cycle under which tertiary flow commences (*11*). The procedures specified in AASHTO TP 79 and the NCHRP Project 9-19 were followed in the execution of the unconfined RPLD test. As stated earlier, the same 100mm (4 inch) diameter by

150mm (6 inch) tall specimens used for dynamic modulus testing were used in the RLPD test. For this test, the specimens were subjected to a repeated haversine compressive loading pulse of 207 kPa (30 psi) for 0.1 seconds followed by 0.9 seconds of rest using a Material Testing Systems (MTS) servohydraulic machine. The test was performed in an environmental chamber at a temperature of 54.4°C (130 °F) and all specimens were conditioned at 54.4°C (130 °F) for 4 hours prior to testing. The testing was considered complete after 10,000 cycles or once the sample began tertiary deformation.

The axial deformation and cycle data from the RLPD test is then fitted to a mathematical model in order to calculate the cycle in which tertiary flow begins or the FN. In this study the Francken model was used as it was determined to be the best recommended model for the calculation of the flow number by Biligri et. al. in an extensive 2007 study of permanent deformation models. The Francken model was determined to be the best suited model to describe all three phases of permanent deformation (*11*). The composite model is shown below.

$$\varepsilon_p(N) = AN^B + C(e^{DN} - 1) \qquad (1)$$

where, $\varepsilon_p(N) =$ permanent axial strain (%)
$N =$ number cycles, and
$A, B. C$ and $D =$ regression coefficients

The FN is then calculated using the Francken model for each of the test specimens. First, the model is fit to the RLPD test data using numerical optimization. Then after the regression coefficients are determined, the second derivative of the Francken model, also known as the gradient of the strain slope, is calculated and is shown below (*11*).

$$\frac{\delta^2 \epsilon(p)}{\delta N^2} = A * B * (B-1) * N^{(B-2)} + (C * D^2 * e^{D*N}) \qquad (2)$$

For all of the specimens tested, the gradient of the strain slope starts as a negative number that decreases with increasing cycles. The point in which the strain slope goes from negative to positive indicates where the secondary phase of permanent deformation ends and the tertiary flow begins and is the FN.

Fatigue Cracking Resistance

The flexural fatigue test is the most commonly used test to characterize the fatigue life of asphalt concrete at intermediate temperatures and was used in this study to characterize fatigue cracking performance. The flexural fatigue test simulates the strain that asphalt concrete experiences under repeated traffic loads. In this test a rectangular beam is restrained in a third point loading apparatus and subjected to repeated sinusoidal loading approximately one third distance from the beam ends. The stiffness modulus of a beam supported in this manner can be calculated using the equations as follows (*12*):

$$\sigma_t = \frac{3aP}{bd^2} \tag{3}$$

$$\varepsilon_t = \frac{12d\delta}{3L^2-4a^2}$$

$$E = \frac{Pa(3L^2-4a^2)}{4bd^{3\delta}}$$

where,

σ_t = tensile stress
ε_t = tensile strain
δ = vertical deflection
P = applied load
L = beam span
a = distance between load and nearest support
b = beam width
d = beam depth
E = stiffness modulus

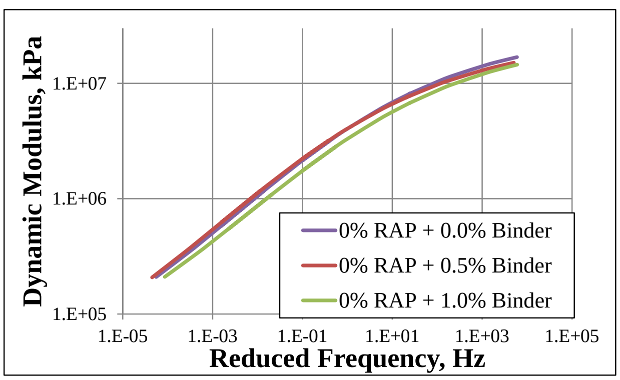
In this study, fatigue testing was performed under a controlled-strain condition with a constant strain level of 400με at a frequency level of 10Hz and an ambient air temperature of 20^{o}C (68^{o}F) using an MTS servohydraulic machine. The initial stiffness modulus of the specimen was determined after 50 load cycles and the failure criteria was defined as a 50% reduction from that initial stiffness. Load and deflection data was continually collected throughout the fatigue test in order to calculate the average stiffness modulus for each loading cycle.

TEST RESULTS, ANALYSIS AND DISCUSSION

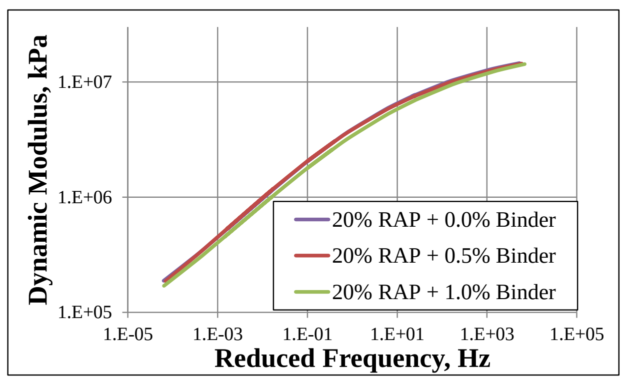
Dynamic Modulus

Figure 3 shows the average sigmoidal dynamic modulus master curves for the three specimens tested at each RAP percentage and binder content as well as a summary plot displaying all of the average dynamic modulus master curves of all binder contents for the four RAP mixes tested. The plot for each mix illustrates the relationship between binder content and the dynamic modulus. As can be seen in the individual RAP mix plots in Figure 3(a), (b), (c) and (d), there is less than 1% difference in dynamic modulus values for the 0% RAP, 20% RAP and 40% RAP mixes between the design (no binder added) and design +0.5% binder mixes. However, there is a significantly larger decrease in dynamic modulus values when comparing the design mix to the mix with the additional 1.0% binder for the 0% RAP, 20% RAP and 40% RAP mixes. On average the dynamic modulus values are approximately 17%, 11% and 21% lower between the design and design +1.0% binder mixes for the 0% RAP, 20% RAP and 40% RAP mixes respectively. The relationship between the dynamic modulus and increasing binder content follows the same general trend for the 100% RAP mixes, except for the case of the 100% RAP mix with no added binder. There is a significant increase in the dynamic modulus between the mix with no additional binder and the mix with the additional 0.5% binder. This increase becomes increasingly larger as reduced frequency increases. As added binder increases from 0.5% to 1.0%, the dynamic modulus remains relatively unchanged, with only an average 2% difference between the dynamic modulus of the two mixes. An average decrease of 12% in dynamic modulus values occurs between the 100% RAP mix with 0.5% additional binder and the mix with 1.5% additional binder.

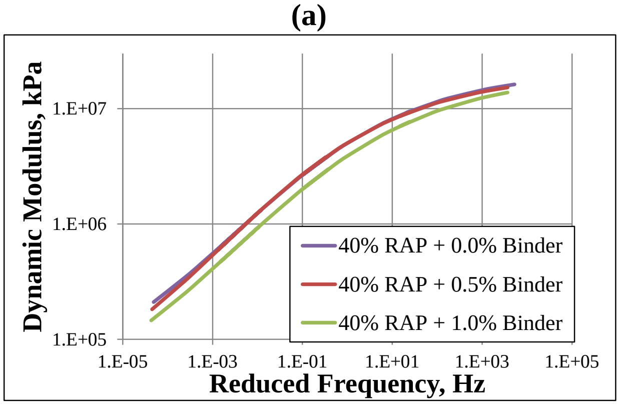
The results also show the effect of RAP percentage on the mix dynamic modulus. As shown in Figure 3(e), the dynamic modulus increases with increasing RAP percentage for the 20%, 40% RAP and 100% RAP mixes. Visual inspection of Figure 3(e) also shows that the 40% RAP shows increased stiffness at intermediate temperatures (frequencies) relative to the 0% and 20% RAP. The average dynamic modulus of the 100% RAP mixes is over 400% higher than the average dynamic modulus of the 20% RAP and 40% RAP mixes at the lowest reduced frequency gradually decreasing to 125% higher for the highest reduced frequency.



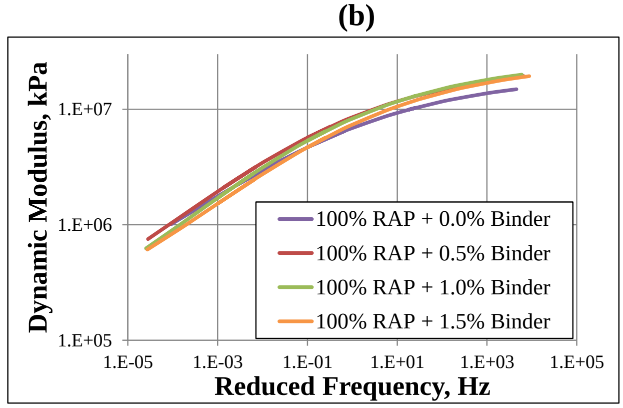
(a)



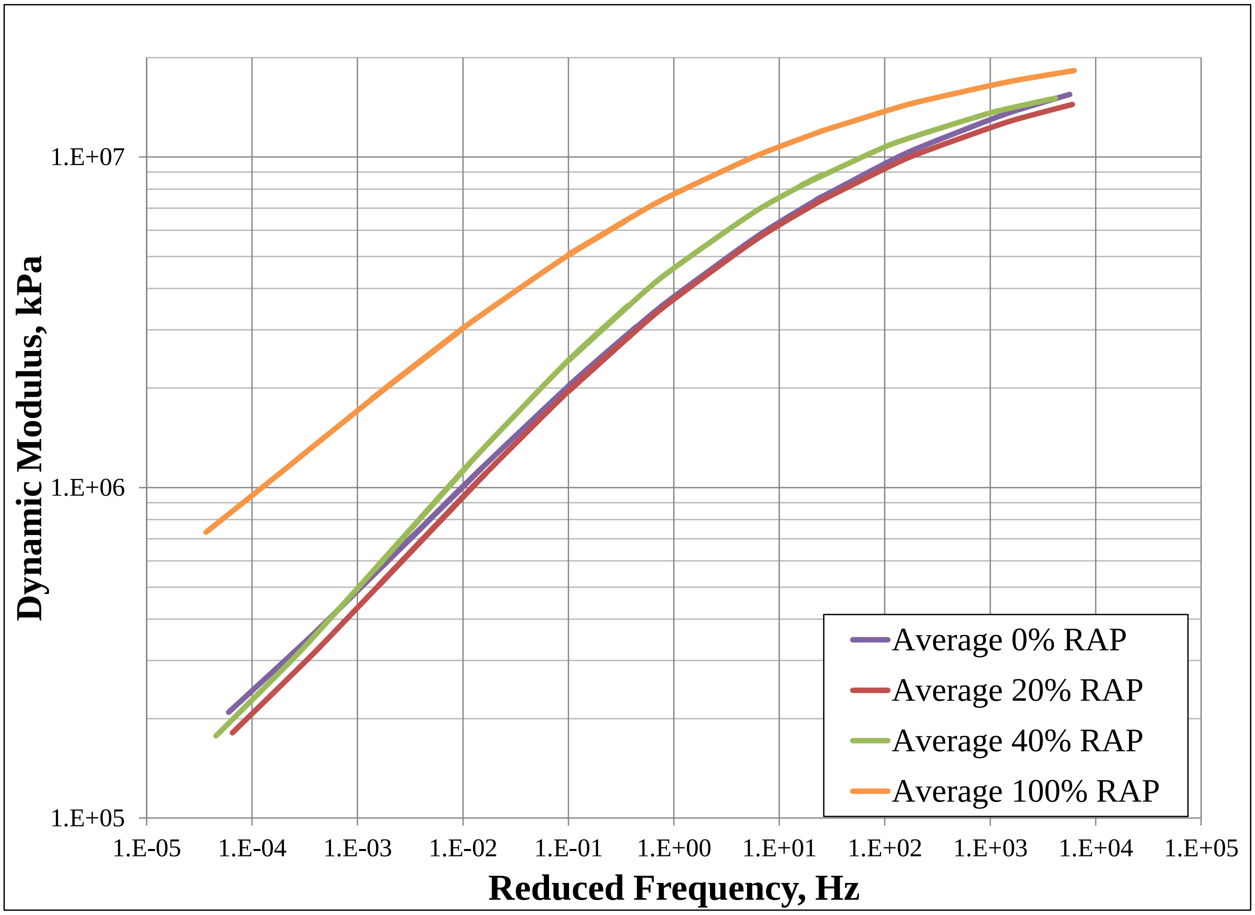
(b)



(c)



(d)



(e)

FIGURE 3 Dynamic modulus master curves a) 0% RAP mixes, b) 20% RAP mixes, c) 40% RAP mixes, d) 100% RAP mixes and e) average dynamic modulus of mixes at each RAP percentage

Flow Number

The flow numbers calculated from the RLPD testing for all the mixes are shown in Figure 4. For both the 0% RAP and 20% RAP mixes, the results show a significant, approximate 100% increase in the flow number between the design +0.0% binder and the design +0.5% binder. For both of those mixes, the addition of 1.0% binder reduced the FN compared to the design +0.5% mix, however the FN was slightly higher than from the FN of the design +0.0%. The 40% RAP mix exhibited a different behavior as the addition of binder resulted in a dramatic decrease in the FN. The 100% RAP mixes exhibited significant resistance to rutting as none of the mixes reached the tertiary flow region within the 10,000 test cycles. Furthermore, the accumulated strain after 10,000 cycles was very low compared to the other mixes and this can be seen in Figure 5. However, as shown in the figure, the permanent strain experienced after 10,000 cycles increased for the 100% RAP mixes as binder content increased.

The results of RLPD testing also show that the FN increased for all of the mixes as the RAP percentage increased for the mixes with 0.0% additional binder.

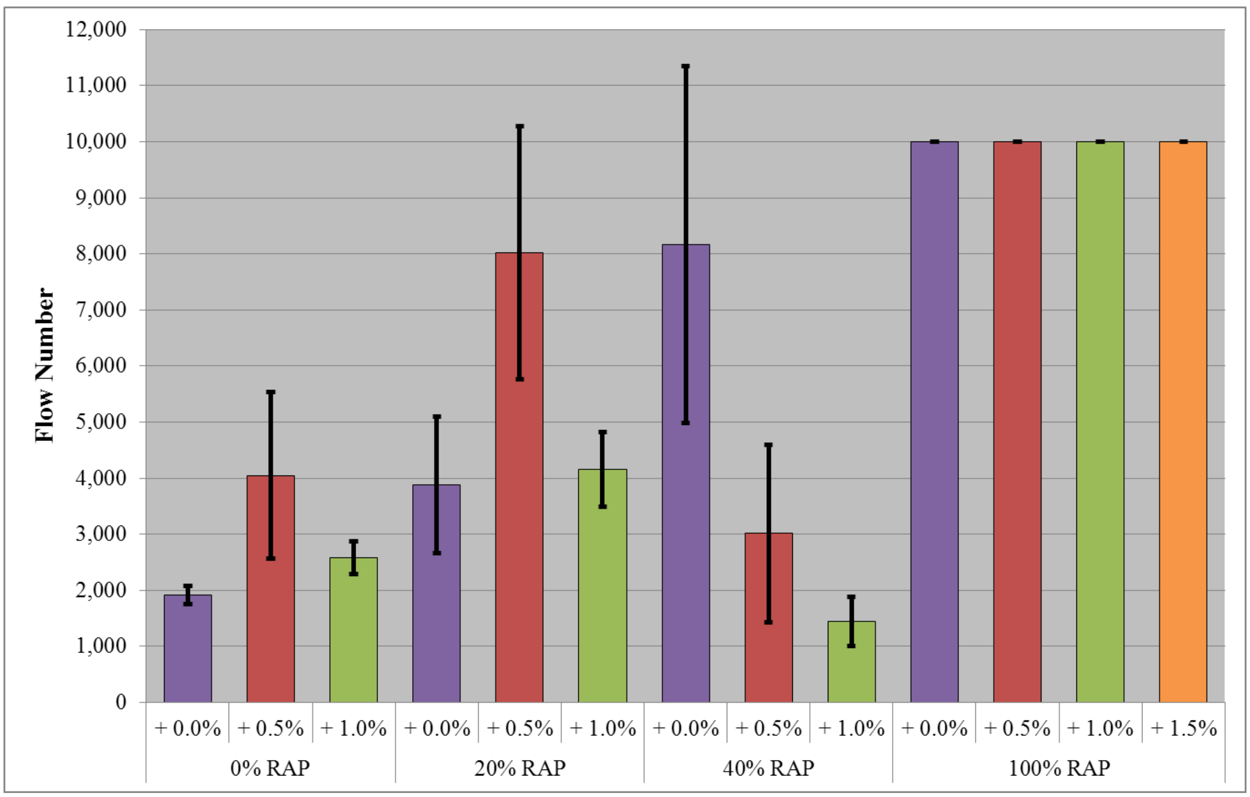


FIGURE 4 Flow number of all mixes

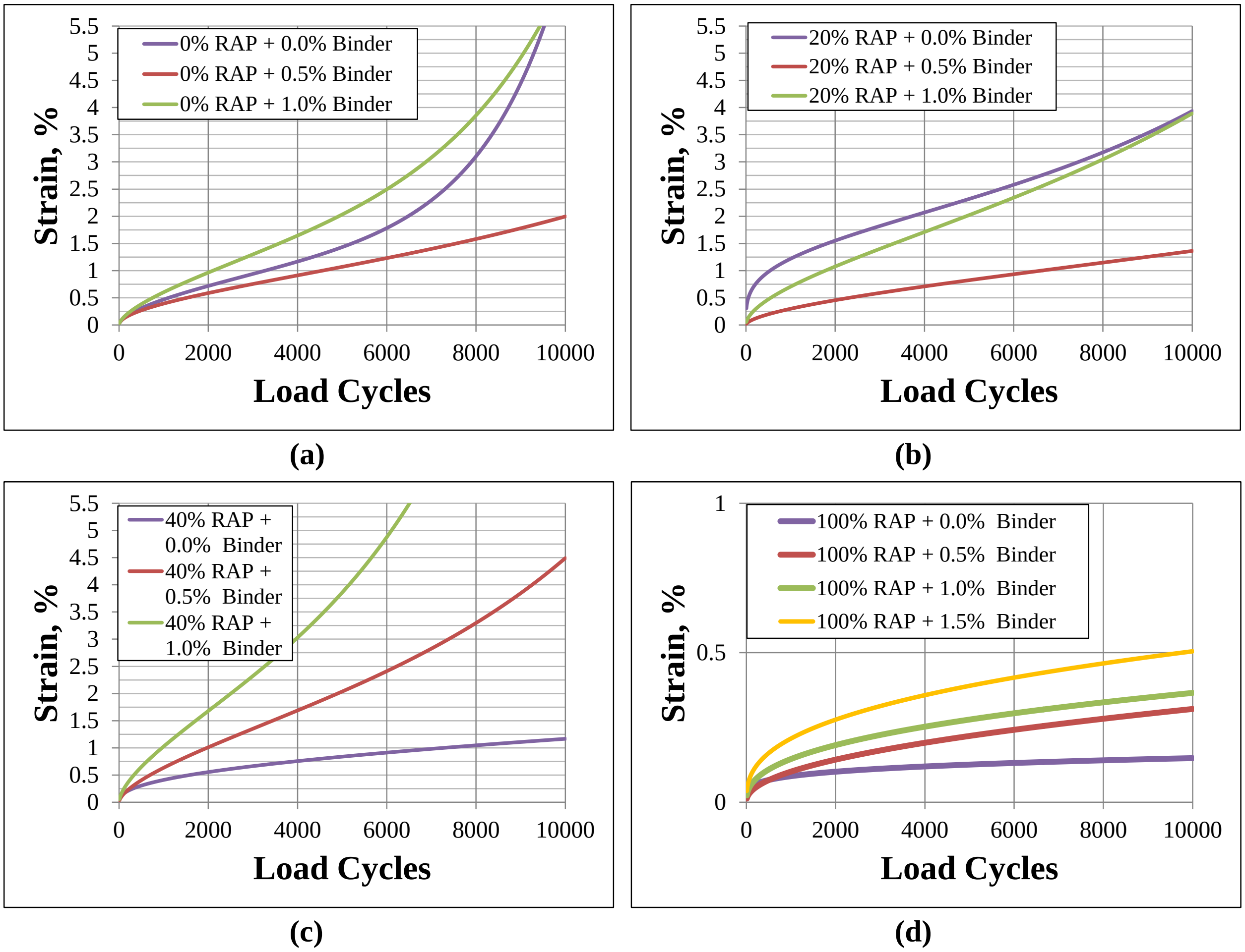
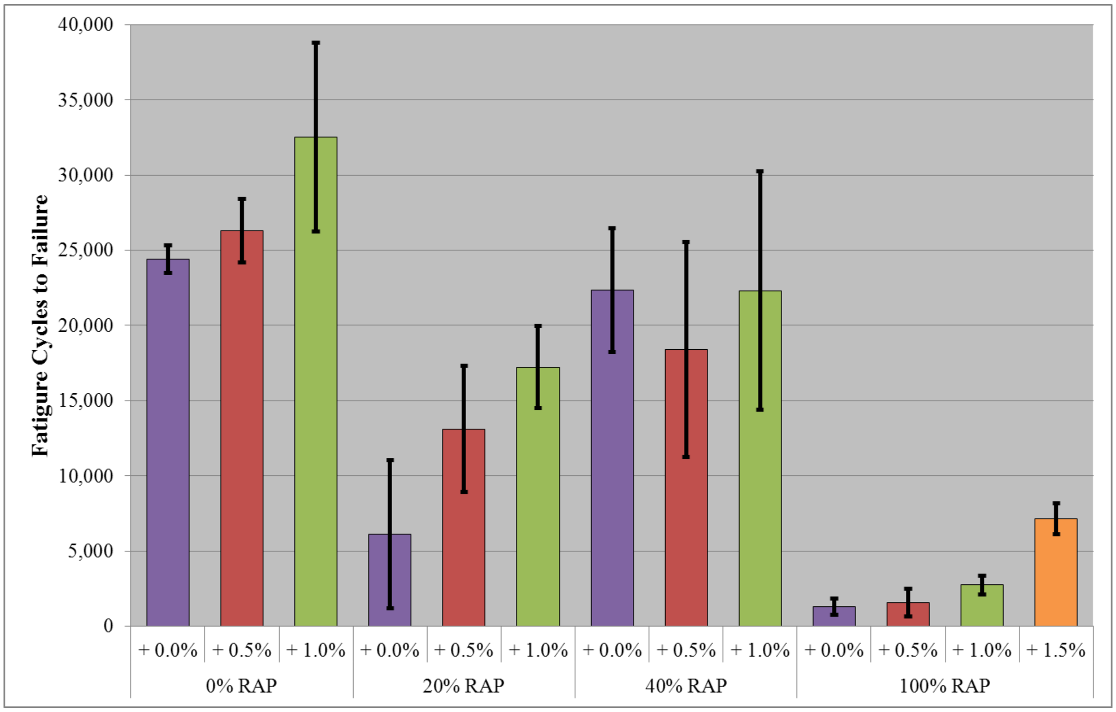


FIGURE 5 Typical flow behavior of a) 0% RAP mixes, b) 20% RAP mixes, c) 40% RAP mixes and d) 100% RAP mixes

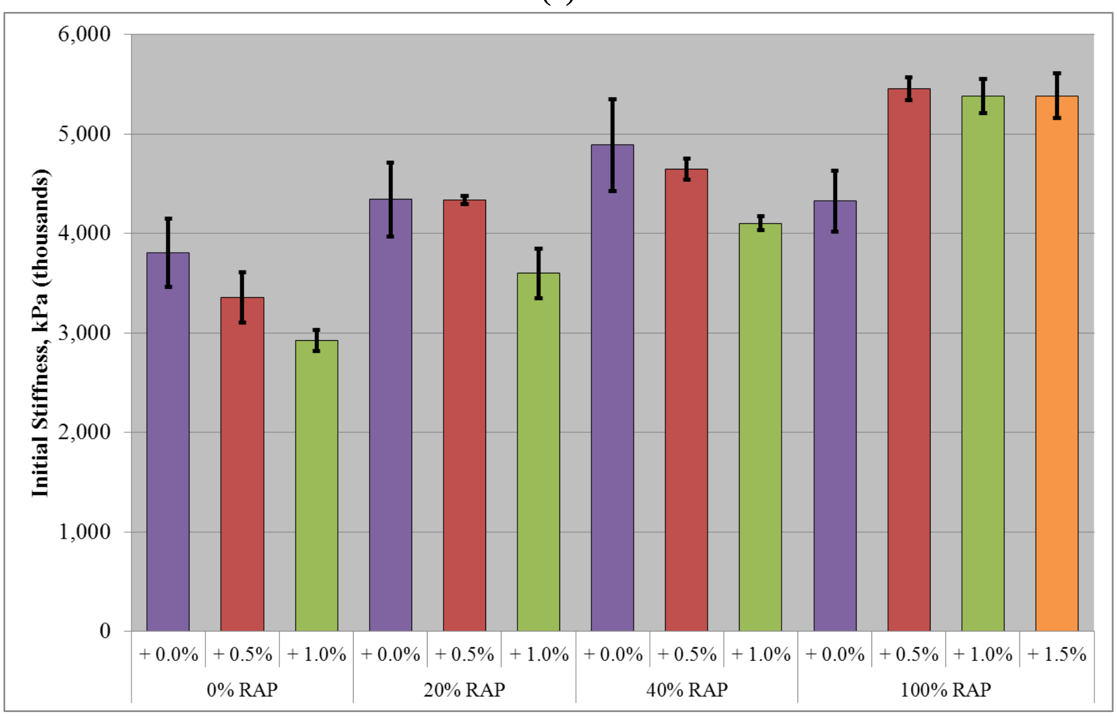
Fatigue Resistance

The average and standard deviation of the fatigue cycles to failure and the initial stiffness during fatigue testing are shown in Figure 6. The results of fatigue testing show that for all but the 40% RAP mix, an increase in binder content led to an increase in fatigue life. For the 40% RAP mix, the addition of binder did not lead to a statistically significant increase or decrease in fatigue life. Conversely, increasing binder content resulted in a decrease in initial stiffness (the stiffness measured during the 50th load cycle which was the average of the 10 cycles between 5 and 6 seconds of testing) for all mixes except the 100% RAP mixes. In the case of the 100% RAP mixes the stiffness initially increased approximately 25% from 0.0% added binder to 0.5% added binder before decreasing with increasing binder content of 1.0% and 1.5%.

The initial stiffness of the beams increased with increasing RAP percentage; excluding the 100% RAP mix with 0.0% added binder. Similar to the results of the dynamic modulus testing, the addition of 0.5% binder to the 100% RAP mix with no added binder led to an increase in stiffness.



(a)



(b)

FIGURE 6 Fatigue resistance: a) average cycles to failure of all mixes and b) average initial stiffness of all mixes

Figure 7 shows the average stiffness of each mix throughout the fatigue test. Focusing on the 0% RAP mixes, by visual inspection of the figure it is observed that as the binder content increases the beams fail in a more gradual manner, i.e., the slope of the stiffness versus fatigue cycle is milder. This same behavior is exhibited by the 20% and 40% RAP mixes as binder is increased. Again upon visual inspection of the stiffness curves it is observed that as the RAP percentage increases, the slope of the curves becomes steeper with the 100% RAP beams exhibiting the most abrupt reduction of stiffness and the 0% RAP the most gradual reduction.

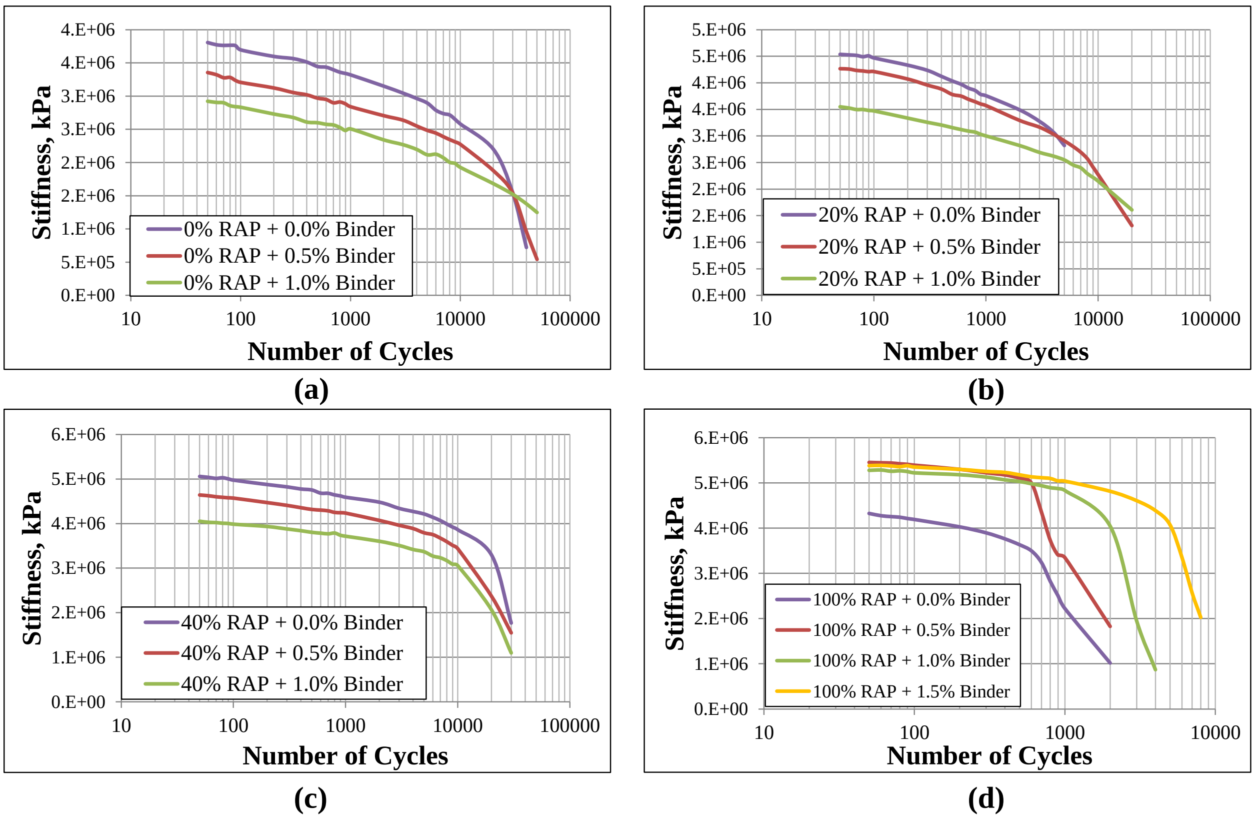


FIGURE 7 Fatigue resistance, Stiffness versus Load Cycles for a) 0% RAP mixes, b) 20% RAP mixes, c) 40% RAP mixes and d) 100% RAP mixes

OBSERVATIONS

This study confirmed that it is possible to improve the performance of asphalt concrete mixes with RAP by adding additional binder. This holds especially true for the 20% RAP mix where the addition of 0.5% or 1.0% binder improves both the fatigue cracking resistance and rutting resistance with only a slight decrease in the dynamic modulus. For the 20% RAP mix specifically, the addition of 0.5% binder led to a 200% increase in fatigue resistance, a 200% increase in rutting resistance and only a 1% decrease in dynamic modulus.

Although both the 0% RAP and 20% RAP mix exhibited similar performance behavior as the percentage of binder was increased, the behavior of the 40% RAP, or "high" RAP mix, was somewhat different. As both the fatigue and rutting resistance of the 0% and 20% RAP mixes improved when comparing the mixes at design binder content to those with the additional 0.5% binder, the 40% RAP exhibited a significant decrease in rutting resistance with added binder while the fatigue resistance remained relatively unchanged. Volumetric mix design data was requested and provided by the asphalt concrete producer for both the 20% RAP and 40% RAP mixes in order to help identify the source of the disparity in performance. As shown in Table 1, the air voids of the plant produced 40% RAP mix was 1.9%, just below the VDOTs lower limit for production of 2.0%. However, as stated earlier, this project required collecting a 40% RAP mix from a private customer as VDOT did not authorize the use of RAP above 30% at the beginning of this study. Asphalt content data from the producer, also shown in Table 1, shows only a difference of approximately 0.2% in binder levels for the 20% and 40% RAP. Further AC testing by ignition oven in this study showed a larger difference in asphalt content between the two mixes, 5.539% and 5.994% for the 20% RAP and 40% RAP mixes respectively. The volumetric and AC data suggest that the 40% RAP mix had initially been designed with more binder and was already at the optimal binder level as incorporating even higher levels of binder to the 40% RAP mix led to poorer performance. This could be a cause for the different performance between the 20% RAP mix and the 40% RAP mix and would need to be further investigated.

As shown in Figure 3(e), at intermediate temperatures (intermediate frequencies) the 40% RAP showed increased dynamic modulus relative to the 0% and 20% RAP mixes, but this effect was diminished at high temperatures (low frequencies). The addition of 1.0% binder to the 40% RAP led the highest average decrease in dynamic modulus at 21%, and a decrease of over 80% in FN determined using the RLPD test which is run at a high temperature of 54.4^{o}C (130 °F). This stiffness behavior is also in accordance with the higher initial stiffness of the 40% RAP mixes during fatigue resistance testing, run at 20^{o}C (68 °F) or intermediate temperature. This behavior further suggests that the 40% RAP mix incorporated a higher binder percentage but needs further investigation.

Another explanation for the reduced rutting resistance for the 40% RAP mixes with added binder is the softer PG binder used in the mix, in this case the PG 64-22 relative to the PG 70-22 binder used in the 0% and 20% RAP mixes. In a 2011 study of 18 asphalt concrete mixes commonly used in Virginia by Apeagyei and Diefenderfer (*13*), results of FN testing indicated that 25% RAP mixes fabricated with PG 64-22 binder had unexpectedly low rutting resistance compared to those using PG 70-22. The use of different binders for the 20% RAP and 40% RAP mixes must be taken into account and the effects should be further studied.

Results of this study also indicate that it is possible to create an asphalt concrete mix in a laboratory setting using 100% RAP which can perform relatively well in dynamic modulus, fatigue resistance and rutting resistance by adding as little as 1.5% virgin binder. 100% RAP alone has the advantage of being extremely stiff with particularly high dynamic modulus and rutting resistance. The shortfall of the 100% RAP material is low fatigue resistance, however, with the addition of 1.5% binder the 100% RAP had a fatigue resistance comparable to the 20% RAP mix at the design binder level currently used in Virginia. The same 100% RAP mix with 1.5% additional binder also had a dynamic modulus between 125% and 300% higher along the range of reduced frequencies and exhibited under 0.6% permanent strain after 10,000 cycles of loading during RLPD testing. Of course, the dynamic modulus, fatigue resistance and rutting resistance while very important, are not the only performance measures of a mix and the fact that the 100% RAP mix with 1.5% added binder outperforms the original 20% RAP mix should not be interpreted as evidence that the 100% RAP mix will perform well in the field. For example, the high dynamic modulus can be a drawback for resistance to temperature cracking. Furthermore, although the fatigue life of the 20% original RAP mix and the 100% RAP mix with 1.5% added binder are similar, Figure 5 shows that accumulation of fatigue damage in the 100% RAP mix is very sudden which is not desirable for cracking resistance.

CONCLUSIONS AND RECOMMENDATIONS

Some specific conclusions and recommendations drawn from this study include the following:

1. The addition of binder can improve the fatigue and rutting resistance performance of RAP asphalt concrete mixes with only slight decreases in dynamic modulus. It is recommended to add that additional binder can be added to the currently used 20% RAP mix. The 40% RAP mix was designed using a RAP correction factor that resulted in a more optimum design binder content and this practice should continue.

2. This result presented in this paper only pertain to mixture performance as measured by rutting resistance, fatigue cracking resistance, and dynamic modulus. More work is being performed to determine the effect the added binder has on mixture volumetric properties obtained following the Superpave mix design procedure number of compaction gyrations.

3. Besides the improvement to fatigue and rutting performance, as the binder content is increased, the compaction energy necessary to achieve the same target air void level decreases. Had the number of gyrations been held constant for mixes of various binder levels, it would be expected that the air void level would decrease for mixes with added binder. Similarly, as binder is added to the mixes, less energy is necessary to achieve the desired compaction.

4. The overall performance of the 100% RAP mix continued to improve with increased binder. At 1.5% additional binder the 100% RAP mix began to exhibit fatigue resistance comparable to that of a currently used 20% RAP and still exhibited extremely high dynamic

modulus and rutting resistance relative to that mix. It is suggested that higher levels of binder be added to the 100% RAP mix in order to further increase the fatigue resistance and to create an optimal mix.

5. Additional performance measures should be evaluated to determine the effects of RAP percentage and binder content. Some additional tests that could be conducted are wheel rutting, permeability, moisture susceptibility and low temperature cracking.

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REFERENCES

1. Daniel, J.S., J.L. Pochily, and D.M. Boisvert, *Can More Reclaimed Asphalt Pavement Be Added?* Transportation Research Record: Journal of the Transportation Research Board, 2010. 2180(1): p. 19-29.

2. Maupin Jr, G., S.D. Diefenderfer, and J.S. Gillespie, *Evaluation of Using Higher Percentages of Recycled Asphalt Pavement in Asphalt Mixes in Virginia.* VTRC Report VTRC08-R22, Charlottesville, Virginia. 2008.

3. Copeland, Audrey. *Reclaimed asphalt pavement in asphalt mixtures: state of the practice*. No. FHWA-HRT-11-021. 2011.

4. West, R., A. Kvasnak, N. Tran, B. Powell, and P. Turner, *Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixes.* Transportation Research Record: Journal of the Transportation Research Board, 2009. 2126(1): p. 100-108.

5. Copeland, Audrey, et al. "Field Evaluation of High Reclaimed Asphalt Pavement-Warm-Mix Asphalt Project in Florida." *Transportation Research Record: Journal of the Transportation Research Board* 2179.1 (2010): 93-101.

6. Li, X., M.O. Marasteanu, R.C. Williams, and T.R. Clyne, *Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures.* Transportation Research Record: Journal of the Transportation Research Board, 2008. 2051(1): p. 90-97.

7. McDaniel, R.S., H. Soleymani, R.M. Anderson, P. Turner, and R. Peterson, *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method.* NCHRP Web Document, 2000. 30.

8. Maupin, G.W., and Diefenderfer, B., *Design of high-binder high-modulus asphalt mixture.* VTRC Report VTRC07-R15, Charlottesville, Virginia. 2006

9. Witczak, M. W., and O. A. Fonseca. "Revised predictive model for dynamic (complex) modulus of asphalt mixtures." Transportation Research Record: Journal of the Transportation Research Board 1540.1 (1996): 15-23.

10. Witczak, M. W., et al. "NCHRP REPORT 465 Simple Performance Test for Superpave Mix Design." *NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM REPORT* (2002).

11. Biligiri, Krishna P., et al. "Rational modeling of tertiary flow for asphalt mixtures." *Transportation Research Record: Journal of the Transportation Research Board* 2001.1 (2007): 63-72.

12. Huang, Y.H., *Pavement Analysis and Design.* Upper Saddle River, NJ: Prentice Hall. 1993

13. Apeagyei, A and Diefenderfer, S., *Asphalt material design inputs for use with the mechanistic empirical pavement design guide*. *VCTIR Report FHWA/VCTIR12-R6,* Charlottesville, Virginia. 2011

CHAPTER III – PAPER 2: A LABORATORY STUDY ON THE EFFECT OF HIGH ASPHALT BINDER CONTENT ON THE VOLUMETRIC PROPERTIES OF ASPHALT CONCRETE MIXES CONTAINING RECLAIMED ASPHALT PAVEMENT

ABSTRACT

The objective of this study is to evaluate the volumetric properties of asphalt concrete mixes with Reclaimed Asphalt Pavement (RAP) and various binder contents. This study builds on a previous study which evaluated the optimal binder content of RAP mixes by measuring performance based on stiffness (dynamic modulus), fatigue resistance, and rutting (flow number). In the prior study, mixes with three different percentages of RAP (0%, 20%, 40%) were evaluated and results showed that a 0.5% increase in binder content improved both the fatigue and rutting resistance of the 0% and 20% RAP mixes with only slight decreases in dynamic modulus. However, the addition of various amounts of binder to the 40% RAP mix led to a significant decrease in rutting resistance with little or no improvement to fatigue resistance. In this study, because adding 0.5% binder to the 0% and 20% mixes resulted in improved mechanical properties, volumetric analysis was performed on the three RAP mixes (0%, 20%, 40%) with three binder contents (design, design + 0.5% and design + 1.0%) to determine how the increased binder content affected mix volumetric properties. The volumetric properties results, specifically asphalt content and air voids at N_{design}, revealed that the 40% RAP mix already contained the optimum binder content during plant production which very likely contributed to its decreased resistance to rutting once additional binder was added in the laboratory. Additionally, the gyratory compaction effort that would result in the optimal binder content from earlier performance testing, $N_{4\%}$, was calculated for each mix. Results indicate that the Voids in the Total Mix (VTM) for the optimally performing 20% and 40% RAP mixes were well below current Virginia Department of transportation (VDOT) production standards. In addition, $N_{4\%}$, for the optimally performing 20% and 40% RAP mixes was 50% or less than the current design compaction effort of 65 gyrations.

