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Evaluation of Warm Mix Asphalt Additives for Use in Modified Asphalt Mixtures

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ABSTRACT

The objective of this research effort is to evaluate the use of warm-mix additives with polymer modified and terminal blend tire rubber asphalt mixtures from Nevada and California. The research completed over two stages: first stage evaluated two different WMA technologies; Sasobit and Advera, and second stage evaluated one additional WMA technology; Evotherm.

The experimental program covered the evaluation of resistance of the mixtures to moisture damage, the performance characteristics of the mixtures, and mechanistic analysis of mixtures in simulated pavements.

In the both stages, the mixture resistance to moisture damage was evaluated using the indirect tensile test and the dynamic modulus at multiple freeze-thaw cycles, and the resistance of the various asphalt mixtures to permanent deformation using the Asphalt Mixture Performance Tester (AMPT). Resistance of the untreated mixes to fatigue cracking using the flexural beam fatigue was only completed for the first stage.

One source of aggregates was sampled in, two different batches, three warm mix asphalt technologies (Advera, Sasobit and Evotherm) and three asphalt binder types (neat, polymer-modified, and terminal blend tire rubber modified asphalt binders) typically used in Nevada and California were evaluated in this study.

This thesis presents the resistance of the first stage mixtures to permanent deformation and fatigue cracking using two warm-mix additives; Advera and Sasobit, and the resistance to moisture damage and permanent deformation of the second stage mixtures with only one warm-mix additive; Evotherm.

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CHAPTER 1 INTRODUCTION

Technologies that appear to allow reduction in the temperatures at which asphalt mixtures are produced and placed are being investigated for their potential impact on the performance of asphalt pavements. These technologies are known as Warm Mix Asphalt (WMA) additives. The immediate benefit of producing WMA mixtures is the reduction in the consumption of energy required to produce the traditional hot mix asphalt (HMA), WMA additives improve workability and compactability of mixtures to a point where they can be produced at lower temperatures. With the decreased production temperatures comes the benefit of reduced emissions, fumes, dust production and odors, as well as an extended mix haul distance, but it creates two major concerns: the reduction of the evaporation of the moisture from the aggregates which might lead to an increase potential of moisture damage in asphalt pavement, and the decrease in the hardening of the bitumen which can lead to premature permanent deformation failure of the pavement.

A total of four WMA technologies are available. The organic additives or waxes (Sasobit) and chemical additives (Evotherm), are mixed with the binder, and they work on reducing binder viscosity so the binder flows at lower mixing temperatures and coating the entire aggregates surfaces in the mix. The water bearing Zeolites; (Advera) are added to the mix during the mixing process, this will allow the small particles to release moisture into the mix creating a foaming effect, and thus achieving a sufficient coating of the aggregates. Finally the water based technology or Foaming works by injecting highly pressurized water into the binder during the mixing process, the foaming technology was not tested in this thesis.

1.1. Objective

The purpose of this study is to evaluate the use of WMA additives with polymer modified and terminal blend tire rubber asphalt mixtures, designed according to Nevada Department of Transportation (NDOT) and California Department of Transportation (Caltrans) specifications using the Hveem mix design.

The experimental program was divided into three phases: phase I evaluated the effect of WMA additives on the resistance of mixtures to moisture damage, phase II assessed the mechanical properties and performance characteristics of the mixtures produced at lower temperatures, and phase III checked the effect of the warm-mix additives on the performance life of the asphalt pavement.

1.2. Scope

The aggregates were sampled from a single source at a hard rock quarry in Lockwood, northern Nevada, which supplies hot mix aggregates to Nevada and California. A total of three binder types were used in this research:

- PG64-22, an unmodified asphalt binder that meets Caltrans specifications for PG64-16, NDOT does not specify the use of this binder, but it is widely used by municipal agencies in northern Nevada.
- PG64-28NV/PM is a polymer modified binder that meets both NDOT and Caltrans specifications.
- PG64-28NV/TR is a terminal blend tire rubber asphalt binder that meets both NDOT and Caltrans specifications.

All binders used in this research were supplied by the Paramount Petroleum Company.

As for the WMA additives, three types of technologies were evaluated in this research. In stage I, Sasobit and Advera were used, and in stage II, Evotherm was also used. For each stage of the research, mix designs were performed and the performance was compared to a control HMA mix. The research was divided into two stages based on the fact that two different batches of aggregates and binder were sampled at different times but always from the same sources.

HMA designs were performed in the laboratory following NDOT and Caltrans Hveem mix design, and they were used as control mixes. The laboratory designed WMA mixtures also were complying with NDOT and Caltrans Hveem design, and were verified using the draft Proposed Standard Practice for Design of WMA that is developed by the National Cooperative Highway Research Program (NCHRP) Project NCHRP 9-43(1).

The following laboratory experiment was conducted to evaluate the mixtures resistance to moisture damage:

- Impact of residual moisture on untreated mixtures: the objective is to identify the effect of residual moisture in the aggregate on the resistance of WMA mixes to moisture damage.
- Impact of antistrip additives: this part was designed to determine if the use of anti-stripping agents will improve the resistance of the mixtures to moisture damage.

The different mixtures were subjected to either none, one, or six freeze-thaw (F-T) cycles in order to replicate the effect of moisture damage. The resistance of the mixtures to moisture damage was measured in term of their indirect tensile strength

(ITS), tensile strength ratio (TSR), dynamic modulus (E*), and dynamic modulus ratio at different F-T cycles.

The impact of WMA additives on the performance characteristics of the mixtures was addressed. Some properties were evaluated at the un-aged stage, for example the permanent deformation which is a short-term distress mode, and others at the aged stage, like fatigue cracking which is a long-term distress mode. The laboratory tests employed to measure those two modes of failure are:

- Repeated load permanent deformation /Flow Number
- Bending beam fatigue cracking

The permanent deformation evaluation was performed for mixes using Sasobit, Advera and Evotherm while the fatigue cracking was only evaluated for mixes using Sasobit and Advera without any anti-strip additives.

CHAPTER 2 BACKROUND

Rutting is a permanent deformation failure due to traffic loading. It can occur in any layer of the pavement and is mainly due to the aggregate gradation, shape, and texture. Binder grade and content and air voids contents of the mix influence the development of rutting in the asphalt layer.

As the WMA technologies are getting more and more popular, more studies are being conducted in order to assess the performance of these new technologies. WMA mixtures use lower mixing temperatures which creates a tendency towards rutting and moisture susceptibility, due to aggregates used in the mix not being completely dry.

Research shows that the use of hydrated lime play an important role in increasing the indirect tensile strength and the tensile strength ratio of WMA mixtures whether the aggregates are completely dry or not.

In 2010, Xiao et al. conducted a study to investigate the effect of different WMA additives, percent of hydrated lime, and moisture content of aggregates, on rutting resistance using the Asphalt Pavement Analyzer (APA) (1). An experimental program was designed to test three aggregates sources, three WMA additives (Asphamin, Sasobit, and Evotherm), two moisture percentage (0%, and ~0.5% by weight of dry aggregate), two hydrated lime contents (1% and 2% by weight of dry aggregates), and one binder grade (PG64-22). For each source of aggregates a blend gradation was designed to satisfy the specifications set by the South Carolina Department of Transportation (SCDOT) for a surface type B mixture. The researchers aimed to achieve 0.5% moisture content in their mixes, for that purpose hot water, at the rate of 3.0% by weight of aggregates, was added during the mixing procedure. SCDOT volumetric specifications requires determining the optimum binder content of all mixtures so they will achieve a 4.0% air voids, based on that criteria the binder content in all mixes was determined. Superpave gyratory specimens were evaluated to identify the influence of mixture type, based on the gyration number. The weights of the samples were recorded before and after heating the aggregates to the mixing temperatures, and the weight loss in each mixture was recorded to determine the effect of moisture and hydrated lime, then a set of dry and wet samples were prepared, conditioned in the APA chamber at 64˚C for six hours, and then tested in the APA to evaluate the rut depth.

An analysis of the number of gyration showed that as the researchers increased the moisture and/or lime content for mixes with aggregates from one source, it becomes easier to compact them regardless of the WMA additive. The number of gyration increased for the other two aggregate sources. As for the rut depth analysis, it was noticed that the WMA additive Sasobit exhibited a higher rutting resistance for both wet and dry sets, the 1% lime improved the resistance of the dry set, when the 2% lime improved the resistance of the wet set. The statistical comparison between the two sets indicated that the influence of WMA additives and lime content on rutting resistance in terms of the dry and wet conditions is generally not significant, while the aggregate source had a significant influence. Also a relationship was developed between the rut depth and the number of gyrations, and as expected, the rut depth decreased for both wet and dry sets with the increase of the number of gyrations.

An expended analysis was conducted to further study the effect of aggregate source, WMA additives, and moisture and lime content on rut depth. A rut depth distribution was performed: the mixes were categorized into dry and wet groups, and the rut ranges were plotted for each variable based on the frequency of occurring. The results came to verify the findings from previous analysis. Two aggregate sources exhibited higher rut depth compared to the third source. The WMA additive Sasobit had lower rut depth with an increase in the lime and moisture.

The researchers found that the mixtures containing moisture have a greater weight loss than the control mixes during the short term aging due to the additional moisture and the rutting resistance of the mixtures is related to the aggregate source regardless of the WMA additive, lime and moisture content. The Sasobit mix exhibited the best rutting resistance, while the Asphamin and Evotherm additives showed a similar rutting resistance as the control mix. Finally, the mixtures containing moisture were able to satisfy the pavement performance criteria without any additional treatment.

Zelelew et al. conducted a study to evaluate the WMA permanent deformation performance using the flow number and Hamburg wheel-track, as well as the effect of warm mix additives on PG grading of binders (2).

Eight binder grades were used in the study to evaluate the effect of WMA additives on the PG grade of the asphalt binder:

1. PG64-22 plus LEA supplied by United
2. Sasobit terminal blend
3. PG64-22 supplied by United without Gencor water foaming
4. PG64-22 supplied by United plus Gencor water foaming
5. Base PG64-22 supplied by United
6. Base PG64-22 supplied by Valero

7. PG64-22 supplied by United plus Advera lab blended
8. PG64-22 supplied by United plus LEA lab blended

Using the AASHTO Standard Specification for Performance-Graded Asphalt Binder the PG grade of each asphalt binder was verified and the master curves were generated. The PG grade of the Sasobit terminal blend was PG70-22 and all other binder types graded as PG64-22. It was concluded that both Advera and LEA WMA technologies would not alter the PG of the asphalt binder.

The AASHTO M320-09 Table 3, Multiple Stress Creep Recovery (MSCR), test method was used. The Sasobit terminal blend binder again exhibited higher stiffness and lower average non-recoverable creep compliance at both stress levels. Again by performing a frequency sweep tests the binders master curves were generated, Sasobit exhibited the highest shear values compared to other binders.

Based on the findings from the binder study it was concluded that Sasobit should exhibit better resistance to permanent shear deformation.