INTRODUCTION

The general consensus of past investigations concerning RAP in asphalt concrete indicate that the incorporation of RAP generally improves both stiffness and rutting resistance (*1-3*) but the aged and hardened RAP binder leads to a decrease in fatigue cracking resistance (*4*). In a previous study, the optimal binder content for mixes containing RAP was evaluated by testing the performance of three RAP mixes (0%, 20%, 40%) at three various binder contents (design, design + 0.5%, design + 1.0%) (*5*). The performance of the mixes was evaluated using stiffness (dynamic modulus), rutting resistance (flow number (FN)) and fatigue resistance as the performance criteria. The objective of the study was to determine if adding virgin binder to RAP mixes could potentially offset the decrease in fatigue cracking resistance. Results of the study indicated that adding both 0.5% and 1.0% binder to the 0% and 20% RAP improved both the fatigue and rutting resistance with only slight decreases in dynamic modulus. However, while adding binder to the 40% RAP mix also resulted in improved fatigue resistance, it also resulted in a significant decrease in rutting resistance (*5*). The volumetric properties of the three mixes were therefore evaluated to better understand why the 40% RAP mix performed differently compared to the 0% and 20% RAP mixes.

The 0% and 20% RAP mixes (before adding additional binder), being mixes approved by the Virginia Department of Transportation (VDOT), were designed using the Superpave methodology with the binder content selected at an N_{design} compactive effort of 65 gyrations according to the VDOT standard for traffic loading between 300,000 and 3 million ESALs (*6*). Although the study was sponsored by VDOT to evaluate high RAP mixes, at the time VDOT did not allow mixes with more than 30% RAP. Therefore the 40% RAP mix was obtained from a private project from the same producer that supplied the 20% RAP mix.

Using Superpave design, the design binder content is selected for the aggregate trial blend and asphalt content which yield 4% voids in the total mix (VTM) at the design number of gyrations (N_{design})(*7*). Since the introduction of Superpave in 1993, many states that began using Superpave have been concerned that the method produced mixes that are low in asphalt content (*8*). The basis for this argument being that the specified design compactive gyrations, N_{design}, leads to densities in the lab that are not representative of densities eventually achieved in the field under traffic (*9*). In 2003, Maupin studied the effects of increasing binder content on Virginia's surface mixes and found that as much as 0.5% asphalt could be added to the nine studied mixes with beneficial results in fatigue and rutting resistance (*10*). Not long after the study, VDOT reduced the N_{design} compactive effort from the original 75 to 65 gyrations in order to improve pavement durability (*11*).

This decision to reduce the number of gyrations was later validated by the NCHRP 573 researchers who concluded that the current four Superpave N_{design} levels, already consolidated from the 28 original levels, be reduced in order to improve in place density and also help contractors design mixes that could be more easily compacted in the field (*12*). The report also stated that if larger increases in optimum asphalt content are desired, a reduction in N_{design} should be accompanied by a small increase in voids in the mineral aggregate (VMA) (*12*). A consequence of adding binder to mixes is that for the same compaction effort, additional binder will result in a lower VTM. This justifies the reduced number of design gyrations in order to keep the same VTM of 4% with the general consensus that too low VTM, less than 2.0%, will result in rutting issues whereas too high VTM leads to durability issues (*12*). A Techbrief released by the FHWA in 2011 addressed Superpave mix design and gyratory compaction levels in response to concern from states that Superpave design was resulting in mixes with low binder content. The FHWA brief states that the primary concern with reducing gyratory compaction levels in order to increase binder content is a resultant decrease in rutting resistance. They recommended that any reduction in gyratory levels be accompanied by rutting performance tests including FN or the Asphalt Pavement Analyzer (APA) rutting test (*8*). Another concern of adding binder is creating mixes with excessive asphalt content that may lose stability during compaction and become tender. The specification for mix density at $N_{initial}$, or $\%G_{mm}$ *at* $N_{initial}$, dates back to the introduction of Superpave and was developed with the purpose of predicting the potential for mixes to become tender and eliminate them from the field (*12*).

SCOPE AND OBJECTIVE

This study is part of a research effort to evaluate the effect of increased asphalt content (AC) on the performance of asphalt mixtures containing different percentages of RAP. The performance of the mixes was previously evaluated using dynamic modulus, FN, and fatigue resistance tests and is reported in another publication (*5*). This article presents the results of the evaluation of the volumetric properties of the mixtures which is an essential part of Superpave mix design. Mixes with three different percentages of RAP (0%, 20%, 40%) and three different percentages of asphalt binder (design, design +0.5%, and design +1.0%) were evaluated. The volumetric properties of a mix containing 100% RAP, an extreme case for RAP in HMA, were also evaluated at three additional virgin asphalt binder contents. In addition, the gyratory compactive effort which would yield a VTM of 4%, $N_{4\%}$, was predicted for all of the mixes in the study.

RESEARCH PLAN, MATERIALS AND TESTS

The scope of this work consists of obtaining a virgin asphalt mix, two asphalt mixes with RAP, stockpiled RAP and asphalt binders used in the Commonwealth of Virginia; making virgin and recycled mixes of increased virgin binder content; determining the volumetric properties of the mixes; predicting the gyratory compaction level that would produce 4% VTM for each mix; and analyzing the results. A flow chart of this process is shown in Figure 8.

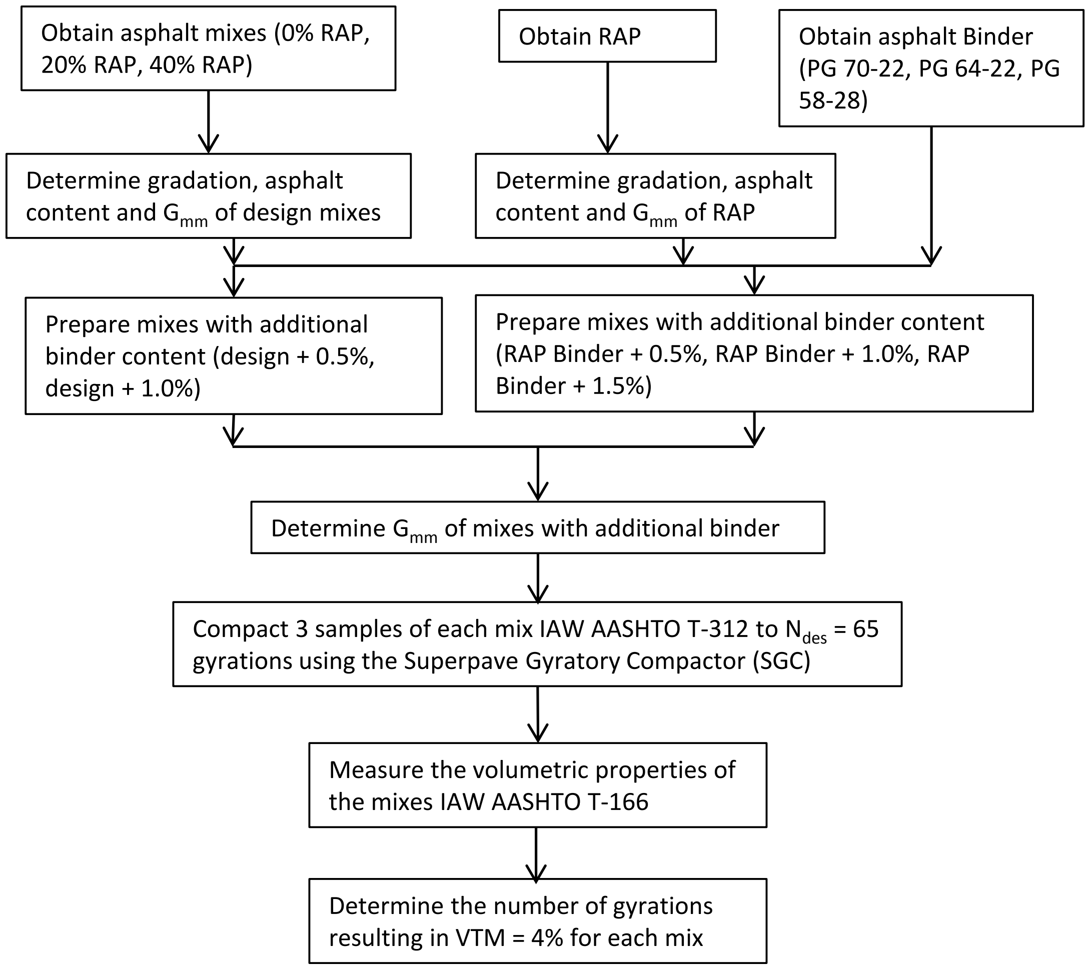

FIGURE 8 Test plan employed in study

Three SM-9.5 asphalt concrete surface mixes typically used in Virginia were obtained from asphalt concrete producers in Northern Virginia. A control mix, SM-9.5D, containing 0% RAP (PG 70-22), an SM-9.5D mix containing 20% RAP (PG 70-22) and an SM-9.5A mix containing 40% RAP (PG 64-22) were used in this study. The 0% and 20% RAP mixes were both VDOT approved mixes whereas the 40% RAP mix, a RAP percentage not approved by VDOT at the time of this project, was obtained from a private project. Additionally, 100% stockpiled RAP used in the 20% and 40% RAP mixes was also obtained from the producer. The theoretical maximum specific gravity (G_{mm}) of each of the three mixes was determined using the Rice method following AASHTO T 209. The ignition oven was used to determine the asphalt content (AC) of the plant mix material. The process followed was adapted from the Virginia Test Method 102. When material was heated and separated to conduct the G_{mm} testing, three samples exceeding 1500g (3.3 lbs) were taken for use in the ignition oven, to determine the AC. An ignition oven correction factor was unable to be developed due to a lack of material. Sieve analysis following AASHTO T 27 was then performed on two of the burned samples after asphalt content testing. The G_{mm} and asphalt content for each plant mix and the RAP are summarized in Table 4. Gradation curves were produced based on the average of the two sieve analysis for each mix and the stockpiled RAP material and are shown in Figure 9.

TABLE 4 Properties of asphalt mixes and stockpiled RAP

	Original Binder Grade	Added Binder Grade	Asphalt Content	G_{mm}
0% RAP	PG 70-22	PG 70-22	5.629	2.686
20% RAP	PG 70-22	PG 70-22	5.539	2.614
40% RAP	PG 64-22	PG 64-22	5.994	2.603
100% RAP	unk	PG 58-28	5.770	2.623

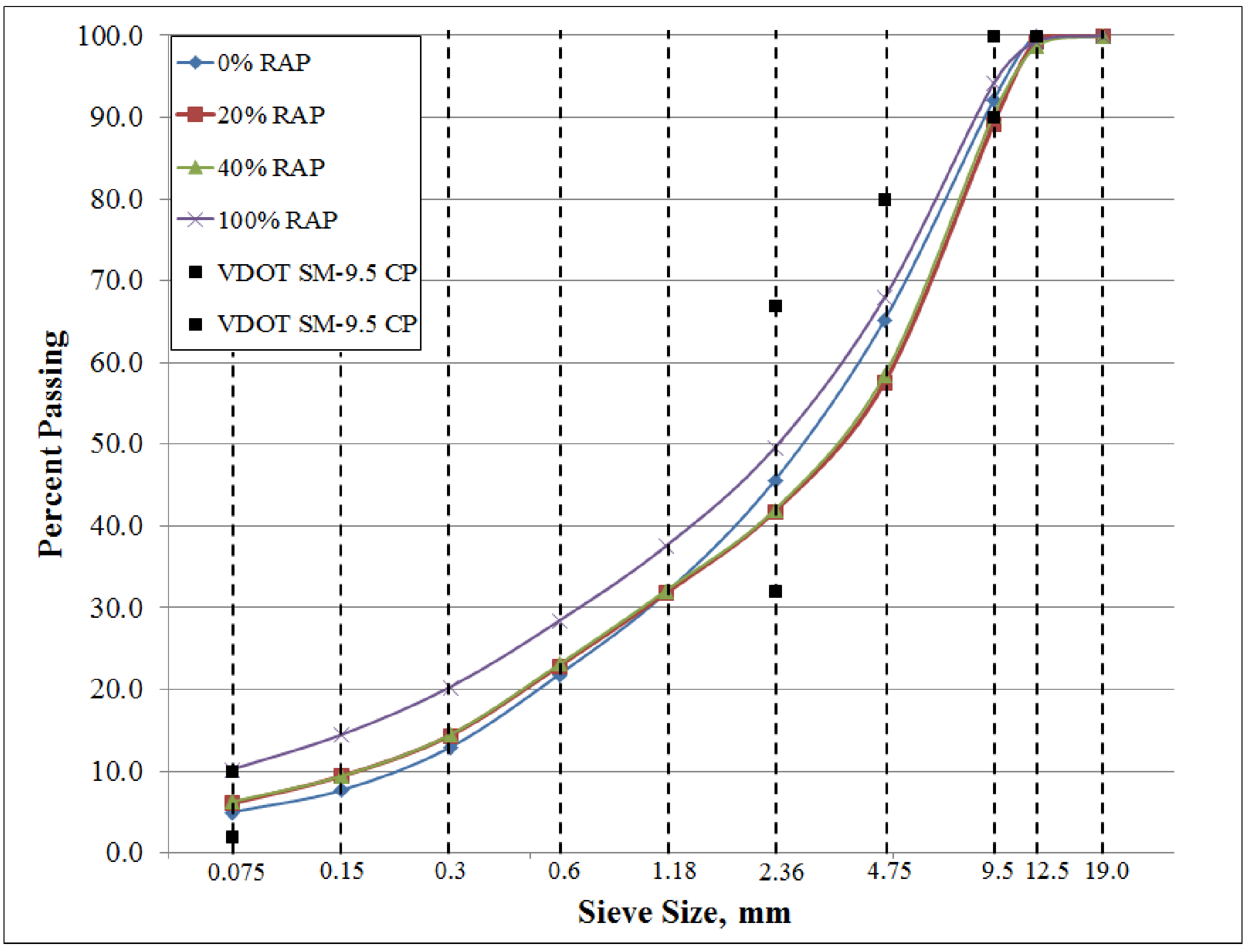

FIGURE 9 Gradation of mixes and RAP

Sample Preparation

The three asphalt concrete mixes, as well as the 100% RAP, were then modified by adding increased amounts of asphalt binder. Two levels of increased binder content were evaluated for the 0% RAP, 20% RAP and 40% RAP mixes: design, design + 0.5% and design + 1.0%. The original, or design, binder contents for the 0% RAP and 20% RAP mixes were determined by the producer in accordance with VDOT specifications. Selection of the design binder content for the 40% RAP mix, which was used on a private project, was not subject to VDOT specifications. The original + 1.00% level was used, as it was suggested by Maupin and Diefenderfer (*9*), that it might be the additional asphalt content needed to see appreciable improvement in fatigue cracking resistance. Four levels of binder content were evaluated for the mix containing 100% RAP; RAP with no added binder, RAP + 0.5% added binder, RAP + 1.0% added binder and RAP + 1.5% added binder. PG 70-22 binder was added to both the 0% RAP and 20% RAP mixes and PG 64-22 binder was added to the 40% RAP mix, the same binder grades used in initial production. PG 58-28 binder was used for the 100% RAP mix and was chosen because it has been argued that the softer binder would blend and mix with the aged RAP binder to decrease the stiffness of the overall mix (*4*).

All mixing of additional asphalt binder samples followed the following procedure. The 0% RAP, 20% RAP 40% RAP mixes as well as the 100% RAP material were placed in ovens preheated to 154°C. The PG 70-22, PG 64-22 and PG 58-28 binders were placed in a separate oven and preheated to 160°C, 154°C and 148°C respectively. Once the mixing temperatures were reached, the material was removed from the oven, placed in a preheated mixing bucket and weighed. The heated binder was then added to the material as a percentage based on the amount of material in the bucket. The materials were then mixed for approximately five minutes using a preheated mixing arm on an electric mixer, until the aggregates were sufficiently coated with the virgin binder. The G_{mm} of the mixes with added binder was also determined using the Rice method after mixing was complete.

The scope of this study included preparing one set of three cylindrical specimens for volumetric testing for each mix. Samples were prepared and compacted following the procedure specified in AASHTO T 312 "Preparing Hot-Mix Asphalt (HMA) Specimens by Means of the Superpave Gyratory Compactor (SGC)." Prior to compacting, both the ram pressure and the internal angle of the SGC were calibrated to 600 ± 18 kPa and 1.16 ± 0.02° respectively. Samples of approximately 5,000 g were heated in an oven to a temperature of 148°C (300°F) for the 0% and 20% RAP and 143 °C (290°F) for the 40% and 100% RAP, then funneled into a preheated mold. Samples were then compacted with a compactive effort of 65 gyrations, the design compactive effort required for asphalt concrete mixtures produced for VDOT, at 30 gyrations per minute. After compaction, the samples were extracted from the mold and placed on a smooth, flat surface too cool over night at room temperature. For the most part the 100% RAP mix with no added binder held together quite well after removal from the mold, however, the edges and surfaces did become a bit crumbly as the specimens were moved around for testing. The height of all compacted samples fell within 115 ± 5mm, and during compaction, both specimen height and gyration data were continuously collected.

Superpave Volumetric Properties

The volumetric properties of the compacted samples were determined using AASHTO T 166 "Bulk Specific Gravity of Compacted Hot Mix Asphalt Using Saturated Surface-Dry Specimens." Specimens were dried to a constant mass and the dry mass was measured. Then each specimen was immersed in water for 4 ± 1 minute in water at 25 ± 1 °C (77 ± 1.8°F) and the immersed mass was recorded. Then, the specimens were quickly removed from the water, blotted dry with a damp towel and the surface dry mass was measured. Next the Bulk Specific Gravity of each core was determined using equation 1 below (*7*).

$$Bulk\ Specific\ Gravity\ (BSG) of\ Core = \frac{A}{B-C} \tag{1}$$

where: A = Weight of core in air,
1. B = weight of SSD core in air,
C = weight of core in water

The bulk specific gravity of the mix (G_{mb}) was then calculated using equation 2 below:

$$G_{mb} = \frac{BSG\ specimen\ 1 + BSG\ specimen\ 2 + BSG\ specimen\ 3}{3} \tag{2}$$

Utilizing the theoretical maximum specific gravity (G_{mm}), the VTM was determined using equations 3 below (*7*).

$$VTM = 100x\ (1 - \left(\frac{G_{mb}}{G_{mm}}\right)) \tag{3}$$

where: G_{mb} = bulk specific gravity of mix
G_{mm} = maximum specific gravity of mix (Rice)

The VMA of the mixes was determined using equations 4, 5 and 6 below. For the 0% RAP, 20% RAP and 40% RAP mixes, the effective specific gravity of the aggregate (G_{se}) and correction factor or offset value (CF) given by the producer were used to calculate the bulk specific gravity of the aggregate (G_{sb}) used in the VMA calculation (*7*).

$$VMA = 100 - \left[\frac{(G_{mb}\ x\ P_s)}{G_{sb}}\right] \tag{4}$$

where, G_{mb} = bulk specific gravity of mix
$P_s = Percent\ stone\ (100 - asphalt\ content)$
G_{sb} = bulk specific gravity of aggregate = $G_{se} - CF$, (5)

where, CF = field correction factor (given by producer)

G_{se} = effective specific gravity of the aggregate = $\frac{P_s}{\frac{100}{G_{mm}}-\frac{P_b}{G_b}}$ (6)

where $P_b = asphalt\ content$

$G_b = binder\ specific\ gravity$

For the 100% RAP mix, the G_{sb} of the RAP aggregate was determined using an empirical relationship between the G_{sb} and G_{se} developed and used by the Minnesota Department of Transportation shown in equation 7 (*13*).

$$G_{sb} = 0.9397G_{se} + 0.0795 \quad (7)$$

The VFA for each mix was then calculated using the VTM and VMA values using equation 8 (*7*).

$$VFA = \left[\frac{(VMA-VTM)}{VMA}\right] x\ 100 \quad (8)$$

Once calculated the VTM, VMA and VFA values as well as the Density at N_{inital} were compared to the 2007 VDOT specifications (*6*) shown in Table 5.

TABLE 5 Excerpt from 2007 VDOT Road and Bridge Specifications Section 211, Table II-14 Mix Design Criteria

Mix Type	VTM (%) Production[a]	VFA (%) Design	VFA (%) Production[b]	Min. VMA (%)	Fines/Asphalt Ratio	No. of Gyrations			Density (%) at N_{ini}
						N_{Design}	$N_{Initial}$	N_{Max}	
SM-9.5A[a,b]	2.0-5.0	73-79	68-84	15	0.6-1.2	65	7	100	≤ 90.5
SM-9.5D[a,b]	2.0-5.0	73-79	68-84	15	0.6-1.2	65	7	100	≤ 89.0

[a]**Asphalt content should be selected at 4% air voids**

[b]**During production of an approved mix, VFA should be controlled within these limits**

Gyrations to Achieve 4% VTM, $N_{4\%}$

In order to determine the number of gyrations which would result in 4% VTM, $N_{4\%}$, for each mix, a method developed by Vavrik and Carpenter (*14*) and the Illinois Department of Transportation was utilized. The Illinois method uses statistical regression to determine the number of gyrations at which a mixture is compacted to a specified air voids level. The developers of this method pointed out that the initial portion of the total densification curve, %G_{mm} versus gyrations, for a mix follows a logarithmic relationship. It is possible to use this relationship to predict $N_{4\%}$ for a mix by using gyratory data up until the "locking point" or the point at which the mixes' aggregate skeleton locks together and subsequent compaction causes only degradation of the aggregate with minimal further compaction (*12*). The locking point was also developed by the Illinois DOT and was first defined as the "first gyration in a set of three gyrations of the same height that was preceded by two gyrations of the same height". The definition of the locking point was then refined by Vavrik and Carpenter who said the set of three gyrations at the same height were preceded by two sets of two gyrations at the same height (*12*). The Illinois method has proven to be more accurate than the Superpave procedure for back calculating gyrations and works especially well for mixtures with smaller maximum nominal aggregate sizes (*14*).

Using the Illinois method the $N_{4\%}$ was determined by converting the compaction height data for each gyration to $\%G_{mm}$. This was accomplished using the G_{mm} of the loose sample and the corrected G_{mb} following the Superpave mix design procedure. The G_{mb} was estimated using equation 9 below (*14*).

$$G_{mb}(estimated) = \frac{W_m/V_{mx}}{\gamma_w} \quad (9)$$

where, $G_{mb}(estimated) =$ estimated bulk specific gravity of `specimen during compaction
$W_m =$ mass of specimen, grams
$\gamma_w =$ density of water, 1 g/cm^3
$V_{mx} =$ volume of compaction mold, cm^3

A correction factor was then established because the estimated G_{mb} assumes a smooth sided specimen it must be adjusted due to the fact that in reality, compacted specimens have surface irregularities. The correction factor, C, was calculated using equation 10 (*14*).

$$C = \frac{G_{mb}(measured)}{G_{mb}(estimated)} \quad (10)$$

The corrected G_{mb} at any gyration level was then calculated using equation 11 and the density or $\%G_{mm}$ at each gyration was calculated using equation 12 (*14*). These equations were also used to calculate the density at $N_{initial}$ or in the case of this study, the $\%G_{mm}$ at 7 gyrations.

$$G_{mb}(corrected) = C\ x\ G_{mb}(estimated) \quad (11)$$

$$\%G_{mm}@gyration\ n = \frac{G_{mb}(corected@gyration\ n)}{G_{mm}} \quad (12)$$

A least squares linear statistical regression was then performed on the $\%G_{mm}$ and the logarithm of the gyrations, truncated to the locking point for each sample. The result of the regression are the compaction slope (α) and intercept (β) given by equation 13 below (*14*).

$$\beta = y - \alpha x \qquad \alpha = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{13}$$

where, β = intercept of compaction curve
α = slope of compaction curve
x = log(N_{gyr}), independent variable
$\bar{x}$ = average value of x
y = %G_{mm}, dependent variable
$\bar{y}$ = average value of y

Using the compaction slope and intercept, the number of gyrations to reach 4% VTM or a density of 96% G_{mm} was calculated using equation 14 below (*14*).

$$N_{4\%} = 10^{[(\%G_{mm} - \beta)/\alpha]} \tag{14}$$

TEST RESULTS, ANALYSIS AND DISCUSSION

Superpave Volumetric Properties

The results of the volumetric testing are displayed in Table 6 below for all of the mixes and binder contents.

TABLE 6 Volumetric data for all mixes

		Design	Design + 0.5%	Design + 1.0%	
0% RAP	[a]Asphalt Content (%)	5.629	6.129	6.629	
	G_{mm}	2.686	2.668	2.648	
	VTM (%)	4.1	2.3	1.3	
	VMA (%)	17.2	16.80	17.90	
	VFA (%)	76.1	86.4	92.9	
	Desnsity @ $N_{initial}$ (%)	88.4	89.9	90.6	
20% RAP	[a]Asphalt Content (%)	5.539	6.039	6.539	
	G_{mm}	2.614	2.595	2.576	
	VTM (%)	3.0	0.9	0.4	
	VMA (%)	16.1	16.1	17.8	
	VFA (%)	81.0	94.1	97.7	
	Desnsity @ $N_{initial}$ (%)	89.4	91.5	92.3	
40% RAP	[a]Asphalt Content (%)	5.994	6.494	6.994	
	G_{mm}	2.603	2.568	2.563	
	VTM (%)	1.9	0.6	0.1	
	VMA (%)	16.2	16.96	18.3	
	VFA (%)	88.0	96.2	99.3	
	Desnsity @ $N_{initial}$ (%)	90.7	92.9	93.9	
		RAP Binder+0%	**RAP Binder+0.5%**	**RAP Binder+1.0%**	**RAP Binder+1.5%**
100% RAP	[a]Asphalt Content (%)	5.770	6.270	6.770	7.270
	G_{mm}	2.626	2.623	2.587	2.586
	VTM (%)	5.6	1.6	0.5	0.2
	VMA (%)	16.8	14.5	14.6	15.7
	VFA (%)	66.7	88.7	96.9	98.5
	Desnsity @ $N_{initial}$ (%)	86.7	91.8	94.4	95.7

[a]Asphalt Content (%) measured using ignition oven at VTTI (no correction factor)

The VTM at N_{design} for each RAP percentage decreased as binder was added for all of the mixes in the study. This reduction in VTM is obvious upon visual inspection of the mix curves displaying the VTM versus gyrations which are shown in Figure 10. The VTM of the 0% RAP and 20% RAP design mixes were within VDOT production limit standards, between 2.0% and 5.0%, while the VTM of the 40% RAP design mix was below the specified level at 1.9%. Note that the 40% RAP mix was not a mix supplied to VDOT but rather to a private costumer.

Additionally, the AC of the 40% RAP mix was approximately the same as the ACs of the 0% RAP and 20% RAP with 0.5% added binder, or about 6%. As 0.5% binder was added to the three mixes the VTM decreased significantly by 44%, 69%, and 67% for the 0% RAP, 20% RAP and 40% RAP mixes respectively. Adding 1.0% binder led to a reduction in VTM of 69% for the 0% RAP, 86% for the 20% RAP and 93% for the 40% RAP. The VTM of the 40% RAP mix at design binder content, 1.9%, was between the VTM values for the 0% and 20% RAP at design + 0.5% binder. A plot showing the VTM of each mix and binder content as well as the VDOT VTM specifications is shown in Figure 11.

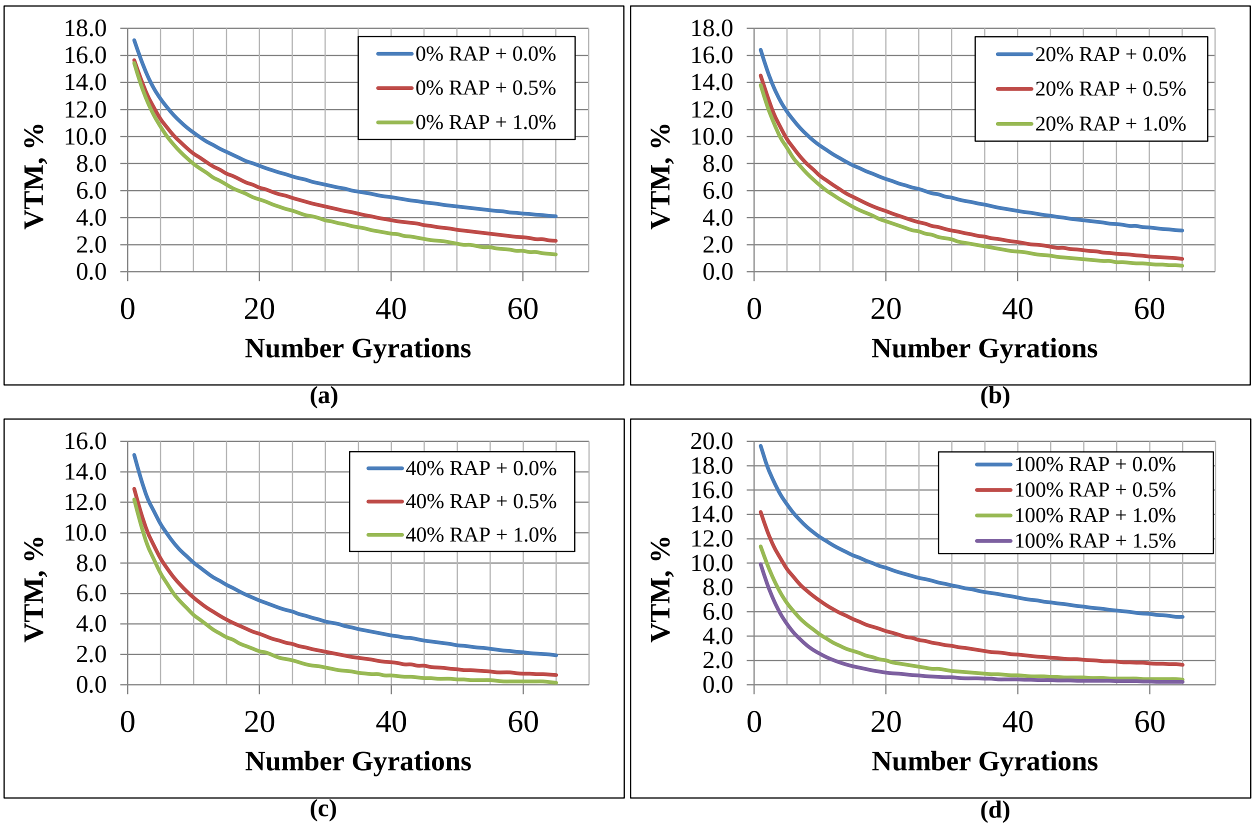

FIGURE 10 VTM versus gyrations for a) 0% RAP, b) 20% RAP, c) 40% RAP and d) 100% RAP

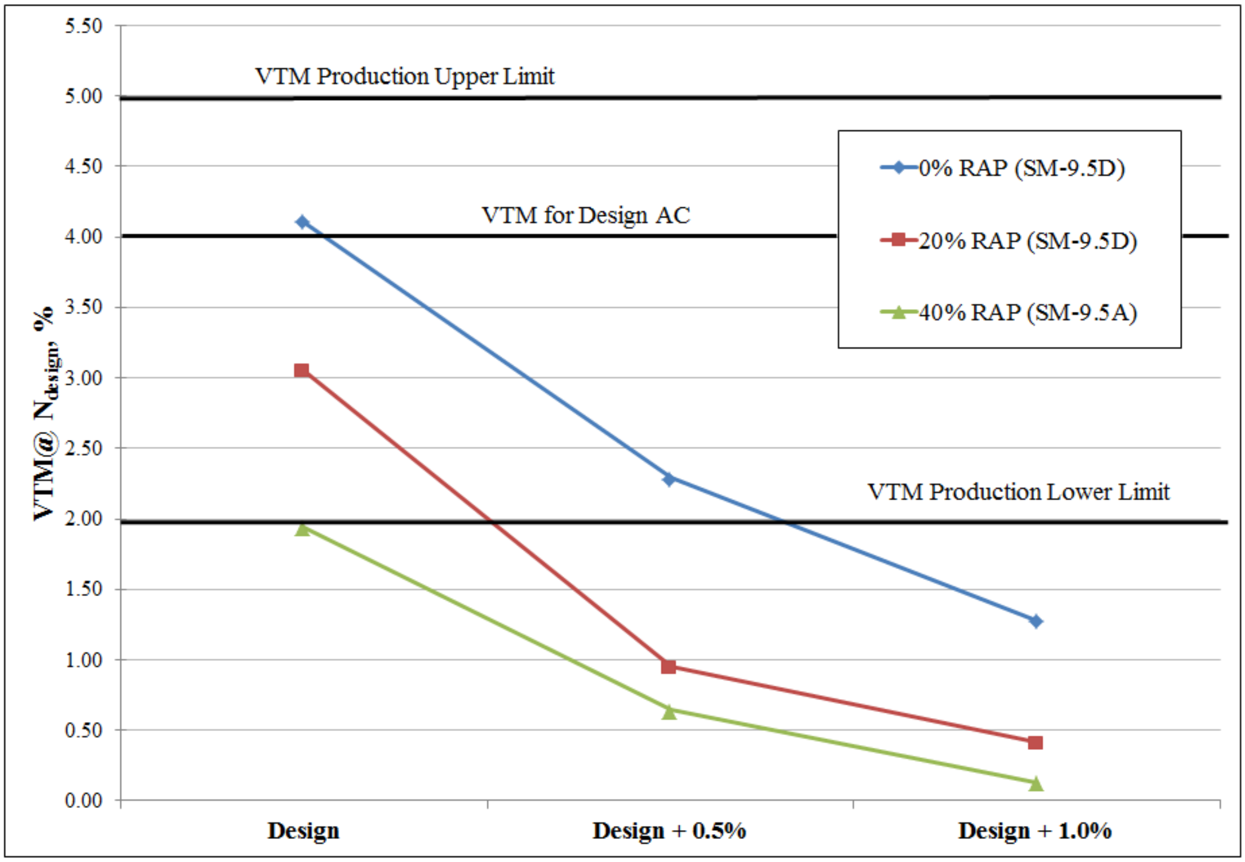

FIGURE 11 VTM at N_{design} for all mixes (with VDOT specifications)

Addition of asphalt binder to the design mixes also led to significant increases in VFA as VTM decreased and VMA generally increased. A plot of the VFA at N_{design} for each mix as well as the VDOT VFA range specification is shown in Figure 12 The 0% RAP at design binder content and design + 0.5% binder and the 20% RAP at design binder content were the only mixes that fell within VDOT production specifications for VFA. The 40% RAP mix at design binder content was already at 88% VFA, above the VDOT threshold of 84%. At design + 0.5% binder, the 20% RAP and 40% RAP mixes well above the limits of 94% and 95%, increasing to 98% and 99% at design + 1.0% binder. Asphalt binder was visibly bleeding out of 20% and 40% RAP design + 1.0% binder specimens coating both the top and bottom specimen papers upon extraction from the SGC molds.

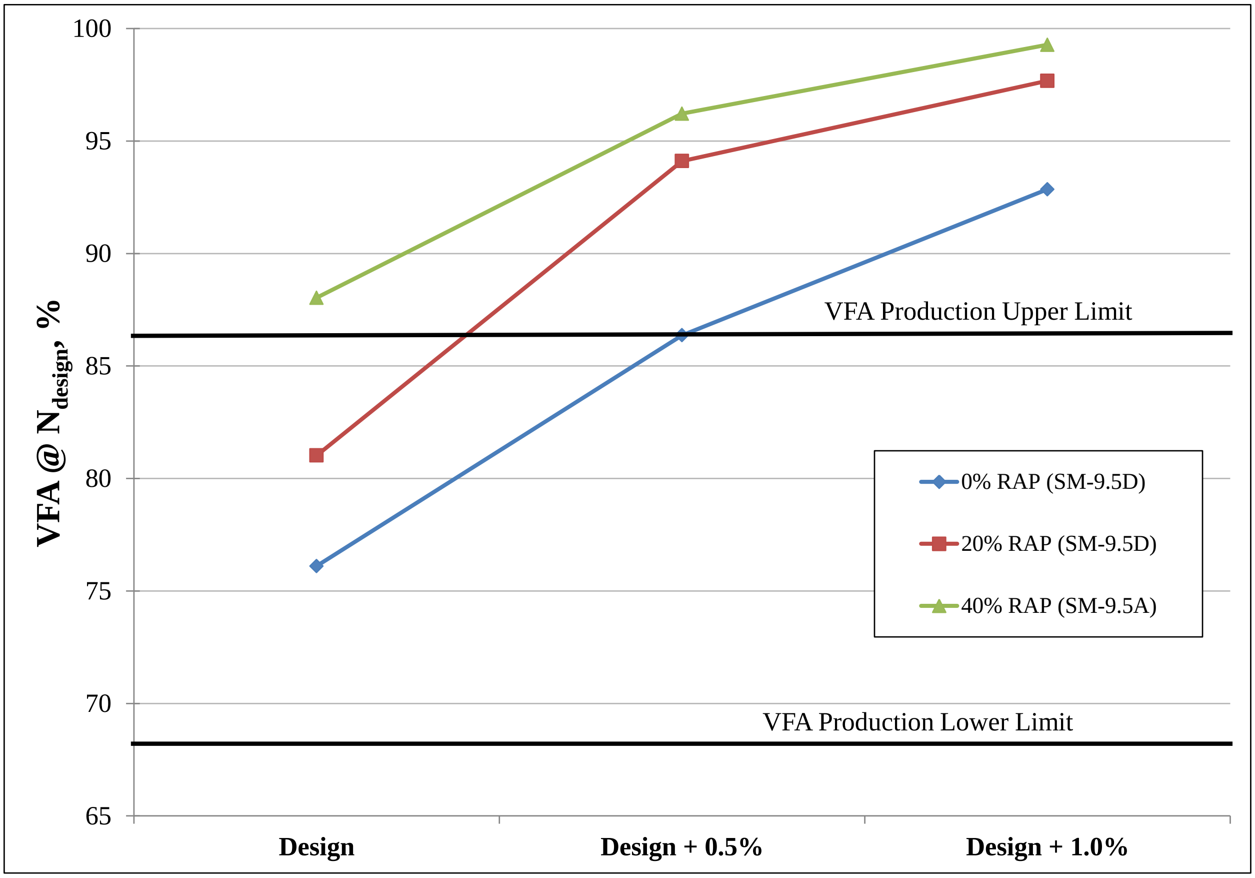

FIGURE 12 VFA at N_{design} for all mixes (with VDOT specifications)

As asphalt binder was added to the mixes, the density at $N_{initial}$ increased. A plot of the density at $N_{initial}$ for each mix as well as VDOT density at $N_{initial}$ specifications is shown in Figure 13. Due to the fact that the 0% RAP and 20% RAP were SM-9.5D mixes using PG70-22 binder and the 40% RAP mix was a SM-9.5A mix using PG64-22 binder, the VDOT specifications for density at $N_{initial}$ are different. The 0% RAP mix at design binder content was the only mix that met the maximum density specification. The 20% RAP and 40% RAP mixes at design binder content were 0.4% and 0.3% above the limit respectively. At 0.5% added binder, all of the mixes had densities well above the specified limits, increasing by an average of approximately 2%. The addition of 1.0% binder led to an increase in density of 2.2% for the 0% RAP, 2.9% for the 20% RAP and 3.2% for the 40% RAP.

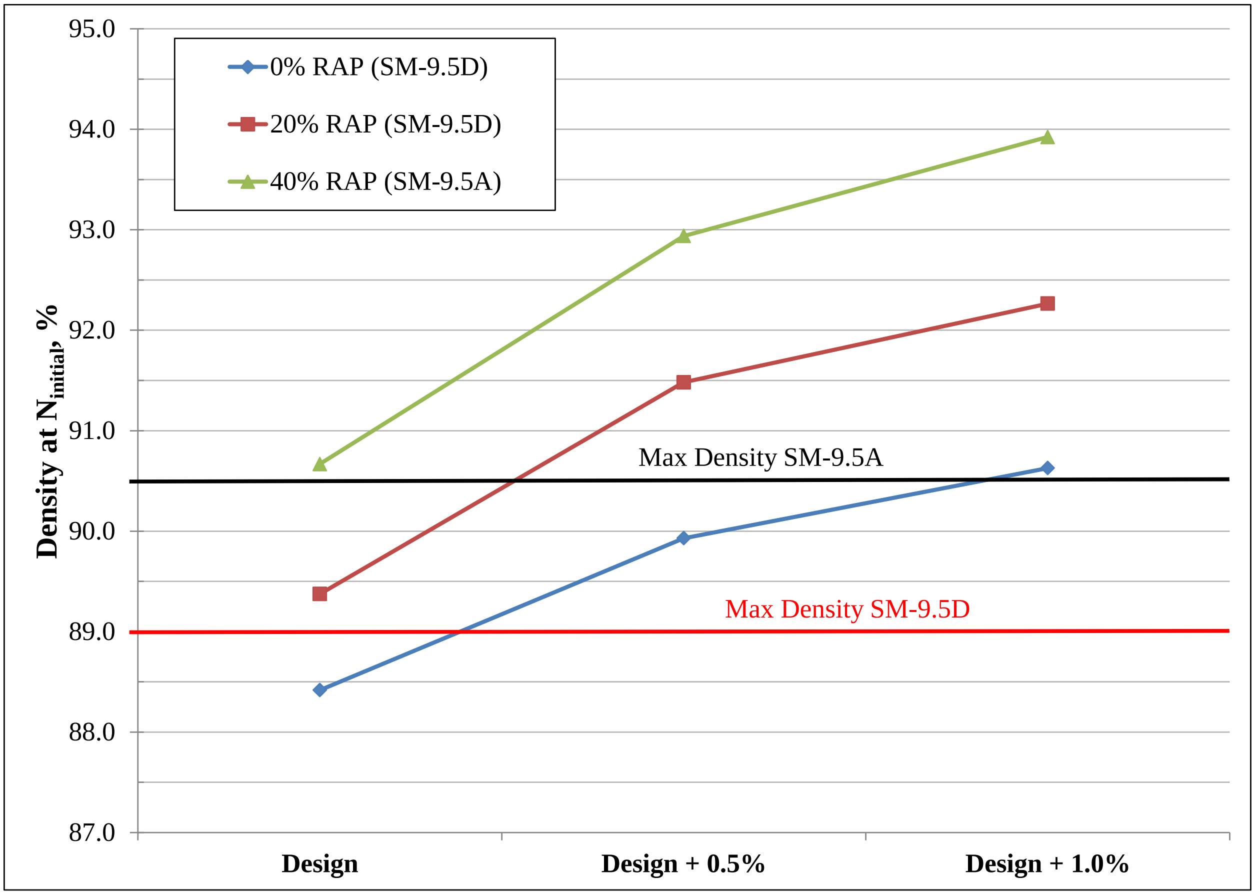

FIGURE 13 Density at $N_{initial}$ for all mixes (with VDOT specifications)

Gyrations to Achieve 4% VTM, $N_{4\%}$

The results of the analysis following the Illinois method to predict $N_{4\%}$ are shown in Table 7. Additionally, a plot of $N_{4\%}$ for each mix and binder content is shown in Figure 14. Visual inspection of Figure 14 indicates that $N_{4\%}$ decreases as binder is added for all mixes with only the $N_{4\%}$ of the 0% RAP mix at design binder content above the VDOT design compactive effort of 65 gyrations. For the 20% and 40% RAP mixes at design binder content it was predicted that only 47 and 33 gyrations would be necessary to yield 4% air voids respectively. For the 40% RAP mix, this is approximately half of the specified design compactive effort. At design + 0.5% binder the predicted $N_{4\%}$ for the 0% RAP mix was reduced by approximately 40% and at 1.0% added binder the $N_{4\%}$ was 55% less than that of the design mix. The 20% RAP and 40% RAP mixes followed a similar trend, with reductions in $N_{4\%}$ of 49% and 25% respectively when 0.5% binder was added. Adding 1.0% to both these mixes led to a 60% reduction in $N_{4\%}$. The gyratory height data for the 0% RAP mixes showed none of them experienced “locking points” during the 65 gyrations of compaction. The 20% RAP mix at design binder content also did not have a locking point, however, the other two 20% RAP mixes and all three of the 40%

RAP mixes did have locking points with the average locking point decreasing with additional binder.

TABLE 7 Summary of predicted gyrations to 4% VTM, $N_{4\%}$, data for all mixes

Mix		Specimen	VTM, %	Correction	α	β	Locking Point	Predicted $N_{4\%}$	Average
0% RAP	Design	0.0-1	4.1	1.112	0.0768	0.8206	--	65	67
		0.0-2	4.1	1.107	0.0772	0.8186	--	68	
		0.0-3	4.1	1.114	0.0779	0.8176	--	67	
	Design + 0.5%	0.5-1	2.3	1.109	0.0808	0.8309	--	40	39
		0.5-2	2.2	1.108	0.0819	0.8304	--	38	
		0.5-3	2.3	1.108	0.0797	0.8340	--	38	
	Design + 1.0%	0.1-1	1.3	1.106	0.0855	0.834	--	30	30
		0.1-2	1.3	1.105	0.084	0.837	--	29	
		0.1-3	1.3	1.104	0.083	0.838	--	30	
20% RAP	Design	20.0-1	3.1	1.108	0.0774	0.8299	--	48	47
		20.0-2	3.0	1.108	0.0799	0.8268	--	46	
		20.0-3	3.0	1.110	0.0795	0.8271	--	47	
	Design + 0.5%	20.5-1	1.0	1.105	0.0805	0.8487	61	24	24
		20.5-2	0.9	1.108	0.0785	0.8519	60	24	
		20.5-3	1.0	1.106	0.0736	0.8593	62	23	
	Design + 1.0%	20.1-1	0.4	1.105	0.0808	0.856	57	19	19
		20.1-2	0.5	1.102	0.0832	0.8518	52	20	
		20.1-3	0.4	1.105	0.0809	0.8566	55	19	
40% RAP	Design	40.0-1	1.8	1.105	0.0774	0.8440	62	32	33
		40.0-2	2.0	1.107	0.0798	0.8383	61	34	
		40.0-3	2.0	1.109	0.0795	0.8271	61	33	
	Design + 0.5%	40.5-1	0.6	1.104	0.0759	0.8641	51	18	18
		40.5-2	0.6	1.104	0.0745	0.8672	50	18	
		40.5-3	0.7	1.106	0.0740	0.8694	46	17	
	Design + 1.0%	40.1-1	0.2	1.106	0.0777	0.874	39	13	13
		40.1-2	0.1	1.105	0.0769	0.8754	41	13	
		40.1-3	0.2	1.106	0.0767	0.8726	44	14	
100% RAP	Rap Binder	100.0-1	5.5	1.111	0.0835	0.7925	--	101	100
		100.0-2	5.6	1.105	0.0827	0.7959	--	96	
		100.0-3	5.7	1.106	0.0820	0.7955	--	101	
	RAP Binder + 0.5%	100.5-1	1.7	1.102	0.0773	0.8538	47	24	24
		100.5-2	1.6	1.104	0.0766	0.8547	48	24	
		100.5-3	1.7	1.103	0.0786	0.8495	47	25	
	RAP Binder + 1.0%	100.1-1	0.4	1.103	0.0726	0.8837	39	11	12
		100.1-2	0.4	1.102	0.0723	0.8838	41	11	
		100.1-3	0.5	1.103	0.0742	0.8783	44	13	
	RAP Binder + 1.5%	100.15-1	0.2	1.111	0.0662	0.908	24	6	7
		100.15-2	0.3	1.103	0.0662	0.902	29	8	
		100.15-3	0.2	1.113	0.067	0.902	28	7	

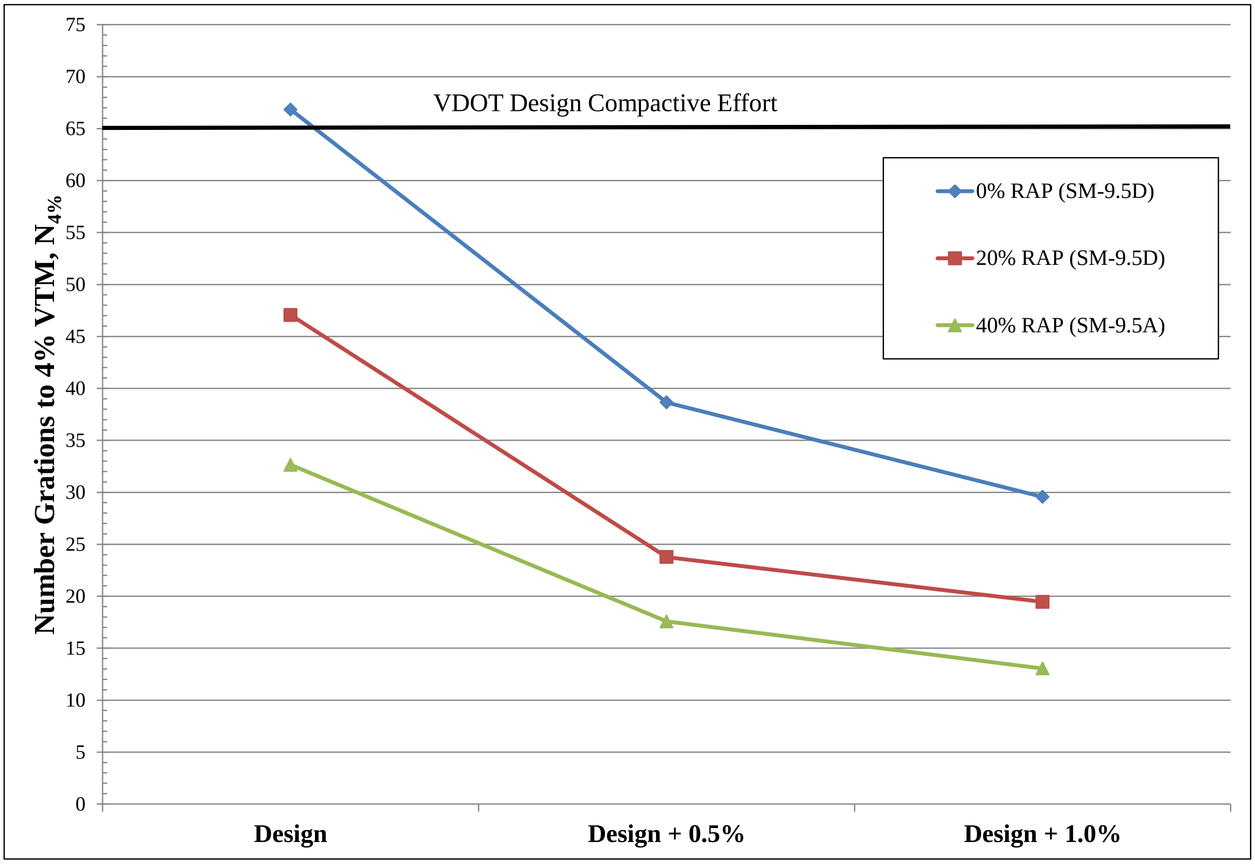

FIGURE 14 Predicted number of gyrations to 4% VTM, $N_{4\%}$

OBSERVATIONS

As this study was a follow on to a previous investigation on the performance behavior of RAP mixes at various binder contents, the volumetric analysis can help explain the results of the previously completed performance tests as well as determine if the currently utilized design procedure results in asphalt contents which are less then optimal for RAP mixes. In the prior study, dynamic modulus testing indicated that there were only slight decreases in stiffness when binder was added to the 0%, 20% and 40% RAP mixes. Additionally, the addition of binder generally improved the fatigue cracking resistance of all three mixes. Unexpectedly, the 40% RAP mix at the design binder content showed higher fatigue resistance relative the 20% RAP mixes at all three binder contents. The 0% RAP and 20% RAP mixes also saw increased FNs at the design + 0.5% and design + 1.0% binder levels. However, when binder was added to the 40% RAP mix the flow number decreased significantly. One of the explanations for this decrease is the use of the softer PG64-22 binder in the 40% RAP mix, however, the volumetric properties also offer an explanation to this behavior. A plot depicting FNs and VTM at N_{design} for all of the mixes is shown below in Figure 15. The VTM of the 40% RAP mix at design binder content was 1.9%, significantly lower than that of the 0% RAP and 20% RAP design mixes but in between the VTM values for the 0% and 20% RAP mixes with 0.5% added binder. With the addition of 0.5% binder, the 0% RAP and 20% RAP exhibited an increase in FN as well as a decrease in VTM from 4.1 to 2.3 and 3.0 to 0.9 respectively. For the 0% RAP and 20% RAP, the design + 0.5% binder level proved to be the optimal mix for the three binder levels tested across all three performance tests. With the addition of 0.5% binder the 40% RAP mix experienced a decrease in VTM from 1.9% to 0.6% and a subsequent decrease in FN and this decrease in VTM and FN continued with the addition of 1.0% binder. At design + 1.0% binder, both the 0% RAP and 20% RAP mixes exhibited decreases in both VTM and FN from the design + 0.5% binder mixes. It is likely that this trend would have continued if these mixes had been tested with even higher additional binder levels which would have also resulted in lower VTM values. Whereas the addition of 0.5% binder led to an increase in FN for the 0% RAP and 20% RAP mixes before FN was reduced with the addition of 1.0% binder, FN for the 40% RAP mixes steadily decreased with additional binder. This relationship shows that the 40% RAP mix was most probably already at optimal binder content when tested with no additional binder, which is the reason for the lower initial VTM.

As stated earlier, the general consensus is that too low VTM, less than 2.0%, will result in mixes with lower rutting resistance (*12*). The results of this study indicate that for the 20% RAP, the greatest rutting resistance, or highest FN, was the design + 0.5% binder mix with 0.9% VTM at N_{design}. The 40% RAP mix at design binder content and 1.9% VTM at N_{design} exhibited the highest rutting resistance overall. For both the 20% and 40% RAP, once the VTM fell below 0.5%, the rutting resistance decreased.

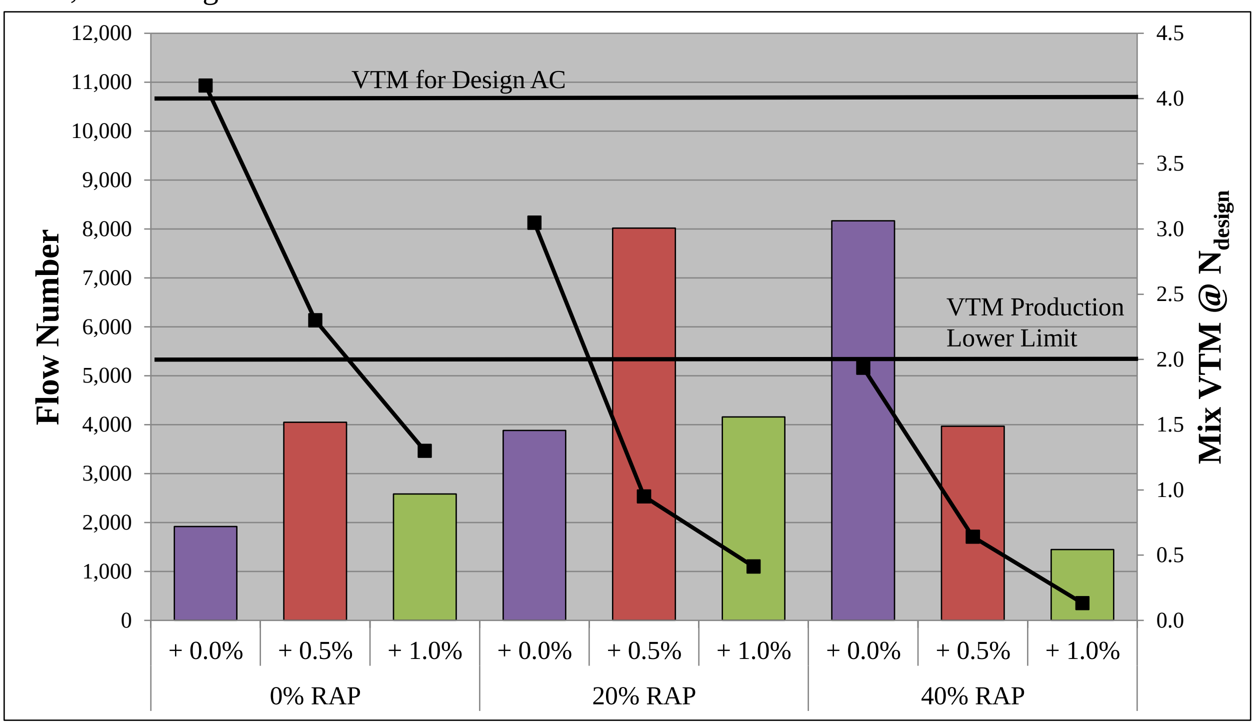

FIGURE 15 Flow number and VTM at N_{design} for all mixes

Figure 16 below shows the FN and asphalt content for all mixes. Upon visual inspection of the plot it can be seen that the optimal FN for all mixes occurs at an AC of approximately 6%. For the case of the 0% and 20% RAP, this was the AC resulting from adding 0.5% binder and for the 40% RAP, this was the initial asphalt content of the design mix received from the producer. This is another indication that the 40% RAP mix, not having to meet VDOT specifications, was originally designed with higher binder that resulted in a lower VTM at N_{design}.

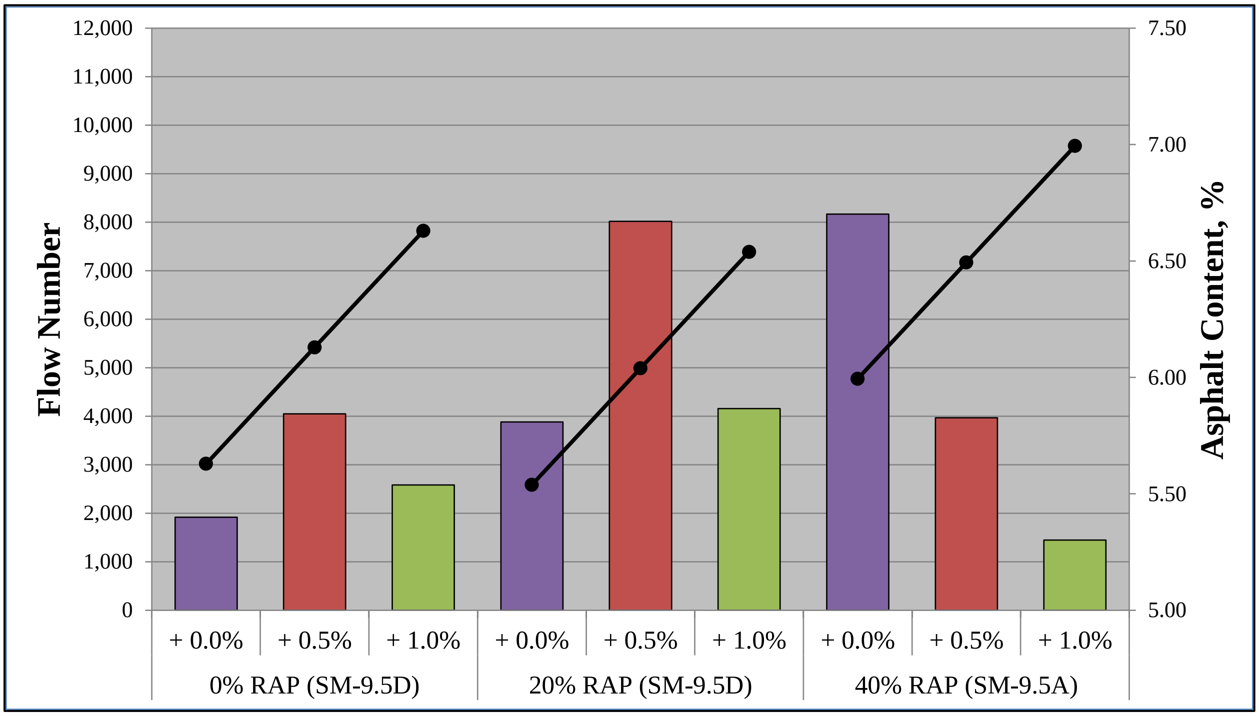

FIGURE 16 Flow number and asphalt content for all mixes

As recommended by the FHWA, any consideration for reduction in design gyrations in order to achieve mixes with higher asphalt binder must be combined with an evaluation of the rutting resistance of mixes resulting from lower design compaction effort (*8*). Figure 17 shows the FN and predicted $N_{4\%}$ for the 0%, 20% and 40% RAP mixes. Upon visual inspection it is obvious that the mixes for which rutting resistance was highest would have yielded 4% VTM at significantly lower design gyrations than currently specified. In the case of the 20% RAP and 40% RAP, the mix with the highest FN had asphalt binder contents that would have resulted in 4% VTM with 25 and 33 gyrations respectively, approximately 50% or less than the 65 gyrations currently used. Additionally, the optimally performing RAP mixes, the 20% design + 0.5% binder and 40% at design binder content, both had average locking points of 61. This means that additional gyrations past 61 mainly result in degradation of the aggregate skeleton.

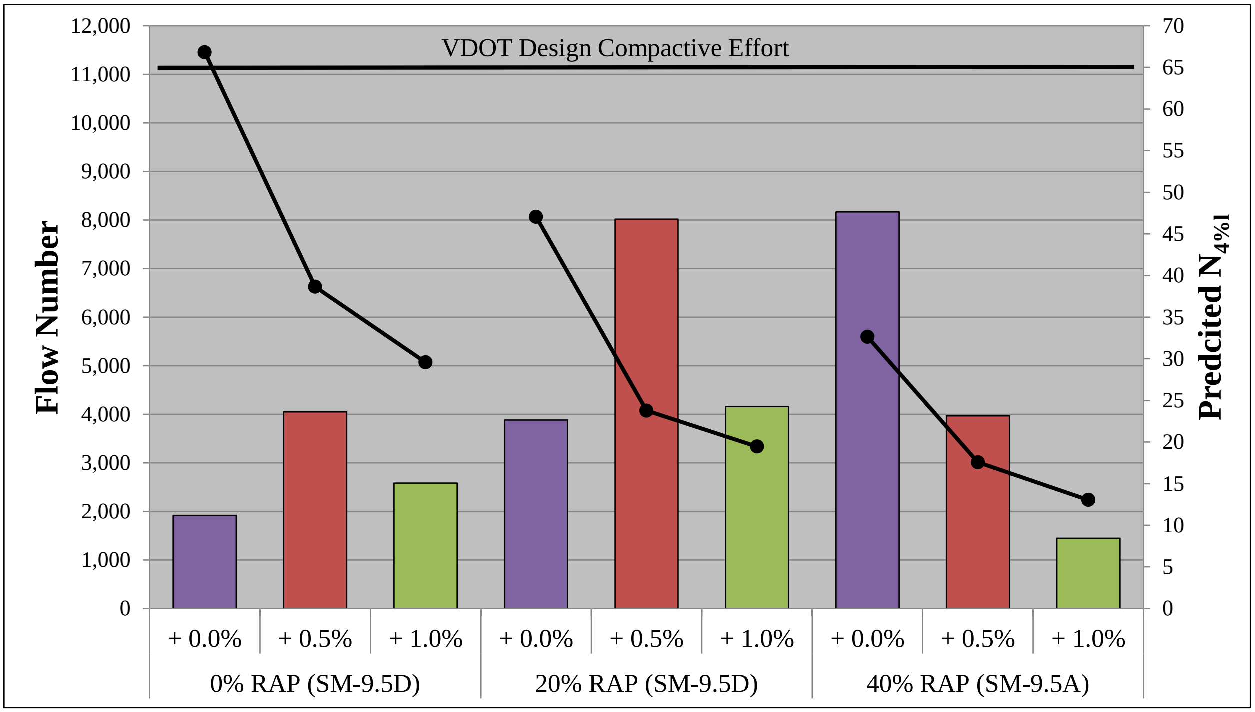

FIGURE 17 Flow number and mix density at $N_{initial}$ for all mixes

As stated earlier, a concern of excessive binder is producing mixes which do not meet the density at $N_{initial}$ and could possibly become tender during construction. Only one of the mixes, the 0% RAP at design binder content, met the current VDOT specification for density at $N_{initial}$. A study performed as part of NCHRP Report 573 determined that 36% of 40 HMA samples with design traffic between 0.3 million and 3 million ESALs (the same design traffic level as the mixes in this study) failed the $N_{initial}$ requirement, with only one of the mixes actually being tender in the field. In that study all of the mixes exhibited exceptional rutting resistance (*12*). The optimally performing mixes in this study would not necessarily become tender due to added binder; however, this would require further evaluation in the field.

100% RAP

In the previous study, the performance of a laboratory mix containing 100% RAP was evaluated as the extreme case of a high RAP mixture. The 100% RAP mixes at the four added binder levels (0.0%, 0.5%, 1.0%, 1.5%) all exhibited extremely high stiffness (dynamic modulus) and rutting resistance (FN). In fact none of the mixes exhibited more than 0.5% strain during the Repeated Load Permanent Deformation (RLPD) test. However, the 100% RAP mixes did not perform well during fatigue resistance testing, with the exception of the 1.5% added binder mix. The fatigue cycles to failure for the 100% RAP + 1.5% binder mix was greater than that of the 20% RAP mix at design binder content. As shown in Figure 18(a) below, the higher fatigue resistance of the 100% RAP + 1.5% binder mix was achieved with VTM at N_{design}

dropping to 0.2%. Figure 18(b) shows that the predicted design gyrations to achieve 4% VTM for 100% RAP mix with 1.5% added binder is only 7 gyrations. So for 1.5% added binder content and as shown in Table 7, the design VTM is achieved at $N_{initial}$. The volumetric analysis of the 100% RAP samples proved that improving the fatigue resistance of 100% RAP by adding binder creates mixes with poor volumetric properties. The extremely low VTM and the extremely high density at $N_{initial}$ along with the gradation of the 100% RAP would likely result in an unstable mix during construction.

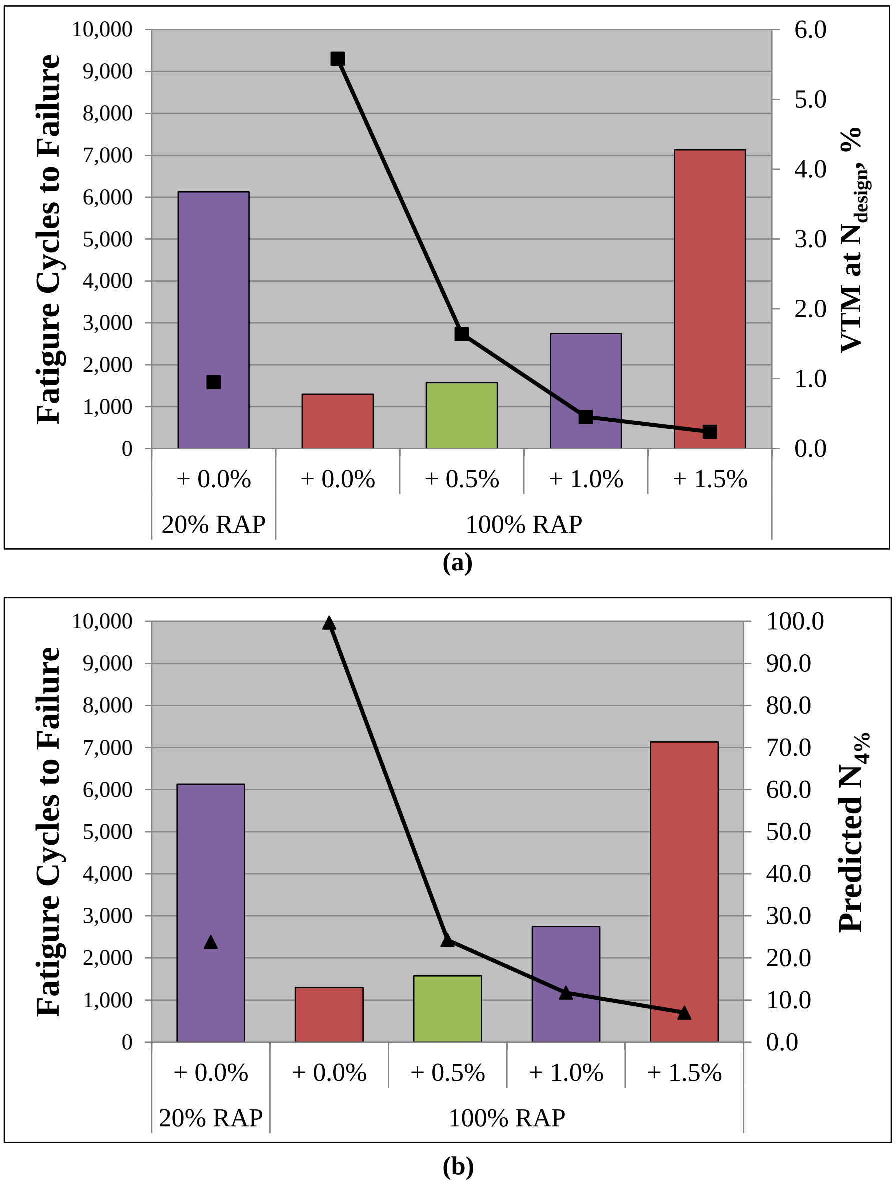

FIGURE 18 Fatigue cycles to failure and a) VTM at N_{design} for 100% RAP mixes and b) predicted $N_{4\%}$ for 100% RAP mixes

CONCLUSIONS AND RECOMMENDATIONS

Some specific conclusions and recommendations drawn from this study include the following:

1. The optimally performing 20% and 40% RAP mixes in this study had VTM below the VDOT production specifications and VFA above the VDOT production specifications. Designing these mixes for a VTM of 4%, at the current number of design gyrations specified by VDOT, would not yield the optimal binder content based on performance evaluated with dynamic modulus, flow number and fatigue resistance.

2. The number of gyrations which would yield 4% VTM for the optimally performing RAP mixes was significantly lower than the current design compactive effort. In order to achieve the optimal binder content for the same gradation, the design gyrations would need to be lowered.

3. The optimally performing mixes in this study had density at $N_{initial}$ above current specifications. Further evaluation is necessary to determine if these mixes will truly be tender or unstable in the field.

4. FN testing along with volumetric analysis showed that decreasing gyrations from the current design level to achieve higher asphalt content would not necessarily result in higher rutting potential for the 20% RAP or 40% RAP mixes. FN determined from Repeated Load Permanent Deformation (RLPD) was the only test used to evaluate rutting potential in this study. It is recommended to supplement the RLPD test with another rutting test such as the Asphalt Pavement Analyzer to confirm this result.

5. Though the addition of 1.5% binder to 100% RAP material resulted in adequate fatigue resistance relative to current RAP mixes, the volumetric properties which result from additional asphalt will likely result in an unstable mix.

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REFERENCES

1. Hong, F., D.H. Chen, and M.M. Mikhail, Long-Term Performance Evaluation of Recycled Asphalt Pavement Results from Texas. Transportation Research Record: Journal of the Transportation Research Board, 2010. 2180(1): p. 58-66

2. Li, X., M.O. Marasteanu, R.C. Williams, and T.R. Clyne, Effect of Reclaimed Asphalt Pavement (Proportion and Type) and Binder Grade on Asphalt Mixtures. Transportation Research Record: Journal of the Transportation Research Board, 2008. 2051(1): p. 90-97.

3. West, R., A. Kvasnak, N. Tran, B. Powell, and P. Turner, Testing of Moderate and High Reclaimed Asphalt Pavement Content Mixes. Transportation Research Record: Journal of the Transportation Research Board, 2009. 2126(1): p. 100-108

4. McDaniel, R.S., H. Soleymani, R.M. Anderson, P. Turner, and R. Peterson, *Recommended Use of Reclaimed Asphalt Pavement in the Superpave Mix Design Method.* NCHRP Web Document 30, 2000.

5. Boriack, P.C., Katicha, S.W., Flintsch, G.W. “Laboratory Study on Effect of High RAP and High Asphalt Binder Content on Stiffness, Fatigue Resistance, and Rutting Resistance of Asphalt Concrete,” paper 14-2844, *93rd Annual Meeting of the Transportation Research Board*, Jan 12-116, 2014, Washington, DC.

6. Virginia Department of Transportation. *2007 Road and Bridge Specifications: Section 211 – Asphalt Concrete*, Richmond, VA, 2013.

7. Design, Superpave Mix. "Superpave Series No. 2 (SP-2)." *Asphalt Institute, Lexington, KY* (1996).

8. “TechBrief: Superpave mix design and gyratory compaction levels”, FHWA TechBrief No. FHWA-HIF-11-031, 2010.

9. Brown, E. R., and R. B. Mallick. An Initial Evaluation of N-design Superpave Gyratory Compactor. Proceedings of the Association of Asphalt Paving Technologists, Vol. 67, 1998, pp. 101–116.

10. Maupin, G.W. (2003) “Additional asphalt to increase the durability of Virginia’s superpave mixes” VTRC Report VTRC03-R15, Charlottesville, Virginia

11. Aguiar-Moya, José P., Jorge A. Prozzi, and Maghsoud Tahmoressi. "Optimum Number of Superpave Gyrations Based on Project Requirements." Transportation Research Record: Journal of the Transportation Research Board 2001.1 (2007): 84-92.

12. Prowell, Brian D., and E. Ray Brown. *NCHRP Report 573: Superpave Mix Design: Verifying Gyration Levels in the Ndesign Table*. TRB, National Research Council, Washington D.C., 2006.

13. MnDOT Materials Lab. *1815: Determination of RAP aggregate bulk specific gravity*, laboratory testing manual. Minnesota Department of Transportation, 2007.

14. Vavrik, William R., and Samuel H. Carpenter. "Calculating air voids at specified number of gyrations in Superpave gyratory compactor." *Transportation Research Record: Journal of the Transportation Research Board* 1630.1 (1998): 117-125.

CHAPTER IV – SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

SUMMARY

The use of RAP in pavements has become more popular due to recent economic pressures as well as initiatives towards using more sustainable construction practices and materials. While the use of lower percentages of RAP, 10 to 20%, has been common practice in many states for years (*1*); there is now an increased desire to use higher percentages of RAP in order to further capitalize on the environmental and economic benefits of recycling. However, many states transportation agencies have been hesitant to authorize the use high RAP pavements because the performance of these mixtures cannot yet be accurately predicted. One reason for this is the complex interaction between the aged and hardened RAP binder and the virgin binder, which is not yet fully understood (*2*). Another is the overall variability inherent to RAP material which can affect fines content and aggregate gradation of the mix (*1*). While there are many tangible upsides to using higher percentages of RAP, practitioners must be cautious to ensure that both durability and stability of the mixtures is maintained.

This thesis studied the performance of asphalt concrete mixes with three different percentages of RAP (0%, 20% and 40%) at three binder contents (design, design + 0.5%, and design+ 1.0%). Additionally, the performance of a laboratory mix containing 100% RAP was investigated as an extreme case of RAP in asphalt concrete. The 100% RAP mix was tested at four added binder contents (0.0%, 0.5%, 1.0% and 1.5%). Performance of the mixtures was evaluated based on three criteria: stiffness (dynamic modulus), rutting resistance (FN) and fatigue resistance (flexural beam). Additionally, the Superpave volumetric properties of the mixes were determined to identify the effect of additional binder and the number of gyrations to reach a VTM of 4% was predicted for each mix and compared to current VDOT compaction levels.

FINDINGS

The main findings from this study are summarized below.

1) 0% and 20% RAP Mixes

- Increasing binder content resulted in increased fatigue and rutting resistance for the 0% and 20% RAP mixes with only slight decreased in dynamic modulus. Specifically, adding 0.5% binder to the 20% RAP mix resulted in 200% increase in fatigue resistance, a 200% increase in rutting resistance and only a 1% decrease in dynamic modulus. The optimally performing 20% RAP mix had 0.5% added binder and had a VTM of 2.3% at N_{design}. The predicted gyrations to achieve VTM of 4% or $N_{4\%}$ for the 20% RAP + 0.5% binder mix was 24 gyrations. The optimally performing 0% RAP mix had a VTM of 2.3 at N_{design} and $N_{4\%}$ of 39 gyrations.
- Both the 0% and 20% RAP were plant produced mixes designed to meet VDOT specifications. The VTM, VFA and VMA for these mixes at design binder content

were within VDOT production specifications. As binder was added to these mixes, performance improved however, the mixes with added binder no longer met the current volumetric specifications except for the VMA.

2) 40% RAP Mixes

- Increasing binder content resulted in a decrease in rutting resistance with little change to fatigue resistance for the 40% RAP mix. The addition of 0.5% binder and 1.0% binder to the 40% RAP mix resulted in a 60% and 80% decrease in FN respectively. The addition of 1.0% binder resulted in a 21% decrease in dynamic modulus for the 40% RAP mix. The optimally performing 40% RAP mix had no added binder and had a VTM of 1.9% at N_{design}. $N_{4\%}$ for the 40% RAP + 0.0% binder mix was predicted to be 33 gyrations.
- The 40% RAP mix used in this study was collected from a private customer as VDOT did not authorize 40% RAP at the time of this study and, therefore, the mix did not have to meet VDOT design and production specifications. Nevertheless, the VTM and VFA of the mix would not have met VDOT production standards. However, the VMA of the mix would have met specifications indicating that sufficient volume was available for both asphalt binder and air voids. The low VTM and high VFA indicates that additional binder had already been added to the 40% RAP mix compared to the 0% and 20% RAP mixes. This also corresponds to ignition oven asphalt content testing which showed that the 40% RAP mix contained almost 0.5% more asphalt binder than the 20% RAP mix initially. As binder was added to the 40% RAP mix, the performance decreased indicating that the initial binder content provided for the optimal performance (for the performed tests).

2) 100% RAP Mixes

- Both stiffness and rutting resistance of the 100% RAP mixes were considerably higher than all other mixes, while the fatigue resistance was significantly lower until 1.5% binder was added to the mix. On average the dynamic modulus of the 100% RAP mixes was 400% higher than the other mixes at the lowest reduced frequency and 125% higher at the highest reduced frequency. None of the 100% RAP mixes exhibited tertiary flow during RLPD testing with all mixes experiencing less than 0.5% strain. The 100% RAP mixes with 0%, 0.5% and 1.0% added binder had the lowest average fatigue cycles to failure at 1300, 1572 and 2746 cycles respectively. Only the 100% RAP + 1.5% binder mix had an average fatigue cycles to failure comparable to the other mixes at 7131 cycles, which was higher than the 20% RAP + 0.0% binder, but lower than all other tested mixes The optimally performing 100% RAP mix had 1.5% added binder and had a VTM of 0.2% at N_{design}. The predicted gyrations to achieve VTM of 4%, or $N_{4\%}$, for the 20% RAP + 0.5% binder mix was only 7 gyrations.

- Though the 100% RAP mix showed extremely high stiffness and rutting resistance, the fatigue resistance only reached an acceptable level once 1.5% binder was added. At this binder level the 100% RAP mix had only 0.2% VTM, a VFA of 98.5% and a density at $N_{initial}$ of 95.7% indicating that this would not be a stable mix in the field.

CONCLUSIONS

It was found that the percentage of RAP and the percentage of binder had significant effects on the performance and volumetric properties of the mixes. Results indicated that a "high RAP mix", the 40% RAP mix with no additional binder, achieved performance comparable to the 0% and 20% RAP mixes after 0.5% binder was added to these mixes (plant produced). For both the 0% and 20% RAP it was found that both fatigue resistance and rutting resistance improved when binder was added to the plant produced mixes, with the design + 0.5% binder mixes performing optimally for both RAP percentages. For the 40% RAP it was found that the mix at the initial, or design, binder content was the optimally performing mix and adding binder only decreased performance especially rutting resistance. Both asphalt content and volumetric testing of the 40% RAP mix indicated that it was initially produced at a higher binder content relative to the other two mixes. For the optimally performing 20% and 40% RAP mixes, the VTM at N_{design} was below current VDOT production standards at 0.9% and 1.9% respectively. Additionally, the predicted design gyrations to achieve 4% VTM were 24 and 33 respectively, significantly lower than the currently specified design compaction gyrations of 65. Evaluation of a laboratory produced 100% RAP mix indicated that although the addition of 1.5% binder to 100% RAP material resulted in adequate fatigue resistance relative to current RAP mixes, the volumetric properties which result from additional asphalt will likely result in an tender or unstable mix during construction.

RECOMMENDATIONS

This thesis investigated the effects of RAP and additional asphalt binder on the performance and volumetric properties of asphalt concrete. Below are several recommendations to further elaborate on these effects and improve upon the methodology. These include, but are not limited to the following:

1) This study was limited to three performance tests including dynamic modulus, flow number and fatigue resistance. Additional performance measures should be evaluated to determine the effects of RAP percentage and binder content. Some additional tests that could be conducted are wheel rutting, permeability, moisture susceptibility and low temperature cracking.
2) The "high RAP" mix used in this study was not a VDOT approved mix as VDOT was not allowing 40% RAP mixes at the time of this study. Future research on high RAP mixes should include mixes which were designed to meet VDOT design and production specifications.
3) Three different performance grades of asphalt binder were used in this study with only one performance grade per RAP percentage. Results of testing and the true effects of

high RAP percentage and high binder content could be better distinguished if mixes were tested over all three performance grades.

4) PG 58-28 binder was added to the 100% RAP mix in this study. It is recommended to use an even softer binder to better balance the extreme stiffness and rutting resistance provided by the RAP material and optimize fatigue resistance without such an adverse effect on volumetric properties.
5) It is recommended that VDOT implement the results of this study and further evaluate whether current design and volumetric specifications need to be altered in order that asphalt concrete mixes containing RAP be designed with the optimal level of binder.

REFERENCES

1. McDaniel, Rebecca, and R. Michael Anderson. *Recommended use of reclaimed asphalt pavement in the Superpave mix design method: Guidelines*. No. 253. Transportation Research Board, National Research Council, 2001.