WMA mixtures were tested following NCHRP Report 465 for the AMPT test specimen fabrication and the NCHRP 9-19 draft AASHTO test protocol recommendations to calculate the flow number (FN). The mixtures were also tested following AASHTO T324 test protocol for the Hamburg Wheel Tracking (HWT) test. To determine the test temperature for the flow number, the LTPPBind Version 3.1 software was used. A temperature of 51.8˚C was chosen along with two other temperatures of 45.8˚C and 57.8˚C. The tests were conducted under a confinement pressure consistent with NCHRP 9-30A project. Overall, the FN values decreased with the increase in temperature. The lab mixtures exhibited higher FN values than the field mixtures. The

Sasobit and the Gencor foaming exhibited the lowest FN. For the HWT, the lab mixtures exhibited higher stripping inflection point than the field mixtures. A conclusion was drawn from the test results that the laboratory mixtures conditioning is more severe than the mixtures produced in the asphalt plan.

In summary, for an identical mix design with different WMA additives, the Sasobit mixtures exhibited better permanent deformation resistance. The WMA mixtures were found to be susceptible to moisture damage due to the lower temperature used during production which leads to a less aging.

Bennert et al. evaluated the impact of mixing temperature on the permanent deformation and fatigue properties of different WMA mixtures. The study also proposed a modified mixing procedure for the moisture damage evaluation (3). A single binder (PG76-22) and three WMA technologies (Evotherm 3D, Rediset and Sasobit) were used in the research. All mixes were prepared at 315˚F, 270˚F and 230˚F.

The PG grading was run for each binder type as well as a MSCR test following AASHTO procedure. It was found that the WMA technologies have a slight effect on increasing or decreasing the high temperature binder grade. In the MSCR test, the non-recoverable creep compliance and percent recovery were found to change slightly due to the effect of the WMA additives. Mix designs were developed for each binder, and performance tests were carried out. Different mixing and compaction temperatures were used, but all loose mixes were conditioned for 2h at the recommended compaction temperature. The dynamic modulus master curves were measured for all mixtures following AASHTO TP79. Comparing the master curves at different mixing temperatures, it was noticed that there is an obvious decrease in the stiffness due to the lower mixing temperature regardless of the existence of a WMA additive. To further investigate the drop or reduction in the dynamic modulus, the researchers plotted, at each temperature, the average dynamic modulus of each mix. From those plots, it was observed that minimal changes occur at the lower testing temperatures, while higher reductions occur at higher testing temperatures. In order to assess the meaning of those reductions, the dynamic modulus of mixtures with PG70-22 and PG64-22, prepared at a mixing temperature of 315˚F, were measured without any WMA additives. The reduction in the dynamic modulus at lower mixing temperature (230˚F) was found to be approximately equivalent to reducing the PG grade from PG76-22 to PG64-22. It was concluded that 45 to 50% reduction in the dynamic modulus is similar to reducing the PG from PG76-22 to PG64-22.

To study the effect of WMA technologies on permanent deformation, an unconfined repeated load permanent deformation test was ran following AASHTO TP79 at a temperature of 54.4˚C determined according to LTTPBind 3.1 software. At the high mixing temperature, the WMA technologies were actually increasing the FN, as the mixing temperature decreased, the FN decreased as well except for the 1% and 1.5% Sasobit mixtures which at a 270˚F mixing temperature were able to maintain a close FN to the one obtained at the higher mixing temperature. FN for mixtures with PG70-22 and PG64-22 prepared at 315˚F were ran. Then by comparing the FN values obtained to the PG76-22 mixture FN mixed at 315˚F, it was determined that a 60% reduction in the FN of the PG76-22 mixture at 315˚F is equivalent to a drop in the PG to PG70-22, and an 80% reduction in the FN equals a drop to PG64-22.

Using the Overlay Tester, the cracking in the different mixtures was evaluated following TxDOT Tex-248-F, and as expected, with a decrease in mixing temperature, there is an increase in the initial fatigue performance.

For the moisture damage potential, two test were conducted, the TSR (AASHTO T283) and the HWT (AASHTO T324). This part evaluated the effect of mixing HMA at lower temperature of 270˚F as compared to a mixing temperature of 315˚F. Two source of aggregates with different level of absorption, one type of binder PG76-22, and three moisture contents of 0, 3 and 6% were evaluated. A special mixing method was designed to reproduce and simulate the production in a drum plant using moist aggregates following early WMA research conducted by Hurley and Prowell (2005). The data showed that all mixes failed the 80% TSR except for the ones with 0% moisture and mixed at 315˚F. Also with the decrease of temperature and increase in moisture there was a clear reduction in the tensile strength and TSR for all mixes. Same conclusion were made for the Hamburg Wheel Tracking tests.

As a summary of the findings, the study indicated that the dependency of mixture performance on the mixing temperature should be considered before adopting a WMA technology and a minimum mixing temperature should be established. This was drawn from the observation of the reduction of the mixture stiffness and FN at high temperature with the decrease in the mixing temperature. The moisture content of the aggregate have a significant effect on the mixture performance therefore, it is advised that proper measures are taken to minimize the moisture damage.

CHAPTER 3 PROPERTIES OF WMA MIXTURES – PREVIOUS WORK ON PHASE I

This ongoing research project is evaluating different WMA technologies. A brief summary of the previous work done by Ms Corina B Wong with two WMA technologies; Sasobit and Advera, will be described in this chapter (4).

For this purpose an experimental plan was identified and put together for the purpose of identifying the different properties of the developed mixtures and their performance characteristics through a series of tests. Table 1 throughTable 6 present the complete summary of the Mixtures developed by Ms Corina B Wong as well as the complete experimental program developed, the sign "X" will mark the previous work done and will be summarized in this chapter while the sign "--"will refer to the additional work that was carried on by the author of this thesis.

3.1. Experimental Program

To evaluate the effect of two warm mix technologies, Sasobit and Advera, a research effort was developed. Laboratory HMA mixes were designed and used as a control mix to compare with the laboratory WMA mixes.

A total of six HMA mixes were designed using one source of aggregate, two asphalt binder types (PG64-28NV/PM and PG64-28NV/TR) and two anti-strip additives (Lime and liquid anti-strip Morlife 5000), following a Hveem mix design according to NDOT Type 2C and Caltrans ¾" max Type A specifications. The laboratory WMA mixtures were designed to meet aggregate coating and compactibility requirements as per the draft Proposed Standard for Design of WMA mixtures. The aggregate coating and compactibility testing was conducted on asphalt mixtures without anti-strip additives.

Those properties were assumed to remain constant as the anti-strip additives were added. The WMA technologies evaluated were Sasobit and Advera. As a part of the mix design, all mixes were subjected to indirect tensile testing as described in Nevada Test Method T341 and Caltrans Test Method CT371.

One of the main concerns for the WMA is the mixture moisture damage susceptibility caused by the lower production temperatures. This research effort aimed to addressed the impact of moisture susceptibility by focusing on several factors related to the resistance of asphalt mixtures to moisture damage as discussed in the following sections:

3.1.1.1. Impact of Residual Moisture on the Resistance of Untreated WMA Mixtures to Moisture Damage.

Laboratory produced WMA mixtures were evaluated with and without residual moisture in the aggregate to study the effect of insufficient aggregate drying during production. The measured properties included Dynamic Modulus (E*) at 0, 1 and 6 Freeze-Thaw (F-T) cycles with and without residual moisture.

3.1.2. Impact of Warm Mix Additives on the Resistance of Anti-strip treated WMA mixtures to Moisture.

The objective was to determine if the use of anti-stripping agent will improve the moisture resistance of WMA mixtures. Aggregates with residual moisture were used and the E* at 0 and 6 F-T were evaluated.

3.1.3. Impact of Long Term – Aging on the Resistance of WMA Mixtures to Moisture Damage.

Untreated WMA mixtures at multiple aging levels were evaluated by comparing the E* at 0 and 6 F-T using aggregates with residual moisture.

As a part of the mix design procedure, the tensile strength and the tensile strength ratio data were compared for different mixtures and the results complied with previous research, the WMA additives reduce the tensile strength and the tensile strength ratio of the mixtures, this can be adjusted by adding an anti-strip agent.

3.2. Summary and Conclusions

In conclusion the researchers that conducted the first part of Phase I concluded the following:

1. For the short term aged, untreated mixtures subjected to 0, 1 and 6 F-T cycles, using an unmodified binder (PG64-22), a large drop in the dynamic modulus is observed between the HMA and WMA. The Sasobit WMA mixtures were minimally impacted by the residual moisture presence in the aggregates.

   As for the mixtures using a modified binder (PG64-28NV/PM and PG64-28NV/TR), the WMA mixtures performed as well as the HMA or even better in the case of Sasobit, and the residual moisture did not have a significant effect on the dynamic modulus.

2. For the short term aged, lime and liquid treated mixtures subjected to 0 and 6 F-T, the lime treated mixtures performed the best with respect to moisture damage. Sasobit mixtures were able to show similar performance to HMA with and without anti-strip additives, whereas Advera mix performed worst. The terminal blend tire rubber modified mixtures showed similar performance to the polymer modified mixtures for HMA and WMA with and without Lime.

3. Finally, for the long term aged, untreated mixtures subjected to 0 and 6 F-T cycles, the WMA Advera mix performed the worst, though the rubber modified showed a

better performance than the polymer modified with Advera, while Sasobit always had a similar performance to the HMA.

CHAPTER 4 PROPERTIES OF WMA MIXTURES – ADDITIONAL WORK ON PHASE I

4.1. Experimental program

Phase I of the research was divided into 2 stages.

The previous work involved the development of different HMA mix designs and the verification of the WMA mixtures, then the analysis of the resistance to moisture damage of those different mixtures for short term and long term aging either with or without anti-strip additives. The findings of the previous work were summarized in CHAPTER 3.

The Additional work, which is a part of this thesis, was dedicated to evaluate the performance characteristics of the previously developed mixtures by determining their resistance to permanent deformation and to fatigue cracking (Table 5 Table 6). The results and findings of this stage will be discussed in this chapter.

4.2. Permanent Deformation

The resistance of various mixes to permanent deformation was evaluated by measuring the FN for each mix following AASHTO TP 79-11 test protocol. The 4 inches x 6 inches samples with 7.0 ± 0.5% air voids were tested at 58˚C (LTPPBind Version 3.1) under repeated haversine axial compressive load pulse of 0.1s followed by 0.9s rest period without confinement. The resulting permanent axial strains are measured as a function of the load cycles and numerically differentiated to calculate the FN. The FN is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain during the repeated-load test. The experiment for phase I is detailed in Table 5.

4.2.1. Analysis of the FN Data

The main concern was that the lower mixing temperature of the WMA will not provide sufficient stiffness during the early life of the asphalt pavement which will lead to early failure in rutting (Table 5).