2. Copeland, Audrey. *Reclaimed asphalt pavement in asphalt mixtures: state of the practice*. No. FHWA-HRT-11-021. 2011.

APPENDIX A – DYNAMIC MODULUS TEST RESULTS

Table A1. Average Dynamic Modulus for All Mixes

	Frequency	0% + 0.0%	0% + 0.5%	0% + 1.0%
	Hz	kPa	kPa	kPa
4.4°C	25	17157377	15452447	14770993
	10	15462420	13920537	13216980
	5	14256810	12874040	12172460
	1	11599657	10615418	9878431
	0.5	10505713	9687944	8926741
	0.1	8241739	7642653	6782662
21.1°C	25	8182375	7739415	6713399
	10	6830601	6608656	5659872
	5	5890694	5750448	4876245
	1	4002805	4028677	3279994
	0.5	3319588	3357329	2695415
	0.1	2204473	2301323	1812091
37.8°C	25	3179811	3258994	2847634
	10	2535894	2601685	2285235
	5	2000310	2093827	1814836
	1	1268175	1328416	1157886
	0.5	961549	1023935	883286
	0.1	549849	591653	513571
54.4°C	25	1135532	1120742	714501
	10	856313	862717	546508
	5	671046	677659	432002
	1	458425	454899	296449
	0.5	346655	342878	227432
	0.1	204300	203831	137708

	Frequency	20% + 0.0%	20% + 0.5%	20% + 1.0%
	Hz	kPa	kPa	kPa
4.4°C	25	14831020	14797793	14786013
	10	13630747	13444650	13151120
	5	12665590	12522370	12159433
	1	10467213	10428714	9977057
	0.5	9543434	9535641	9074646
	0.1	7576638	7575531	7145862
21.1°C	25	7619781	7508414	6765213
	10	6453960	6328616	5722175
	5	5617595	5519270	4968387
	1	3868729	3847102	3411491
	0.5	3203369	3211711	2823995
	0.1	2111461	2131026	1849036
37.8°C	25	3050456	3042932	2583792
	10	2494380	2482509	2104333
	5	1977309	1989896	1663806
	1	1209926	1209682	1014403
	0.5	900115	904948	755151
	0.1	481957	487617	407792
54.4°C	25	1077414	1123431	948063
	10	813869	866375	725804
	5	631482	673353	567895
	1	420139	433642	379779
	0.5	318509	325767	289683
	0.1	184066	185338	167462

	Frequency	40% + 0.0%	40% + 0.5%	40% + 1.0%
	Hz	kPa	kPa	kPa
4.4°C	25	16847707	15552517	13984093
	10	15570090	14479750	12833373
	5	14658997	13628287	11955503
	1	12443953	11618047	9941242
	0.5	11496263	10739390	9066024
	0.1	9253553	8654163	7116051
21.1°C	25	9073281	9176272	7678064
	10	7964667	8029595	6540126
	5	7032336	7059164	5685487
	1	5040994	5006716	3893443
	0.5	4210696	4190139	3204161
	0.1	2818530	2764208	2026195
37.8°C	25	4027175	3795469	3008914
	10	3231991	3036424	2342447
	5	2561443	2411910	1810162
	1	1521153	1422483	1089698
	0.5	1122868	1063652	871264
	0.1	581485	554703	453303
54.4°C	25	1285895	1253956	938580
	10	933903	911971	678719
	5	706842	693343	513871
	1	492784	434835	330866
	0.5	385121	325361	247952
	0.1	207970	177409	142237

	Frequency	100% + 0.0%	100% + 0.5%	100% + 1.0%	100% + 1.5%
	Hz	kPa	kPa	kPa	kPa
4.4°C	25	15215103	19868117	20572317	19695573
	10	14410323	18595347	19016130	18595423
	5	13750833	17857130	18075023	17640947
	1	12275353	15829493	15965337	15419813
	0.5	11610317	15013453	15086360	14493940
	0.1	10015788	13110443	13064537	12422700
21.1°C	25	10154112	12916037	12944517	11741653
	10	9232569	11466273	11420097	10378928
	5	8526774	10545567	10465602	9447480
	1	6884334	8479550	8246276	7353285
	0.5	6218063	7666645	7407218	6546622
	0.1	4812115	5840936	5460961	4785110
37.8°C	25	6506798	7139722	6458631	5695839
	10	5664156	6027669	5386255	4762027
	5	5024716	5279854	4655336	4097690
	1	3642396	3688438	3135872	2767508
	0.5	3131019	3124278	2612761	2305548
	0.1	2174248	2070561	1679418	1499586
54.4°C	25	3467923	3177742	2777244	2488954
	10	2944288	2562903	2228684	2002140
	5	2525187	2117564	1832275	1650211
	1	1711269	1362202	1156802	1077036
	0.5	1451862	1126593	951840	894112
	0.1	1026567	770948	645983	625793

Table A2. Dynamic Modulus Test Results for 0% RAP + 0.0% Binder Samples

0% RAP + 0.0% Binder (4.4°C)				
Frequency	Sample A0-4	Sample A0-5	Sample A0-6	Average
Hz	kPa	kPa	kPa	kPa
25	17078670	17085810	17307650	17157377
10	15278370	15407800	15701090	15462420
5	14068280	14230030	14472120	14256810
1	11460720	11622410	11715840	11599657
0.5	10377420	10531690	10608030	10505713
0.1	8082009	8194809	8448400	8241739

0% RAP + 0.0% Binder (21.1°C)				
Frequency	Sample A0-4	Sample A0-5	Sample A0-6	Average
Hz	kPa	kPa	kPa	kPa
25	8249017	8439395	7858712	8182375
10	6838507	7107929	6545367	6830601
5	5893116	6133188	5645779	5890694
1	3967335	4190272	3850808	4002805
0.5	3288624	3477269	3192872	3319588
0.1	2150516	2328447	2134457	2204473

0% RAP + 0.0% Binder (37.8°C)				
Frequency	Sample A0-4	Sample A0-5	Sample A0-6	Average
Hz	kPa	kPa	kPa	kPa
25	3209170	3152394	3177868	3179811
10	2542397	2524009	2541276	2535894
5	2016981	1969554	2014395	2000310
1	1272881	1245407	1286236	1268175
0.5	966510.2	937354.6	980782.1	961549
0.1	547369.4	532935.4	569241.9	549849

0% RAP + 0.0% Binder (54.4°C)				
Frequency	Sample A0-4	Sample A0-5	Sample A0-6	Average
Hz	kPa	kPa	kPa	kPa
25	1113587	1168005	1125005	1135532
10	841949.3	884228.9	842759.3	856313
5	663038.8	691156.3	658942.1	671046
1	457176.8	474259	443839.6	458425
0.5	349767.8	359726.6	330469.9	346655
0.1	210941.9	215860.6	186098.9	204300

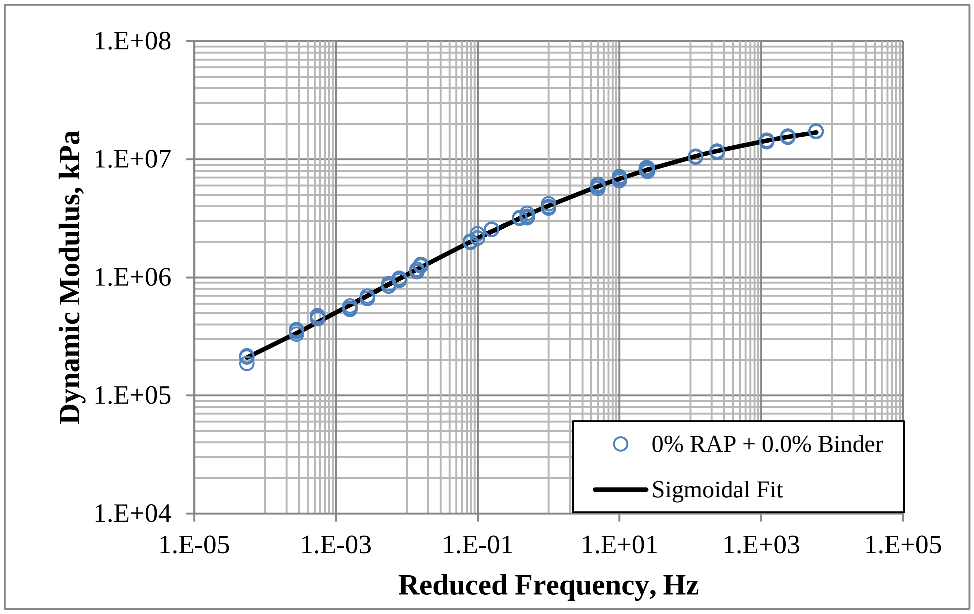

Figure A1. Dynamic Modulus Master Curve for Samples Containing 0% RAP + 0.0% Binder

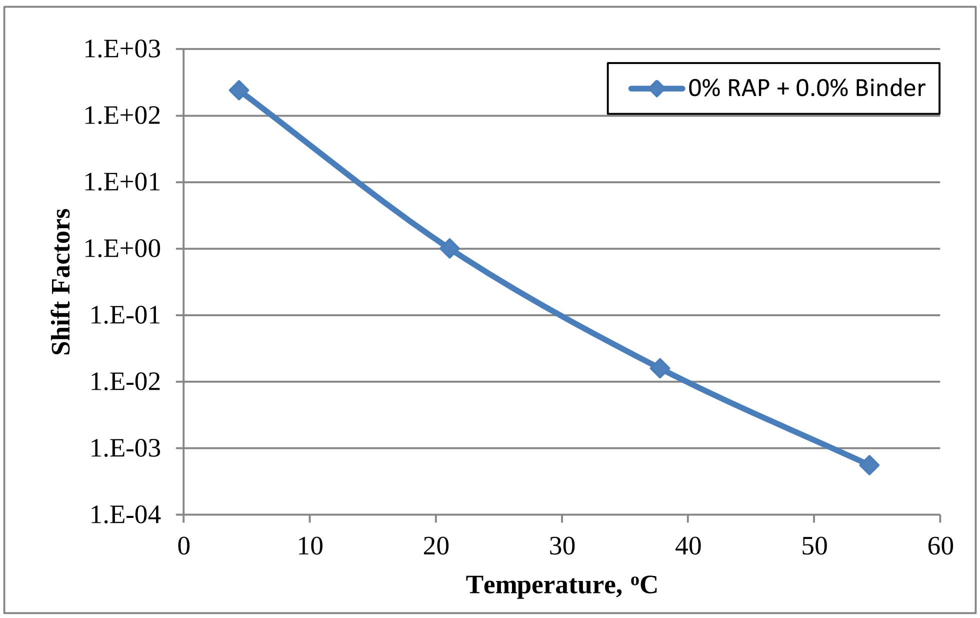

Figure A2. Shift Factors for 0% RAP + 0.0% Binder Master Curve

Table A3. Dynamic Modulus Test Results for 0% RAP + 0.5% Binder Samples

0% RAP + 0.5% Binder (4.4°C)				
Frequency	Sample B0-1	Sample B0-5	Sample B0-6	Average
Hz	kPa	kPa	kPa	kPa
25	16088140	14131880	16137320	15452447
10	14343260	12785590	14632760	13920537
5	13206190	11852490	13563440	12874040
1	10707100	9824564	11314590	10615418
0.5	9700254	8954688	10408890	9687944
0.1	7593641	6978144	8356173	7642653

0% RAP + 0.5% Binder (21.1°C)				
Frequency	Sample B0-1	Sample B0-5	Sample B0-6	Average
Hz	kPa	kPa	kPa	kPa
25	7897929	7301414	8018903	7739415
10	6683520	6255383	6887066	6608656
5	5790890	5452465	6007989	5750448
1	4017912	3828861	4239258	4028677
0.5	3331339	3196891	3543756	3357329
0.1	2255622	2205203	2443145	2301323

0% RAP + 0.5% Binder (37.8°C)				
Frequency	Sample B0-1	Sample B0-5	Sample B0-6	Average
Hz	kPa	kPa	kPa	kPa
25	3127415	3305570	3343996	3258994
10	2460830	2647424	2696801	2601685
5	1942871	2152811	2185800	2093827
1	1244178	1355014	1386055	1328416
0.5	945162.9	1053390	1073252	1023935
0.1	540239.9	609944.1	624775.4	591653

0% RAP + 0.5% Binder (54.4°C)				
Frequency	Sample B0-1	Sample B0-5	Sample B0-6	Average
Hz	kPa	kPa	kPa	kPa
25	1088208	1118232	1155785	1120742
10	827004.9	863384.6	897760.5	862717
5	650337	675119.5	707521.6	677659
1	446877.3	448588.2	469230.6	454899
0.5	334177	338202	356254.3	342878
0.1	192933.3	206486	212072.8	203831

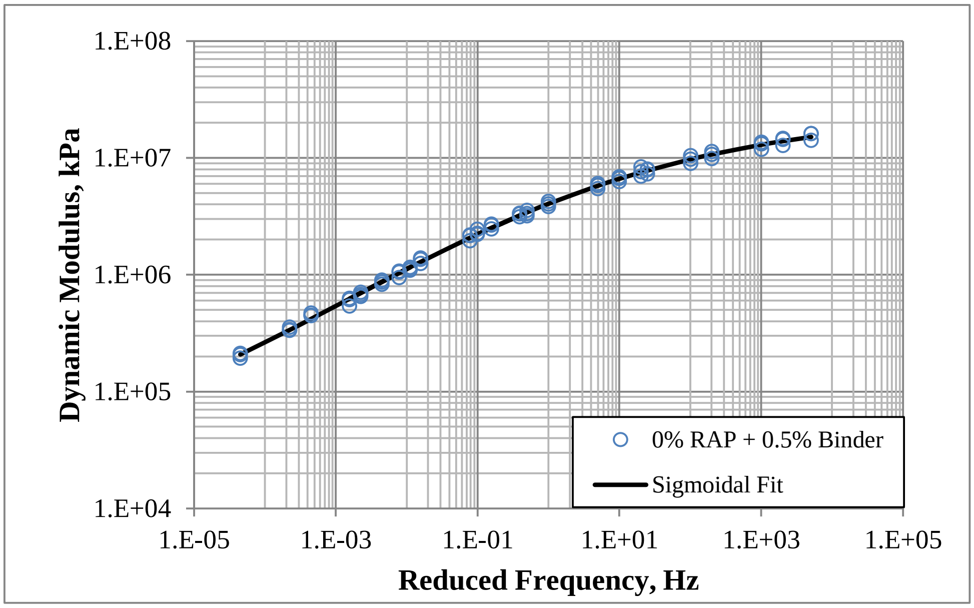

Figure A3. Dynamic Modulus Master Curve for Samples Containing 0% RAP + 0.5% Binder

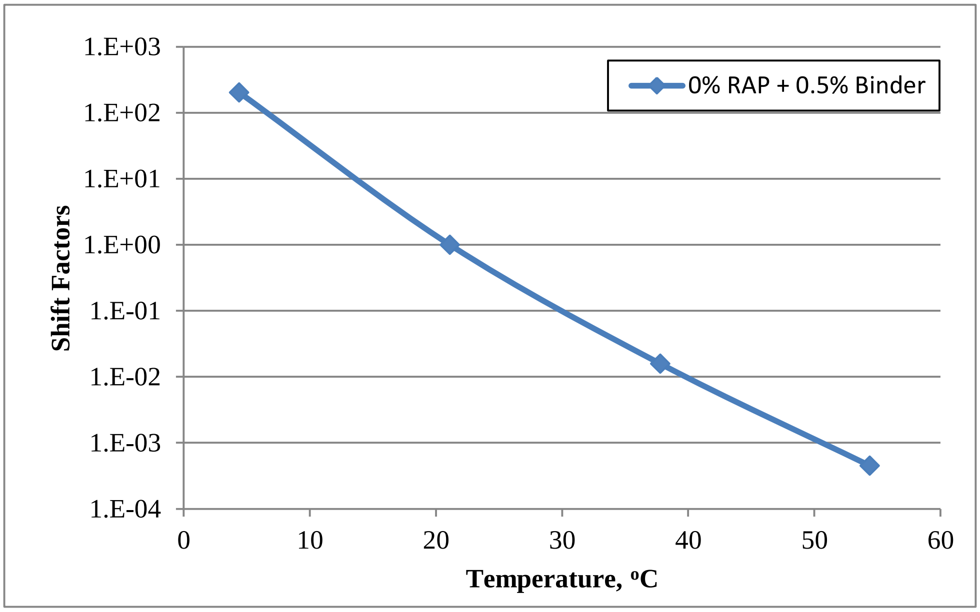

Figure A4. Shift Factors for 0% RAP + 0.5% Binder Master Curve

Table A4. Dynamic Modulus Test Results for 0% RAP + 1.0% Binder Samples

0% RAP + 1.0% Binder (4.4°C)				
Frequency	Sample C0-3	Sample C0-4	Sample C0-5	Average
Hz	kPa	kPa	kPa	kPa
25	14542230	14367310	15403440	14770993
10	12917100	12771810	13962030	13216980
5	11905890	11723740	12887750	12172460
1	9746009	9480545	10408740	9878431
0.5	8821329	8549160	9409735	8926741
0.1	6680104	6463456	7204425	6782662

0% RAP + 1.0% Binder (21.1°C)				
Frequency	Sample C0-3	Sample C0-4	Sample C0-5	Average
Hz	kPa	kPa	kPa	kPa
25	6718044	6375708	7046446	6713399
10	5733138	5288035	5958443	5659872
5	4964163	4535315	5129258	4876245
1	3413365	2972265	3454351	3279994
0.5	2818574	2421759	2845913	2695415
0.1	1909875	1606661	1919737	1812091

0% RAP + 1.0% Binder (37.8°C)				
Frequency	Sample C0-3	Sample C0-4	Sample C0-5	Average
Hz	kPa	kPa	kPa	kPa
25	2836424	2727430	2979047	2847634
10	2272765	2188051	2394890	2285235
5	1799727	1724328	1920454	1814836
1	1150195	1105283	1218180	1157886
0.5	877541	839081.3	933235.3	883286
0.1	512034.6	483020.8	545656.4	513571

0% RAP + 1.0% Binder (54.4°C)				
Frequency	Sample C0-3	Sample C0-4	Sample C0-5	Average
Hz	kPa	kPa	kPa	kPa
25	1094826	1037589	1075261	714501
10	838143.6	791631.6	814357.9	546508
5	658813.1	623395.4	644733.8	432002
1	451913.6	431800.1	444726.3	296449
0.5	344939.4	326335.4	343826.8	227432
0.1	206965.2	198565.2	212121.6	137708

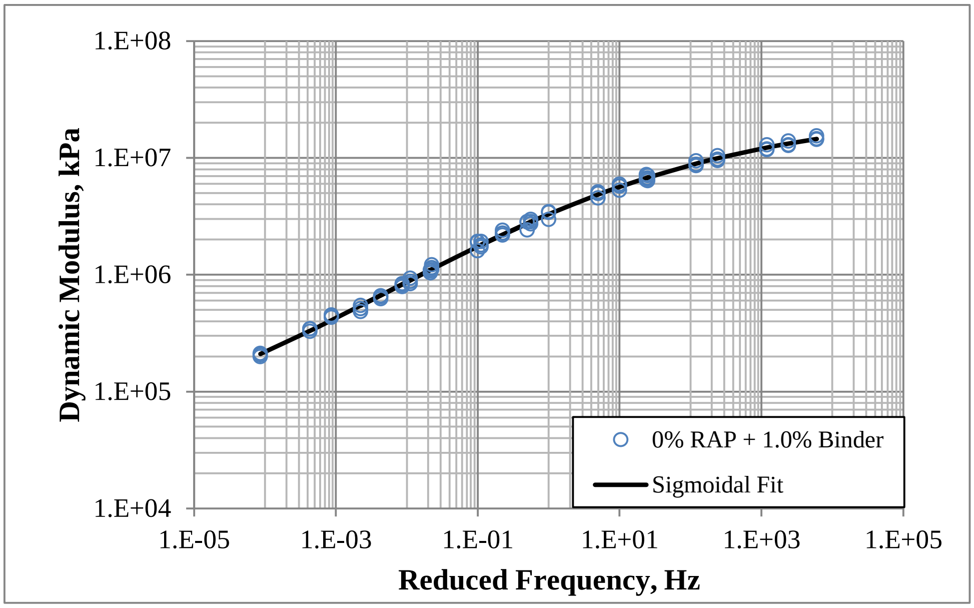

Figure A5. Dynamic Modulus Master Curve for Samples Containing 0% RAP + 1.0% Binder

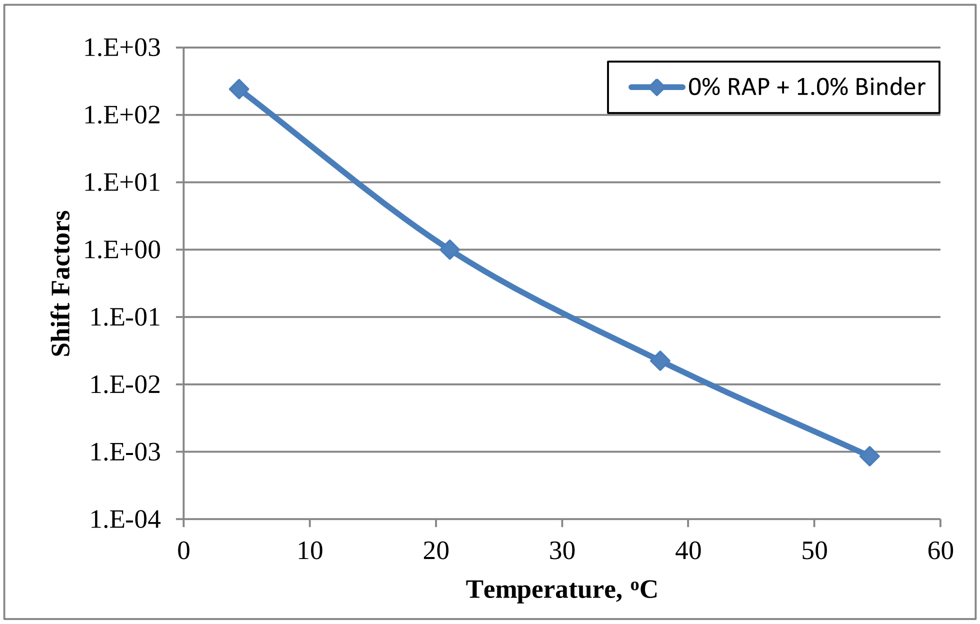

Figure A6. Shift Factors for 0% RAP + 1.0% Binder Master Curve

Table A5. Dynamic Modulus Test Results for 20% RAP + 0.0% Binder Samples

20% RAP + 0.0% Binder (4.4°C)				
Frequency	**Sample A2**	**Sample A3**	**Sample A4**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	15203560	14814600	14474900	14831020
10	13807400	13722180	13362660	13630747
5	12775390	12793180	12428200	12665590
1	10421700	10632990	10346950	10467213
0.5	9491330	9689905	9449068	9543434
0.1	7663377	7617999	7448538	7576638

20% RAP + 0.0% Binder (21.1°C)				
Frequency	**Sample A2**	**Sample A3**	**Sample A4**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	7476950	7760770	7621622	7619781
10	6338979	6551294	6471606	6453960
5	5501687	5698855	5652243	5617595
1	3768255	3908530	3929402	3868729
0.5	3117140	3226646	3266322	3203369
0.1	2049077	2117885	2167422	2111461

20% RAP + 0.0% Binder (37.8°C)				
Frequency	**Sample A2**	**Sample A3**	**Sample A4**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	3023102	3117885	3010382	3050456
10	2466335	2553380	2463424	2494380
5	1956014	2009930	1965983	1977309
1	1193350	1218493	1217936	1209926
0.5	890772	896418	913154	900115
0.1	479878	471563	494431	481957

20% RAP + 0.0% Binder (54.4°C)				
Frequency	**Sample A2**	**Sample A3**	**Sample A4**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	1067756	1075473	1089014	1077414
10	798662	814346	828598	813869
5	617971	631599	644874	631482
1	406948	421036	432433	420139
0.5	308328	317029	330172	318509
0.1	178826	178288	195084	184066

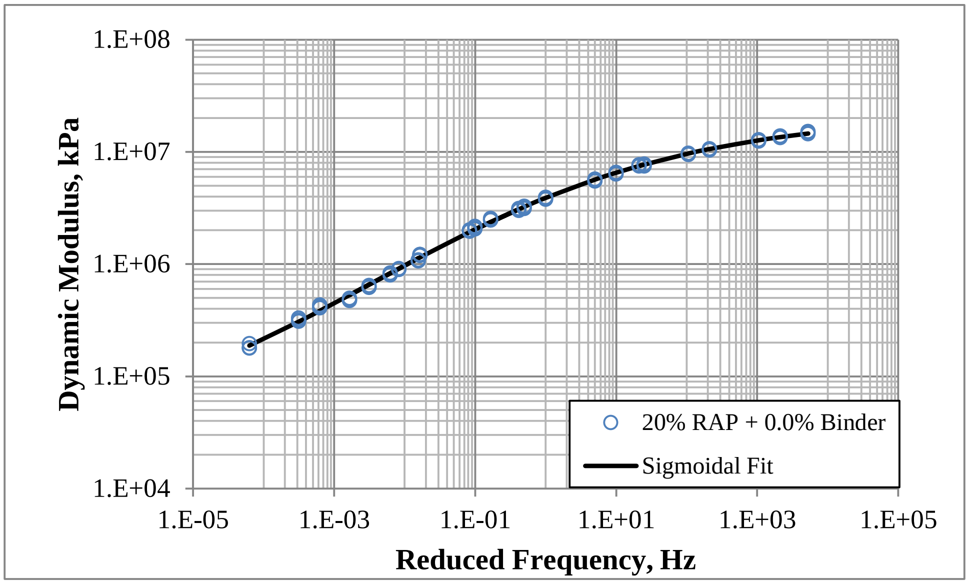

Figure A7. Dynamic Modulus Master Curve for Samples Containing 20% RAP + 0.0% Binder

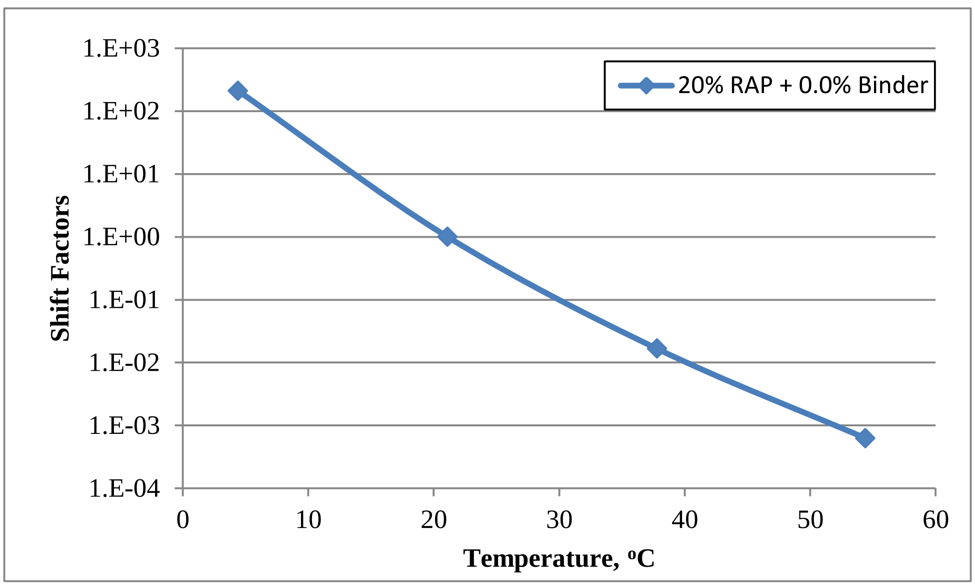

Figure A8. Shift Factors for 20% RAP + 0.0% Binder Master Curve

Table A6. Dynamic Modulus Test Results for 20% RAP + 0.5% Binder Samples

20% RAP + 0.5% Binder (4.4°C)				
Frequency	Sample C1	Sample C2	Sample C3	Average
Hz	kPa	kPa	kPa	kPa
25	16233230	13909860	14250290	14797793
10	14727320	12655280	12951350	13444650
5	13737560	11760210	12069340	12522370
1	11493530	9724723	10067890	10428714
0.5	10538160	8876894	9191868	9535641
0.1	8375242	7121070	7230280	7575531

20% RAP + 0.5% Binder (21.1°C)				
Frequency	Sample C1	Sample C2	Sample C3	Average
Hz	kPa	kPa	kPa	kPa
25	8286523	6821028	7417692	7508414
10	6933731	5845539	6206578	6328616
5	6045691	5106825	5405295	5519270
1	4235075	3570992	3735240	3847102
0.5	3553843	2962841	3118449	3211711
0.1	2345705	2018302	2029072	2131026

20% RAP + 0.5% Binder (37.8°C)				
Frequency	Sample C1	Sample C2	Sample C3	Average
Hz	kPa	kPa	kPa	kPa
25	3233444	2973642	2921710	3042932
10	2611278	2446290	2389959	2482509
5	2101016	1961020	1907652	1989896
1	1273394	1205847	1149804	1209682
0.5	955171	904506	855169	904948
0.1	520485	492080	450285	487617

20% RAP + 0.5% Binder (54.4°C)				
Frequency	Sample C1	Sample C2	Sample C3	Average
Hz	kPa	kPa	kPa	kPa
25	1268354	1098130	1003809	1123431
10	987407	836931	774787	866375
5	770076	653337	596647	673353
1	498858	420430	381640	433642
0.5	373450	317554	286298	325767
0.1	217309	175669	163035	185338

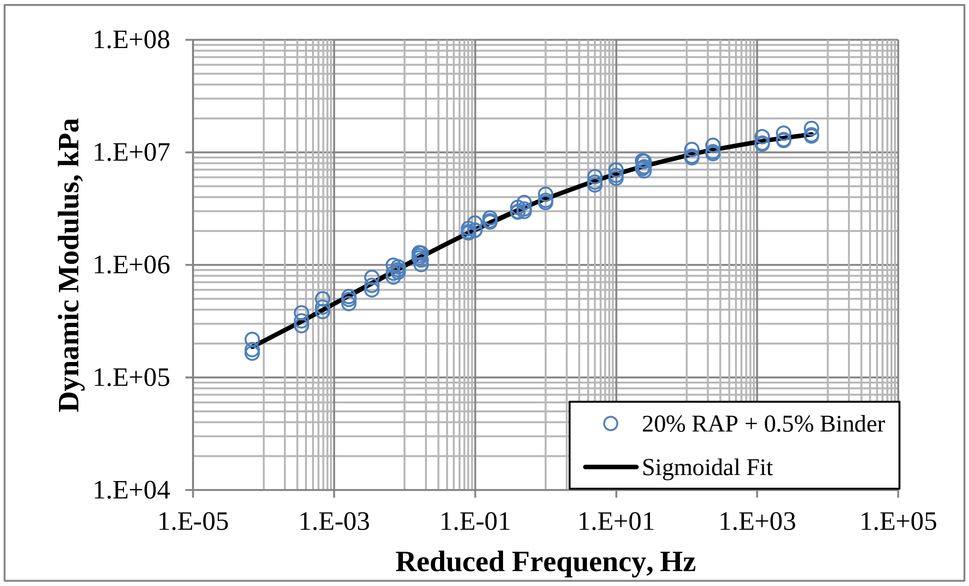

Figure A9. Dynamic Modulus Master Curve for Samples Containing 20% RAP +0.5% Binder

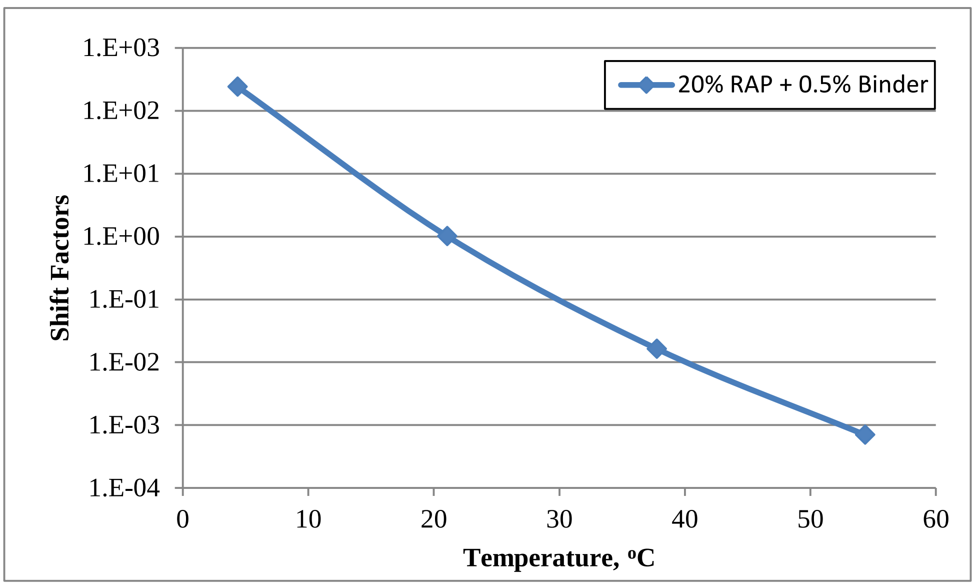

Figure A10. Shift Factors for 20% RAP + 0.5% Binder Master Curve

Table A7. Dynamic Modulus Test Results for 20% RAP + 1.0% Binder Samples

20% RAP + 1.0% Binder (4.4°C)				
Frequency	**Sample E1**	**Sample E2**	**Sample E3**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	15316110	14446980	14594950	14786013
10	13730180	12962240	12760940	13151120
5	12670840	12036710	11770750	12159433
1	10342550	9961510	9627110	9977057
0.5	9373985	9075603	8774351	9074646
0.1	7421304	6957047	7059234	7145862

20% RAP + 1.0% Binder (21.1°C)				
Frequency	**Sample E1**	**Sample E2**	**Sample E3**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	6850845	6600622	6844171	6765213
10	5695608	5631166	5839750	5722175
5	4921223	4906886	5077053	4968387
1	3350821	3363928	3519724	3411491
0.5	2774065	2779026	2918894	2823995
0.1	1788773	1824152	1934183	1849036

20% RAP + 1.0% Binder (37.8°C)				
Frequency	**Sample E1**	**Sample E2**	**Sample E3**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	2508677	2552442	2690257	2583792
10	2041658	2096828	2174512	2104333
5	1608504	1652664	1730249	1663806
1	975405	1007533	1060270	1014403
0.5	722109	749477	793867	755151
0.1	386512	401384	435480	407792

20% RAP + 1.0% Binder (54.4°C)				
Frequency	**Sample E1**	**Sample E2**	**Sample E3**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	897668	1002181	944340	948063
10	684436	764829	728146	725804
5	534770	599611	569305	567895
1	357989	403156	378192	379779
0.5	271233	309281	288535	289683
0.1	153740	183791	164856	167462

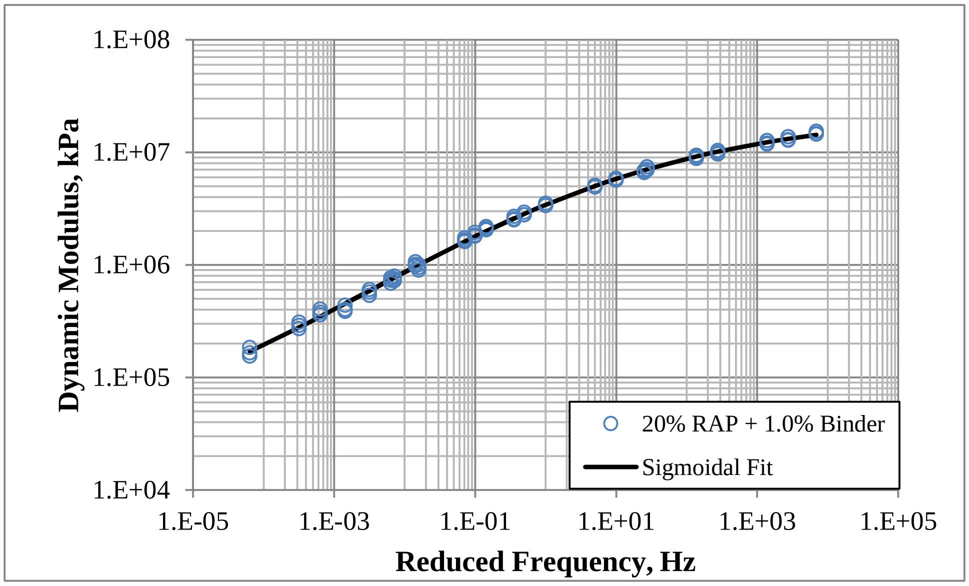

Figure A11. Dynamic Modulus Master Curve for Samples Containing 20% RAP +1.0% Binder

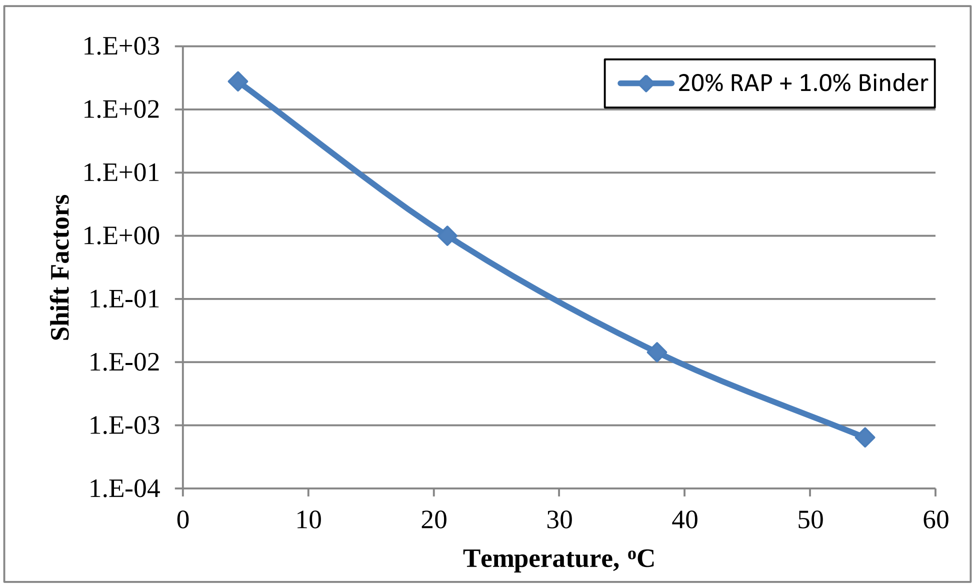

Figure A12. Shift Factors for 20% RAP + 1.0% Binder Master Curve

Table A8. Dynamic Modulus Test Results for 40% RAP + 0.0% Binder Samples

40% RAP + 0.0% Binder (4.4°C)				
Frequency	Sample B1	Sample B2	Sample B3	Average
Hz	kPa	kPa	kPa	kPa
25	15477100	18915240	16150780	16847707
10	14098200	17646290	14965780	15570090
5	13212440	16624270	14140280	14658997
1	11144940	14084150	12102770	12443953
0.5	10259970	13007360	11221460	11496263
0.1	8287945	10385280	9087435	9253553

40% RAP + 0.0% Binder (21.1°C)				
Frequency	Sample B1	Sample B2	Sample B3	Average
Hz	kPa	kPa	kPa	kPa
25	8030882	9708535	9480426	9073281
10	7019919	8489806	8384277	7964667
5	6165654	7488101	7443254	7032336
1	4373991	5352878	5396112	5040994
0.5	3630094	4455481	4546514	4210696
0.1	2397416	2984683	3073492	2818530

40% RAP + 0.0% Binder (37.8°C)				
Frequency	Sample B1	Sample B2	Sample B3	Average
Hz	kPa	kPa	kPa	kPa
25	3493310	4364432	4223784	4027175
10	2786261	3470013	3439699	3231991
5	2189222	2745969	2749137	2561443
1	1292676	1619180	1651602	1521153
0.5	943384	1194503	1230717	1122868
0.1	475359	620670	648427	581485

40% RAP + 0.0% Binder (54.4°C)				
Frequency	Sample B1	Sample B2	Sample B3	Average
Hz	kPa	kPa	kPa	kPa
25	1119026	1370637	1368021	1285895
10	809056	993937	998715	933903
5	607219	757038	756270	706842
1	374525	484260	619568	492784
0.5	277541	363096	514725	385121
0.1	152771	198652	272486	207970

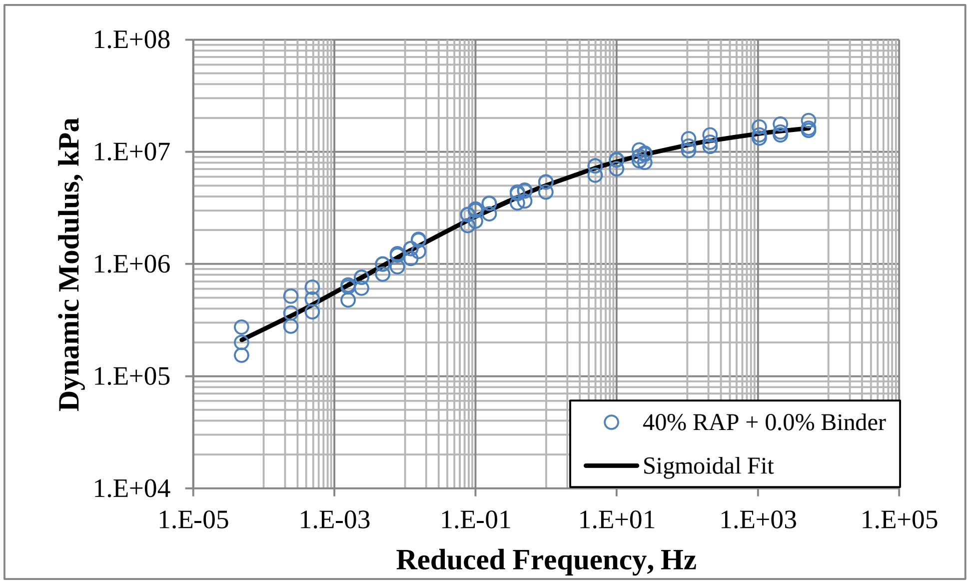

Figure A13. Dynamic Modulus Master Curve for Samples Containing 40% RAP +0.0% Binder

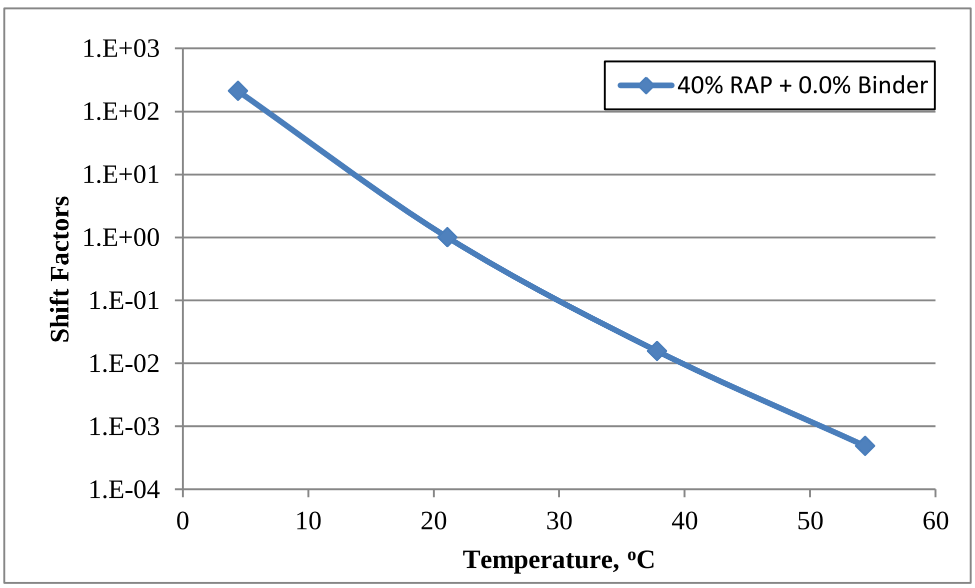

Figure A14. Shift Factors for 40% RAP + 0.0% Binder Master Curve

Table A9. Dynamic Modulus Test Results for 40% RAP + 0.5% Binder Samples

40% RAP + 0.5% Binder (4.4°C)				
Frequency	Sample D1	Sample D3	Sample D4	Average
Hz	kPa	kPa	kPa	kPa
25	15100220	14773540	16783790	15552517
10	14061870	13918850	15458530	14479750
5	13183500	13153940	14547420	13628287
1	11235030	11255200	12363910	11618047
0.5	10400930	10404880	11412360	10739390
0.1	8452107	8272175	9238208	8654163

40% RAP + 0.5% Binder (21.1°C)				
Frequency	Sample D1	Sample D3	Sample D4	Average
Hz	kPa	kPa	kPa	kPa
25	8924171	8915632	9689014	9176272
10	8128123	7615568	8345093	8029595
5	7165611	6694374	7317507	7059164
1	5120797	4759560	5139790	5006716
0.5	4278306	3996445	4295665	4190139
0.1	2840326	2681281	2771017	2764208

40% RAP + 0.5% Binder (37.8°C)				
Frequency	Sample D1	Sample D3	Sample D4	Average
Hz	kPa	kPa	kPa	kPa
25	3865241	3744486	3776680	3795469
10	3056461	3046660	3006151	3036424
5	2426134	2429156	2380441	2411910
1	1437342	1438780	1391326	1422483
0.5	1076392	1074068	1040495	1063652
0.1	564679	557242	542188	554703

40% RAP + 0.5% Binder (54.4°C)				
Frequency	Sample D1	Sample D3	Sample D4	Average
Hz	kPa	kPa	kPa	kPa
25	1251182	1250688	1259999	1253956
10	916329	902312	917273	911971
5	700057	680426	699546	693343
1	442929	412615	448962	434835
0.5	330633	305863	339587	325361
0.1	175439	167460	189330	177409

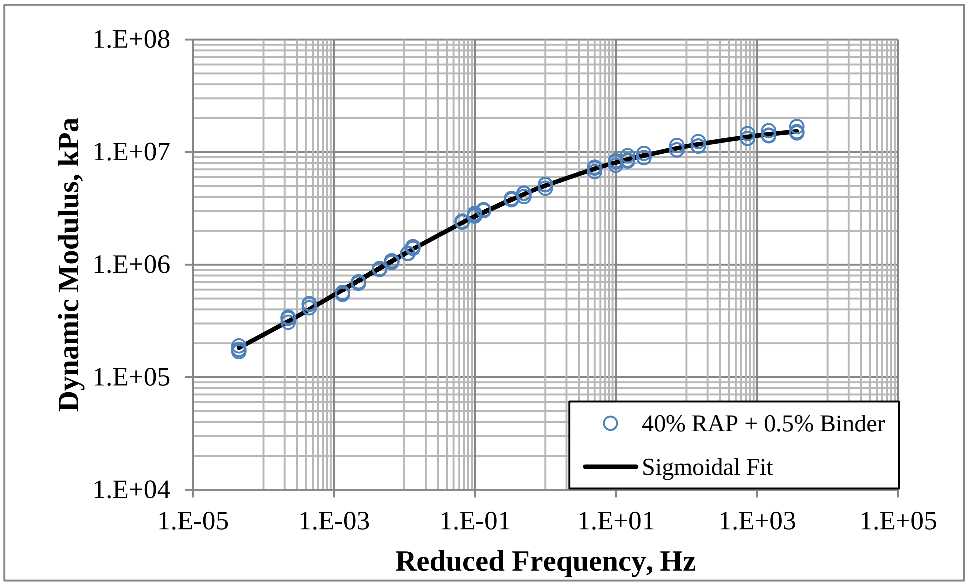

Figure A15. Dynamic Modulus Master Curve for Samples Containing 40% RAP +0.5% Binder

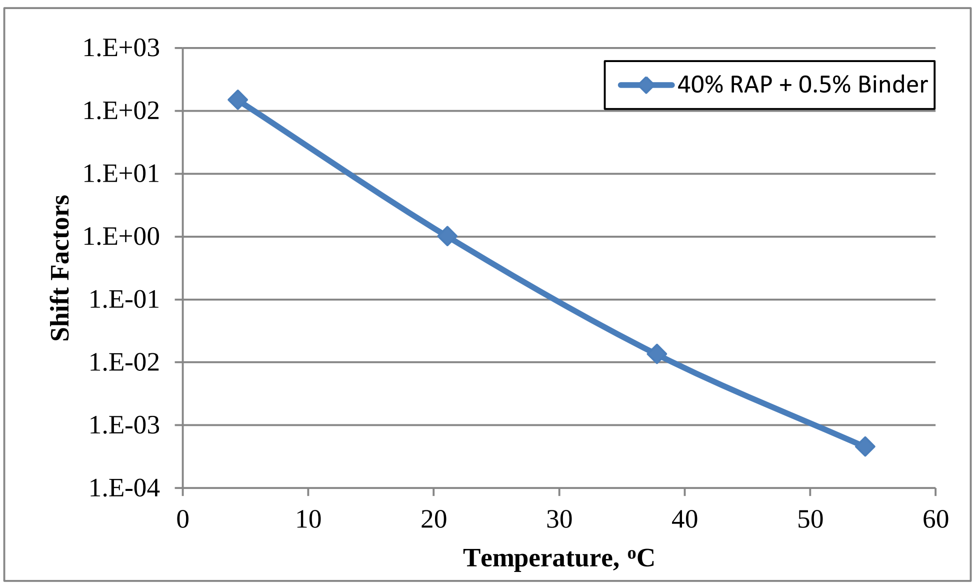

Figure A16. Shift Factors for 40% RAP + 0.5% Binder Master Curve

Table A10. Dynamic Modulus Test Results for 40% RAP + 1.0% Binder Samples

40% RAP + 1.0% Binder (4.4°C)				
Frequency	Sample F5	Sample F10	Sample F11	Average
Hz	kPa	kPa	kPa	kPa
25	14577700	13483690	13890890	13984093
10	13404830	12421330	12673960	12833373
5	12488940	11598060	11779510	11955503
1	10446810	9624933	9751983	9941242
0.5	9549629	8761047	8887397	9066024
0.1	7626732	6741554	6979866	7116051

40% RAP + 1.0% Binder (21.1°C)				
Frequency	Sample F5	Sample F10	Sample F11	Average
Hz	kPa	kPa	kPa	kPa
25	8139616	7559781	7334794	7678064
10	6861174	6526069	6233135	6540126
5	6005289	5649490	5401681	5685487
1	4194261	3807209	3678859	3893443
0.5	3497647	3103064	3011772	3204161
0.1	2257587	1922810	1898187	2026195

40% RAP + 1.0% Binder (37.8°C)				
Frequency	Sample F5	Sample F10	Sample F11	Average
Hz	kPa	kPa	kPa	kPa
25	3207291	3018493	2800959	3008914
10	2561096	2270850	2195396	2342447
5	2021989	1718123	1690374	1810162
1	1189432	989568	1090093	1089698
0.5	887871	712414	1013508	871264
0.1	466250	363428	530233	453303

40% RAP + 1.0% Binder (54.4°C)				
Frequency	Sample F5	Sample F10	Sample F11	Average
Hz	kPa	kPa	kPa	kPa
25	1077506	876914	861321	938580
10	786507	622169	627480	678719
5	598410	468998	474205	513871
1	377977	303639	310981	330866
0.5	281482	229142	233231	247952
0.1	154440	137500	134771	142237

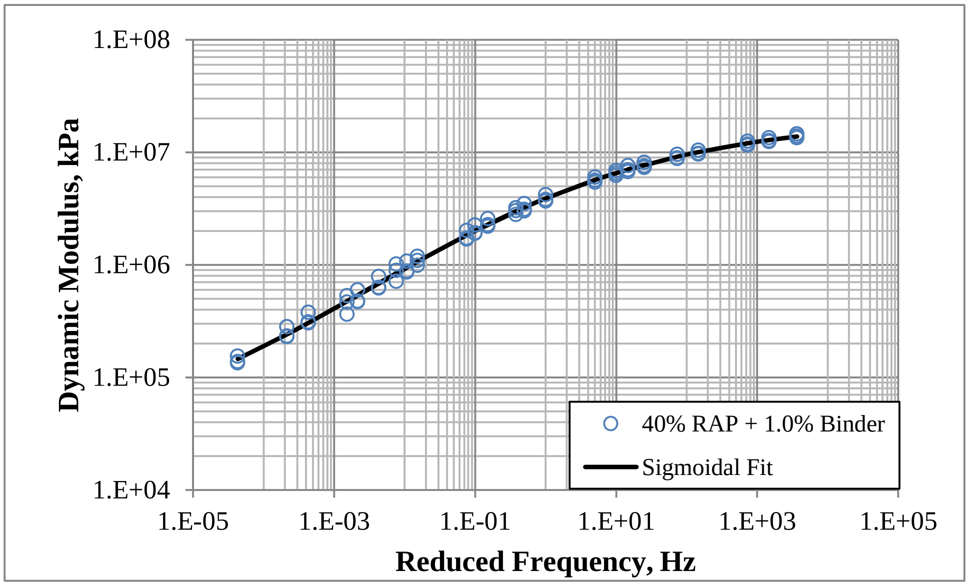

Figure A17. Dynamic Modulus Master Curve for Samples Containing 40% RAP +1.0% Binder

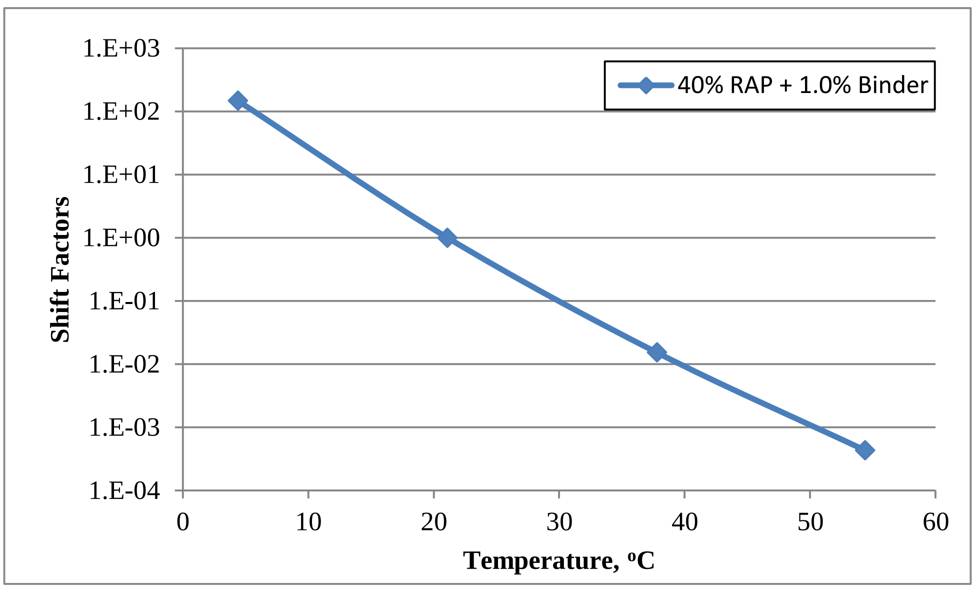

Figure A18. Shift Factors for 40% RAP + 1.0% Binder Master Curve

Table A11. Dynamic Modulus Test Results for 100% RAP + 0.0% Binder Samples

100% RAP + 0.0% Binder (4.4°C)				
Frequency	**Sample G100**	**Sample G300**	**Sample G500**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	17769360	14418650	13457300	15215103
10	17086610	13580950	12563410	14410323
5	16324290	12977010	11951200	13750833
1	14555720	11615950	10654390	12275353
0.5	13801260	11001540	10028150	11610317
0.1	12136960	9487972	8422432	10015788

100% RAP + 0.0% Binder (21.1°C)				
Frequency	**Sample G100**	**Sample G300**	**Sample G500**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	11817840	9459928	9184568	10154112
10	10622890	8644760	8430056	9232569
5	9804333	8016756	7759234	8526774
1	7895579	6492195	6265227	6884334
0.5	7164234	5885547	5604409	6218063
0.1	5479093	4593174	4364078	4812115

100% RAP + 0.0% Binder (37.8°C)				
Frequency	**Sample G100**	**Sample G300**	**Sample G500**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	6934830	6139228	6446335	6506798
10	5979450	5360704	5652313	5664156
5	5316066	4755412	5002671	5024716
1	3828611	3439874	3658703	3642396
0.5	3299878	2954176	3139003	3131019
0.1	2292980	2049904	2179861	2174248

100% RAP + 0.0% Binder (54.4°C)				
Frequency	**Sample G100**	**Sample G300**	**Sample G500**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	3633129	3421949	3348691	3467923
10	3073437	2877707	2881720	2944288
5	2638686	2462632	2474244	2525187
1	1767859	1676378	1689571	1711269
0.5	1501374	1419408	1434804	1451862
0.1	1049185	1009592	1020925	1026567

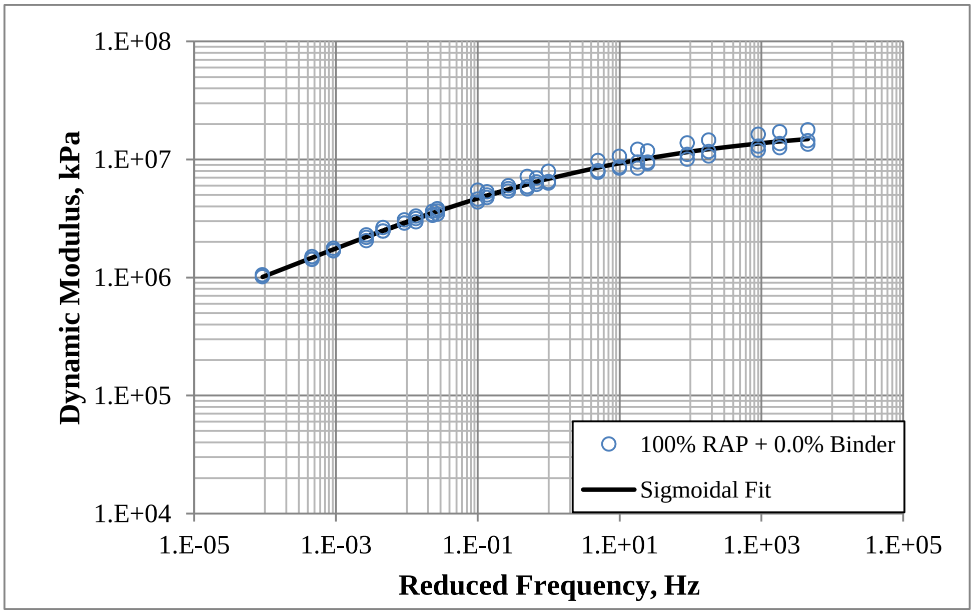

Figure A19. Dynamic Modulus Master Curve for Samples Containing 100% RAP +0.0% Binder

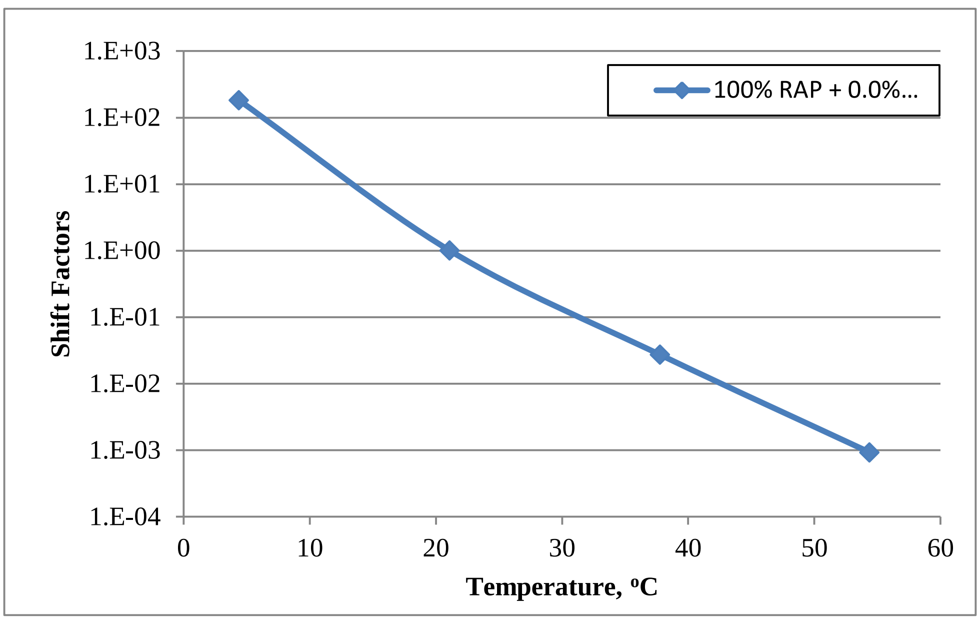

Figure A20. Shift Factors for 100% RAP + 0.0% Binder Master Curve

Table A12. Dynamic Modulus Test Results for 100% RAP + 0.5% Binder Samples

100% RAP + 0.5% Binder (4.4°C)				
Frequency	Sample F100	Sample F200	Sample F400	Average
Hz	kPa	kPa	kPa	kPa
25	21121020	18330590	20152740	19868117
10	19743770	17201590	18840680	18595347
5	18882030	16701210	17988150	17857130
1	16631260	14861290	15995930	15829493
0.5	15861560	13987200	15191600	15013453
0.1	14532770	11523120	13275440	13110443

100% RAP + 0.5% Binder (21.1°C)				
Frequency	Sample F100	Sample F200	Sample F400	Average
Hz	kPa	kPa	kPa	kPa
25	12694510	12399270	13654330	12916037
10	11178830	11078550	12141440	11466273
5	10210910	10187520	11238270	10545567
1	8080085	8165804	9192760	8479550
0.5	7246944	7344996	8407996	7666645
0.1	5376233	5576236	6570340	5840936

100% RAP + 0.5% Binder (37.8°C)				
Frequency	Sample F100	Sample F200	Sample F400	Average
Hz	kPa	kPa	kPa	kPa
25	6781485	6869178	7768502	7139722
10	5748808	5837645	6496555	6027669
5	4983443	5091635	5764484	5279854
1	3402019	3514947	4148348	3688438
0.5	2836496	2958407	3577932	3124278
0.1	1823752	1936852	2451080	2070561

100% RAP + 0.5% Binder (54.4°C)				
Frequency	Sample F100	Sample F200	Sample F400	Average
Hz	kPa	kPa	kPa	kPa
25	2983397	3269391	3280437	3177742
10	2385842	2655961	2646906	2562903
5	1956110	2204567	2192015	2117564
1	1248772	1416874	1420960	1362202
0.5	1029661	1175924	1174193	1126593
0.1	705586	802716	804543	770948

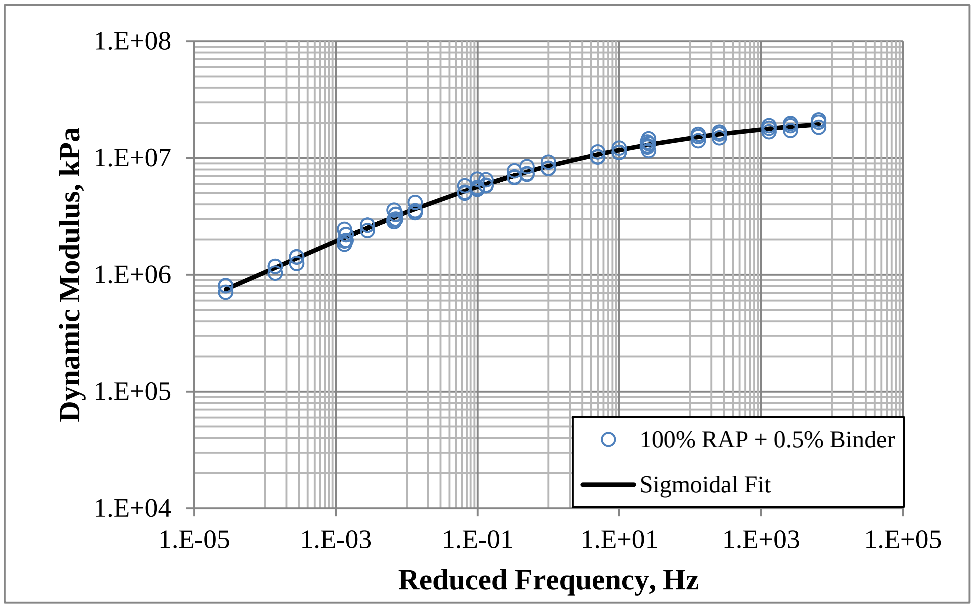

Figure A21. Dynamic Modulus Master Curve for Samples Containing 100% RAP +0.5% Binder

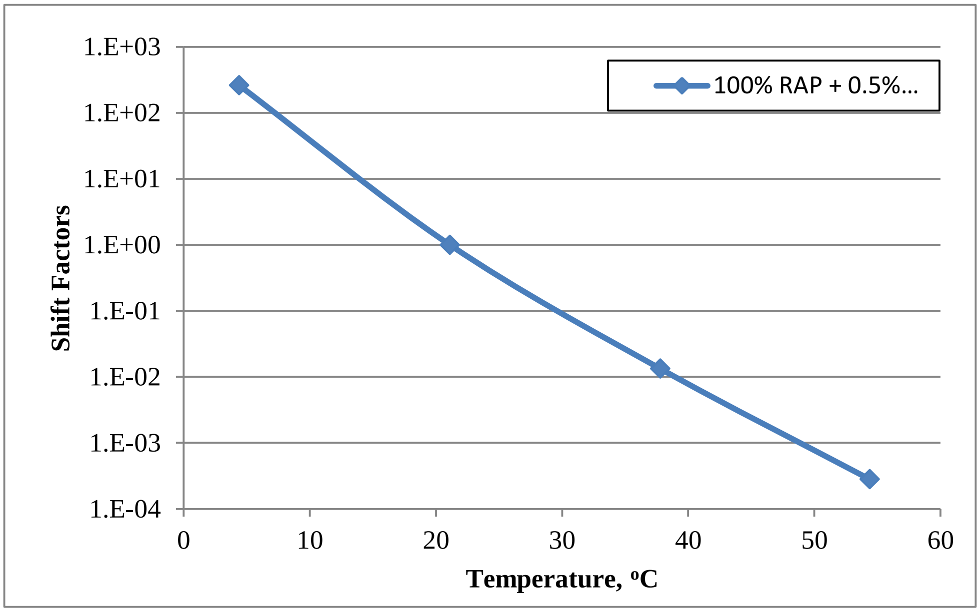

Figure A22. Shift Factors for 100% RAP + 0.5% Binder Master Curve

Table A13. Dynamic Modulus Test Results for 100% RAP + 1.0% Binder Samples

100% RAP + 1.0% Binder (4.4°C)				
Frequency	Sample D100	Sample D400	Sample D500	Average
Hz	kPa	kPa	kPa	kPa
25	20576440	21319450	19821060	20572317
10	18772300	19961030	18315060	19016130
5	17851180	18965290	17408600	18075023
1	15743810	16715770	15436430	15965337
0.5	14902960	15809140	14546980	15086360
0.1	12963010	13799150	12431450	13064537

100% RAP + 1.0% Binder (21.1°C)				
Frequency	Sample D100	Sample D400	Sample D500	Average
Hz	kPa	kPa	kPa	kPa
25	12419780	13497850	12915920	12944517
10	10927940	11892130	11440220	11420097
5	9945876	10941310	10509620	10465602
1	7756726	8683019	8299082	8246276
0.5	6879383	7868130	7474142	7407218
0.1	4982504	5840794	5559586	5460961

100% RAP + 1.0% Binder (37.8°C)				
Frequency	Sample D100	Sample D400	Sample D500	Average
Hz	kPa	kPa	kPa	kPa
25	6420458	6654387	6301049	6458631
10	5315891	5571041	5271832	5386255
5	4549397	4852930	4563682	4655336
1	3020880	3307918	3078818	3135872
0.5	2486793	2778600	2572889	2612761
0.1	1559778	1812288	1666188	1679418

100% RAP + 1.0% Binder (54.4°C)				
Frequency	Sample D100	Sample D400	Sample D500	Average
Hz	kPa	kPa	kPa	kPa
25	2606484	3009395	2715854	2777244
10	2028674	2438367	2219012	2228684
5	1627075	2029303	1840448	1832275
1	991396.2	1299352	1179659	1156802
0.5	793934.6	1080031	981555.8	951840
0.1	519889.4	740425	677635.8	645983

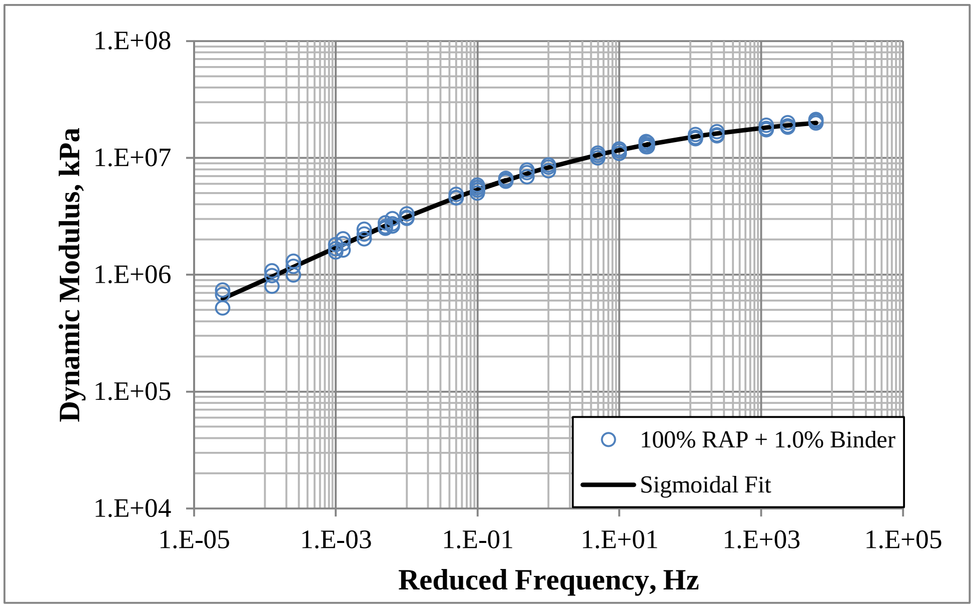

Figure A23. Dynamic Modulus Master Curve for Samples Containing 100% RAP +1.0% Binder

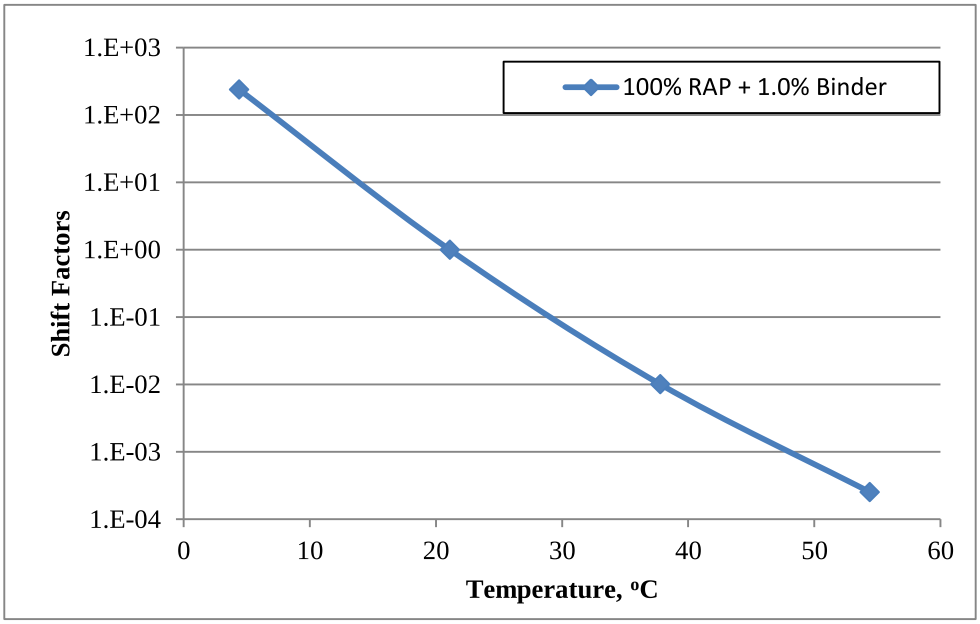

Figure A24. Shift Factors for 100% RAP + 1.0% Binder Master Curve

Table A14. Dynamic Modulus Test Results for 100% RAP + 1.5% Binder Samples

100% RAP + 1.5% Binder (4.4^{o}C)				
Frequency	**Sample E400**	**Sample E500**	**Sample E600**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	21085890	18241600	19759230	19695573
10	19943100	17255250	18587920	18595423
5	18920330	16339700	17662810	17640947
1	16453920	14214970	15590550	15419813
0.5	15433830	13394720	14653270	14493940
0.1	13255760	11656290	12356050	12422700

100% RAP + 1.5% Binder (21.1^{o}C)				
Frequency	**Sample E400**	**Sample E500**	**Sample E600**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	11961420	10795000	12468540	11741653
10	10394880	9586645	11155260	10378928
5	9425216	8725424	10191800	9447480
1	7228230	6818040	8013585	7353285
0.5	6407097	6063464	7169306	6546622
0.1	4580152	4472952	5302225	4785110

100% RAP + 1.5% Binder (37.8^{o}C)				
Frequency	**Sample E400**	**Sample E500**	**Sample E600**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	5384769	5369640	6333109	5695839
10	4446371	4533277	5306434	4762027
5	3806279	3909151	4577640	4097690
1	2532405	2653454	3116666	2767508
0.5	2099518	2216809	2600318	2305548
0.1	1360605	1453916	1684236	1499586

100% RAP + 1.5% Binder (54.4^{o}C)				
Frequency	**Sample E400**	**Sample E500**	**Sample E600**	**Average**
Hz	**kPa**	**kPa**	**kPa**	**kPa**
25	2218070	2500597	2748196	2488954
10	1768798	2029573	2208048	2002140
5	1449494	1683526	1817614	1650211
1	941869.1	1111991	1177247	1077036
0.5	781650.7	926980.8	973703.8	894112
0.1	551293.7	655205.1	670881.5	625793

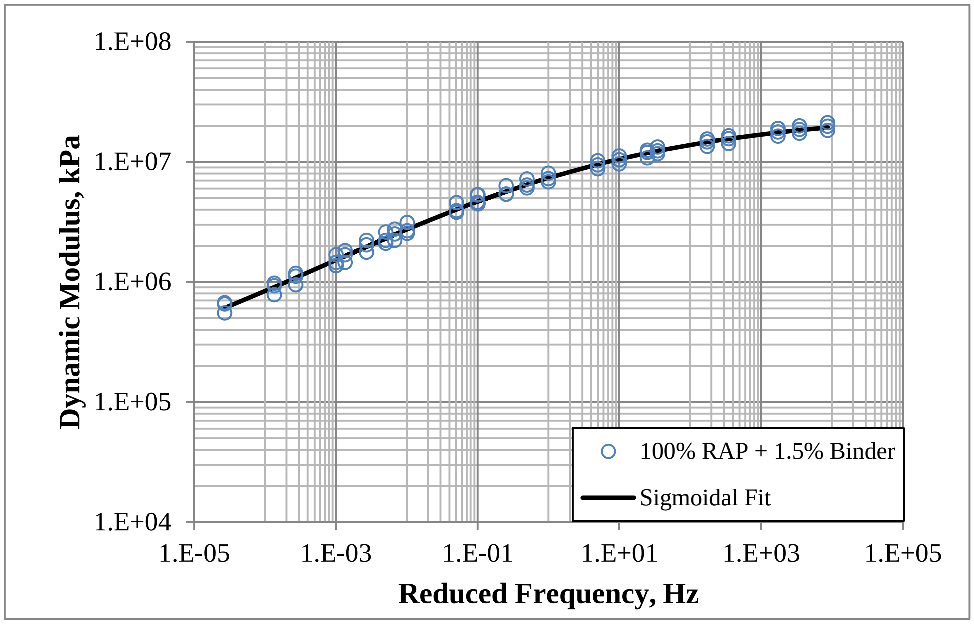

Figure A25. Dynamic Modulus Master Curve for Samples Containing 100% RAP +1.5% Binder

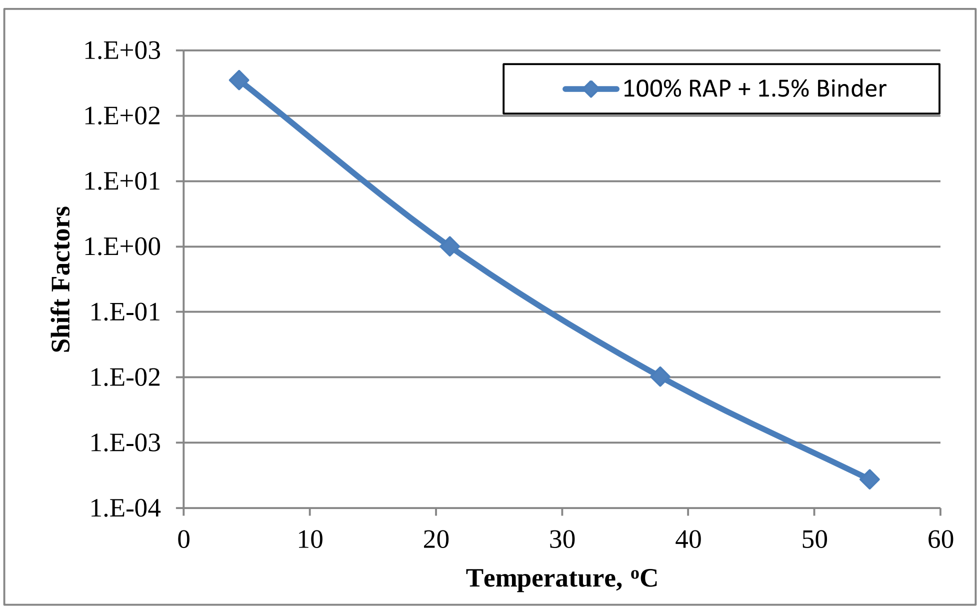

Figure A26. Shift Factors for 100% RAP + 1.5% Binder Master Curve

APPENDIX B – FLOW NUMBER TEST RESULTS

Table B1. Flow Number for all Samples

0% RAP

0% + 0.0%		0% + 0.5%		0% + 1.0%	
Avg FN	SD	Avg FN	SD	Avg FN	SD
1917	168	4050	1481	2583	287

0% + 0.0%		0% + 0.5%		0% + 1.0%	
Sample	FN	Sample	FN	Sample	FN
A0-4	2100	B0-1	2540	C0-3	2370
A0-5	1880	B0-5	5500	C0-4	2470
A0-6	1770	B0-6	4110	C0-5	2910
AVG	1917	**AVG**	4050	**AVG**	2583

40% RAP

40% + 0.0%		40% + 0.5%		40% + 1.0%	
Avg FN	SD	Avg FN	Avg FN	Avg FN	SD
8167	3175	3967	886	1447	441

40% + 0.0%		40% + 0.5%		40% + 1.0%	
Sample	FN	Sample	FN	Sample	FN
B5	4500	D3	4830	F5	1940
B7	10000	D5	4010	F10	1090
B8	10000	D6	3060	F11	1310
AVG	8167	**AVG**	3967	**AVG**	1447

20% RAP

20% + 0.0%		20% + 0.5%		20% + 1.0%	
Avg FN	SD	Avg FN	SD	Avg FN	SD
3880	1211	8017	2251	4157	662

20% + 0.0%		20% + 0.5%		20% + 1.0%	
Sample	FN	Sample	FN	Sample	FN
A5	4870	C1	8482	E1	3630
A7	4240	C2	10000	E2	3940
A8	2530	C3	5570	E3	4900
AVG	3880	**AVG**	8017	**AVG**	4157

100% RAP

100% + 0.0%		100% + 0.5%		100% + 1.0%		100% + 1.5%	
Avg FN	SD	Avg FN	SD	Avg FN	SD	Avg FN	SD
10000	0	10000	0	10000	0	10000	0

100% + 0.0%		100% + 0.5%		100% + 1.0%		100% + 1.5%	
Sample	FN	Sample	FN	Sample	FN	Sample	FN
G100	10000	E100	10000	D100	10000	F400	10000
G200	10000	E200	10000	D400	10000	F500	10000
G300	10000	E300	10000	D500	10000	F600	10000
AVG	10000	**AVG**	10000	**AVG**	10000	**AVG**	10000