Figure 1 through Figure 4 show the FN of the different mixtures from Phase I of the study at the 58˚C testing temperature which was determined to be the critical temperature for permanent deformation for mixtures with high PG of 64˚C. Overall the mixtures with PG64-22 Advera, untreated, lime-treated and liquid-treated, showed the lowest FN; while PG64-22 Sasobit showed a close FN to the PG64-22 HMA mix with the FN of the PG64-22 Sasobit untreated was slightly higher than the FN of the PG64-22 HMA mix.

From different literature reviews, it was noticed that Sasobit will increase the high end temperature of the binder by few degrees, which means that it can create a stiffer binder, this could be the case here with untreated and lime-treated mixtures, where Sasobit, by mixing it with the binder, would have added some stiffness to it, though reversing the effect of the lower WMA mixing temperature. For that a FN of the PG64-22 WMA Sasobit was observed to be close to the HMA mixtures. As for Advera, the different literature reviews suggested that it will not alter the PG of the binder, which implies that the drop in the FN is directly related to the lower WMA mixing temperature. There was no significant change in the FN for the PG64-22 WMA mixtures with Advera and Sasobit after adding lime or liquid anti-strip, while a significant increase in the FN of the PG64-22 HMA was observed for the liquid-treated mixture, it is believed that the liquid anti-strip has somehow chemically reacted with PG64-22 to produce a better resisting mixture to permanent deformation, while this reaction did not occur when Sasobit and Advera were introduced into the mixture.

In the case of the PG64-28NV mixtures, the PG64-28NV Advera had the lowest FN while the PG64-28NV Sasobit had a better performance than the control PG64-28NV HMA.

Again the Sasobit behavior can be associated with its effect on the binder PG, in addition, a higher WMA mixing temperature was employed for the PG64-28NV which helped in creating a more stable mix. Advera, as well, had the same effect as for the previous mixtures with PG64-22 as a result the same conclusion can be drawn. The addition of lime to the PG64-28NV mixtures significantly affected the FN, it can be observed that those mixtures had the highest FN, and in the case of Sasobit, it is noticed that the addition of 1% lime with 3% Sasobit created a highly stable mix with a PG64-28NV binder. For the liquid-treated mixtures, the FN was higher than the untreated mixtures. That could also be associated to a reaction between the liquid anti-strip and the polymers to create a slightly more stable mix, even though it was not as significant as the effect of the hydrated lime.

In the case of the PG64-28NV/TR mixtures, Advera untreated and liquid-treated showed a slightly better FN than the control HMA, while the addition of lime-treated PG64-28NV/TR Advera mixtures showed an increase in the FN compared to the untreated and liquid-treated with PG64-28NV/TR Advera, its value did not exceed the one for the lime-treated PG64-28NV/TR HMA. The PG64-28NV/TR Sasobit had a higher FN for the untreated and liquid-treated between all the PG64-28NV/TR mixtures, however in the case of the lime-treated mixtures, the control HMA again showed the better performance. The same behavior trend was observed for both Advera and Sasobit compared to the control mix, thus it is believed that the binder type or the existence of rubber in the binder was the reason behind this. This conclusion was drawn mostly from the behavior of the PG64-28NV/TR Advera mixture, which FN values were slightly higher than the HMA while with different binder it would be lower. Sasobit trend was constant with all mixtures. Only in the case of PG64-28NV/TR lime-treated mixture that the HMA had the higher FN and not the Sasobit, this behavior should be more closely investigated to come up with the right conclusion and explanation of this particular data.

It was also observed that PG64-28NV mixtures exhibited higher FN than the PG64-28TR.

Adding lime to all the mixes mostly improved their FN especially in the case of mixtures with PG64-28NV which showed a significantly high FN, the PG64-22 Advera, was an exception.

The liquid anti-strip had a minor effect on the FN, and even in some cases it decreased the FN of some mixtures. Figure 1 presents a summary of the FN of untreated mixtures, Figure 2 for the Lime-treated mixtures, and Figure 3 for the liquid-treated mixtures. Figure 4 presents a summary of the FN for all mixtures from Phase I.

4.3. Resistance to Fatigue Cracking

The resistance of the un-treated asphalt mixtures to fatigue cracking was evaluated using the flexural beam fatigue test according to AASHTO T321-07 test procedure. A 2.5x2.0x15 inches beam specimen is subjected to a 4-point bending with free rotation and horizontal translation at all load and reaction points. This produces a constant bending moment over the center portion of the specimen. Constant strain tests were conducted at three different strain levels, using a repeated harversine load at a frequency of 10 Hz. Initial flexural stiffness was measured at the 50th load cycle. Fatigue life or failure is defined as the number of cycles corresponding to a 50% reduction in the initial stiffness. Table 6 details the experimental program

The following model was used to characterize the fatigue behavior of the various mixtures:

$$N_f = k_1 \left(\frac{1}{\varepsilon} \right)^{k_2}$$

Where N_f is the fatigue life (number of load repetitions to fatigue damage), ε is the applied tensile strain and k_1 and k_2 are experimentally determined coefficients.

4.3.1. Analysis of Fatigue Cracking Data

Figure 5 shows the mixtures with PG64-22 asphalt binder. It can be noticed that the PG64-22 Sasobit mixture exhibited a higher resistance to fatigue cracking at high strain levels. The PG64-22 Advera mixture has significantly lower fatigue resistance compared to the PG64-22 Sasobit mixture. In addition, the PG64-22 Sasobit mixture exhibited a higher fatigue performance at high strain levels compared to HMA mixture, while Advera mixture had shown a lower fatigue performance than HMA mixture. The PG64-22 HMA cured for two hours at the WMA compaction temperature showed a close behavior to the regular PG64-22 HMA mixture. This implies that the long term aging process could have masked the effect of the short term aging that was performed at WMA compaction temperature. Therefore, it can be concluded that introducing Sasobit WMA additive to the PG64-22 mixture improved the fatigue resistance of the mixture at high strain.

Figure 6 shows the fatigue behavior of mixtures with PG64-28NV. Similar to the PG64-22 mixtures, the PG64-28NV Sasobit appeared to have a better fatigue performance than the PG64-28NV HMA at high strain levels. Meanwhile, PG64-28NV Advera mixture exhibited, in general, similar trend of behavior of the PG64-28NV Sasobit, however its resistance to fatigue cracking at low strain levels was the lowest. The PG64-28NV HMA cured for 2h at the WMA compaction temperature still exhibited a similar fatigue behavior as the regular PG64-28NV HMA. It can be concluded that both WMA mixtures exhibited a higher resistance at high strains than the HMA and a lower resistance than the HMA at low strain level. The existence of polymer in the asphalt binder improved the fatigue performance of all mixtures at low strain levels.

Figure 7 is a comparison of mixtures with PG64-28NV/TR. In this case PG64-28NV/TR Advera behavior was similar to the PG64-28NV/TR HMA as well as to the PG64-28NV/TR HMA cured for 2h at the WMA compaction temperature, while the mixture with PG64-28NV/TR Sasobit exhibited a lower resistance to fatigue cracking compared to all other mixtures. Unlike the previous trends observed with PG64-22 and PG64-28NV WMA mixtures, the PG64-28NV/TR WMA Advera had higher fatigue resistance compared to the PG64-28NV/TR WMA Sasobit mixture.Comparing the different mixtures at three different strain levels it can be noticed that:

Figure 8shows a sole comparison between all HMA mixtures using neat, polymer modified, and asphalt rubber modified asphalt binders. It can be concluded that polymer modified binder (PG64-28NV) significantly improved the fatigue performance while the asphalt rubber modified asphalt binder had a minimal fatigue resistance improvement compared to the neat binder. Mixtures cured for 2 hours at the WMA compaction temperature exhibited similar trend as the HMA mixtures (Figure 9).

Figure 10 shows a comparison between all Advera WMA mixtures using neat, polymer modified, and asphalt rubber modified asphalt binders. It can be concluded that both polymer as well as asphalt rubber modification significantly improved the fatigue performance compared to the neat binder. Similar fatigue resistance improvements were accomplished for the Sasobit WMA mixtures (Figure 11).

The Sasobit WMA technology when combined with PG64-22 and PG64-28NV mostly showed a good resistance to fatigue cracking at the three strain levels, where Advera was more effective when it was combined with PG64-28NV/TR. In most cases, the HMA mixtures had the better fatigue resistance except for the PG64-22 WNA Sasobit at the high strain level.

What was expected is that the WMA mixtures with a lower curing time, which means a less aging effect on the binder, would have a better resistance to fatigue cracking. To assess the aging effect, HMA mixes were cured for two hours following the same procedure as the WMA mixes prior to testing. Those mixtures exhibited a close behavior to the HMA and even in some cases their resistance to fatigue cracking would even be higher than the HMA, this can lead to two conclusions: a) long term aging possibly can mask the short term aging effect and b) the resistance to fatigue cracking of the different WMA mixtures is significantly affected by the WMA additive while the lower WMA temperatures play a minimal role in the resistance to fatigue cracking.

Also it was observed that mixtures with PG64-28NV/TR binder showed a somehow close behavior between the HMA and WMA mixtures, while the PG64-22 and

PG64-28NV mixtures had showed a difference between the HMA and WMA, so it can be concluded that for fatigue resistance the binder type plays the most important role and it will dictate the behavior of a mixture, as well the impact of the WMA additives is significantly critical on the resistance to fatigue cracking.

4.4. 3D-Move Analysis

In order to combine the impact of the dynamic modulus (E*) of the mixtures with their performance characteristics in terms of resistance to fatigue cracking, a 3D-Move analysis was conducted on two pavement structure; thin (4 inches) and thick (8 inches). To estimate the number of load repetition to fatigue failure N_f, the model previously developed using the Beam Fatigue test method was used along with the tensile strain calculated by 3D-Move.

A dynamic and a static analysis were performed for both structures. For the dynamic analysis, the vehicle speed was 40mph. The response points at the bottom of the asphalt were taken at three different positions; under the center of the tire, at the edge of the tire and in between the dual tires. The input data for the dynamic as well as the static analysis is shown in Table 10 through Table 18.

The layer properties for the asphalt layer in the static analysis were assumed to be as follows:

Asphalt Layer

- Material Type : Linear Elastic
- Young Modulus: Dynamic Modulus determined from the Master curve at 70˚F and 10 Hz.
- Poisson's Ratio Static: 0.35

- Unit Weight: 0.086 lb/in^3

Unbound base layer:

- Young's Modulus: 25000psi
- Damping ratio: 5%
- Poisson's Ratio: 0.4
- Unit weight: 0.07 lb/in^3

Subgrade Layer:

- Young's Modulus: 7000psi
- Damping ratio: 5%
- Poisson's Ratio: 0.45
- Unit weight: 0.065 lb/in^3

In the static analysis of the thin pavement, the dynamic modulus value of each mixture at 30Hz and 70˚F was used (Figure 12), while for the thick pavement static analysis, the dynamic modulus value of each mixture at 10Hz and 70˚F was used (Figure 15). Those frequencies were used based on the M-EPDG table (54).