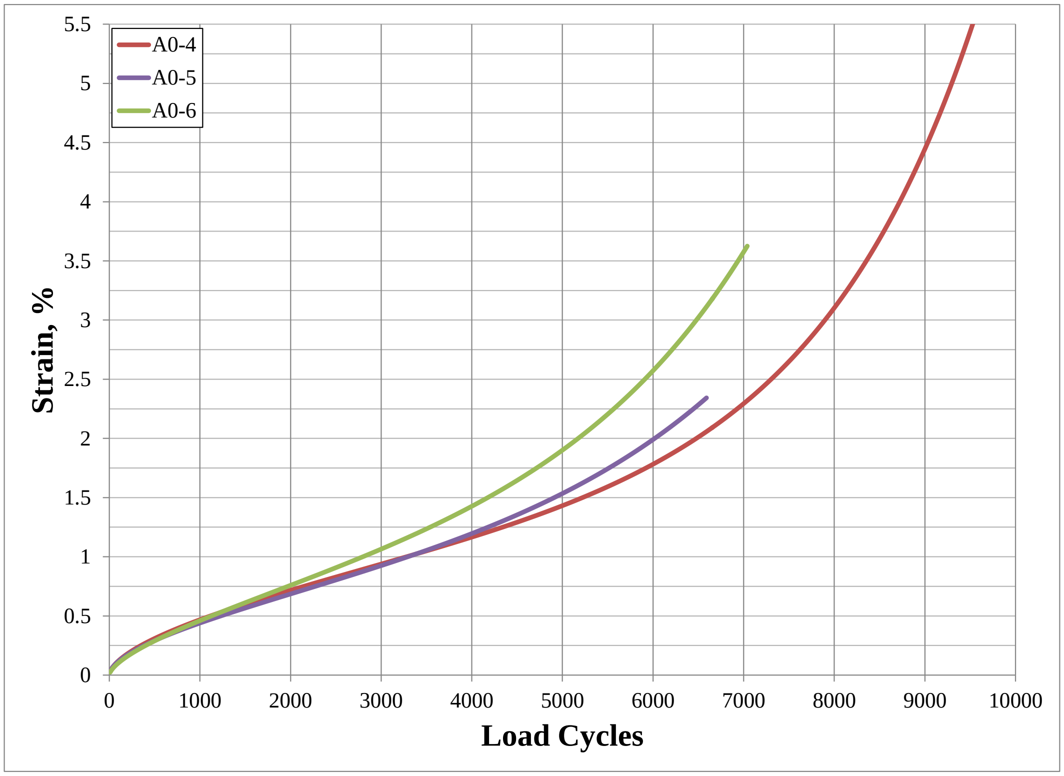

Figure B1. Flow Behavior Curves for Samples Containing 0% RAP + 0.0% Binder

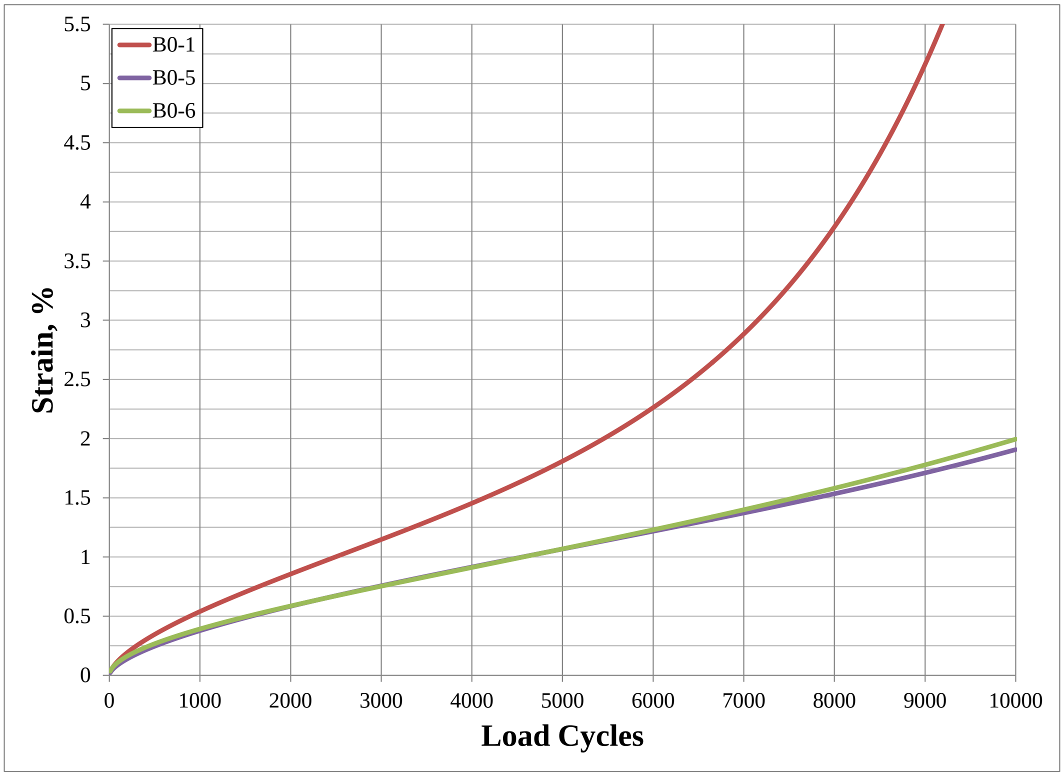

Figure B2. Flow Behavior Curves for Samples Containing 0% RAP + 0.5% Binder

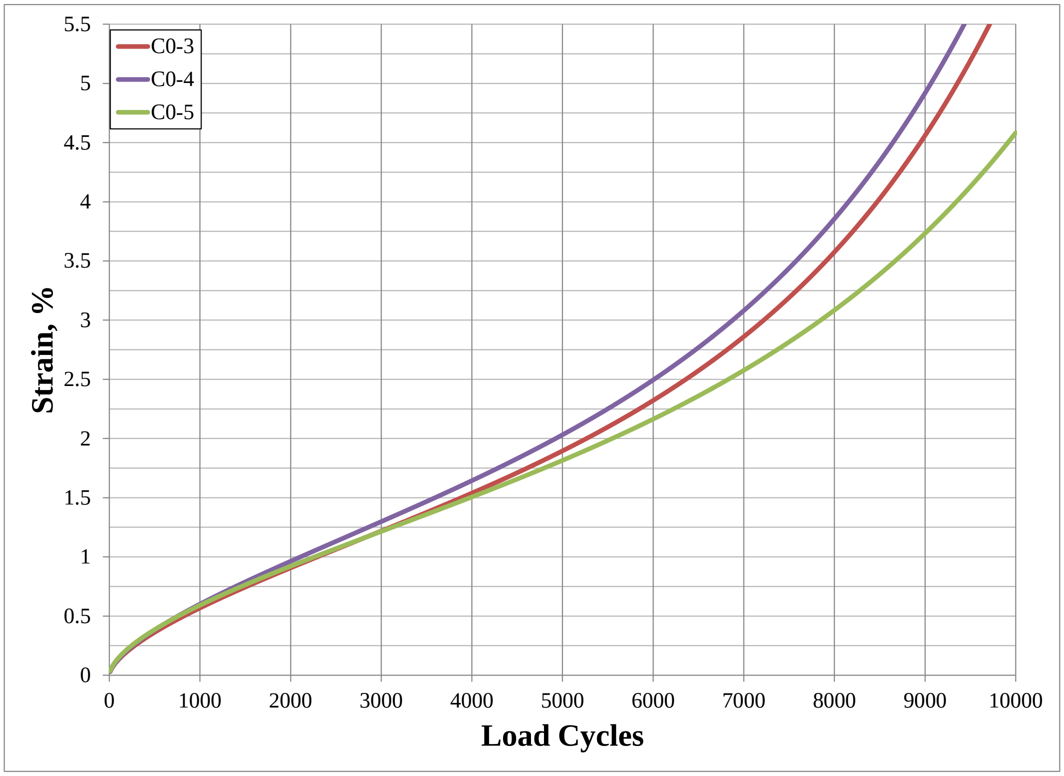

Figure B3. Flow Behavior Curves for Samples Containing 0% RAP + 1.0% Binder

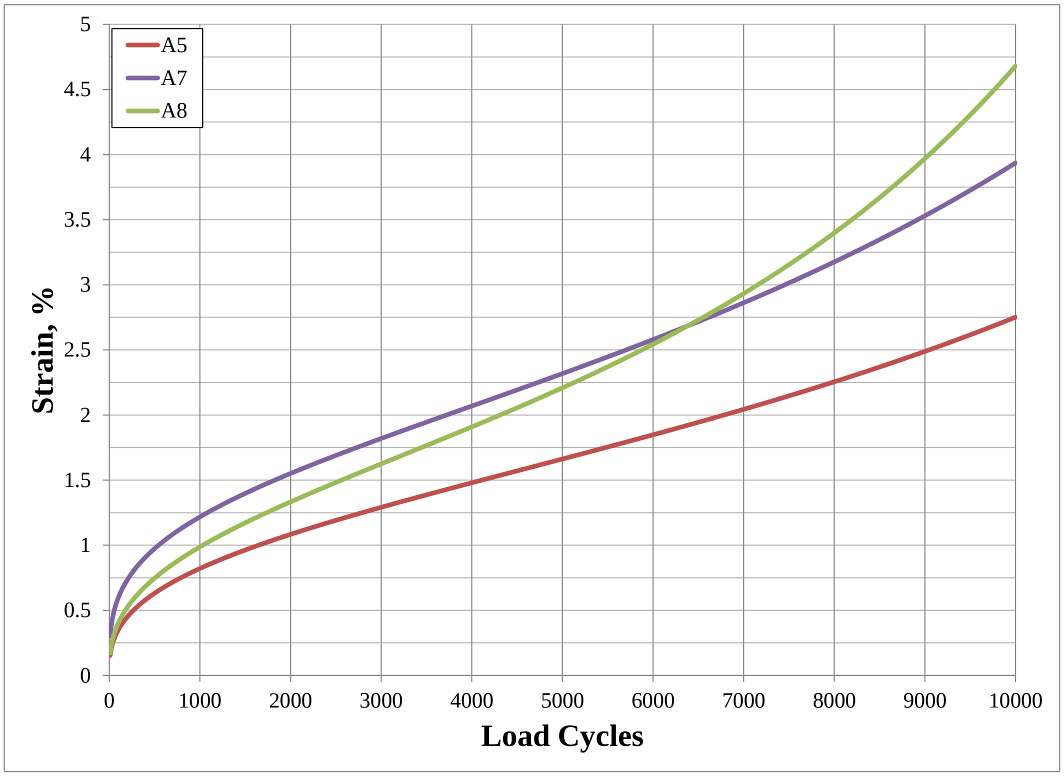

Figure B4. Flow Behavior Curves for Samples Containing 20% RAP + 0.0% Binder

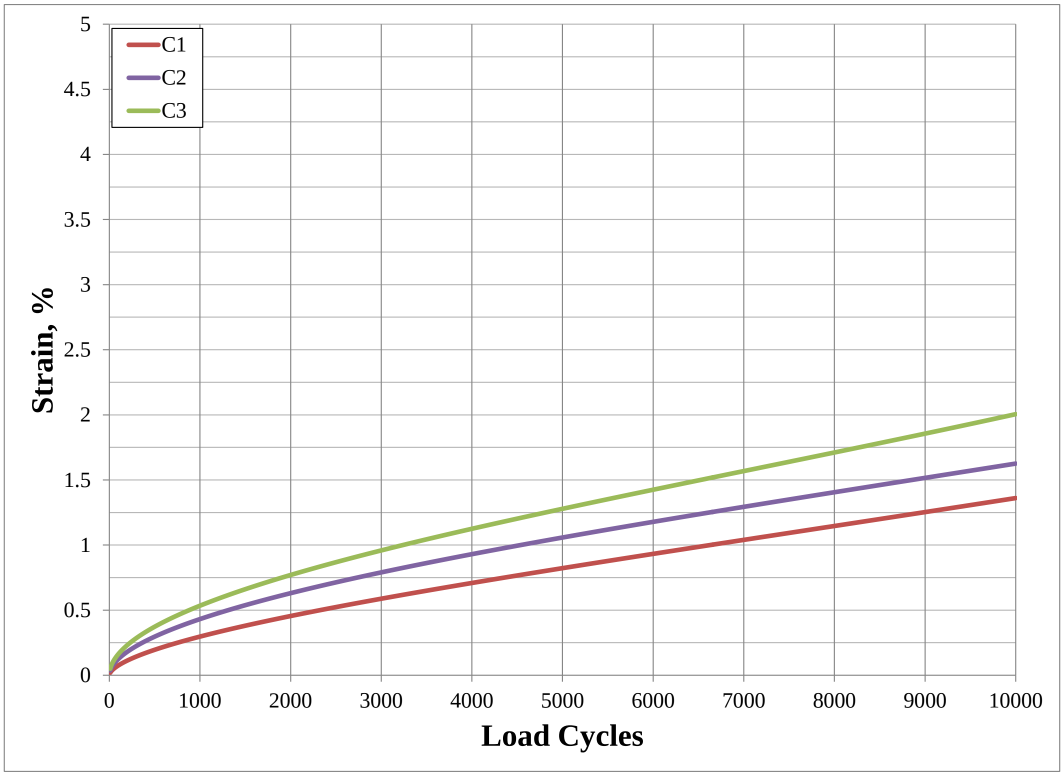

Figure B5. Flow Behavior Curves for Samples Containing 20% RAP + 0.5% Binder

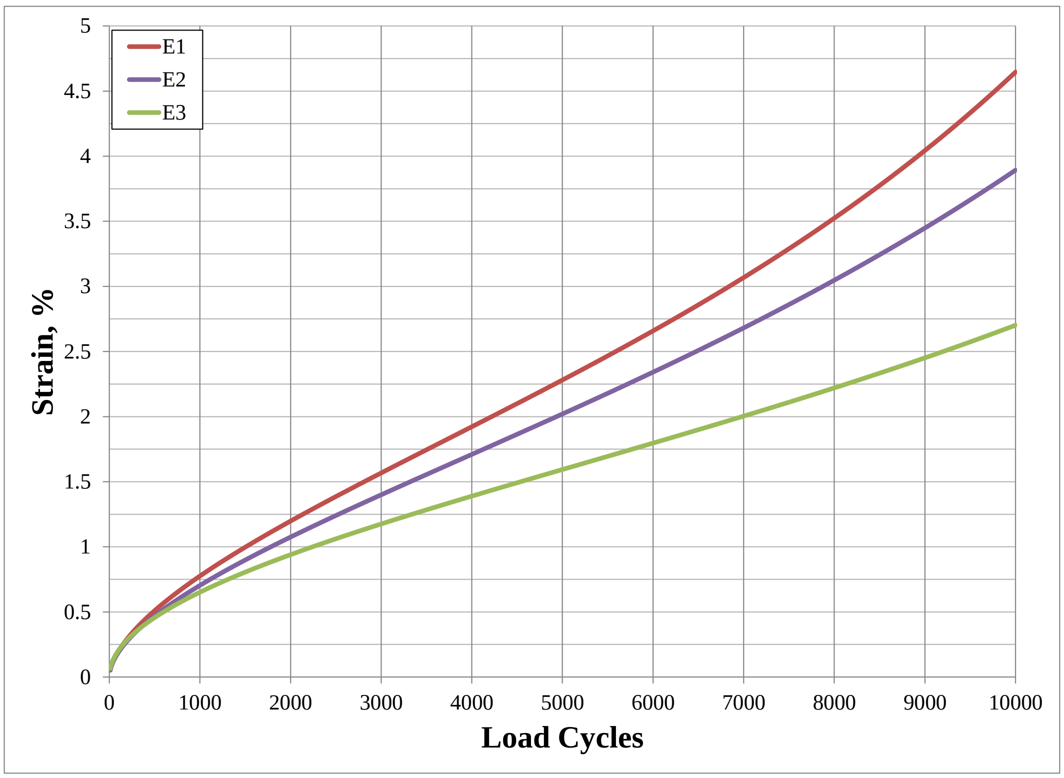

Figure B6. Flow Behavior Curves for Samples Containing 20% RAP + 1.0% Binder

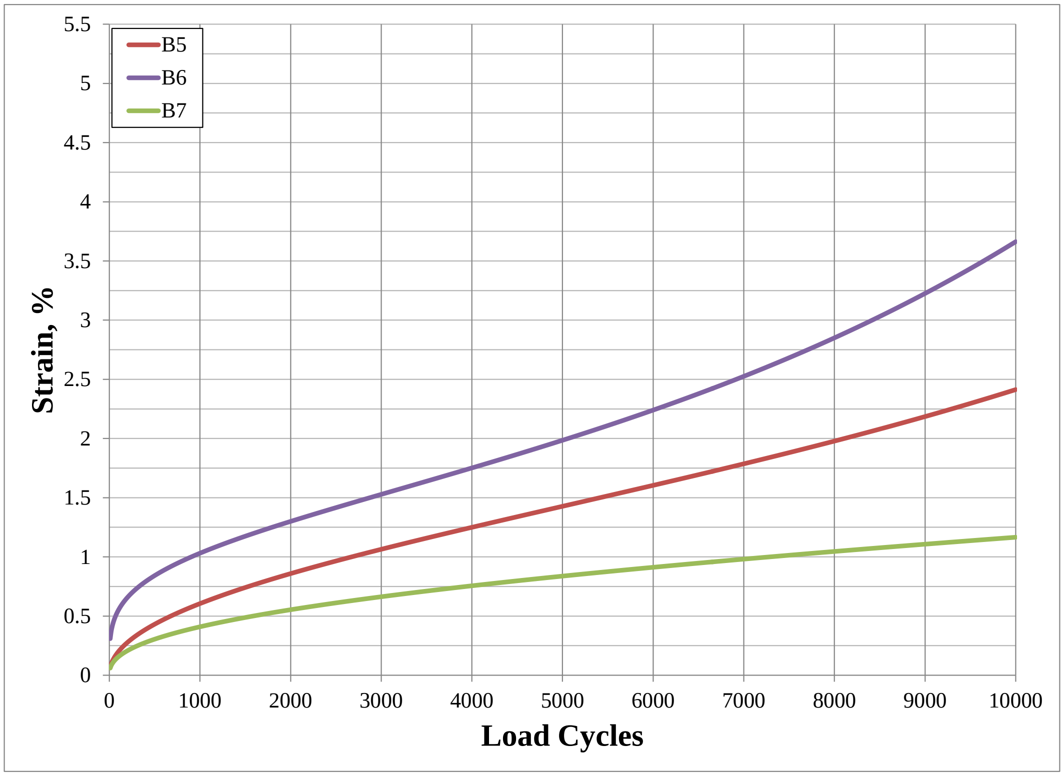

Figure B7. Flow Behavior Curves for Samples Containing 40% RAP + 0.0% Binder

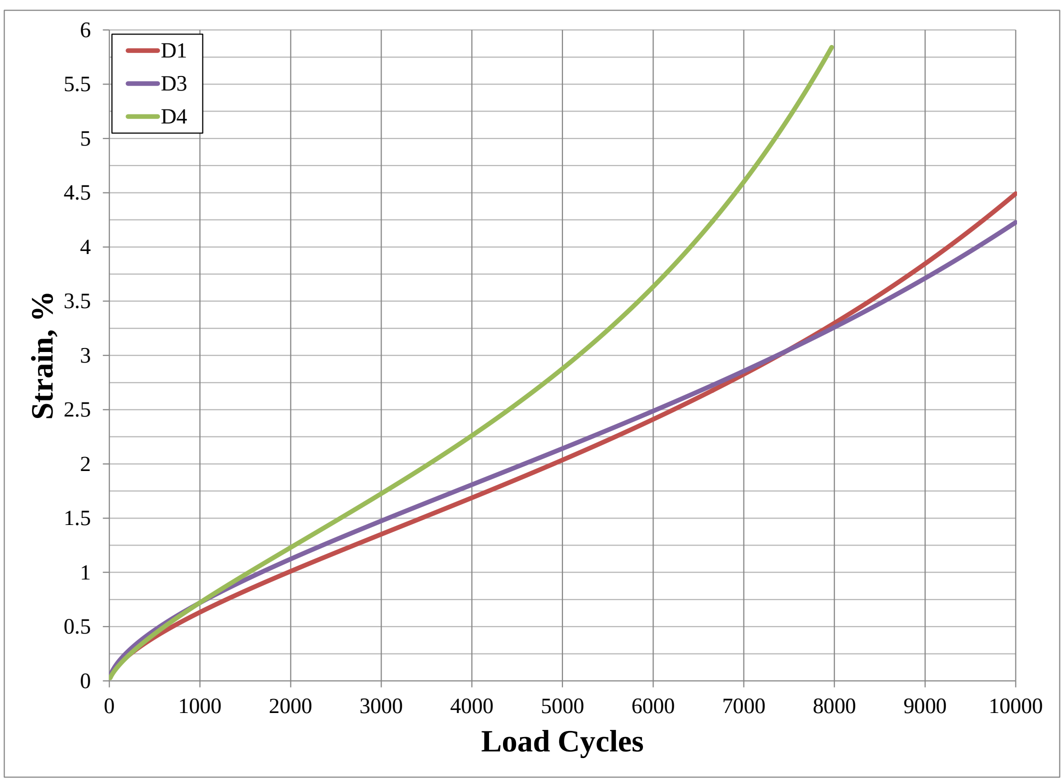

Figure B8. Flow Behavior Curves for Samples Containing 40% RAP + 0.5% Binder

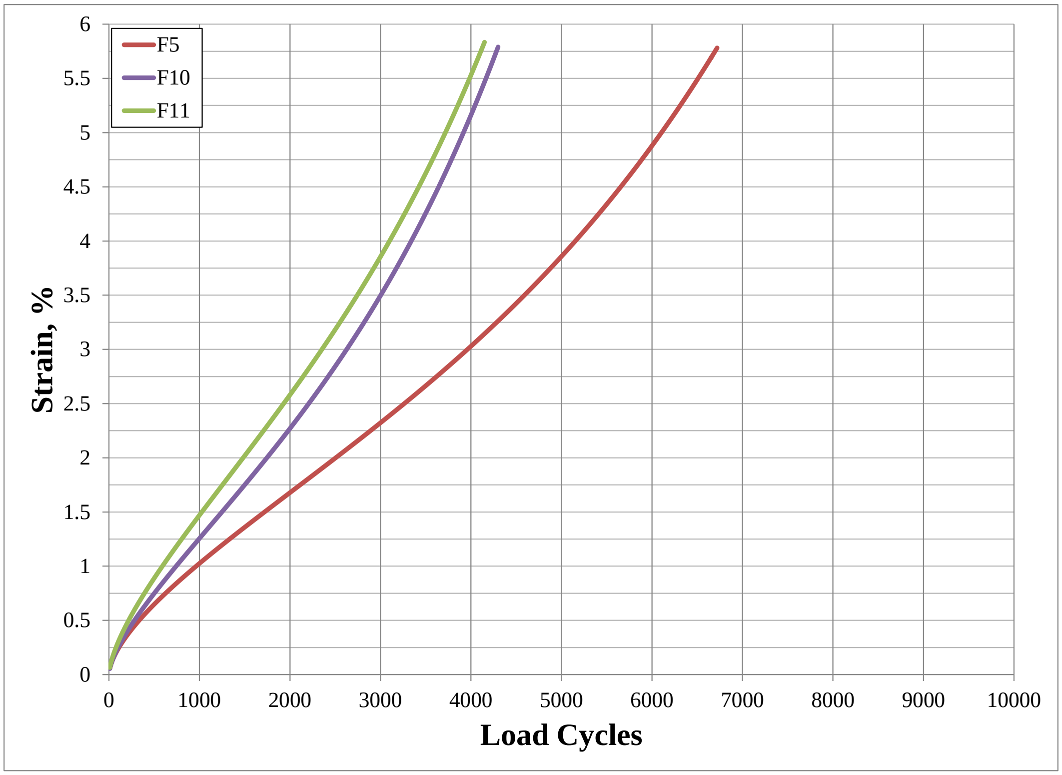

Figure B9. Flow Behavior Curves for Samples Containing 40% RAP + 1.0% Binder

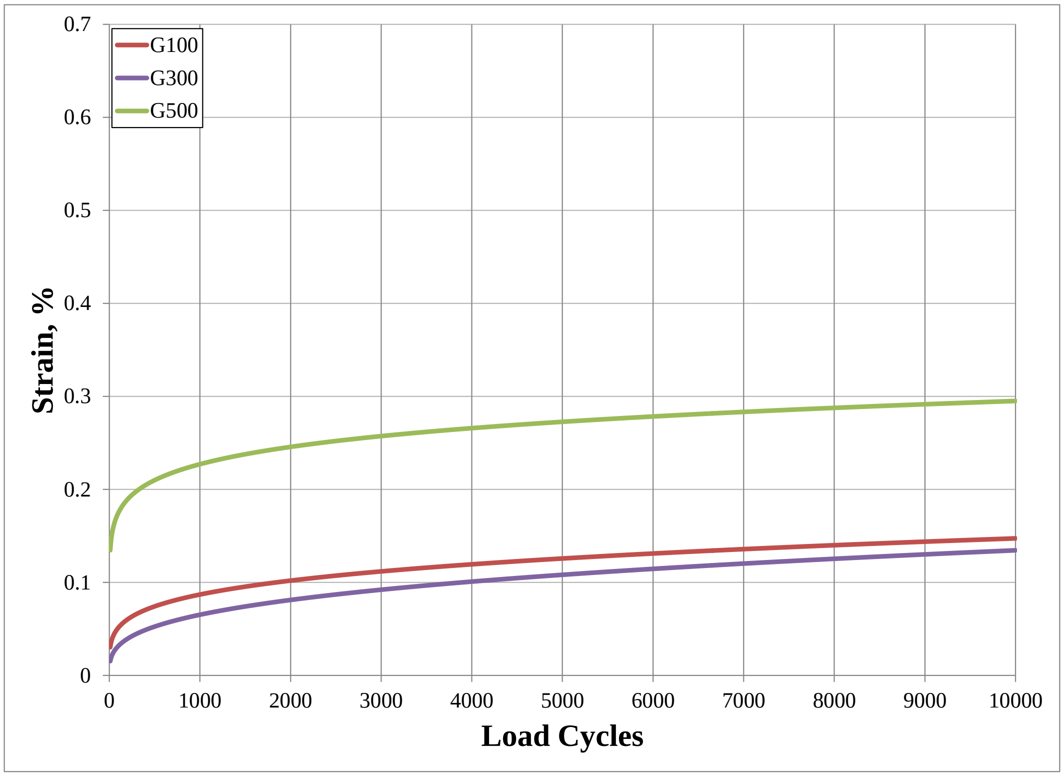

Figure B10. Flow Behavior Curves for Samples Containing 100% RAP + 0.0% Binder

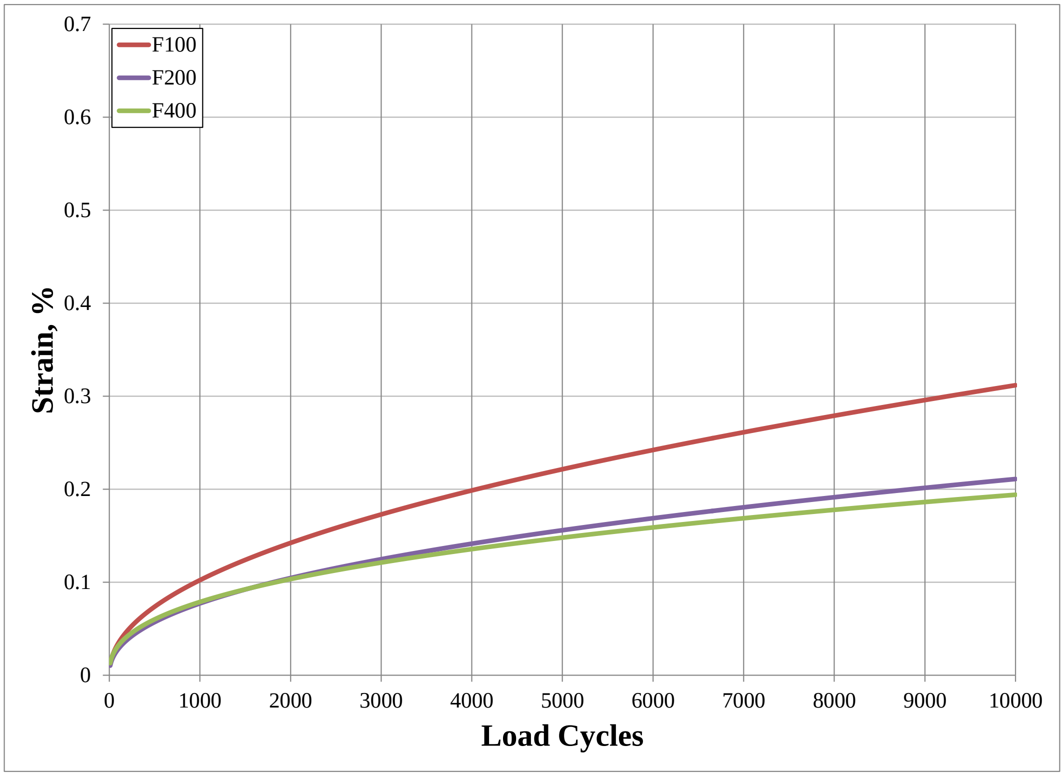

Figure B11. Flow Behavior Curves for Samples Containing 100% RAP + 0.5% Binder

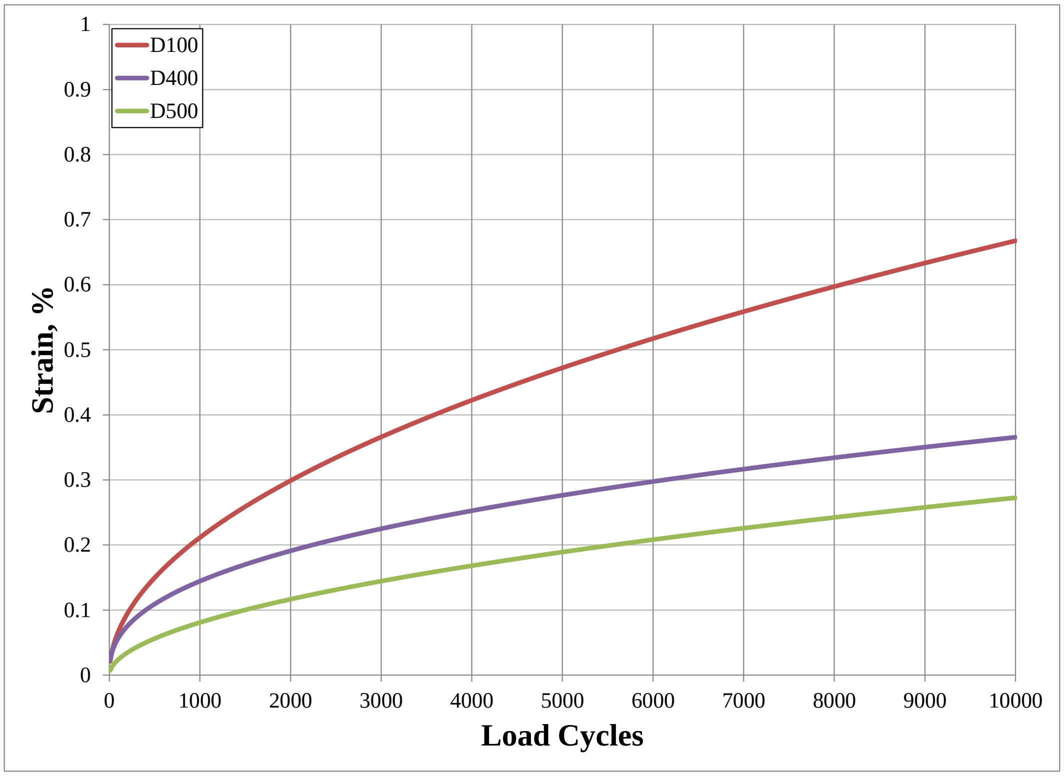

Figure B12. Flow Behavior Curves for Samples Containing 100% RAP + 1.0% Binder

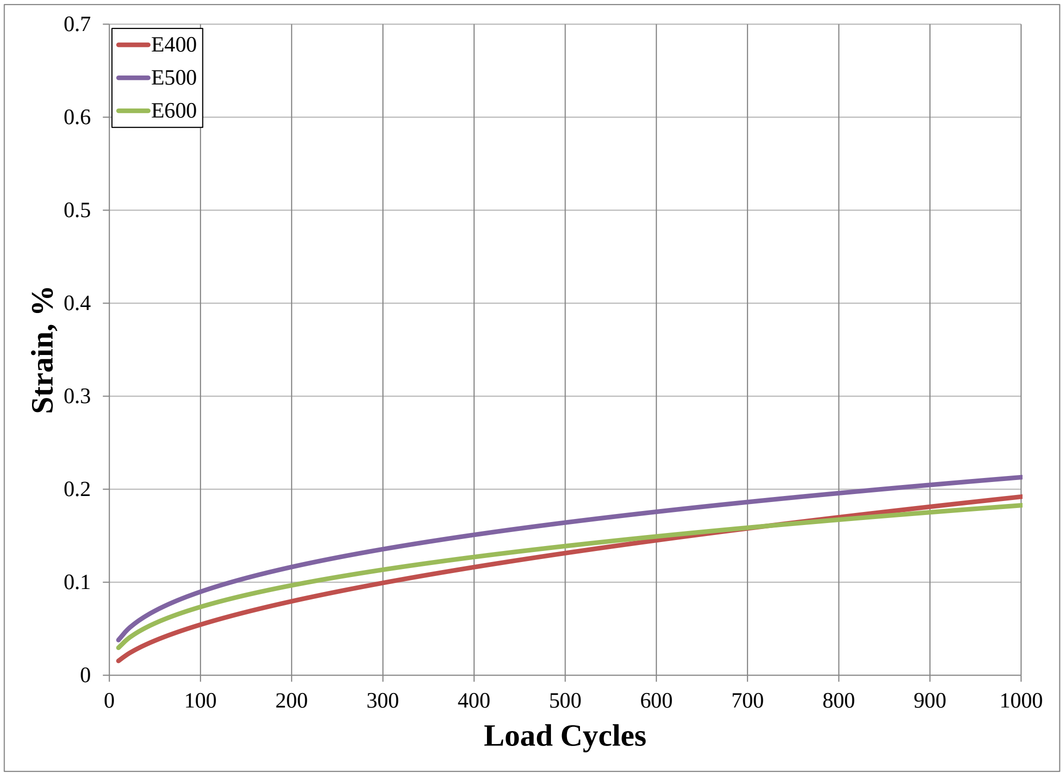

Figure B13. Flow Behavior Curves for Samples Containing 100% RAP + 1.5% Binder

APPENDIX C – FATIGUE RESISTANCE TEST RESULTS

Table C1. Initial Stiffness and Cycles to Failure for all Mixes

Sample	% RAP	% Binder	Stiffness	Average	Cycles to Failure	Average
	%	*%*	*kPa*	*kPa*	*#*	*#*
A0-7	0	0.0	4078179	3806903	24714	24397
A0-9	0	0.0	3918601		25118	
A0-11	0	0.0	3423930		23358	
B0-1	0	0.5	3562140	3355091	27851	26321
B0-7	0	0.5	3425866		23911	
B0-8	0	0.5	3077268		27201	
C0-2	0	1.0	2928981	2922834	26354	32505
C0-3	0	1.0	2816063		32257	
C0-4	0	1.0	3023459		38904	
A5	20	0.0	4694554	4340333	5532	6127
A11	20	0.0	4377783		11323	
A14	20	0.0	3948662		1526	
C3	20	0.5	4330386	4333279	16271	13102
C5	20	0.5	4295519		14696	
C7	20	0.5	4373932		8338	
E2	20	1.0	3612231	3598348	18451	17232
E11	20	1.0	3342464		14104	
E13	20	1.0	3840349		19141	
B4	40	0.0	5409662	4888022	25245	22340
B10	40	0.0	4707912		19434	
B12	40	0.0	4546491		936	
D7	40	0.5	4745985	4646637	48978	18399
D11	40	0.5	4653756		23457	
D13	40	0.5	4540170		13342	
F6	40	1.0	4179191	4102126	31470	22320
F8	40	1.0	4070142		17279	
F9	40	1.0	4057044		18211	
G400	100	0.0	4217818	4324955	1214	1300
G500	100	0.0	4667776		789	
G600	100	0.0	4089270		1897	
F100	100	0.5	5559285	5453719	2533	1572
F300	100	0.5	5338682		1472	
F400	100	0.5	5463190		710	
D100	100	1.0	5559285	5379308	3425	2746
D200	100	1.0	5352885		2562	
D300	100	1.0	5225753		2250	
E200	100	1.5	5291519	5381557	7654	7131
E300	100	1.5	5635664		7789	
E400	100	1.5	5217487		5950	

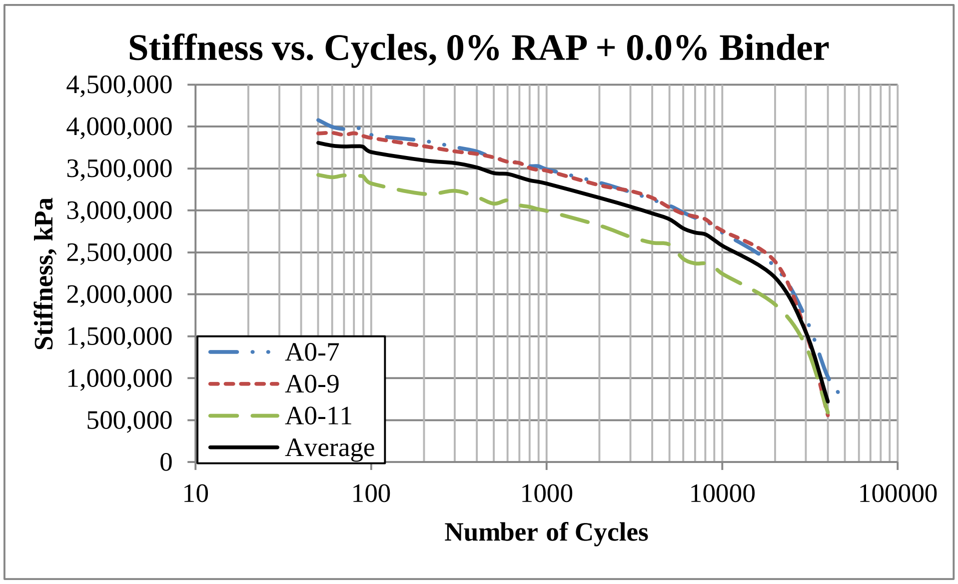

Figure C1. Fatigue Resistance Curves for Samples Containing 0% RAP + 0.0% Binder

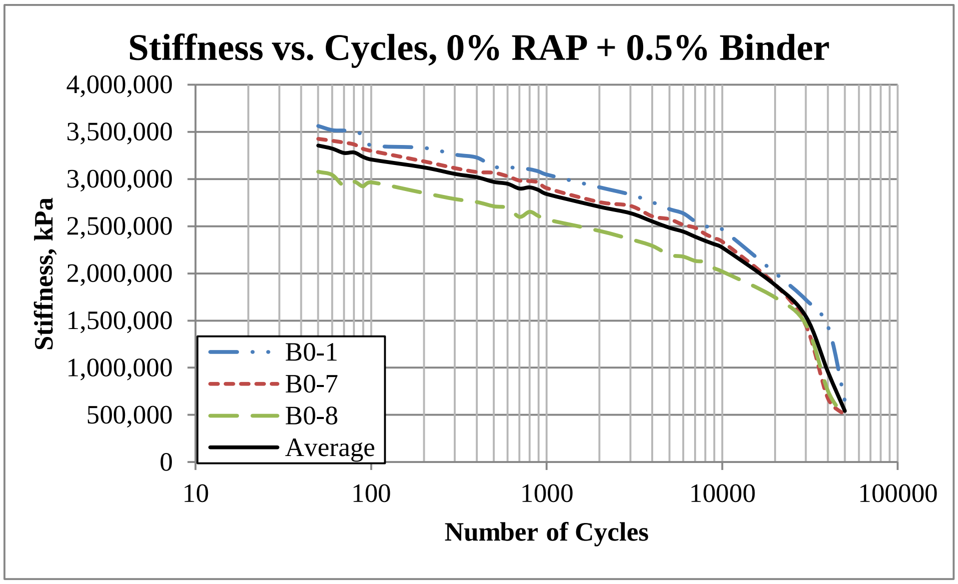

Figure C2. Fatigue Resistance Curves for Samples Containing 0% RAP + 0.5% Binder

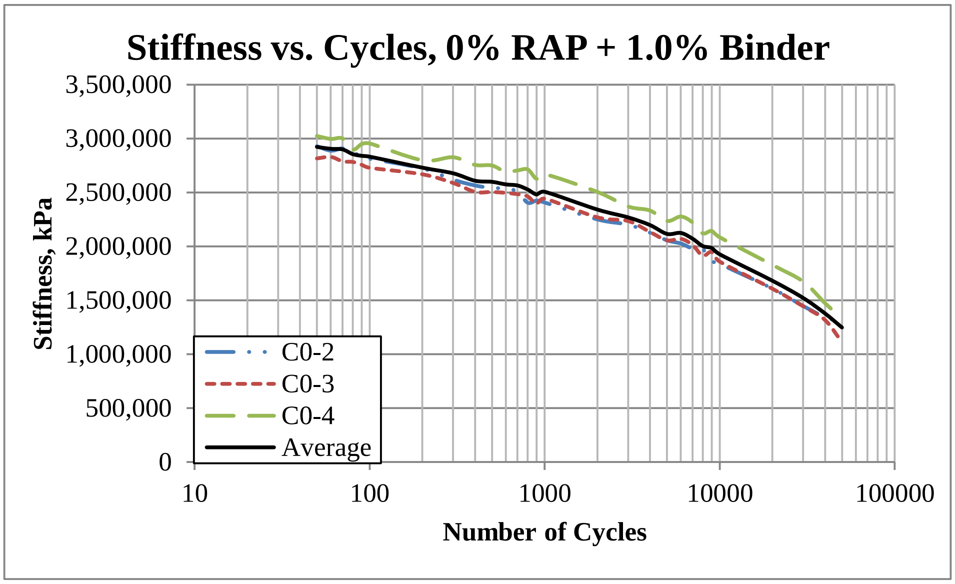

Figure C3. Fatigue Resistance Curves for Samples Containing 0% RAP + 1.0% Binder

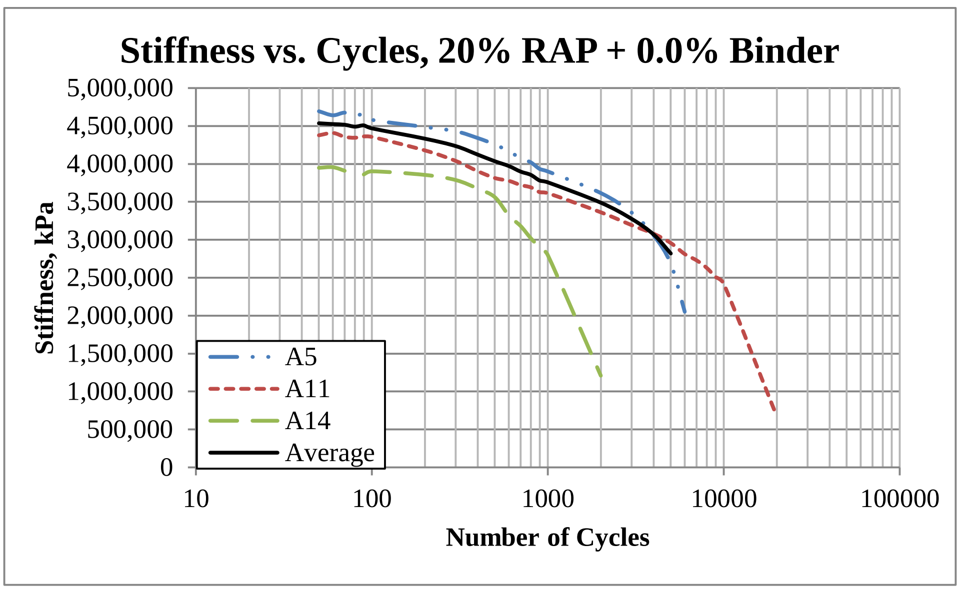

Figure C4. Fatigue Resistance Curves for Samples Containing 20% RAP + 0.0% Binder

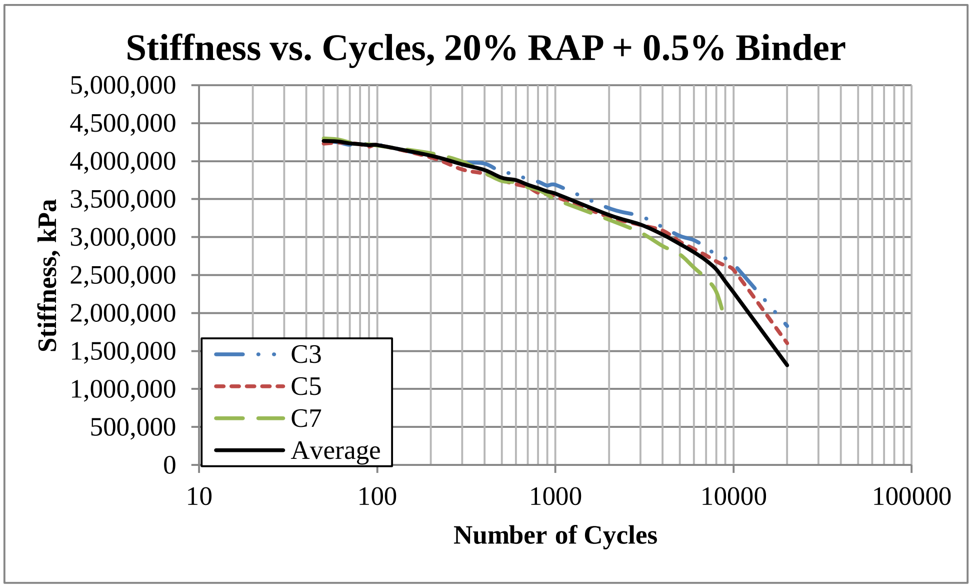

Figure C5. Fatigue Resistance Curves for Samples Containing 20% RAP + 0.5% Binder

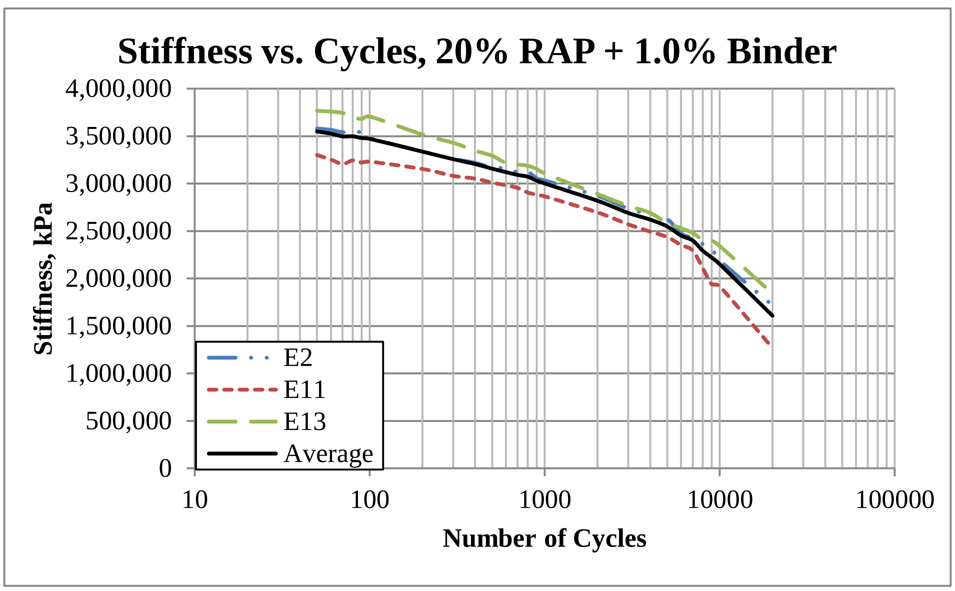

Figure C6. Fatigue Resistance Curves for Samples Containing 20% RAP + 1.0% Binder

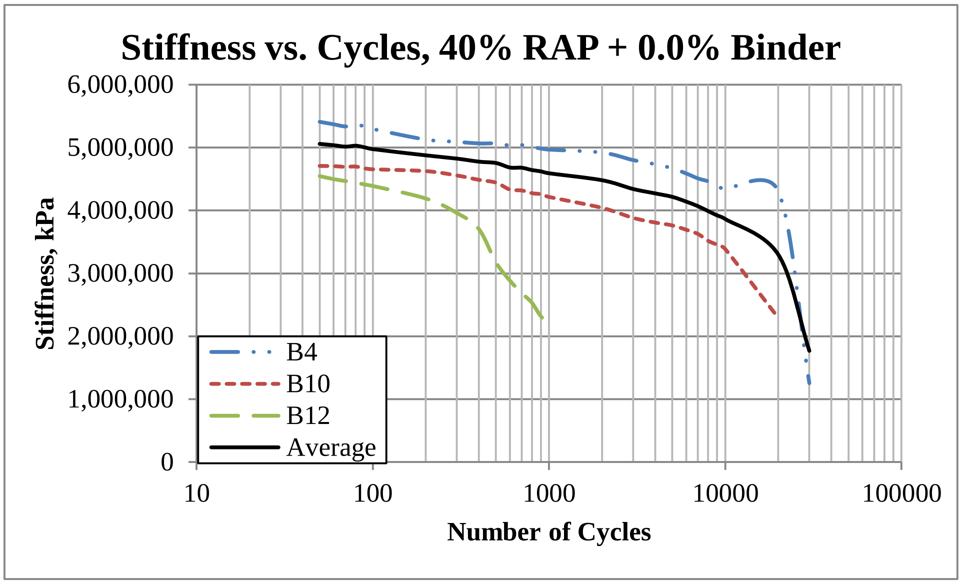

Figure C7. Fatigue Resistance Curves for Samples Containing 40% RAP + 0.0% Binder

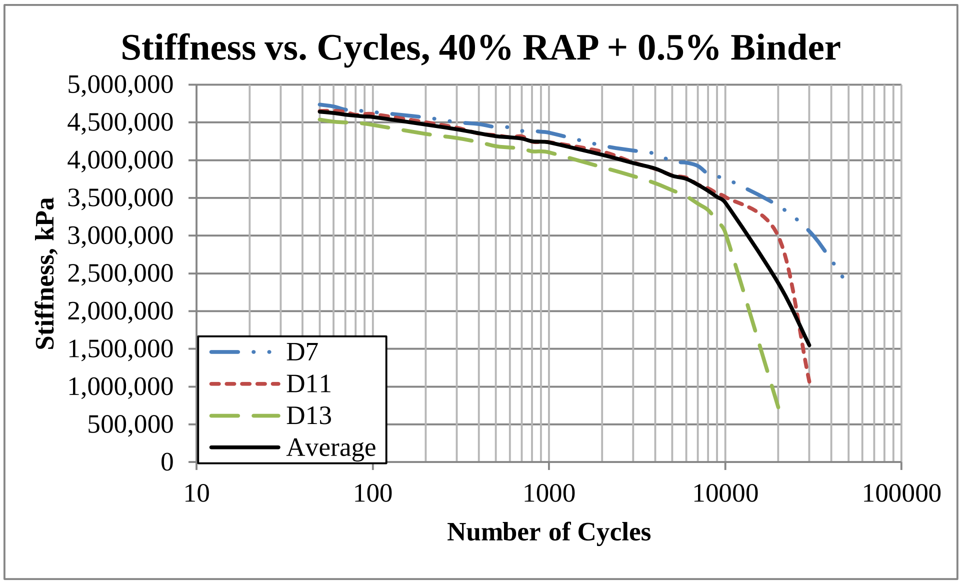

Figure C8. Fatigue Resistance Curves for Samples Containing 40% RAP + 0.5% Binder

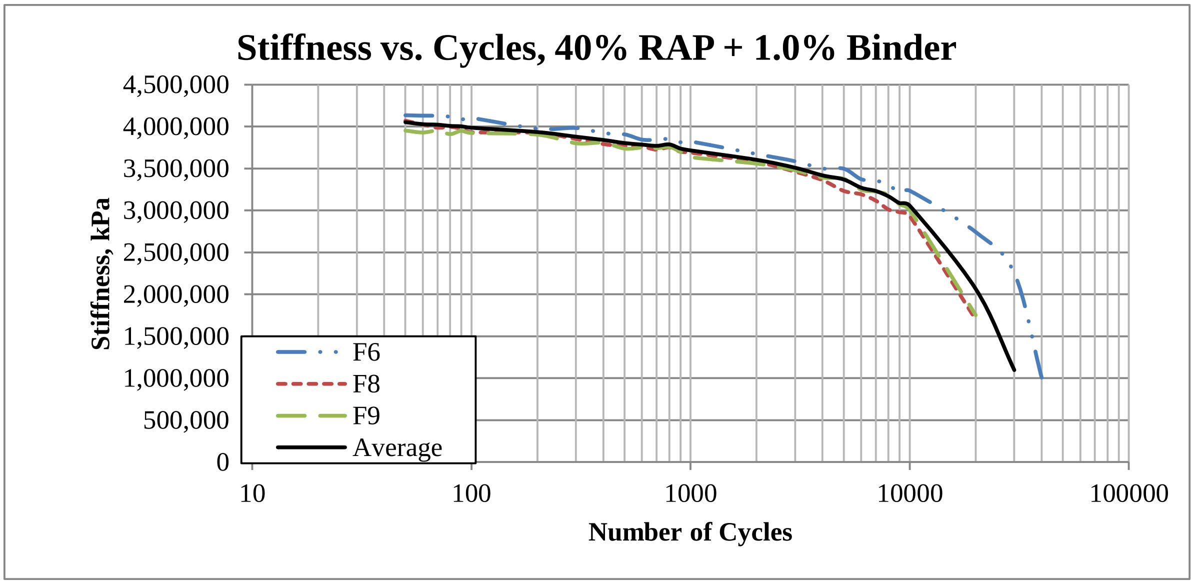

Figure C9. Fatigue Resistance Curves for Samples Containing 40% RAP + 1.0% Binder

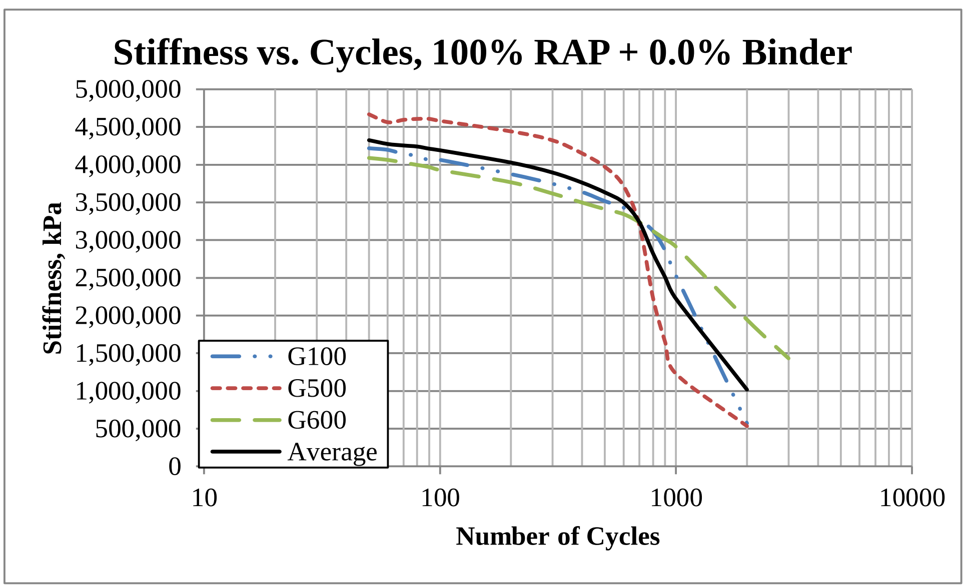

Figure C10. Fatigue Resistance Curves for Samples Containing 100% RAP + 0.0% Binder

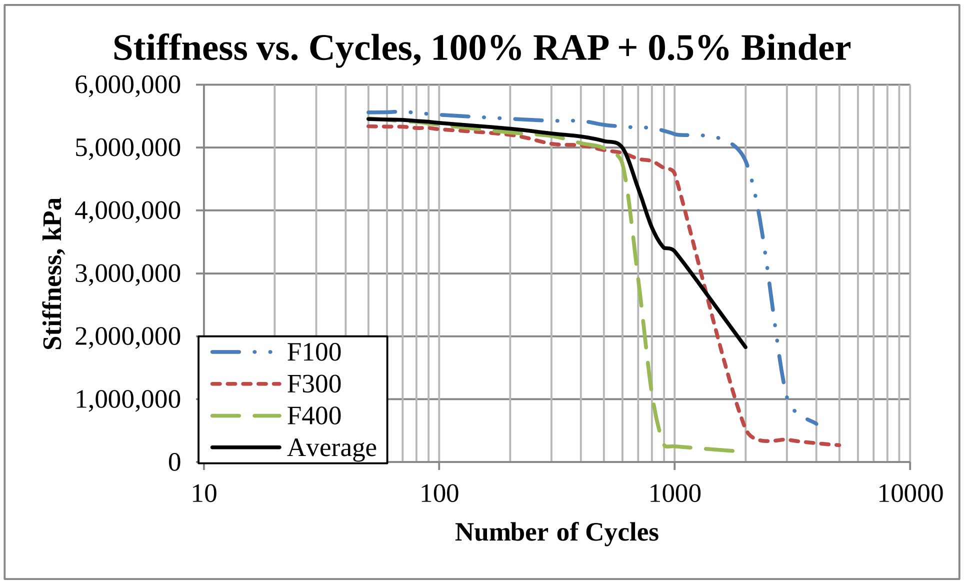

Figure C11. Fatigue Resistance Curves for Samples Containing 100% RAP + 0.5% Binder

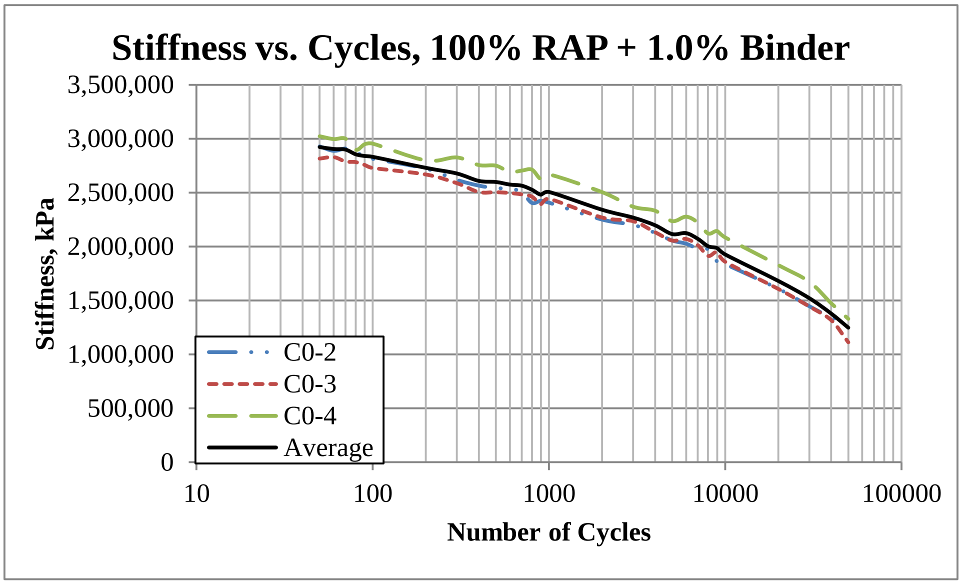

Figure C12. Fatigue Resistance Curves for Samples Containing 100% RAP + 1.0% Binder

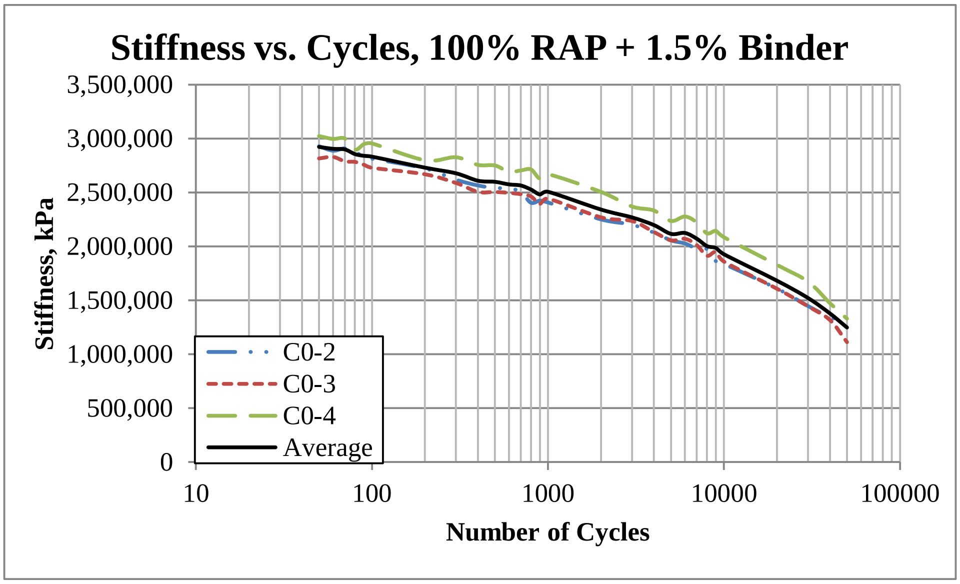

Figure C13. Fatigue Resistance Curves for Samples Containing 100% RAP + 1.5% Binder

APPENDIX D – VOLUMETRIC PROPERTY TEST RESULTS

Table D1. Volumetric Properties for 0% RAP + 0.0% Binder Samples

Lab Data			
Specimen	0.0-1	0.0-2	0.0-3
Weight Air, g	5043.2	5056.7	5064.9
Weight SSD, g	5048.1	5062.5	5068.8
Weight Water, g	3091.1	3098.4	3102.4
Difference	1957.0	1964.1	1966.4
BSG (core)	2.577	2.575	2.576
G_{mm}	2.686	2.686	2.686
Density	95.9	95.9	95.9
VTM (core), %	4.1	4.1	4.1
Height @ N_{des}, mm	113.3	113.2	114.0
Height @ N_I, mm	122.8	122.8	123.7
Desnity @ N_I, mm	88.5	88.4	88.4
Average Density N_I		88.4	
Avg. VTM, %		4.1	
G_{mb}		2.576	
VMA		17.2	
VFA		76.1	

P_b, %	5.629	
P_s, %	94.371	
G_b	1.03	
G_{se}	2.971	
Correction Factor	0.036	**from producer**
G_{sb} (aggregate)	2.935	

G_{mb} (estimate)	2.317	2.325	2.312
W_m, g	5043.2	5056.7	5064.9
V_{mx}, (cm3)	2177.1	2175.1	2190.5
Gmb (measured)	2.577	2.575	2.576
Correction	1.112	1.107	1.114

Table D2. Volumetric Properties for 0% RAP + 0.5% Binder Samples

Lab Data			
Specimen	0.5-1	0.5-2	0.5-3
Weight Air, g	5030.3	5036.7	5033.0
Weight SSD, g	5033.9	5039.9	5036.9
Weight Water, g	3103.4	3108.9	3106.1
Difference	1930.5	1931.0	1930.8
BSG (core)	2.606	2.608	2.607
G_{mm}	2.668	2.668	2.668
Density	97.7	97.8	97.7
VTM (core), %	2.3	2.2	2.3
Height @ N_{des}, mm	111.4	111.3	111.3
Height @ N_I, mm	121.2	121.0	120.7
Desnity @ N_I, mm	89.8	89.9	90.1
Average Density N_I		89.9	
Avg. VTM, %		2.3	
G_{mb}		2.607	
VMA		16.8	
VFA		86.4	

P_b, %	6.129	
P_s, %	93.871	
G_b	1.03	
G_{se}	2.977	
Correction Factor	0.036	**from producer**
G_{sb} (aggregate)	2.941	

G_{mb} (estimate)	2.350	2.355	2.353
W_m, g	5030.3	5036.7	5033.0
V_{mx}, (cm3)	2140.6	2138.6	2138.6
Gmb (measured)	2.606	2.608	2.607
Correction	1.109	1.108	1.108

Table D3. Volumetric Properties for 0% RAP + 1.0% Binder Samples

Lab Data			
Specimen	0.1-1	0.1-2	0.1-3
Weight Air, g	5023.3	5019.3	5018.2
Weight SSD, g	5026.1	5021.8	5020.6
Weight Water, g	3103.9	3102.3	3101.2
Difference	1922.2	1919.5	1919.4
BSG (core)	2.613	2.615	2.614
G_{mm}	2.648	2.648	2.648
Density	98.7	98.7	98.7
VTM (core), %	1.3	1.3	1.3
Height @ N_{des}, mm	110.6	110.4	110.3
Height @ N_I, mm	120.6	120.2	120.1
Desnity @ N_I, mm	90.5	90.7	90.7
Average Density N_I		90.6	`
Avg. VTM, %		1.3	
G_{mb}		2.614	
VMA		17.9	
VFA		92.9	

P_b, %	6.629	
P_s, %	93.371	
G_b	1.03	
G_{se}	3.008	
Correction Factor	0.036	**from producer**
G_{sb} (aggregate)	2.972	

G_{mb} (estimate)	2.364	2.366	2.368
W_m, g	5023.3	5019.3	5018.2
V_{mx}, (cm3)	2125.2	2121.3	2119.4
Gmb (measured)	2.613	2.615	2.614
Correction	1.106	1.105	1.104

Table D4. Height and VTM versus Gyration for all 0% RAP Samples

	0.0-1		0.0-2		0.0-3		0.5-1		0.5-2		0.5-3		0.1-1		0.1-2		0.1-3	
Gyration	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %
1	131.1	17.1	130.9	17.1	132	17.2	129.2	15.8	129.1	15.7	128.6	15.4	129.5	15.7	128.5	15.2	128.6	15.3
2	128.8	15.6	128.8	15.8	129.9	15.8	127	14.3	127.1	14.4	126.6	14.1	126.9	14.0	126.4	13.8	126.5	13.9
3	127	14.4	127	14.6	128	14.6	125.2	13.1	125.3	13.2	124.9	12.9	125.1	12.7	124.5	12.4	124.6	12.6
4	125.5	13.4	125.5	13.5	126.7	13.7	123.9	12.2	123.9	12.2	123.6	12.0	123.5	11.6	123.2	11.5	123.1	11.5
5	124.5	12.7	124.5	12.8	125.4	12.8	122.8	11.4	122.7	11.3	122.4	11.2	122.5	10.9	121.9	10.6	122	10.7
6	123.6	12.1	123.5	12.1	124.6	12.3	121.9	10.7	121.9	10.7	121.5	10.5	121.4	10.1	121	9.9	119.9	9.2
7	122.8	11.5	122.8	11.6	123.7	11.6	121.2	10.2	121	10.1	120.7	9.9	120.6	9.5	120.2	9.3	120.1	9.3
8	122.1	11.0	122.1	11.1	123.1	11.2	120.5	9.7	120.4	9.6	120.1	9.5	119.9	9.0	119.5	8.8	119.5	8.9
9	121.6	10.6	121.5	10.7	122.4	10.7	119.9	9.3	119.8	9.2	119.5	9.0	119.3	8.5	118.9	8.3	118.8	8.3
10	121.1	10.2	121	10.3	121.9	10.3	119.3	8.8	119.3	8.8	119	8.6	118.8	8.1	118.3	7.8	118.4	8.0
11	120.6	9.9	120.5	10.0	121.5	10.0	118.9	8.5	118.9	8.5	118.6	8.3	118.3	7.7	117.9	7.5	118	7.7
12	120.2	9.6	120.1	9.7	121	9.7	118.5	8.2	118.4	8.1	118.2	8.0	117.9	7.4	117.5	7.2	117.6	7.4
13	119.8	9.3	119.8	9.4	120.7	9.4	118.1	7.9	118	7.8	117.8	7.7	117.4	7.0	117.1	6.9	117.2	7.1
14	119.5	9.0	119.4	9.1	120.3	9.1	117.8	7.6	117.7	7.6	117.5	7.5	117.1	6.8	116.8	6.7	116.7	6.7
15	119.2	8.8	119.1	8.9	120	8.9	117.4	7.3	117.4	7.3	117.1	7.1	116.8	6.5	116.4	6.3	116.3	6.4
16	118.9	8.6	118.8	8.7	119.7	8.7	117.2	7.2	117.1	7.1	116.9	7.0	116.4	6.2	116.1	6.1	116	6.1
17	118.6	8.3	118.5	8.4	119.4	8.4	116.9	6.9	116.8	6.8	116.6	6.7	116.2	6.1	115.8	5.9	115.7	5.9
18	118.3	8.1	118.2	8.2	119.1	8.2	116.6	6.7	116.5	6.6	116.3	6.5	115.9	5.8	115.6	5.7	115.4	5.6
19	118.1	8.0	118	8.0	118.9	8.1	116.4	6.5	116.3	6.4	116.1	6.3	115.6	5.6	115.3	5.4	115.2	5.5
20	117.9	7.8	117.8	7.9	118.6	7.8	116.1	6.3	116	6.2	115.9	6.2	115.4	5.4	115.1	5.3	115	5.3
21	117.7	7.6	117.5	7.7	118.4	7.7	116	6.2	115.8	6.0	115.7	6.0	115.2	5.3	114.9	5.1	114.8	5.1
22	117.5	7.5	117.3	7.5	118.2	7.5	115.7	6.0	115.6	5.9	115.5	5.9	115	5.1	114.6	4.9	114.5	4.9
23	117.3	7.3	117.1	7.3	118	7.4	115.5	5.8	115.4	5.7	115.3	5.7	114.7	4.8	114.5	4.8	114.2	4.6
24	117.1	7.2	117	7.3	117.8	7.2	115.4	5.7	115.3	5.6	115.1	5.5	114.5	4.7	114.3	4.6	114	4.5
25	116.9	7.0	116.8	7.1	117.6	7.0	115.2	5.6	115.1	5.5	114.9	5.4	114.4	4.6	114.1	4.5	113.9	4.4
26	116.7	6.9	116.6	6.9	117.5	7.0	115	5.4	114.9	5.3	114.8	5.3	114.2	4.4	113.9	4.3	113.8	4.3
27	116.6	6.8	116.5	6.9	117.3	6.8	114.9	5.3	114.7	5.1	114.6	5.1	114	4.3	113.7	4.1	113.6	4.1
28	116.4	6.6	116.3	6.7	117.1	6.6	114.7	5.1	114.6	5.1	114.4	4.9	113.9	4.2	113.6	4.0	113.5	4.1
29	116.3	6.5	116.1	6.5	117	6.6	114.6	5.1	114.4	4.9	114.3	4.9	113.7	4.0	113.5	3.9	113.4	4.0
30	116.2	6.5	116	6.5	116.8	6.4	114.4	4.9	114.3	4.8	114.2	4.8	113.5	3.8	113.3	3.8	113.2	3.8
31	116	6.3	115.9	6.4	116.7	6.3	114.3	4.8	114.2	4.7	114	4.6	113.4	3.7	113.2	3.7	113	3.6
32	115.9	6.2	115.7	6.2	116.6	6.2	114.2	4.7	114	4.6	113.9	4.5	113.3	3.7	113	3.5	112.8	3.5
33	115.8	6.1	115.6	6.1	116.5	6.2	114	4.6	113.9	4.5	113.8	4.4	113.2	3.6	112.9	3.4	112.7	3.4
34	115.6	6.0	115.5	6.1	116.3	6.0	113.9	4.5	113.8	4.4	113.7	4.4	113	3.4	112.8	3.4	112.6	3.3
35	115.5	5.9	115.4	6.0	116.2	5.9	113.8	4.4	113.7	4.3	113.5	4.2	112.9	3.3	112.7	3.3	112.5	3.2
36	115.4	5.8	115.3	5.9	116.1	5.8	113.7	4.3	113.5	4.1	113.4	4.1	112.8	3.2	112.6	3.2	112.5	3.2
37	115.3	5.7	115.2	5.8	116	5.8	113.6	4.2	113.4	4.0	113.3	4.0	112.7	3.1	112.4	3.0	112.4	3.1
38	115.2	5.6	115	5.6	115.9	5.7	113.4	4.1	113.3	4.0	113.2	3.9	112.6	3.1	112.3	2.9	112.4	3.1
39	115.1	5.6	114.9	5.6	115.8	5.6	113.3	4.0	113.2	3.9	113.1	3.9	112.5	3.0	112.2	2.8	112.3	3.0
40	115	5.5	114.9	5.6	115.7	5.5	113.2	3.9	113.1	3.8	113	3.8	112.4	2.9	112.1	2.7	112.2	2.9
41	114.9	5.4	114.8	5.5	115.6	5.4	113.1	3.8	113	3.7	112.9	3.7	112.3	2.8	112.1	2.7	112.1	2.9
42	114.8	5.3	114.7	5.4	115.5	5.4	113.1	3.8	112.9	3.6	112.8	3.6	112.2	2.7	111.9	2.6	112	2.8
43	114.7	5.2	114.6	5.3	115.4	5.3	113	3.7	112.8	3.5	112.8	3.6	112.1	2.6	111.9	2.6	111.9	2.7
44	114.7	5.2	114.5	5.2	115.3	5.2	112.9	3.6	112.8	3.5	112.7	3.5	112	2.5	111.8	2.5	111.9	2.7
45	114.6	5.1	114.4	5.2	115.2	5.1	112.8	3.5	112.6	3.4	112.6	3.4	111.9	2.5	111.7	2.4	111.7	2.5
46	114.5	5.1	114.3	5.1	115.2	5.1	112.7	3.5	112.6	3.4	112.5	3.3	111.8	2.4	111.6	2.3	111.6	2.4
47	114.4	5.0	114.3	5.1	115.1	5.0	112.6	3.4	112.5	3.3	112.4	3.3	111.8	2.4	111.5	2.2	111.6	2.4
48	114.3	4.9	114.2	5.0	115	4.9	112.5	3.3	112.4	3.2	112.4	3.3	111.7	2.3	111.5	2.2	111.5	2.3
49	114.3	4.9	114.1	4.9	114.9	4.9	112.5	3.3	112.3	3.1	112.3	3.2	111.6	2.2	111.4	2.1	111.4	2.2
50	114.2	4.8	114	4.8	114.9	4.9	112.4	3.2	112.2	3.0	112.2	3.1	111.5	2.1	111.3	2.0	111.3	2.2
51	114.1	4.7	114	4.8	114.8	4.8	112.3	3.1	112.2	3.0	112.1	3.0	111.4	2.0	111.2	2.0	111.3	2.2
52	114.1	4.7	113.9	4.7	114.7	4.7	112.2	3.0	112.1	2.9	112.1	3.0	111.4	2.0	111.2	2.0	111.2	2.1
53	114	4.6	113.8	4.7	114.7	4.7	112.2	3.0	112	2.8	112	2.9	111.3	1.9	111.1	1.9	111.1	2.0
54	113.9	4.6	113.8	4.7	114.6	4.6	112.1	2.9	112	2.8	111.9	2.8	111.2	1.8	111	1.8	111.1	2.0
55	113.9	4.6	113.7	4.6	114.5	4.5	112	2.9	111.9	2.8	111.9	2.8	111.2	1.8	111	1.8	111	1.9
56	113.8	4.5	113.6	4.5	114.5	4.5	112	2.9	111.8	2.7	111.8	2.7	111.1	1.8	110.9	1.7	110.9	1.8
57	113.8	4.5	113.6	4.5	114.4	4.4	111.9	2.8	111.8	2.7	111.7	2.6	111.1	1.8	110.8	1.6	110.9	1.8
58	113.7	4.4	113.5	4.4	114.3	4.4	111.8	2.7	111.7	2.6	111.7	2.6	111	1.7	110.8	1.6	110.8	1.7
59	113.6	4.3	113.5	4.4	114.3	4.4	111.8	2.7	111.6	2.5	111.6	2.6	110.9	1.6	110.7	1.5	110.7	1.6
60	113.6	4.3	113.4	4.3	114.2	4.3	111.7	2.6	111.6	2.5	111.6	2.6	110.9	1.6	110.7	1.5	110.7	1.6
61	113.5	4.2	113.4	4.3	114.2	4.3	111.7	2.6	111.5	2.4	111.5	2.5	110.8	1.5	110.6	1.4	110.6	1.5
62	113.5	4.2	113.3	4.2	114.1	4.2	111.6	2.5	111.4	2.3	111.4	2.4	110.8	1.5	110.6	1.4	110.5	1.4
63	113.4	4.1	113.3	4.2	114.1	4.2	111.6	2.5	111.4	2.3	111.4	2.4	110.7	1.4	110.5	1.3	110.5	1.4
64	113.4	4.1	113.2	4.1	114	4.1	111.5	2.4	111.3	2.2	111.3	2.3	110.7	1.4	110.4	1.3	110.4	1.4
65	113.3	4.1	113.2	4.1	114	4.1	111.4	2.3	111.3	2.2	111.3	2.3	110.6	1.3	110.4	1.3	110.3	1.3

Table D5. Volumetric Properties for 20% RAP + 0.0% Binder Samples

Lab Data			
Specimen	20.0-1	20.0-2	20.0-3
Weight Air, g	5009.0	5007.5	5005.7
Weight SSD, g	5013.9	5012.1	5012.3
Weight Water, g	3036.3	3036.6	3037.9
Difference	1977.6	1975.5	1974.4
BSG (core)	2.533	2.535	2.535
G_{mm}	2.614	2.614	2.614
Density	96.9	97.0	97.0
VTM (core), %	3.1	3.0	3.0
Height @ N_{des}, mm	114.0	113.9	114.1
Height @ N_I, mm	123.6	123.6	123.8
Desnity @ N_I, mm	89.4	89.4	89.4
Average Density N_I		89.4	
Avg. VTM, %		3.0	
G_{mb}		2.534	
VMA		16.1	
VFA		81.0	

P_b, %	5.539	
P_s, %	94.461	
G_b	1.03	
G_{se}	2.873	
Correction Factor	0.021	**from producer**
G_{sb} (aggregate)	2.852	

G_{mb} (estimate)	2.287	2.288	2.283
W_m, g	5009.0	5007.5	5005.7
V_{mx}, (cm3)	2190.5	2188.6	2192.4
Gmb (measured)	2.533	2.535	2.535
Correction	1.108	1.108	1.110

Table D6. Volumetric Properties for 20% RAP + 0.5% Binder Samples

Lab Data			
Specimen	20.5-1	20.5-2	20.5-3
Weight Air, g	5016.0	5017.8	5016.9
Weight SSD, g	5019.3	5021.4	5020.8
Weight Water, g	3067.3	3071.0	3067.7
Difference	1952.0	1950.4	1953.1
BSG (core)	2.570	2.573	2.569
G_{mm}	2.595	2.595	2.595
Density	99.0	99.1	99.0
VTM (core), %	1.0	0.9	1.0
Height @ N_{des}, mm	112.3	112.5	112.4
Height @ N_I, mm	121.5	122.1	121.5
Desnity @ N_I, mm	91.5	91.3	91.6
Average Density N_I		91.5	
Avg. VTM, %		0.9	
G_{mb}		2.570	
VMA		16.1	
VFA		94.1	

P_b, %	6.039	
P_s, %	93.961	
G_b	1.03	
G_{se}	2.901	
Correction Factor	0.021	**from producer**
G_{sb} (aggregate)	2.880	

G_{mb} (estimate)	2.325	2.321	2.323
W_m, g	5016.0	5017.8	5016.9
V_{mx}, (cm3)	2157.8	2161.7	2159.8
Gmb (measured)	2.570	2.573	2.569
Correction	1.105	1.108	1.106

Table D7. Volumetric Properties for 20% RAP + 1.0% Binder Samples

Lab Data			
Specimen	20.1-1	20.1-2	20.1-3
Weight Air, g	5021.1	5024.7	5028.3
Weight SSD, g	5024.1	5026.9	5030.9
Weight Water, g	3068.0	3065.9	3072.0
Difference	1956.1	1961.0	1958.9
BSG (core)	2.567	2.562	2.567
G_{mm}	2.576	2.576	2.576
Density	99.6	99.5	99.6
VTM (core), %	0.4	0.5	0.4
Height @ N_{des}, mm	112.5	112.5	112.7
Height @ N_I, mm	121.5	121.5	121.5
Desnity @ N_I, mm	92.3	92.1	92.4
Average Density N_I		92.3	`
Avg. VTM, %		0.4	
G_{mb}		2.565	
VMA		17.8	
VFA		97.7	

P_b, %	6.539	
P_s, %	93.461	
G_b	1.03	
G_{se}	2.936	
Correction Factor	0.021	**from producer**
G_{sb} (aggregate)	2.915	

G_{mb} (estimate)	2.323	2.324	2.322
W_m, g	5021.1	5024.7	5028.3
V_{mx}, (cm3)	2161.7	2161.7	2165.5
Gmb (measured)	2.567	2.562	2.567
Correction	1.105	1.102	1.105

Table D8. Height and VTM versus Gyration for all 20% RAP Samples

	20.0-1-1		20.0-1-2		20.0-1-3		20.5-1		20.5-2		20.5-3		20.1-1		20.1-2		20.1-3	
Gyration	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %
1	132.1	16.4	132.4	16.6	132.2	16.3	129.8	14.3	131.1	14.9	129.8	14.3	129.7	13.6	130.2	14.1	130.5	13.9
2	129.8	14.9	129.8	14.9	130	14.9	127.7	12.9	128.7	13.3	127.6	12.8	127.6	12.1	127.7	12.4	127.9	12.2
3	127.9	13.6	127.9	13.6	128.1	13.6	125.8	11.6	126.6	11.9	125.8	11.6	125.7	10.8	126	11.2	125.9	10.8
4	126.4	12.6	126.5	12.7	126.6	12.6	124.3	10.5	125.3	11.0	124.4	10.6	124.2	9.7	124.5	10.1	124.6	9.9
5	125.3	11.8	125.3	11.9	125.5	11.8	123.2	9.7	123.9	10.0	123.2	9.7	123.2	9.0	123.4	9.3	123.3	8.9
6	124.3	11.1	124.4	11.2	124.7	11.3	122.3	9.1	123	9.3	122.3	9.0	122.2	8.3	122.3	8.5	122.4	8.3
7	123.6	10.6	123.6	10.6	123.8	10.6	121.5	8.5	122.1	8.7	121.5	8.4	121.5	7.7	121.5	7.9	121.5	7.6
8	122.9	10.1	122.9	10.1	123.2	10.2	120.8	7.9	121.5	8.2	120.7	7.8	120.8	7.2	120.8	7.4	120.9	7.1
9	122.3	9.7	122.4	9.8	122.5	9.7	120.2	7.5	120.9	7.7	120.2	7.4	120.2	6.7	120.2	6.9	120.3	6.6
10	121.8	9.3	121.8	9.3	122.1	9.4	119.7	7.1	120.2	7.2	119.6	7.0	119.7	6.3	119.6	6.4	119.7	6.2
11	121.4	9.0	121.4	9.0	121.6	9.0	119.2	6.7	119.8	6.9	119.2	6.7	119.2	6.0	119.1	6.0	119.3	5.9
12	121	8.7	120.9	8.6	121.2	8.7	118.8	6.4	119.3	6.5	118.8	6.3	118.8	5.6	118.7	5.7	118.8	5.5
13	120.6	8.4	120.6	8.4	120.8	8.4	118.4	6.1	118.9	6.2	118.4	6.0	118.4	5.3	118.3	5.4	118.4	5.2
14	120.2	8.1	120.2	8.1	120.5	8.2	118	5.8	118.5	5.9	118	5.7	118	5.0	118	5.2	118.1	4.9
15	119.9	7.9	119.9	7.9	120.1	7.9	117.7	5.5	118.2	5.6	117.7	5.5	117.7	4.8	117.6	4.8	117.7	4.6
16	119.6	7.6	119.6	7.7	119.9	7.7	117.4	5.3	117.9	5.4	117.4	5.2	117.4	4.5	117.3	4.6	117.5	4.4
17	119.3	7.4	119.3	7.4	119.6	7.5	117.1	5.0	117.6	5.2	117.1	5.0	117.1	4.3	117.1	4.4	117.2	4.2
18	119.1	7.3	119.1	7.3	119.3	7.2	116.9	4.9	117.3	4.9	116.8	4.7	116.9	4.1	116.8	4.2	116.9	3.9
19	118.8	7.0	118.8	7.0	119.1	7.1	116.6	4.6	117.1	4.8	116.6	4.6	116.6	3.9	116.5	3.9	116.7	3.8
20	118.6	6.9	118.6	6.9	118.8	6.8	116.4	4.5	116.9	4.6	116.4	4.4	116.4	3.7	116.3	3.8	116.4	3.5
21	118.4	6.7	118.4	6.7	118.6	6.7	116.2	4.3	116.6	4.3	116.2	4.3	116.2	3.5	116.1	3.6	116.2	3.4
22	118.2	6.5	118.1	6.5	118.4	6.5	116	4.1	116.4	4.2	116	4.1	116	3.4	115.9	3.4	116	3.2
23	118	6.4	118	6.4	118.2	6.4	115.8	4.0	116.2	4.0	115.8	3.9	115.8	3.2	115.7	3.3	115.9	3.1
24	117.8	6.2	117.8	6.2	118	6.2	115.6	3.8	116	3.9	115.6	3.8	115.6	3.0	115.5	3.1	115.7	2.9
25	117.7	6.1	117.6	6.1	117.9	6.1	115.4	3.6	115.9	3.8	115.4	3.6	115.5	2.9	115.4	3.0	115.5	2.8
26	117.5	6.0	117.4	5.9	117.7	6.0	115.3	3.6	115.7	3.6	115.3	3.5	115.3	2.8	115.2	2.9	115.4	2.7
27	117.3	5.8	117.2	5.8	117.5	5.8	115.1	3.4	115.5	3.4	115.1	3.3	115.2	2.7	115.1	2.8	115.2	2.5
28	117.2	5.7	117.1	5.7	117.4	5.7	115	3.3	115.4	3.4	115	3.3	115	2.5	114.9	2.6	115.1	2.4
29	117	5.6	116.9	5.5	117.2	5.6	114.8	3.1	115.2	3.2	114.9	3.2	114.9	2.4	114.8	2.5	115	2.3
30	116.9	5.5	116.8	5.4	117.1	5.5	114.7	3.0	115.1	3.1	114.7	3.0	114.8	2.3	114.7	2.4	114.9	2.3
31	116.7	5.3	116.7	5.4	116.9	5.3	114.6	3.0	115	3.0	114.6	2.9	114.6	2.2	114.5	2.3	114.8	2.2
32	116.6	5.3	116.5	5.2	116.8	5.3	114.5	2.9	114.8	2.8	114.5	2.8	114.5	2.1	114.4	2.2	114.6	2.0
33	116.5	5.2	116.4	5.1	116.7	5.2	114.4	2.8	114.7	2.8	114.4	2.7	114.4	2.0	114.3	2.1	114.5	1.9
34	116.4	5.1	116.3	5.0	116.5	5.0	114.2	2.6	114.6	2.7	114.3	2.7	114.3	1.9	114.2	2.0	114.4	1.8
35	116.3	5.0	116.2	4.9	116.4	4.9	114.2	2.6	114.5	2.6	114.2	2.6	114.2	1.8	114.1	1.9	114.3	1.7
36	116.1	4.9	116.1	4.9	116.3	4.8	114	2.5	114.4	2.5	114.1	2.5	114.1	1.8	114	1.8	114.3	1.7
37	116	4.8	115.9	4.7	116.2	4.8	114	2.5	114.3	2.4	114	2.4	114	1.7	113.9	1.8	114.2	1.7
38	115.9	4.7	115.8	4.6	116.1	4.7	113.9	2.4	114.2	2.3	113.9	2.3	113.9	1.6	113.8	1.7	114.1	1.6
39	115.8	4.6	115.7	4.5	116	4.6	113.8	2.3	114.1	2.2	113.8	2.2	113.8	1.5	113.7	1.6	114	1.5
40	115.7	4.5	115.6	4.5	115.9	4.5	113.7	2.2	114	2.2	113.8	2.2	113.7	1.4	113.7	1.6	113.9	1.4
41	115.6	4.4	115.5	4.4	115.8	4.4	113.6	2.1	113.9	2.1	113.7	2.1	113.7	1.4	113.6	1.5	113.8	1.3
42	115.6	4.4	115.4	4.3	115.7	4.4	113.5	2.0	113.8	2.0	113.6	2.1	113.6	1.3	113.5	1.4	113.8	1.3
43	115.5	4.4	115.3	4.2	115.6	4.3	113.5	2.0	113.8	2.0	113.5	2.0	113.5	1.2	113.4	1.3	113.7	1.2
44	115.4	4.3	115.2	4.1	115.5	4.2	113.4	1.9	113.7	1.9	113.5	2.0	113.4	1.1	113.4	1.3	113.6	1.1
45	115.3	4.2	115.2	4.1	115.4	4.1	113.3	1.9	113.6	1.8	113.4	1.9	113.4	1.1	113.3	1.2	113.6	1.1
46	115.2	4.1	115.1	4.0	115.3	4.0	113.2	1.8	113.5	1.7	113.3	1.8	113.3	1.1	113.2	1.1	113.5	1.1
47	115.1	4.0	115	4.0	115.3	4.0	113.2	1.8	113.5	1.7	113.3	1.8	113.2	1.0	113.2	1.1	113.4	1.0
48	115	3.9	114.9	3.9	115.2	3.9	113.1	1.7	113.4	1.6	113.2	1.7	113.2	1.0	113.1	1.1	113.4	1.0
49	115	3.9	114.8	3.8	115.1	3.9	113.1	1.7	113.3	1.6	113.2	1.7	113.1	0.9	113.1	1.1	113.3	0.9
50	114.9	3.9	114.8	3.8	115	3.8	113	1.6	113.3	1.6	113.1	1.6	113.1	0.9	113	1.0	113.3	0.9
51	114.8	3.8	114.7	3.7	115	3.8	112.9	1.5	113.2	1.5	113.1	1.6	113	0.8	113	1.0	113.2	0.8
52	114.8	3.8	114.6	3.6	114.9	3.7	112.9	1.5	113.2	1.5	113	1.5	113	0.8	112.9	0.9	113.2	0.8
53	114.7	3.7	114.6	3.6	114.8	3.6	112.8	1.4	113.1	1.4	112.9	1.5	112.9	0.7	112.9	0.9	113.1	0.7
54	114.6	3.6	114.5	3.5	114.7	3.5	112.8	1.4	113	1.3	112.9	1.5	112.9	0.7	112.9	0.9	113.1	0.7
55	114.6	3.6	114.4	3.5	114.7	3.5	112.7	1.3	113	1.3	112.8	1.4	112.8	0.6	112.8	0.8	113	0.6
56	114.5	3.5	114.4	3.5	114.6	3.4	112.7	1.3	112.9	1.2	112.8	1.4	112.8	0.6	112.8	0.8	113	0.6
57	114.4	3.4	114.3	3.4	114.5	3.3	112.6	1.2	112.9	1.2	112.8	1.4	112.7	0.5	112.8	0.8	113	0.6
58	114.4	3.4	114.3	3.4	114.5	3.3	112.6	1.2	112.8	1.1	112.7	1.3	112.7	0.5	112.7	0.7	112.9	0.5
59	114.3	3.4	114.2	3.3	114.4	3.3	112.5	1.2	112.8	1.1	112.7	1.3	112.7	0.5	112.7	0.7	112.9	0.5
60	114.3	3.4	114.1	3.2	114.4	3.3	112.5	1.2	112.7	1.0	112.6	1.2	112.6	0.4	112.7	0.7	112.9	0.5
61	114.2	3.3	114.1	3.2	114.3	3.2	112.4	1.1	112.7	1.0	112.6	1.2	112.6	0.4	112.6	0.6	112.8	0.4
62	114.2	3.3	114	3.1	114.2	3.1	112.4	1.1	112.7	1.0	112.5	1.1	112.6	0.4	112.6	0.6	112.8	0.4
63	114.1	3.2	114	3.1	114.2	3.1	112.4	1.1	112.6	0.9	112.5	1.1	112.5	0.4	112.6	0.6	112.8	0.4
64	114.1	3.2	113.9	3.0	114.1	3.0	112.3	1.0	112.6	0.9	112.5	1.1	112.5	0.4	112.6	0.6	112.7	0.4
65	114	3.1	113.9	3.0	114.1	3.0	112.3	1.0	112.5	0.9	112.4	1.0	112.5	0.4	112.5	0.5	112.7	0.4