The dynamic analysis using 3D-Move calculated the pavement responses based on the master curve developed for each mixture. Thus, in order to compare the response calculated through a static analysis to the ones obtained through the dynamic analysis, proper dynamic modulus was assigned to each pavement structure, and through comparing the maximum tensile strain at the bottom of the asphalt layer for both thin and thick pavement (Figure 14 Figure 15), it was found that the frequencies that were chosen for the static analysis have resulted in a pavement response that is significantly similar to the dynamic analysis, with the maximum tensile strains calculated through the dynamic analysis slightly higher than the ones obtained through a static analysis (Figure 16).

The resistance to fatigue cracking of the different mixtures was evaluated using the model developed through lab testing. It was observed that the K_2 factor had a significant effect on the behavior of the mixtures (Figure 17) as well as the strains obtained from the 3D-Move analysis. Both structures thin and thick, showed a similar behavior where the HMA mixtures had the highest resistance to fatigue cracking followed by the WMA Sasobit mixture then WMA Advera mixture. PG64-28NV HMA mixtures exhibited the highest resistance to fatigue cracking (Figure 18 and Figure 19). To better evaluate the resistance to fatigue cracking of WMA mixtures, the ratio of the maximum tensile strain of the WMA mixtures to the corresponding HMA maximum tensile strain was plotted (Figure 20). A strain ratio higher than 100% indicates a higher strain at the bottom of the WMA pavement compared to its control HMA. Additionally the ratio of the number of repetition to fatigue failure of the WMA mixtures to the corresponding HMA control mixture was also plotted (Figure 21). N_f ratio higher than 100% indicates a higher fatigue life of the WMA mixtures compared to the HMA. In the case of the PG64-22 WMA the tensile strain ratio was higher than 100%, indicating that those mixtures will have a lower resistance to fatigue cracking, which was reflected by a low N_f ratio. With PG64-28NV WMA mixtures, the tensile strain ratio was about 80%, which indicates a higher fatigue life of those WMA mixtures over HMA mixtures. However, by examining Figure 21, Nf ratio for PG64-28NV WMA mixtures is observed to be lower than 60%. This can be explained by the fact that the fatigue resistance is not only dependent on the calculated maximum tensile strain at the bottom of the pavement layer, it is also highly affected by the K_2 factor obtained from the fatigue relation (Figure 17). A closer look at those factors will reveal that the HMA K_2 factor was significantly higher than the WMA, which in this case will explain why the fatigue life ratio of the PG64-28NV WMA mixtures is significantly lower than 100%. In the case of the PG64-28NV/TR WMA mixtures, it was observed that the WMA Advera mixtures exhibited a strain ratio slightly higher than 100%, while WMA Sasobit showed a strain ratio slightly lower than 100% . Again taking into account the K_2 factors for those mixtures where WMA Advera and Sasobit mixtures had a value lower than the control HMA mixture, PG64-28NV/TR WMA Sasobit exhibited a really close behavior to the control mixture which was reflected in a N_f ratio approaching 100%, indicating similar fatigue life compared to the HMA mixtures. The PG64-28NV/TR Advera showed a high reduction in the N_f ratio, which is associated with a higher strain level and a lower K_2 factor.

CHAPTER 5 PROPERTIES OF WMA MIXTURES – PHASE II

5.1. Experimental Program

Phase II of this research program aimed to evaluate one WMA technology, Evotherm. Using the same source of aggregates and same source of binder as phase I, new mix designs for HMA and WMA mixtures were developed. The reason behind it was that the researchers found and observed that the properties of the aggregates as well as the binders would differ depending on the sampling time even if there was no change in the source.

Evotherm aimed to improve the workability and compactability of the mixtures and to allow them to be produced at a lower temperature than the conventional HMA. This reduction in temperature created two major concerns: a) an increase potential of moisture damage due to the reduction of evaporation of the moisture from the aggregates and b) insufficient or decrease hardening of the asphalt binder which might lead to a premature permanent deformation.

An experimental program was placed together in order to address those concerns: evaluate the resistance to moisture damage (Table 23 and Table 24) and permanent deformation of the mixtures (Table 25).

5.2. Materials

5.2.1. Asphalt Binder

A total of three asphalt binders were evaluated in this research: PG64-22, a neat binder typically used in California and widely employed by municipal agencies in northern Nevada, PG64-28NV/PM, a binder that meets both NDOT and Caltrans specifications for polymer-modified asphalt binders, and PG64-28NV/TR, a binder that meets both NDOT and Caltrans specs for terminal blend asphalt binders. A full Superpave PG was performed for each type of binder and the results are shown in Table 30 and Table 32.

5.2.1.1. Cleaveland Open Cup (AASHTO T48)

The Cleveland Open Cup is used to determine the flashpoint of an asphalt binder. This is a safety test conducted to determine the temperature at which an asphalt binder will ignite in the presence of a flame; the purpose is to make sure that this temperature will be above any mixing temperature. An original binder is placed in a cup shape container and heated at a prescribed rate, a small flame is passed periodically above the cup until the specimen will emit enough vapor to flash. The temperature at which this flash is observed is reported as the flash point of the binder.

5.2.1.2. Rotational viscometer (RV AASHTO T316)

The rotational viscometer is a fundamental rheological test to determine the asphalt binder viscosity at high temperature (135˚C) in order to ensure that the binder is fluid enough to be poured and mixed during the construction phase. The Brookfield viscometer applies a rotational speed of 20 rpm to a cylindrical spindle submerged in an asphalt binder at a constant temperature of 135˚C, then measures the torque required to maintain this speed constant. From the measured torque the device will calculate the viscosity of the binder.

5.2.1.3. Rolling Thin Oven (RTFO AASHTO T240)

The RTFO is a device developed by Caltrans to simulate the short term aging of an asphalt binder. A specified amount of binder (35g) is poured into jars and placed in a rotating rack. The samples are exposed to a high temperature (163˚C) for a specified amount of time (85 min), and as they are rotating, they will be exposed to an air jet.

The binder is short term aged due to the oxidation and volatilization.

The samples from this test are used to determine the Mass Loss of a binder and are used for the DSR and the PAV.

5.2.1.4. Pressure Aging Vessel (PAV AASHTO R28)

The PAV simulates the in service aging of an asphalt binder by exposing the binder to high temperature, high pressure (2.1 KPa), for a specified amount of time (20 h).

The long term aging of the binder is mainly caused by oxidation.

A 50g RTFO sample is placed in a pan and then transferred into the PAV where it is subjected to a defined temperature and pressure for 20 hours. The test temperature depends on the expected climate conditions. After 20 hours, the air is released gradually over a specified amount of time (10 min), and the samples are transferred into a vacuum chamber to release the trapped air. The samples are then stored for other testing such as the DSR, BBR, and the DTT.

5.2.1.5. Dynamic Shear Rheometer (DSR AASHTO T315)

The dynamic shear rheometer is used to characterize the viscous and elastic properties of the asphalt binder at high and intermediate temperatures. The DSR measures the complex shear modulus G* and the phase angle δ of an asphalt binder at the desired temperatures and frequency. It is a test used to analyze the binder performance in rutting and fatigue.

The procedure consists of placing the asphalt binder sample in between circular parallel plates, a 25 mm plate for the original and RTFO aged binder, and an 8 mm for the PAV aged binder, the PAV aged binder is stiffer than the original and RTFO binder which requires the use of a smaller sample in order to be capable of measuring the binder properties. Then an oscillating shear stress is applied to the sample for a specified temperature. The DSR will automatically calculate the complex modulus G* and the phase angle δ and either G*/sin (δ) or G*x sin (δ).

Rutting Performance:

Rutting is a stress controlled cyclic loading phenomenon that occurs in the early stages of the pavement at high temperatures. Through the principle of energy dissipated per cycle of loading we concluded that the work dissipated per cycle of loading is inversely proportional to G*/sin (δ), so in order to minimize the dissipated energy we want a large G* (greater stiffness behavior) and a lower δ (less viscous behavior). As the binder ages, it stiffness increases thus the rutting resistance increases.

For this the G*/sin (δ) was chosen as a parameter for measuring rutting for an original and RTFO aged binder (early stages of the pavement life) and was limited to a minimum.

Fatigue Performance:

Fatigue is a strain controlled phenomenon, it occurs at intermediate temperatures on pavements that have been subjected to the aging process. Using the energy dissipation principle per cycle of loading, it was concluded that the work dissipated is proportional to G*x sin (δ), so by minimizing G* and sin (δ) we obtain a binder that is less stiff and more elastic thus a better resistance to fatigue cracking.

In conclusion, fatigue performance is analyzed by using a PAV aged binder subjected to intermediate temperatures, and G* x sin (δ) was chosen as a parameter for measuring fatigue and was limited to a maximum.

5.2.1.6. Bending Beam Rheometer (BBR AASHTO T313)

The bending beam rheometer determines the low temperatures stiffness and relaxation of an asphalt binder. It tests the binder to determine if it will potentially crack or fail under the thermal cracking stresses. The BBR applies a constant load on a simply supported binder beam placed in a fluid bath at low temperatures; it measures the deflection of the beam. Knowing the beam dimensions it calculates the creep stiffness "S (t)" which is a measure of how the binder resists to the creep loading, and the stress relaxation parameter m-value. We want a binder with good relaxation or high relaxation value, and a low stiffness which will indicate low stresses in the pavement at low temperatures.

5.2.1.7. Binder Grading

Table 30 throughTable 32 show the testing summary of the three binders as well as the true PG determined through testing, and all three either complied or exceeded the requirements for their PG grades. Also Figure 22 through Figure 27 show the plots required to determine the grading of each of the three binders tested.

5.2.2. Aggregates Properties

One aggregate blend was selected for each stage meeting both the Nevada DOT Type 2C specifications and Caltrans Type A specifications as described respectively by the NDOT Standard Specifications for Road and Bridge Construction and Caltrans Standard Specification (Table 27).

Some aggregate blend properties as well as the Superpave consensus properties were measured according to NDOT and Caltrans Standard specifications as shown below:

- Specific gravity and absorption of coarse aggregate (AASHTO T85)
- Specific gravity and absorption of fine aggregate (AASHTO T84)
- Coarse aggregate angularity (Nev. T230 and CTM 205)
- Fine Aggregate Angularity (AASHTO T304 (A))
- Sand Equivalent Test (CTM 217)
- Flat and Elongated Particles (AASHTO D4791)

Table 29 summarizes the testing results and the each stockpile gradation is shown in Table 28.

5.2.3. WMA Additives

For stage one, two WMA technologies were employed; Advera and Sasobit, and for stage two; only Evotherm was also used.

Advera is an aluminosilicate or hydrated flowing powdered zeolite, it contains moisture which is structurally and chemically bound in the powder. The moisture is released into the mix which causes a micro-foaming effect in the asphalt binder thus improving its workability. Advera is recommended to be added directly at a rate of 0.2-0.3% by total weight of the mix during the mixing procedure.