Table D9. Volumetric Properties for 40% RAP + 0.0% Binder Samples

Lab Data			
Specimen	40.0-1	40.0-2	40.0-3
Weight Air, g	5026.1	5035.0	5037.2
Weight SSD, g	5028.5	5037.6	5040.2
Weight Water, g	3061.5	3064.5	3065.4
Difference	1967.0	1973.1	1974.8
BSG (core)	2.555	2.552	2.551
G_{mm}	2.603	2.603	2.603
Density	98.2	98.0	98.0
VTM (core), %	1.8	2.0	2.0
Height @ N_{des}, mm	113.1	113.7	114.0
Height @ N_I, mm	122.3	123.1	123.2
Desnity @ N_I, mm	90.8	90.5	90.7
Average Density N_I		90.7	
Avg. VTM, %		1.9	
G_{mb}		2.553	
VMA		16.2	
VFA		88.0	

P_b, %	5.994	
P_s, %	94.006	
G_b	1.03	
G_{se}	2.884	
Correction Factor	0.021	**from producer**
G_{sb} (aggregate)	2.863	

G_{mb} (estimate)	2.313	2.305	2.300
W_m, g	5026.1	5035.0	5037.2
V_{mx}, (cm3)	2173.2	2184.7	2190.5
Gmb (measured)	2.555	2.552	2.551
Correction	1.105	1.107	1.109

Table D10. Volumetric Properties for 40% RAP + 0.5% Binder Samples

Lab Data			
Specimen	40.5-1	40.5-2	40.5-3
Weight Air, g	5041.7	5039.8	5041.9
Weight SSD, g	5043.1	5041.7	5044.5
Weight Water, g	3080.4	3079.1	3079.3
Difference	1962.7	1962.6	1965.2
BSG (core)	2.569	2.568	2.566
G_{mm}	2.584	2.584	2.584
Density	99.4	99.4	99.3
VTM (core), %	0.6	0.6	0.7
Height @ N_{des}, mm	112.8	112.8	113.1
Height @ N_I, mm	120.9	120.6	120.6
Desnity @ N_I, mm	92.7	93.0	93.1
Average Density N_I		92.9	
Avg. VTM, %		0.6	
G_{mb}		2.567	
VMA		17.0	
VFA		96.2	

P_b, %	6.494	
P_s, %	93.506	
G_b	1.03	
G_{se}	2.912	
Correction Factor	0.021	**from producer**
G_{sb} (aggregate)	2.891	

G_{mb} (estimate)	2.326	2.325	2.320
W_m, g	5041.7	5039.8	5041.9
V_{mx}, (cm3)	2167.5	2167.5	2173.2
Gmb (measured)	2.569	2.568	2.566
Correction	1.104	1.104	1.106

Table D11. Volumetric Properties for 40% RAP + 1.0% Binder Samples

Lab Data			
Specimen	40.1-1	40.1-2	40.1-3
Weight Air, g	5046.4	5043.3	5050.8
Weight SSD, g	5048.7	5046.4	5053.5
Weight Water, g	3077.9	3078.4	3079.6
Difference	1970.8	1968.0	1973.9
BSG (core)	2.561	2.563	2.559
G_{mm}	2.565	2.565	2.565
Density	99.8	99.9	99.8
VTM (core), %	0.2	0.1	0.2
Height @ N_{des}, mm	113.4	113.2	113.6
Height @ N_I, mm	120.4	120.3	120.9
Desnity @ N_I, mm	94.0	94.0	93.7
Average Density N_I		93.9	`
Avg. VTM, %		0.1	
G_{mb}		2.561	
VMA		18.3	
VFA		99.3	

P_b, %	6.994	
P_s, %	93.006	
G_b	1.03	
G_{se}	2.935	
Correction Factor	0.021	**from producer**
G_{sb} (aggregate)	2.914	

G_{mb} (estimate)	2.316	2.319	2.314
W_m, g	5046.4	5043.3	5050.8
V_{mx}, (cm3)	2179.0	2175.1	2182.8
Gmb (measured)	2.561	2.563	2.559
Correction	1.106	1.105	1.106

Table D12. Height and VTM versus Gyration for all 40% RAP Samples

	40.0-1-1		40.0-1-2		40.0-1-3		40.5-1		40.5-2		40.5-3		40.1-1		40.1-2		40.1-3	
Gyration	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %
1	130.3	14.8	131.5	15.2	131.9	15.3	128.9	13.0	128.8	13.0	128.6	12.7	129.1	12.3	128.6	12.1	129.3	12.4
2	128	13.3	129.4	13.9	129.3	13.6	126.8	11.6	126.4	11.3	126.4	11.2	126.6	10.6	126.4	10.5	127.1	10.8
3	126.2	12.0	127.4	12.5	127.4	12.3	125	10.3	124.6	10.0	124.6	9.9	124.7	9.2	124.5	9.2	125.2	9.5
4	125	11.2	126.1	11.6	126.1	11.4	123.6	9.3	123.4	9.2	123.4	9.0	123.4	8.3	123.2	8.2	123.9	8.5
5	123.8	10.3	124.9	10.8	125	10.6	122.6	8.5	122.2	8.3	122.2	8.1	122.2	7.4	122	7.3	122.6	7.6
6	123	9.7	124	10.1	124	9.9	121.6	7.8	121.4	7.7	121.4	7.5	121.3	6.7	121.1	6.6	121.8	7.0
7	122.3	9.2	123.1	9.5	123.2	9.3	120.9	7.3	120.6	7.0	120.6	6.9	120.4	6.0	120.3	6.0	120.9	6.3
8	121.6	8.7	122.5	9.0	122.5	8.8	120.3	6.8	120	6.6	119.9	6.3	119.8	5.5	119.6	5.4	120.3	5.8
9	121	8.2	122	8.6	122	8.4	119.7	6.3	119.5	6.2	119.3	5.9	119.2	5.0	119.1	5.0	119.7	5.3
10	120.5	7.9	121.4	8.2	121.5	8.1	119.2	5.9	118.9	5.7	118.9	5.6	118.7	4.6	118.5	4.6	119.1	4.8
11	120.1	7.6	121	7.9	121	7.7	118.7	5.5	118.5	5.4	118.5	5.2	118.3	4.3	118.1	4.2	118.8	4.6
12	119.7	7.2	120.5	7.5	120.6	7.4	118.4	5.3	118.1	5.1	118	4.8	117.9	4.0	117.7	3.9	118.3	4.2
13	119.3	6.9	120.1	7.2	120.2	7.1	118	5.0	117.8	4.8	117.7	4.6	117.5	3.7	117.3	3.6	118	4.0
14	119	6.7	119.8	7.0	119.9	6.8	117.7	4.7	117.4	4.5	117.4	4.3	117.2	3.4	117	3.3	117.7	3.7
15	118.7	6.5	119.4	6.6	119.6	6.6	117.4	4.5	117.1	4.3	117.1	4.1	116.9	3.2	116.7	3.1	117.3	3.4
16	118.4	6.2	119.2	6.5	119.3	6.4	117.1	4.2	116.9	4.1	116.8	3.9	116.7	3.0	116.5	2.9	117.1	3.2
17	118.1	6.0	118.9	6.3	119	6.1	116.9	4.1	116.6	3.9	116.6	3.7	116.4	2.7	116.2	2.7	116.8	3.0
18	117.9	5.8	118.6	6.0	118.7	5.9	116.6	3.8	116.4	3.7	116.4	3.5	116.2	2.6	116	2.5	116.6	2.8
19	117.6	5.6	118.4	5.9	118.5	5.7	116.4	3.7	116.2	3.5	116.1	3.3	116	2.4	115.8	2.3	116.4	2.6
20	117.4	5.4	118.1	5.6	118.3	5.6	116.2	3.5	116	3.4	116	3.2	115.8	2.2	115.6	2.2	116.2	2.5
21	117.2	5.3	117.9	5.5	118.1	5.4	116	3.3	115.8	3.2	115.8	3.0	115.7	2.2	115.5	2.1	116	2.3
22	117	5.1	117.7	5.3	117.9	5.2	115.8	3.2	115.6	3.0	115.6	2.9	115.5	2.0	115.3	1.9	115.9	2.2
23	116.8	4.9	117.5	5.1	117.7	5.1	115.6	3.0	115.5	2.9	115.5	2.8	115.3	1.8	115.1	1.7	115.7	2.1
24	116.6	4.8	117.4	5.1	117.5	4.9	115.5	2.9	115.3	2.8	115.3	2.6	115.2	1.7	115	1.7	115.6	2.0
25	116.5	4.7	117.2	4.9	117.4	4.8	115.4	2.8	115.2	2.7	115.2	2.5	115.1	1.6	114.9	1.6	115.5	1.9
26	116.3	4.5	117	4.7	117.2	4.7	115.2	2.7	115	2.5	115.1	2.4	114.9	1.5	114.8	1.5	115.3	1.7
27	116.2	4.5	116.9	4.6	117	4.5	115.1	2.6	114.9	2.4	115	2.4	114.8	1.4	114.6	1.3	115.2	1.6
28	116	4.3	116.7	4.5	116.9	4.4	114.9	2.4	114.8	2.4	114.9	2.3	114.7	1.3	114.5	1.2	115.1	1.5
29	115.9	4.2	116.6	4.4	116.7	4.3	114.8	2.3	114.7	2.3	114.8	2.2	114.6	1.2	114.5	1.2	115	1.5
30	115.7	4.0	116.4	4.2	116.6	4.2	114.7	2.2	114.6	2.2	114.7	2.1	114.5	1.1	114.4	1.1	114.9	1.4
31	115.6	4.0	116.3	4.2	116.5	4.1	114.6	2.2	114.5	2.1	114.6	2.0	114.4	1.0	114.3	1.1	114.8	1.3
32	115.5	3.9	116.2	4.1	116.4	4.0	114.5	2.1	114.4	2.0	114.5	1.9	114.3	1.0	114.2	1.0	114.7	1.2
33	115.4	3.8	116	3.9	116.2	3.9	114.4	2.0	114.3	1.9	114.4	1.8	114.3	1.0	114.1	0.9	114.6	1.1
34	115.3	3.7	115.9	3.8	116.1	3.8	114.3	1.9	114.2	1.8	114.3	1.8	114.2	0.9	114.1	0.9	114.6	1.1
35	115.1	3.5	115.8	3.7	116	3.7	114.2	1.8	114.1	1.8	114.3	1.8	114.1	0.8	114	0.8	114.5	1.0
36	115	3.5	115.7	3.7	115.9	3.6	114.2	1.8	114	1.7	114.2	1.7	114.1	0.8	113.9	0.7	114.4	0.9
37	114.9	3.4	115.6	3.6	115.8	3.5	114.1	1.7	114	1.7	114.1	1.6	114	0.7	113.9	0.7	114.4	0.9
38	114.8	3.3	115.5	3.5	115.7	3.4	114	1.6	113.9	1.6	114	1.5	114	0.7	113.9	0.7	114.3	0.9
39	114.7	3.2	115.4	3.4	115.6	3.4	113.9	1.5	113.8	1.5	114	1.5	113.9	0.6	113.8	0.6	114.3	0.9
40	114.6	3.1	115.3	3.3	115.5	3.3	113.9	1.5	113.8	1.5	113.9	1.4	113.9	0.6	113.8	0.6	114.2	0.8
41	114.6	3.1	115.2	3.2	115.4	3.2	113.8	1.5	113.7	1.4	113.9	1.4	113.9	0.6	113.7	0.5	114.2	0.8
42	114.5	3.0	115.1	3.2	115.3	3.1	113.7	1.4	113.6	1.3	113.8	1.3	113.8	0.5	113.7	0.5	114.1	0.7
43	114.4	3.0	115.1	3.2	115.3	3.1	113.7	1.4	113.6	1.3	113.8	1.3	113.8	0.5	113.7	0.5	114.1	0.7
44	114.3	2.9	115	3.1	115.2	3.0	113.6	1.3	113.5	1.2	113.7	1.2	113.8	0.5	113.6	0.4	114	0.6
45	114.2	2.8	114.9	3.0	115.1	2.9	113.6	1.3	113.5	1.2	113.7	1.2	113.7	0.4	113.6	0.4	114	0.6
46	114.2	2.8	114.8	2.9	115	2.9	113.5	1.2	113.4	1.1	113.6	1.1	113.7	0.4	113.6	0.4	114	0.6
47	114.1	2.7	114.7	2.8	115	2.9	113.4	1.1	113.4	1.1	113.6	1.1	113.7	0.4	113.5	0.4	113.9	0.5
48	114	2.6	114.7	2.8	114.9	2.8	113.4	1.1	113.3	1.1	113.6	1.1	113.7	0.4	113.5	0.4	113.9	0.5
49	114	2.6	114.6	2.7	114.8	2.7	113.3	1.0	113.3	1.1	113.5	1.1	113.7	0.4	113.5	0.4	113.9	0.5
50	113.9	2.5	114.5	2.7	114.7	2.6	113.3	1.0	113.2	1.0	113.5	1.1	113.6	0.3	113.5	0.4	113.9	0.5
51	113.8	2.4	114.5	2.7	114.7	2.6	113.2	0.9	113.2	1.0	113.4	1.0	113.6	0.3	113.5	0.4	113.8	0.4
52	113.8	2.4	114.4	2.6	114.6	2.5	113.2	0.9	113.2	1.0	113.4	1.0	113.6	0.3	113.4	0.3	113.8	0.4
53	113.7	2.4	114.3	2.5	114.6	2.5	113.2	0.9	113.1	0.9	113.4	1.0	113.6	0.3	113.4	0.3	113.8	0.4
54	113.7	2.4	114.3	2.5	114.5	2.4	113.1	0.9	113.1	0.9	113.4	1.0	113.6	0.3	113.4	0.3	113.8	0.4
55	113.6	2.3	114.2	2.4	114.5	2.4	113.1	0.9	113.1	0.9	113.3	0.9	113.6	0.3	113.4	0.3	113.8	0.4
56	113.5	2.2	114.2	2.4	114.4	2.4	113	0.8	113	0.8	113.3	0.9	113.5	0.3	113.4	0.3	113.7	0.3
57	113.5	2.2	114.1	2.3	114.3	2.3	113	0.8	113	0.8	113.3	0.9	113.5	0.3	113.3	0.2	113.7	0.3
58	113.4	2.1	114.1	2.3	114.3	2.3	113	0.8	113	0.8	113.3	0.9	113.5	0.3	113.3	0.2	113.7	0.3
59	113.4	2.1	114	2.2	114.2	2.2	112.9	0.7	113	0.8	113.2	0.8	113.5	0.3	113.3	0.2	113.7	0.3
60	113.3	2.0	114	2.2	114.2	2.2	112.9	0.7	112.9	0.7	113.2	0.8	113.5	0.3	113.3	0.2	113.7	0.3
61	113.3	2.0	113.9	2.1	114.1	2.1	112.9	0.7	112.9	0.7	113.2	0.8	113.5	0.3	113.3	0.2	113.7	0.3
62	113.2	1.9	113.9	2.1	114.1	2.1	112.8	0.6	112.9	0.7	113.2	0.8	113.5	0.3	113.3	0.2	113.6	0.2
63	113.2	1.9	113.9	2.1	114.1	2.1	112.8	0.6	112.9	0.7	113.2	0.8	113.5	0.3	113.3	0.2	113.6	0.2
64	113.2	1.9	113.8	2.1	114	2.0	112.8	0.6	112.9	0.7	113.1	0.7	113.4	0.2	113.3	0.2	113.6	0.2
65	113.1	1.8	113.7	2.0	114	2.0	112.8	0.6	112.8	0.6	113.1	0.7	113.4	0.2	113.2	0.1	113.6	0.2

Table D13. Volumetric Properties for 100% RAP + 0.0% Binder Samples

Lab Data			
Specimen	0.0-1	0.0-2	0.0-3
Weight Air, g	4944.3	4939.5	4952.8
Weight SSD, g	4962.5	4957.0	4969.4
Weight Water, g	2971.0	2965.3	2968.7
Difference	1991.5	1991.7	2000.7
BSG (core)	2.483	2.480	2.476
G_{mm}	2.626	2.626	2.626
Density	94.5	94.4	94.3
VTM (core), %	5.5	5.6	5.7
Height @ N_{des}, mm	115.1	114.5	115.2
Height @ N_I, mm	125.0	125.7	125.0
Desnity @ N_I, mm	87.1	86.0	86.9
Average Density N_I		86.7	
Avg. VTM, %		5.6	
G_{mb}		2.479	
VMA		16.8	
VFA		66.7	

G_{se}	2.902	
P_s	94.230	
P_b	5.770	
G_b	1.028	
G_{sb}	2.817	Illinois
G_{sb}	2.807	Minnesota

G_{mb} (estimate)	2.236	2.245	2.237
W_m, g	4944.3	4939.5	4952.8
V_{mx}, (cm3)	2211.6	2200.1	2213.6
Gmb (measured)	2.483	2.480	2.476
Correction	1.111	1.105	1.106

Table D14. Volumetric Properties for 100% RAP + 0.5% Binder Samples

Lab Data			
Specimen	100.5-1	100.5-2	100.5-3
Weight Air, g	5015.5	5015.1	5013.5
Weight SSD, g	5017.9	5018.8	5017.4
Weight Water, g	3073.6	3076.7	3072.7
Difference	1944.3	1942.1	1944.7
BSG (core)	2.580	2.582	2.578
G_{mm}	2.623	2.623	2.623
Density	98.3	98.4	98.3
VTM (core), %	1.7	1.6	1.7
Height @ N_{des}, mm	111.5	111.6	111.6
Height @ N_I, mm	119.4	119.5	119.8
Desnity @ N_I, mm	91.8	91.9	91.6
Average Density N_I		91.8	
Avg. VTM, %		1.6	
G_{mb}		2.580	
VMA		14.5	
VFA		88.7	

G_{se}	2.927	
P_s	93.73	
P_b	6.270	
G_b	1.028	
G_{sb}	2.840	Illinois
G_{sb}	2.830	Minnesota

G_{mb} (estimate)	2.341	2.339	2.338
W_m, g	5015.5	5015.1	5013.5
V_{mx}, (cm3)	2142.5	2144.4	2144.4
Gmb (measured)	2.580	2.582	2.578
Correction	1.102	1.104	1.103

Table D15. Volumetric Properties for 100% RAP + 1.0% Binder Samples

Lab Data			
Specimen	100.1-1	100.1-2	100.1-3
Weight Air, g	5019.3	5017.7	5015.2
Weight SSD, g	5021.9	5020.8	5018.8
Weight Water, g	3081.7	3081.2	3078.5
Difference	1940.2	1939.6	1940.3
BSG (core)	2.587	2.587	2.585
G_{mm}	2.598	2.598	2.598
Density	99.6	99.6	99.5
VTM (core), %	0.4	0.4	0.5
Height @ N_{des}, mm	111.4	111.2	111.4
Height @ N_I, mm	117.3	117.1	117.7
Desnity @ N_I, mm	94.6	94.6	94.2
Average Density N_I		94.4	`
Avg. VTM, %		0.5	
G_{mb}		2.587	
VMA		14.6	
VFA		96.9	

G_{se}	2.922	
P_s	93.23	
P_b	6.770	
G_b	1.028	
G_{sb}	2.835	Illinois
G_{sb}	2.825	Minnesota

G_{mb} (estimate)	2.345	2.348	2.343
W_m, g	5019.3	5017.7	5015.2
V_{mx}, (cm3)	2140.6	2136.7	2140.6
Gmb (measured)	2.587	2.587	2.585
Correction	1.103	1.102	1.103

Table D16. Volumetric Properties for 100% RAP + 1.5% Binder Samples

Lab Data			
Specimen	1001.5-1	100.15-2	100.15-3
Weight Air, g	5035.9	5033.1	5036.4
Weight SSD, g	5038.4	5036.2	5038.2
Weight Water, g	3086.9	3083.4	3087.3
Difference	1951.5	1952.8	1950.9
BSG (core)	2.581	2.577	2.582
G_{mm}	2.586	2.586	2.586
Density	99.8	99.7	99.8
VTM (core), %	0.2	0.3	0.2
Height @ N_{des}, mm	112.8	112.1	113.0
Height @ N_I, mm	116.5	116.4	117.3
Desnity @ N_I, mm	95.9	96.1	95.3
Average Density N_I		95.7	
Avg. VTM, %		0.2	
G_{mb}		2.580	
VMA		15.7	
VFA		98.5	
		15.683	
G_{se}	2.935		
P_s	92.73		
P_b	7.270		
G_b	1.028		
G_{sb}	2.847	Illinois	
G_{sb}	2.837	Minnesota	
G_{mb} (estimate)	2.323	2.337	2.320
W_m, g	5035.9	5033.1	5036.4
V_{mx}, (cm3)	2167.5	2154.0	2171.3
Gmb (measured)	2.581	2.577	2.582
Correction	1.111	1.103	1.113

Table D17. Height and VTM versus Gyration for all 100% RAP + 0.0% and 0.5% Binder

	100.0-1		100.0-2		100.0-3		100.5-1		100.5-2		100.5-3	
Gyration	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %
1	135.3	19.6	134.5	19.6	135.3	19.7	127.9	14.3	127.7	14.0	128.1	14.4
2	132.7	18.0	131.7	17.9	132.4	18.0	125.4	12.6	125.5	12.5	125.9	12.9
3	130.5	16.6	129.8	16.7	130.5	16.8	123.7	11.4	123.7	11.2	124	11.5
4	129.1	15.7	128.1	15.6	128.7	15.6	122.2	10.3	122.4	10.2	122.8	10.7
5	127.7	14.8	126.9	14.8	127.6	14.9	121.1	9.5	121.2	9.3	121.5	9.7
6	126.7	14.1	125.8	14.0	126.5	14.2	120.1	8.7	120.4	8.7	120.7	9.1
7	125.7	13.4	125	13.5	125.7	13.6	119.4	8.2	119.5	8.1	119.8	8.4
8	125	12.9	124.2	12.9	124.9	13.1	118.7	7.6	118.9	7.6	119.2	8.0
9	124.3	12.5	123.6	12.5	124.3	12.6	118.1	7.2	118.4	7.2	118.6	7.5
10	123.8	12.1	123	12.1	123.7	12.2	117.7	6.8	117.8	6.7	118.1	7.1
11	123.3	11.7	122.6	11.8	123.2	11.9	117.2	6.4	117.4	6.4	117.6	6.7
12	122.8	11.4	122.1	11.4	122.8	11.6	116.8	6.1	117	6.1	117.2	6.4
13	122.4	11.1	121.7	11.1	122.4	11.3	116.4	5.8	116.7	5.9	116.8	6.1
14	122	10.8	121.4	10.9	122	11.0	116.1	5.6	116.4	5.6	116.5	5.8
15	121.7	10.6	121	10.6	121.6	10.7	115.8	5.3	116	5.3	116.2	5.6
16	121.4	10.4	120.7	10.4	121.4	10.5	115.5	5.1	115.8	5.1	115.9	5.4
17	121.1	10.1	120.3	10.1	121.1	10.3	115.2	4.8	115.5	4.9	115.6	5.1
18	120.8	9.9	120.1	10.0	120.8	10.1	115	4.6	115.3	4.7	115.4	5.0
19	120.5	9.7	119.8	9.7	120.5	9.9	114.8	4.5	115.1	4.5	115.2	4.8
20	120.3	9.5	119.6	9.6	120.3	9.7	114.6	4.3	114.8	4.3	115	4.6
21	120	9.3	119.4	9.4	120	9.5	114.4	4.1	114.7	4.2	114.8	4.5
22	119.8	9.2	119.1	9.2	119.8	9.3	114.2	4.0	114.5	4.0	114.6	4.3
23	119.6	9.0	118.9	9.1	119.6	9.2	114	3.8	114.3	3.9	114.4	4.1
24	119.4	8.9	118.7	8.9	119.4	9.0	113.9	3.7	114.2	3.8	114.3	4.0
25	119.2	8.7	118.5	8.7	119.2	8.9	113.7	3.6	114	3.6	114.1	3.9
26	119	8.6	118.4	8.7	119.1	8.8	113.6	3.5	113.9	3.5	114	3.8
27	118.9	8.5	118.2	8.5	118.9	8.7	113.5	3.4	113.7	3.4	113.8	3.6
28	118.7	8.3	118	8.4	118.7	8.5	113.4	3.3	113.6	3.3	113.7	3.5
29	118.5	8.2	117.9	8.3	118.6	8.4	113.2	3.1	113.5	3.2	113.6	3.4
30	118.4	8.1	117.7	8.1	118.4	8.3	113.2	3.1	113.4	3.1	113.5	3.4
31	118.2	7.9	117.6	8.0	118.3	8.2	113	3.0	113.3	3.0	113.4	3.3
32	118.1	7.9	117.4	7.9	118.1	8.0	113	3.0	113.2	2.9	113.3	3.2
33	118	7.8	117.3	7.8	118	8.0	112.9	2.9	113.1	2.9	113.2	3.1
34	117.8	7.6	117.2	7.7	117.8	7.8	112.8	2.8	113	2.8	113.1	3.0
35	117.7	7.5	117	7.6	117.7	7.7	112.7	2.7	112.9	2.7	113	2.9
36	117.6	7.5	116.9	7.5	117.6	7.7	112.6	2.6	112.8	2.6	112.9	2.8
37	117.5	7.4	116.8	7.4	117.5	7.6	112.6	2.6	112.8	2.6	112.8	2.8
38	117.3	7.2	116.7	7.3	117.4	7.5	112.5	2.5	112.7	2.5	112.8	2.8
39	117.2	7.2	116.6	7.3	117.3	7.4	112.4	2.4	112.6	2.4	112.7	2.7
40	117.1	7.1	116.5	7.2	117.1	7.3	112.4	2.4	112.6	2.4	112.6	2.6
41	117	7.0	116.3	7.0	117	7.2	112.3	2.4	112.5	2.3	112.6	2.6
42	116.9	6.9	116.2	6.9	116.9	7.1	112.3	2.4	112.4	2.3	112.5	2.5
43	116.8	6.8	116.2	6.9	116.8	7.0	112.2	2.3	112.4	2.3	112.4	2.4
44	116.7	6.8	116	6.8	116.7	6.9	112.2	2.3	112.3	2.2	112.4	2.4
45	116.6	6.7	116	6.8	116.6	6.9	112.1	2.2	112.3	2.2	112.3	2.3
46	116.5	6.6	115.9	6.7	116.5	6.8	112.1	2.2	112.2	2.1	112.3	2.3
47	116.4	6.5	115.8	6.6	116.5	6.8	112	2.1	112.2	2.1	112.2	2.2
48	116.3	6.4	115.7	6.5	116.4	6.7	112	2.1	112.1	2.0	112.2	2.2
49	116.2	6.4	115.6	6.5	116.3	6.6	112	2.1	112.1	2.0	112.2	2.2
50	116.2	6.4	115.5	6.4	116.2	6.5	111.9	2.0	112.1	2.0	112.1	2.2
51	116.1	6.3	115.4	6.3	116.1	6.5	111.9	2.0	112	1.9	112.1	2.2
52	116	6.2	115.3	6.2	116.1	6.5	111.9	2.0	112	1.9	112	2.1
53	115.9	6.1	115.3	6.2	116	6.4	111.8	1.9	111.9	1.8	112	2.1
54	115.8	6.0	115.2	6.1	115.9	6.3	111.8	1.9	111.9	1.8	112	2.1
55	115.8	6.0	115.1	6.1	115.8	6.2	111.8	1.9	111.9	1.8	111.9	2.0
56	115.7	5.9	115	6.0	115.8	6.2	111.7	1.8	111.8	1.7	111.9	2.0
57	115.6	5.9	115	6.0	115.7	6.1	111.7	1.8	111.8	1.7	111.9	2.0
58	115.5	5.8	114.9	5.9	115.6	6.1	111.7	1.8	111.8	1.7	111.8	1.9
59	115.5	5.8	114.8	5.8	115.5	6.0	111.7	1.8	111.8	1.7	111.8	1.9
60	115.4	5.7	114.8	5.8	115.5	6.0	111.6	1.7	111.7	1.6	111.8	1.9
61	115.3	5.6	114.7	5.7	115.4	5.9	111.6	1.7	111.7	1.6	111.7	1.8
62	115.3	5.6	114.6	5.6	115.4	5.9	111.6	1.7	111.7	1.6	111.7	1.8
63	115.2	5.5	114.6	5.6	115.3	5.8	111.6	1.7	111.6	1.6	111.7	1.8
64	115.1	5.5	114.5	5.6	115.2	5.7	111.6	1.7	111.6	1.6	111.7	1.8
65	115.1	5.5	114.5	5.6	115.2	5.7	111.5	1.7	111.6	1.6	111.6	1.7

Table D18. Height and VTM versus Gyration for all 100% RAP + 1.0% and 1.5% Binder

	100.1-1		100.1-2		100.1-3		100.15-1		100.15-2		100.15-3	
Gyration	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %	Height,mm	VTM, %
1	125.2	11.4	124.9	11.3	126	12.0	124.4	9.5	124.5	10.3	125.3	10.0
2	123.1	9.9	122.9	9.9	123.8	10.5	122.2	7.9	122	8.4	123.3	8.5
3	121.4	8.6	121.2	8.6	121.9	9.1	120.4	6.5	120.4	7.2	121.4	7.1
4	119.9	7.5	119.9	7.6	120.7	8.2	119	5.4	119	6.1	120	6.0
5	118.9	6.7	118.7	6.7	119.4	7.2	118	4.6	117.9	5.2	118.9	5.1
6	118	6.0	117.9	6.1	118.5	6.5	117.1	3.9	117	4.5	118.1	4.5
7	117.3	5.4	117.1	5.4	117.7	5.8	116.5	3.4	116.4	4.0	117.3	3.8
8	116.7	4.9	116.5	5.0	117.1	5.4	115.9	2.9	115.8	3.5	116.7	3.3
9	116.2	4.5	116	4.5	116.5	4.9	115.5	2.5	115.3	3.1	116.2	2.9
10	115.7	4.1	115.5	4.1	116	4.5	115.1	2.2	114.9	2.8	115.9	2.7
11	115.3	3.8	115.1	3.8	115.6	4.1	114.8	2.0	114.6	2.5	115.5	2.3
12	114.9	3.5	114.7	3.5	115.2	3.8	114.6	1.8	114.3	2.3	115.2	2.1
13	114.6	3.2	114.4	3.2	114.9	3.5	114.4	1.6	114	2.0	115	1.9
14	114.3	2.9	114.1	3.0	114.6	3.3	114.2	1.4	113.8	1.8	114.8	1.7
15	114.1	2.8	113.9	2.8	114.3	3.0	114.1	1.3	113.6	1.6	114.6	1.6
16	113.9	2.6	113.7	2.6	114.1	2.9	113.9	1.2	113.5	1.6	114.5	1.5
17	113.7	2.4	113.4	2.4	113.9	2.7	113.8	1.1	113.4	1.5	114.3	1.3
18	113.5	2.3	113.3	2.3	113.7	2.5	113.7	1.0	113.2	1.3	114.2	1.2
19	113.3	2.1	113.1	2.1	113.5	2.4	113.6	0.9	113.1	1.2	114.1	1.1
20	113.2	2.0	113	2.0	113.4	2.3	113.5	0.8	113	1.1	114	1.0
21	113	1.8	112.8	1.8	113.2	2.1	113.5	0.8	112.9	1.0	113.9	1.0
22	112.9	1.7	112.7	1.7	113.1	2.0	113.4	0.7	112.9	1.0	113.9	1.0
23	112.8	1.7	112.6	1.7	113	1.9	113.4	0.7	112.8	1.0	113.8	0.9
24	112.7	1.6	112.5	1.6	112.9	1.8	113.3	0.7	112.8	1.0	113.7	0.8
25	112.6	1.5	112.4	1.5	112.8	1.7	113.3	0.7	112.7	0.9	113.7	0.8
26	112.5	1.4	112.3	1.4	112.7	1.7	113.3	0.7	112.6	0.8	113.6	0.7
27	112.4	1.3	112.2	1.3	112.6	1.6	113.2	0.6	112.6	0.8	113.6	0.7
28	112.4	1.3	112.2	1.3	112.5	1.5	113.2	0.6	112.6	0.8	113.5	0.6
29	112.3	1.2	112.1	1.2	112.4	1.4	113.2	0.6	112.5	0.7	113.5	0.6
30	112.2	1.1	112	1.1	112.4	1.4	113.2	0.6	112.5	0.7	113.5	0.6
31	112.1	1.0	112	1.1	112.3	1.3	113.1	0.5	112.5	0.7	113.4	0.5
32	112.1	1.0	111.9	1.0	112.2	1.2	113.1	0.5	112.4	0.6	113.4	0.5
33	112	1.0	111.9	1.0	112.2	1.2	113.1	0.5	112.4	0.6	113.4	0.5
34	112	1.0	111.8	1.0	112.1	1.1	113.1	0.5	112.4	0.6	113.4	0.5
35	111.9	0.9	111.8	1.0	112.1	1.1	113.1	0.5	112.4	0.6	113.3	0.4
36	111.9	0.9	111.7	0.9	112	1.0	113.1	0.5	112.4	0.6	113.3	0.4
37	111.9	0.9	111.7	0.9	112	1.0	113	0.4	112.3	0.5	113.3	0.4
38	111.8	0.8	111.7	0.9	111.9	1.0	113	0.4	112.3	0.5	113.3	0.4
39	111.8	0.8	111.6	0.8	111.9	1.0	113	0.4	112.3	0.5	113.3	0.4
40	111.8	0.8	111.6	0.8	111.9	1.0	113	0.4	112.3	0.5	113.3	0.4
41	111.7	0.7	111.6	0.8	111.8	0.9	113	0.4	112.3	0.5	113.2	0.3
42	111.7	0.7	111.5	0.7	111.8	0.9	113	0.4	112.3	0.5	113.2	0.3
43	111.7	0.7	111.5	0.7	111.8	0.9	113	0.4	112.2	0.4	113.2	0.3
44	111.7	0.7	111.5	0.7	111.7	0.8	113	0.4	112.2	0.4	113.2	0.3
45	111.6	0.6	111.5	0.7	111.7	0.8	113	0.4	112.2	0.4	113.2	0.3
46	111.6	0.6	111.5	0.7	111.7	0.8	112.9	0.3	112.2	0.4	113.2	0.3
47	111.6	0.6	111.4	0.6	111.7	0.8	112.9	0.3	112.2	0.4	113.2	0.3
48	111.6	0.6	111.4	0.6	111.6	0.7	112.9	0.3	112.2	0.4	113.2	0.3
49	111.6	0.6	111.4	0.6	111.6	0.7	112.9	0.3	112.2	0.4	113.1	0.3
50	111.6	0.6	111.4	0.6	111.6	0.7	112.9	0.3	112.2	0.4	113.1	0.3
51	111.5	0.5	111.4	0.6	111.6	0.7	112.9	0.3	112.2	0.4	113.1	0.3
52	111.5	0.5	111.4	0.6	111.6	0.7	112.9	0.3	112.2	0.4	113.1	0.3
53	111.5	0.5	111.4	0.6	111.5	0.6	112.9	0.3	112.2	0.4	113.1	0.3
54	111.5	0.5	111.3	0.5	111.5	0.6	112.9	0.3	112.2	0.4	113.1	0.3
55	111.5	0.5	111.3	0.5	111.5	0.6	112.9	0.3	112.1	0.3	113.1	0.3
56	111.5	0.5	111.3	0.5	111.5	0.6	112.9	0.3	112.1	0.3	113.1	0.3
57	111.5	0.5	111.3	0.5	111.5	0.6	112.9	0.3	112.1	0.3	113.1	0.3
58	111.5	0.5	111.3	0.5	111.5	0.6	112.9	0.3	112.1	0.3	113.1	0.3
59	111.4	0.4	111.3	0.5	111.5	0.6	112.8	0.2	112.1	0.3	113.1	0.3
60	111.4	0.4	111.3	0.5	111.4	0.5	112.8	0.2	112.1	0.3	113.1	0.3
61	111.4	0.4	111.3	0.5	111.4	0.5	112.8	0.2	112.1	0.3	113	0.2
62	111.4	0.4	111.3	0.5	111.4	0.5	112.8	0.2	112.1	0.3	113	0.2
63	111.4	0.4	111.3	0.5	111.4	0.5	112.8	0.2	112.1	0.3	113	0.2
64	111.4	0.4	111.3	0.5	111.4	0.5	112.8	0.2	112.1	0.3	113	0.2
65	111.4	0.4	111.2	0.4	111.4	0.5	112.8	0.2	112.1	0.3	113	0.2