Sasobit is the most often used organic additive in the United States. It is a synthetic paraffin wax manufactured by Sasol using the Fischer-Tropsch (FT) process that involves treating hot coal or natural gas (methane) with steam in the presence of a catalyst. It is added directly to the binder at a recommended rate of 1.5 to 3.0% by weight of binder and it works by reducing the viscosity and enhancing the flow.

Evotherm is a water free additive that does not rely on the principles of asphalt binder foaming or other methods of viscosity reduction. It is stated that the additive provides a reduction in the internal friction between the aggregate particles and the thin films of binder when subjected to high shear rates during mixing and high shear stresses during compaction. The recommended dosage rate for Evotherm is 0.4% by total weight of asphalt binder.

5.2.4. Anti-strip Additives

The research evaluated hydrated lime and Morlife 5000, a liquid anti-strip, produced and supplied by the Dow Chemical Company. NDOT mandates the use of lime in all its dense graded asphalt mixtures while Caltrans specifies the use of lime or liquid-antistrip only in moisture susceptible mixtures. Morlife 5000 is stated to improve the bond between the asphalt binder and aggregates thus improving the resistance to moisture damage.

The hydrated lime was added at a rate of 1% to the damp aggregates and the Morlife 5000 was added at a rate of 0.5% by weight of asphalt binder directly to the heated binder.

5.3. Mix Designs

A Hveem mix design was conducted for each HMA and WMA mix for heavy traffic according to NDOT and Caltrans specifications, and the WMA mixtures were verified by the Standard Practice for Design of WMA that is recomended by the National Cooperative Highway Research Program (NCHRP) Project NCHRP 9-43(1). A total of

12 HMA mixes were verified in stage one and two, 18 WMA mixes for stage one, and 9 WMA mixes for stage two. Mixtures with no anti-strip additives are called untreated mixes while mixtures with lime or liquid anti-strip are called lime-treated and liquid-treated mixes, respectively. Summary of the different mixtures designs are presented in Figure 28 throughFigure 45.

The requirement for the Hveem mix design according to both NDOT and Caltrans is to achieve a minimum Hveem Stability of 37 for the deformation resistance (Nev T303/ CTM 366) for a heavy traffic and a minimum unconditioned ITS (NEV 341) of 65 psi and a retained indirect TSR (Nev 341/ CTM 371) of 70%.

Mixing temperatures for the HMA were determined using a viscosity chart as described by AASHTO T312. HMA mixtures were cured for 16±1hours at a 140˚F and then compacted at a temperature of 230˚F using a Kneading Compactor. A set of four samples with different binder contents; 4.5, 5.0, 5.5 and 6.0%, were prepared, conditioned for 1.5 hour at 140˚F before applying a leveling load of 12600 psi. The compacted samples were placed in an oven for 4±1hours at 140˚F before testing for stability.

The optimum binder content (Table 33) was determined at air voids of 4-5% (AASHTO T269), a stability of 37 (Nev T303/ CTM 366), a Void in Mineral Aggregates (VMA) of 13-22% (Nev T 338/ LP-2), Void Filled with asphalt (VFA) of 70-75% (Nev T760/LP-3), a minimum Film Thickness of 8µm (Nev T760) and a Dust Proportion of 0.6-1.3 (LP-4).

Same procedure was applied to the WMA mixtures with few modifications, the mixing temperature was determined following NCHRP 9-43. First the aging index of the binder was determined (Table 34) which identifies a mixing temperature as a starting point. Second a verification of the compactibility and the coating of the aggregates were performed (Table 35 and Table 36). The average number of gyration to 92 % relative density was determined and it should be less than 125% of the value at the recommended compaction temperature.

5.3.1. Compactability of Asphalt Mixtures

WMA compactibility samples are mixed at the proposed mixing temperatures, cured for two hours at the proposed compaction temperature, and then compacted to 8% air voids using a Superpave Gyratory compactor. This procedure is then repeated to another set of WMA samples but with a compaction temperature 55ºF (30ºC) below the proposed compaction temperature and then compacted using a Superpave gyratory compactor to N_{design} gyrations. For this research the design traffic was chosen to be larger than 30 million ESALs, where an N design of 125 gyrations is required according to NCHRP 9-43 recommendations (Table 35). The average number of gyrations for each WMA mixture is shown in Figure 46 below and the data is displayed in Table 38.

5.3.2. Aging Index of Asphalt Binders

The aging index (AI) for each binder was calculated using the G*/sinδ values obtained during the grading of the asphalt binders. The data are used to determine the minimum mixing temperature that the WMA mixtures can be subjected to. The aging indices for the asphalt binders used in this research effort were determined to be 2.2 for PG 64-22, 2.1 for PG 64-28 NV/PM and 1.8 for PG 64-28 NV/TR. The aging indices of the asphalt binders corresponded to minimum mixing temperatures of 235ºF for PG 64-22, 235ºF for PG 64-28 NV/PM, and 220ºF for PG 64-28 NV/TR (Table 34).

5.3.3. Aggregate Coating of Asphalt Mixtures

The aggregate coatings of the mixtures were evaluated using the Standard Test Method for Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures, AASHTO T 195 (Table 36). The testing results are shown in Table 37. The WMA mixtures with PG64-22 met the coating criteria at mixing temperatures 43 to 53˚F below the HMA mixing temperature, as for the mixtures with PG64-28NV and PG64-28TR, the coating criteria are met at mixing temperatures 45˚F below the HMA mixing temperature.

5.3.4. Tensile Strength

The TS and the TSR were evaluated for all the mixtures as part of the mix designs specifications following NDOT test method Nev T341D. The test specimen were cured for 15 ± 3hours at 140˚F ± 5˚C before being compacted in accordance with Nevada Test Method T342 to 8 ±1.0 % air voids using the Kneading compactor and at a compaction temperature of 230˚F ± 5˚F. After extraction from the mold, the compacted specimens were placed into a suitable pan at 77˚F ± 1˚F for a minimum of 15 hours. The dry subset was stored at that temperature in an environmental chamber until testing, while the wet subset was subjected to sufficient vacuum to obtain the required saturation level of 70 to 80 % and then subjected to 1FT before being tested.

For most of the untreated mixtures, the TS of the WMA matched or sometimes exceeded the HMA TS, and the TSR for the untreated WMA mixtures with all binders were clearly higher than the HMA TSR. The only two mixtures that did not meet the specifications of TSR greater than 70% were the PG64-22 HMA and PG64-28NV/TR HMA, while all the mixes had TS values higher than 448KPa (Figure 47).

The lime-treated mixtures showed a clear increase in the TS of the wet samples for all mixes, while it decreased the dry TS for mixtures with PG64-22 and PG64-28TR and increased it for mixtures with PG64-28NV compared to the untreated mixtures. This behavior was observed on both HMA and WMA samples. The addition of the WMA additive Evotherm with Lime decreased the TSR of mixtures with PG64-22 and PG64-28NV while it managed to keep it constant for mixtures with PG64-28TR. The liquid-treated mixtures presented a similar behavior as the lime-treated mixtures, but in the case of the PG64-28TR mixtures, the WMA TSR decreased. All lime-treated and liquid-treated mixtures met the TS specifications as well as the TSR specifications. Also it was observed that Evotherm increased the TS for all dry mixtures, while it only increased the TS for the wet samples with PG64-28NV and PG64-28TR and decreased it for mixtures with PG64-22. Evotherm was able to improve the TSR for all the untreated mixtures, while it reacted negatively with the addition of the anti-strip additives by decreasing the TSR of the lime-treated and liquid-treated mixtures (Figure 50).

5.4. Evaluation of Resistance to Moisture Damage

A major concern regarding WMA mixtures is that the lower mixing temperature will not completely dry the aggregates blend, thus creating a moisture susceptible mix. To address this problem, two tasks were conducted.

5.4.1. Dynamic Modulus (E)*

The resistance of the various mixtures to moisture damage was evaluated by measuring the dynamic modulus of the mixtures before and after different F-T cycles. The F-T cycling followed the procedure outlined in AASHTO T 283-07. A total of two samples from each mixture were evaluated as follows:

- Saturate the samples to 70-80%.
- Subject the saturated samples to a F-T cycling. One F-T cycle consists of freezing the sample at 0°F (-18°C) for 16 hours followed by 24 hours thawing at 140°F (60°C) and 2 hours at 77°F (25°C).
- Subject each sample to either 1 or 6 F-T cycles.
- Conduct |E*| testing.

The unconditioned samples were not subjected to any F-T cycle, and their E* master curve was measured following the AASHTO procedure as described below.

The E* of the various mixtures is evaluated under multiple loading frequency and temperature. The test is conducted at frequencies of 25, 10, 5, 0.5, 0.1 Hz and at temperatures of 40, 70, 100, and 130°F as specified by AASHTO T342-11. Using the viscoelastic behavior of asphalt mixtures, the master curve can be developed as specified by AASHTO PP 61-10.

The E* ratio is the ratio of the E* of a sample subjected to a given number of F-T cycles to the E* of an unconditioned sample, this was found to show a good indication of the moisture resistance of the mixture.

Prior to the E* testing, the HMA mixtures were short-term conditioned by curing the loose mixture at 275°F (135ºC) for 4 hours prior to compaction according to AASHTO R 30 and the WMA mixtures were short-term conditioned by curing the loose mixture at the determined compaction temperature for 2 hours prior to compaction per NCHRP 9-43.

5.4.2. Impact of residual moisture on untreated mixtures

The objective of this task was to identify the effect of aggregate residual moisture on the resistance of the WMA mixes to moisture damage. Laboratory prepared WMA mixes were evaluated with and without residual moisture and with no anti-strip additives, to study the effect of insufficient aggregate drying during production.

Residual moisture is defined as the moisture remaining in the aggregates after heating the wet aggregates to the WMA mixing temperature for a certain calibrated period of time. The calibrated period is determined as the sufficient time to completely dry the wet aggregates at the HMA mixing temperature.

The aggregate blend was mixed with water, 2.0% above the absorption level, and left to marinate for 15 to 18 hours. The saturated aggregates were dried to the calibrated time previously determined and mixed with the asphalt binder.

The level of residual moisture varied depending on the WMA mixing temperature.

The difference in moisture susceptibility of the various mixtures with or without residual moisture was determined by comparing the dynamic modulus E* values at multiple F-T cycles as well as E* ratios after 1 and 6 F-T cycles. Details about the experimental program are shown in Table 23.

For each untreated mixture, the E* master curve was determined after 0, 1 and 6 F-T cycles (Figure 51 through Figure 65). Only the WMA mixtures had both dry aggregates as well as moist aggregates (Table 39).

5.4.2.1. Analysis of the Impact of residual moisture on untreated mixtures

It was observed that the mixtures with PG64-28NV and PG64-28TR always exhibited a lower E* master curve than the mixtures with PG64-22. All mixtures showed a drop in the master curve as they are subjected to more F-T cycles. The E* ratio plots were generated using the dynamic modulus values at 70˚F (21.1˚C) and 10 Hz (Figure 66 through Figure 72). The following trends were observed in the behavior of HMA and WMA mixtures:

- The E* ratios for HMA and WMA mixtures show a significant drop after 1 F-T cycle. At 6 F-T cycles the ratios did not show a high drop compared to 1 F-T cycle. The HMA mixtures cured for two hours at WMA compaction temperatures showed a similar drop for 1 F-T cycle and the 6 F-T cycles.
- The HMA and WMA mixtures with PG64-22 showed higher E* ratios for all F-T cycles except in the case of the HMA cured for 2 hours at WMA compaction temperature. Mixtures with PG64-28NV had the higher E* ratios at 1 F-T cycle and the ones with PG64-22 had the higher E* ratios at 6 F-T cycles.
- The mixtures with PG64-28TR showed a close drop in the E* ratios at 1 F-T cycle as the mixtures with PG64-28NV as well as at 6 F-T cycles, except in the case of the HMA mixtures where the PG64-28NV/TR HMA showed a higher drop in the 6 F-T cycle ratio than the PG64-28NV HMA.

- The HMA mixtures cured for 2 hours at the WMA compaction temperatures did not show any trend in their behavior nor were similar to any of the HMA or the WMA mixtures.

The E* value was also compared to the resulting E* ratio at 70˚F (21.1˚C) and 10 Hz (

Figure 73 through Figure 75). It should be noted that the HMA dynamic modulus samples were subjected to more short-term mixture aging than the WMA samples and the HMA samples cured for 2 hours at the WMA compaction temperature. The following observations can be made:

- The addition of the WMA additive Evotherm to the untreated_Dry mixtures subjected to 0 F-T cycle did not significantly drop the E* value.
- Using moist aggregates, the WMA mixtures with PG64-28NV and PG64-28TR showed a drop in the E* value compared to the HMA E* value while mixtures with PG64-22 had an E* value close to the HMA mixtures.
- In the case if 1F-T cycle, it was observed that WMA mixtures with PG64-22 always exhibited an E* and E* ratio close to the HMA mixtures.
- In the case of the mixtures containing moist aggregates, and at 6 F-T cycle, a higher E* and E* ratio for WMA mixtures were noticed as compared to the HMA mixtures (Figure 73).
- Evotherm reacted differently with PG64-28NV mixtures and a significant drop in the E* value was observed compared to the HMA mixtures. The E* ratios for the WMA mixtures were always lower than the HMA

mixtures except in the case of the WMA with Moist aggregates (Figure 74).

- In case of the mixtures with PG64-28TR, the WMA mixtures with Evotherm showed a significant drop in the E* value for 1 F-T cycle, while at the 6 F-T cycle, it was observed that the WMA mixtures had a higher E* than the HMA mixtures. The E* ratios for the WMA mixtures at 1 F-T cycle were lower than the HMA mixtures, but at 6 F-T cycle, the WMA E* ratio were higher than the HMA (Figure 75).

5.4.3. Impact of Anti-strip Additives

This task was designed to determine if the use of an anti-strip agent will improve the mixture resistance to moisture damage. Aggregates with residual moisture was used to prepare the various mixes and the impact of the anti-strip additive was evaluated by measuring the dynamic modulus E* at 0 and 6 F-T cycles for the various mixes. Details about the experimental program are shown in Table 24 .

5.4.3.1. Analysis of the Impact of Anti-strip Additives

The E* master curve plots for all mixtures are presented in Figure 76 to Figure 93 and the E* ratios for 6 F-T cycle are shown in Figure 94 to Figure 102 for lime-treated mixtures, Figure 103 to Figure 111 for liquid-treated mixtures and for the untreated mixtures Figure 112 to Figure 120.

For the Lime-treated mixtures:

- Mixtures with PG64-22 had a high E* value compared to the other mixtures, and PG64-28NV Evotherm mixtures with moist aggregates exhibited a large E* ratio and were capable of presenting no change in the E* value.

- For the PG64-28NV/TR HMA mixtures, they had a similar behavior for the mixtures with PG64-28NV and even they had a higher E* ratio, while at the WMA levels, their behavior was closer to the WMA mixtures with PG64-22.
- HMA mixtures cured for 2 hours at WMA compaction temperature had the E* ratios for different mixtures dispersed compared to the HMA and WMA mixtures.
- The lime helped all the mixes to maintain a high E* ratio and a close E* value compared to the initial value.
- The addition of Evotherm to the mixtures with PG64-28NV and PG64-28TR decreased the E* value of those mixes compared to the HMA mixtures.
- In case of the mixtures with PG64-22, all had approximately the same E* value.
- The HMA cured for 2 hours at the WMA compaction temperature with PG64-28NV showed a close value of E* to the WMA mixtures, while the mixture with PG64-28TR value was closer to the HMA mixtures.

For the Liquid-treated mixtures:

- The anti-strip additive had approximately the same effect on all HMA and WMA mixtures as they all had a close E* ratio.

- The WMA E* ratio was slightly better than the HMA E* ratios for all mixtures.
- In case of the mixtures with PG64-22, the E* ratio of the HMA cured for 2 hours at WMA compaction temperature had a closer behavior to the WMA mixture, while for mixtures with PG64-28NV and PG64-28TR, its behavior was closer to the HMA mixtures.
- The highest value for the E* was observed for the PG64-22 HMA mixture.
- It was observed that the presence of the WMA Evotherm did reduce the E* value for all mixes, but not in a significant way.

5.5. Impact of WMA Additives on Performance Characteristics of Asphalt Mixtures

This phase of the study evaluated the impact of WMA additives on the performance characteristics of the asphalt mixtures with and without anti-strip additives. The resistance to permanent deformation was evaluated at the un-aged stage because this is a short-term distress mode.

5.5.1. Permanent Deformation

The resistance of various mixes to permanent deformation was evaluated by measuring the FN for each mix following AASHTO TP 79-11 test protocol. The 4 inches x 6 inches samples with a 7.0% air voids were tested at 58˚C (LTPPBind Version 3.1) under repeated haversine axial compressive load pulse of 0.1s followed by 0.9s rest period without confinement. The resulting permanent axial strains are measured as a function of the load cycles and numerically differentiated to calculate the FN. The FN is defined as the number of load cycles corresponding to the minimum rate of change of permanent axial strain during a repeated-load test. The experimental program for phase II is detailed in Table 25 and the average FN values is shown in Table 26.

5.5.1.1. Analysis of FN

The following observations can be made:

- The PG64-28NV/TR HMA cured for 2 hours at the WMA compaction temperature and treated with lime presented the highest FN compared with the other mixtures.
- All PG64-22 mixtures presented a same trend in the behavior, the HMA had the highest FN followed by the HMA cured for 2 hours at the WMA compaction temperature and then by the WMA_Evo.
- Mixtures with PG64-28NV and PG64-28TR presented a higher FN for all cases than the mixtures with PG64-22.
- The untreated and liquid-treated HMA and WMA_Evo with PG64-28NV and PG64-28TR had close FN values.
- The addition of the WMA additive Evotherm was found to highly affect the FN of the mixtures. When using the PG64-22 mixtures a reduction of more than 50% of the FN was observed (Figure 121).
- The WMA(NV)_Evo mixtures showed a reduction in the FN of around 40 % (Figure 122).
- Evotherm performed the best with the untreated mixtures and lime-treated mixtures with PG64-28TR, where a reduction of only 10 to 15% in the FN was observed compared to the HMA FN, while it matched the PG64-28NV mixtures when liquid anti-strip was used (Figure 123).

A summary of the FN for all mixtures is shown in Figure 124; it can be observed that mixtures with PG64-28NV and PG64-28TR had a higher FN than the ones with PG64-22.

CHAPTER 6 Summary and Conclusions

6.1. Summary and Conclusions of Additional Work for Phase I

The additional work on Phase I of this laboratory research documented the resistance of various mixtures to permanent deformation by measuring the FN for each mixture, and also the resistance of untreated mixtures to fatigue cracking using the flexural beam fatigue test and by running a 3D-Move analysis.

The following conclusions can be made:

- The HMA mixtures and WMA Sasobit mixtures with PG64-22 showed a similar resistance to permanent deformation with and without additives.
- The PG64-22 WMA mixtures containing Advera had the lowest resistance to permanent deformation. The addition of anti-strip additives did not improve the mixture resistance to permanent deformation.
- The addition of lime significantly improved the resistance to permanent deformation of the mixtures with PG64-28NV and PG64-28TR.
- The liquid anti-strip did not significantly improve the resistance to permanent deformation, and even reduced the resistance of some mixtures.
- The HMA mixtures with PG64-28NV showed the better resistance to fatigue cracking than other mixtures.
- To better evaluate the fatigue life of the different mixtures, the dynamic modulus effect was incorporated in the 3D-Move fatigue analysis. The addition of a WMA additive will decrease the fatigue life.
- Also it was observed that WMA mixtures with Sasobit always exhibited a higher resistance to fatigue cracking than the Advera mixtures.

- HMA and WMA mixtures with PG64-28NV/TR have exhibited a close behavior in relation to fatigue resistance.
- The measured dynamic modulus was incorporated to evaluate the strain at the bottom of the flexible pavement layer.

6.2. Summary and Conclusions of Phase II

Phase II of this laboratory research effort evaluated the impact of WMA additives on the performance of the asphalt mixtures in term of their resistance to moisture damage and permanent deformation. The research effort included the development of different mixture designs according to NDOT and Caltrans specifications, the evaluation of resistance to moisture damage of the different mixtures using the dynamic modulus test, and the evaluation of the permanent deformation using the FN test.

The following conclusions can be made:

- The residual moisture retained in the aggregates due to the lower mixing temperature of the WMA had a significant effect on reducing the resistance of the mixtures to moisture damage especially with the PG64-28NV and PG64-28TR.
- The use of hydrated lime in the mixtures significantly reduces the effect of residual moisture and totally eliminates it for some mixtures will eliminate it.
- The liquid anti-strip did not significantly improve the resistance to moisture damage in the case of mixtures with PG64-22, while it had a better effect on mixtures with PG64-28NV and PG64-28TR.

- The WMA additive had a significant effect on reducing the FN of mixtures with PG64-22 and PG64-28NV while its effect was minimal on the mixtures with PG64-28TR.
- The lime-treated mixtures with PG64-28NV and PG64-28TR always showed an improvement in the FN compared to the untreated mixtures.
- Mixtures with PG64-22 had a poor resistance to permanent deformation.

This research effort showed that residual moisture have a big impact on the mixtures performance, and proper precautions should be taken like allowing the aggregates to properly dry and employing a proper anti-strip additive. The use of a terminal blend tire rubber modified binder such as the PG64-28TR along with hydrated lime and a WMA additive can create a mixture that has an acceptable resistance to moisture damage and permanent deformation as well as a good resistance to fatigue cracking.

6.3. Comparative Analysis

The research aimed to evaluate different WMA technologies: Advera, Sasobit and Evotherm. However, the remaining materials were only sufficient to perform the additional work from that phase, that meant that a new batch of material had to be sampled. Even though the new batched material had the same source as the previous ones, testing showed a difference in the properties and performance. Because of that difference, the study had to be divided into two phases: this meant developing a mix design for Evotherm different than the ones used for Advera and Sasobit.

A direct comparison between the three WMA technologies will be incorrect, therefore what this discussion will aim to achieve is a behavior comparison and analysis of each WMA technology compared to its relative control HMA mixture. The different experiments will be addressed separately.

The analysis and conclusions of Advera and Sasobit behavior in regards to moisture damage will be drawn from previous work (4).

6.3.1. Resistance to Moisture Damage

- The moisture damage effect was significant on PG64-22 Advera mixture, and that was revealed in the reduction of the dynamic modulus.
- In the case of the PG64-22 Sasobit mixture, the moisture damage was minimal, and a moderate reduction in the dynamic modulus was observed.
- The moisture damage effect was similar with the PG64-22 Evotherm mixture and the PG64-22 Sasobit.
- The dynamic modulus of PG64-28NV Advera mixture was closely similar to the HMA mixture.
- The dynamic modulus of PG64-28NV Sasobit mixture has shown a significant increase compared to the HMA mixture.
- The dynamic modulus of PG64-28NV Evotherm mixture was reduced compared to the HMA mixture and the moisture damage had a significant impact on it.
- The PG64-28NV/TR Advera mixture presented a moderate decrease in the dynamic modulus compared to the HMA mixture
- The dynamic modulus of the PG64-28NV/TR Sasobit mixture were moderately higher than the HMA mixture

- The dynamic modulus of PG64-28NV/TR WMA Evotherm mixture performed similarly to the HMA mixture and was minimally impacted by the effect of the moisture damage.

From those observations it can be concluded that Sasobit would be the better WMA additive, but an additional investigation will reveal that Evotherm had always maintained a high E* ratio followed by Sasobit and then Advera. This will imply that even though Evotherm might reduce the dynamic modulus values of some mixtures at 0 FT, it showed the capability of minimizing the drop in the E* after multiple FT cycles.

6.3.2. Impact of Anti-strip additives

- PG64-22 Mixtures
    - Sasobit and Evotherm WMA mixtures performed closely similar to HMA mixtures.
    - Advera WMA mixture performance was moderately inferior compared to HMA mixture.
    - The addition of lime to all WMA mixtures showed a significant increase in their performance and, after 6 FT cycles, it was noticed that the reduction in the dynamic modulus in comparison to the one at 0 FT could be considered moderate while, in the case of the untreated or liquid-treated mixtures, it was significant.
- PG64-28NV and PG64-28NV/TR mixtures
    - Sasobit WMA mixtures performance was significantly better than the HMA mixtures.

  - Advera WMA mixtures performance was moderately inferior when compared to the HMA mixtures.
  - Evotherm WMA mixtures performance followed a similar trend as the Advera WMA mixture.
  - In the case of mixtures with Evotherm at 0 FT cycle, the addition of a liquid anti-strip produced a slightly better mixture, but after 6FT cycles, the lime-treated mixtures had the better performance. The same trend was observed for PG64-28NV Sasobit and PG64-28NV/TR Advera.

In conclusion, the addition of an anti-strip agent to a mixture will increase its ability to resist moisture damage, in particular the hydrated lime, which has shown a better performance with all type of mixtures in comparison to the liquid anti-strip. In this case, Sasobit was observed to be the more compatible WMA technology with lime, given that it has shown the least reduction in the E* compared to Advera and Evotherm. The interesting observation is that the mixtures with PG64-28NV and PG64-28NV/TR were capable off showing a similar behavior to each other depend less on the WMA additive or the mix design.

6.3.3. Resistance to Permanent Deformation (FN)

- In the case of mixtures with PG64-22 and PG64-28NV, Advera and Evotherm had a similar effect; they both decreased the FN values in a comparable trend depending on the mixture type, untreated, lime-treated or liquid-treated.

- Sasobit on the other hand, was capable of improving the FN for most of the mixtures with PG64-22 and PG64-28NV.
- In the case of untreated and liquid-treated mixtures with PG64-28NV/TR, Sasobit, again, improved the FN while Advera had created a mixture with a FN considerably similar to the HMA control mix.
- Evotherm conversely to Sasobit and Advera, decreased the FN of all mixtures with PG64-28NV/TR.

It was observed that a combination of a modified binder, hydrated lime and any WMA technology would create a significantly more stable mix than an untreated or liquid-treated mixture containing a modified binder and a WMA technology.

From this comparative analysis, two conclusions could be made: a) the hydrated lime have proven to be a better anti-strip additive for the mixtures evaluated in this research, and was sometimes even capable of improving the mixtures performance, and b) the effect of a WMA additive on a mixture is highly dependent on the type of binder used and the existence of an anti-strip agent.

In summary, by identifying an optimum system to determine the binder type, binder content, the WMA additive and the anti-strip additive, a sustainable asphalt pavement can be designed so it will efficiently resist the moisture damage and permanent deformation.

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TABLES

Table 1: Summary of the Mixtures to be Evaluated in the Experimental Program – Previous Work– Phase I (4)

Warm Mix Additive	Anti-Strip Treatment	Asphalt Binder Type		
		PG 64-22	PG 64-28 NV/PM	PG64-28 NVTR/TR
None	Un-treated	X	X	X
	Lime-Treated	X	X	X
	Liquid-Treated	X	X	X
Advera	Un-treated	X	X	X
	Lime-Treated	X	X	X
	Liquid-Treated	X	X	X
Sasobit	Un-treated	X	X	X
	Lime-Treated	X	X	X
	Liquid-Treated	X	X	X

Table 2: Experimental Program to Evaluate the Impact of Residual Moisture in Aggregates – Previous Work – Phase I (4)

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	Residual Moisture	Dynamic Modulus, |E*|, Master Curve		
				$\|E^*\|_{dry}$ After 0 F-T*	$\|E^*\|_{Moist}$ after 1 F-T	$\|E^*\|_{Moist}$ after 6 F-T
PG64-22	Un-treated (i.e. no anti-stripping additives)	None	No	X	X	X
		Advera	No and Yes	X	X	X
		Sasobit	No and Yes	X	X	X
PG64-28NV/PM	Un-treated (i.e. no anti-stripping additives)	None	No	X	X	X
		Advera	No and Yes	X	X	X
		Sasobit	No and Yes	X	X	X
PG64-28NVTR/TR	Un-treated (i.e. no anti-stripping additives)	None	No	X	X	X
		Advera	No and Yes	X	X	X
		Sasobit	No and Yes	X	X	X

* F-T denotes "Freeze-Thaw"

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	Residual Moisture	$\|E^*\|_{dry}$ Master Curve after 0 F-T*	$\|E^*\|_{Moist}$ Master Curve after 6 F-T
PG64-22	Lime-treated	None	No	X	X
		Advera	Yes	X	X
		Sasobit	Yes	X	X
	Liquid-treated	None	No	X	X
		Advera	Yes	X	X
		Sasobit	Yes	X	X
PG64-28NV/PM	Lime-treated	None	No	X	X
		Advera	Yes	X	X
		Sasobit	Yes	X	X
	Liquid-treated	None	No	X	X
		Advera	Yes	X	X
		Sasobit	Yes	X	X
PG64-28NVTR/TR	Lime-treated	None	No	X	X
		Advera	Yes	X	X
		Sasobit	Yes	X	X
	Liquid-treated	None	No	X	X
		Advera	Yes	X	X
		Sasobit	Yes	X	X

* F-T denotes "Freeze-Thaw"

Table 3: Experimental Program to Evaluate the Impact of Long-term Aging – Previous Work– Phase I (4)

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	Residual Moisture	Dynamic Modulus, |E*|, at 70°F and 10 Hz				
				0 days (Dry)	14 days (14 days at room temp)	16 days (2 days at 185°F)	19 days (3 days at 185°F)	31 days (6 F-T* cycles)
PG64-22	Un-treated (i.e. no anti-stripping additives)	None	No	X	X	X	X	X
		Advera	Yes	X	X	X	X	X
		Sasobit	Yes	X	X	X	X	X
PG64-28NV/PM	Un-treated (i.e. no anti-stripping additives)	None	No	X	X	X	X	X
		Advera	Yes	X	X	X	X	X
		Sasobit	Yes	X	X	X	X	X
PG64-28 NVTR/TR	Un-treated (i.e. no anti-stripping additives)	None	No	X	X	X	X	X
		Advera	Yes	X	X	X	X	X
		Sasobit	Yes	X	X	X	X	X

* F-T denotes “Freeze-Thaw”

Table 4: Experimental Program to Evaluate the FN – Additional Work - Phase I

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	Residual Moisture	FN
PG64-22	Untreated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X
	Lime-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X
	Liquid-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X
PG64-28NV/PM	Untreated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X
	Lime-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X
	Liquid-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X
PG64-28NV/TR	Untreated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X
	Lime-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X
	Liquid-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Advera	No	X
		Sasobit	No	X

Table 5: Summary Table of the FN - Additional Work - Phase I

SUMMARY TABLE				
Binder	**Mix**	**FN untreated**	**FN Lime treated**	**FN Liquid treated**
PG64-22	HMA(22)	46	56	83
	WMA(22)_Adv	36	30	33
	WMA(22)_Sas	60	60	51
PG64-28NV	HMA(NV)	54	161	61
	WMA(NV)_Adv	38	111	59
	WMA(NV)_Sas	110	470	121
PG64-28TR	HMA(TR)	35	146	29
	WMA(TR)_Adv	43	66	35
	WMA(TR)_Sas	65	110	52

Table 6: Experimental Program to Evaluate the Fatigue Cracking - Additional Work -Phase

Asphalt Binder Type	**Mixture Type**	**WMA Additives/ Techniques**	**Residual Moisture**	**Beam Fatigue**
PG64-22	Untreated	None	No	--
		None (2h Curing @ WMA Comp Temp)	No	--
		Advera		--
		Sasobit	No	--
PG64-28NV/PM	Untreated	None	No	--
		None (2h Curing @ WMA Comp Temp)	No	--
		Advera		--
		Sasobit	No	--
PG64-28NV/TR	Untreated	None	No	--
		None (2h Curing @ WMA Comp Temp)	No	--
		Advera		--
		Sasobit	No	--

Table 7: Axle Configuration and Contact Pressure Distribution

Axle Configuration and Contact Pressure Distribution

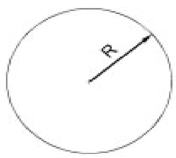
Selected Axle Configuration : User Selected Pre-Defined Axle/Tire Configuration (Uniform Pressu

User Selected Pre-Defined Axle/Tire Configuration (Uniform Pressure)

Reference Title for Axle	:	Dual/Tandem axles	
Tire Pressure	=	120	psi
Tire Load	=	4500	lb

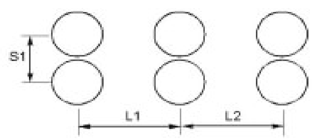
Geometry of Loaded Area

Geometry : Circle



R = 3.455 in

Axle Spacing



L1	=	48	in
L2	=	0	in
S1	=	14	in

Friction

Friction Type :

Note

1. As many as , six Single Loaded Areas can be specified
2. A Single Tire can be represented by using S1 = L1 = L2 = 0
3. A Single Axle Dual Tire can be represented by L1 = L2 = 0 and S1 > 0
4. A Tandem Axle Dual Tire can be represented by L2 = 0 and S1 > 0 , L1 > 0

Table 8: Thin Pavement Structure

Layer No	Layer Type	Material	Thickness (in)
1	Asphalt	Linear Elastic\Viscoelastic	4
2	Base	Linear Elastic	6
3	Subgrade	Linear Elastic	240

Table 9: Thick Pavement Structure

Layer No	Layer Type	Material	Thickness (in)
1	Asphalt	Linear Elastic\Viscoelastic	8
2	Base	Linear Elastic	10
3	Subgrade	Linear Elastic	240

Table 10: Pavement Layer Properties - HMA(22)

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	795290	1058147	1178335	1469377	1596769	1766415
70	173755	293991	360129	564197	670364	831211
100	35626	65001	82981	150501	191788	264597
130	10493	14395	18086	34156	56275	81149

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	18.56	15.52	14.35	11.95	11.11	10.15
70	31.63	29.26	28.35	24.81	23.34	21.32
100	30.83	32.14	32.94	32.6	32.35	31.47
130	25.1	28.1	30.12	33.62	34.83	36.48

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	1.4863	71.8
64	0.6883	75.3
70	0.3301	78.4

A,VTS

A	15.608
VTS	-5.459

Table 11: Pavement Layer Properties - WMA(22)_Adv

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
40	627071	893142	1020631	1341454	1480618	2055257
70	99909	183835	234018	401392	490590	627143
100	18413	33301	43794	88089	117807	171435
130	9101	8441	10160	19450	26955	41648

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
40	22.68	18.93	17.41	14.18	12.98	10.39
70	32.78	32.39	32.04	29.16	27.75	25.62
100	28.72	31.94	33.52	35.3	36	36.09
130	20.78	24.6	27.21	32.13	34.06	36.7

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	1.4863	71.8
64	0.6883	75.3
70	0.3301	78.4

A,VTS

A	15.608
VTS	-5.459

Table 12: Pavement Layer Properties - WMA(22)_Sas

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	428006	602342	688204	922440	1048188	1216867
70	106777	177236	216976	344175	411037	514739
100	22408	37434	46659	85645	109271	152000
130	8412	11618	13837	24845	32604	47108

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	22.7	19.68	18.47	15.71	14.57	13.39
70	30.61	29.5	29.06	26.39	25.28	23.73
100	27.05	29.8	31.29	32.5	33.01	32.97
130	20.44	24.42	26.8	30.46	32.26	34.73

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	1.4863	71.8
64	0.6883	75.3
70	0.3301	78.4

A,VTS

A	15.608
VTS	-5.459

Table 13: Pavement Layer Properties - HMA(NV)

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	380579	556582	636788	860291	962688	1103447
70	67443	124355	157801	273324	335400	427499
100	14446	24990	31930	62402	82367	120004
130	7448	10029	11480	19972	26665	40437

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	24.18	20.78	19.46	16.25	15	13.54
70	32.61	31.89	31.66	29.21	28.09	26.29
100	27.31	30.82	32.58	34.18	34.89	34.69
130	19.27	22.35	24.73	29.23	31.26	36.63

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	0.9309	60.1
64	0.5278	61
70	0.309333	62.6
76	0.183667	64.5

A,VTS

A	11.806
VTS	-4.059

Table 14: Pavement Layer Properties - WMA(NV)_Adv

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
40	472678	735148	872209	1222765	1390332	1613545
70	65825	124667	174867	325996	417660	564584
100	15954	25034	31618	62199	85188	137085
130	8064	10392	11741	19761	26455	39755

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
40	27.16	23.4	21.73	17.61	15.98	14.02
70	34.06	34.41	33.93	31.93	30.82	28.88
100	26.14	30.51	32.8	35.87	37.09	36.89
130	17.82	21.6	24.16	28.94	31.1	33.98

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	0.9309	60.1
64	0.5278	61
70	0.309333	62.6
76	0.183667	64.5

A,VTS

A	11.806
VTS	-4.059

Table 15: Pavement Layer Properties - WMA(NV)_Sas

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	614428	846730	960972	1247373	1377665	1537255
70	130698	222198	274605	443042	532820	664321
100	30414	50169	62589	114739	148156	207839
130	12459	17226	19962	34732	45020	64624

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	20.44	17.75	16.55	13.86	12.79	11.67
70	29.31	28.62	28.27	25.84	24.7	23.05
100	28.08	30.22	31.59	32.55	32.91	32.67
130	21.59	24.76	26.92	29.75	31.28	33.19

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	0.9309	60.1
64	0.5278	61
70	0.309333	62.6
76	0.183667	64.5

A,VTS

A	11.806
VTS	-4.059

Table 16: Pavement Layer Properties - HMA(TR)

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	461655	697245	811776	1097887	1227696	1387721
70	61793	125639	165212	304289	382319	502773
100	10972	19392	26013	56434	79009	122506
130	6154	7585	8702	15657	21719	33794

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	26.6	21.82	19.96	15.78	14.26	12.6
70	36.3	35.78	35.45	32.28	30.77	28.26
100	28.86	33.92	36.1	38.35	39.03	38.87
130	18.99	23.13	26.12	31.83	34.17	37.2

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	0.68875	64.3
64	0.3886	66.2
70	0.225233	68.2

A,VTS

A	12.364
VTS	-4.27

Table 17: Pavement Layer Properties - WMA(TR)_Adv

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	419933	668576	789392	1097404	1231129	1408897
70	46770	98075	135001	275282	360902	493853
100	11405	17869	22616	47809	67336	107541
130	6735	8494	9466	16012	21649	33214

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	**0.5 Hz**	**1 Hz**	**5 Hz**	**10 Hz**	**25 Hz**
40	29.19	24.33	22.35	17.5	15.67	13.57
70	35.9	37.09	37.24	34.88	33.42	30.97
100	25.6	30.91	33.73	37.62	39.11	39.71
130	17.03	20.61	23.06	27.97	30.36	33.23

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	0.68875	64.3
64	0.3886	66.2
70	0.225233	68.2

A,VTS

A	12.364
VTS	-4.27

Table 18: Pavement Layer Properties - WMA(TR)_Sas

Viscoelastic Material Properties

Asphalt Mix Properties

Reference Temperature = 70 °F

Dynamic Modulus

Temp (°F)	Dynamic Modulus E*(psi)					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
40	525907	785911	911611	1218897	1354459	1530342
70	88546	161814	210837	381062	475820	618779
100	19080	31858	40669	81852	111215	167083
130	8572	12937	14547	24983	33235	50082

Phase Angle

Temp (°F)	Phase Angle (Deg)					
	0.1 Hz	0.5 Hz	1 Hz	5 Hz	10 Hz	25 Hz
40	25.37	21.25	19.47	15.51	13.99	12.34
70	33.8	34.24	33.95	30.81	29.19	26.77
100	27.38	31.23	33.37	35.86	36.9	37.25
130	19.78	22.55	24.98	29.17	31.32	34.12

Superpave Binder Test Data

Temp (°F)	G*(psi)	Phase Angle (Deg)
58	0.68875	64.3
64	0.3886	66.2
70	0.225233	68.2

A,VTS

A	12.364
VTS	-4.27

Table 19 : Beam Fatigue N_f for All Mixtures – Phase I

Beam Fatigue test				
		mStrain	mStrain	mStrain
		800.00	500.00	300.00
Mix	Additive	N_f		
PG64-22	HMA(22)	15,882	68,136	331,728
	WMA(22)_Adv	11,247	17,865	29,543
	WMA(22)_Sas	35,648	55,731	90,577
PG64-28NV	HMA(NV)	24,400	177,421	1,532,664
	WMA(NV)_Adv	15,979	40,757	112,767
	WMA(NV)_Sas	25,289	88,385	344,377
PG64-28TR	HMA(TR)	13,753	70,249	413,436
	WMA(TR)_Adv	17,293	70,020	320,137
	WMA(TR)_Sas	10,428	51,423	291,279

Table 20: 3D-Move Dynamic and Static Analysis – Phase I

		mStrain			
Mix	**Additive**	**Thin Pavement Dynamic 3D-Move**	**Thin Pavement Static 3D-Move**	**Thick Pavement Dynamic 3D-Move**	**Thick Pavement Static 3D-Move**
PG64-22	HMA(22)	263.190	244.270	121.890	105.120
	WMA(22)_Adv	301.260	273.590	139.120	127.370
	WMA(22)_Sas	351.250	355.930	157.910	150.530
PG64-28NV	HMA(NV)	367.650	343.090	170.730	170.870
	WMA(NV)_Adv	322.790	292.530	151.540	150.810
	WMA(NV)_Sas	294.400	273.090	134.770	124.910
PG64-28TR	HMA(TR)	335.040	309.010	156.650	154.720
	WMA(TR)_Adv	342.670	315.150	162.100	166.320
	WMA(TR)_Sas	308.620	283.090	143.250	138.140

Table 21: N_f for All Mixtures Calculated from the mStrains Generated From a 3D-Move Dynamic Analysis – Phase I

3D-Move-Dynamic			
		N_f	
Mix	**Additive**	**Thin Pavement Dynamic 3D-Move**	**Thick Pavement Dynamic 3D-Move**
PG64-22	HMA(22)	497,667	5,404,837
	WMA(22)_Adv	29,421	62,959
	WMA(22)_Sas	77,965	166,726
PG64-28NV	HMA(NV)	649,634	16,550,744
	WMA(NV)_Adv	97,461	439,612
	WMA(NV)_Sas	362,095	2,899,358
PG64-28TR	HMA(TR)	281,802	3,940,516
	WMA(TR)_Adv	215,519	1,998,947
	WMA(TR)_Sas	264,571	3,582,232

Table 22: N_f for All Mixtures Calculated from the mStrains Generated From a 3D-Move Static Analysis – Phase I

3D-Move-Static			
		N_f	
Mix	**Additive**	**Thin Pavement Static 3D-Move**	**Thick Pavement Static 3D-Move**
PG64-22	HMA(22)	627,089	8,549,973
	WMA(22)_Adv	32,349	68,673
	WMA(22)_Sas	76,990	174,488
PG64-28NV	HMA(NV)	869,788	16,493,579
	WMA(NV)_Adv	118,576	443,861
	WMA(NV)_Sas	442,286	3,549,369
PG64-28TR	HMA(TR)	373,093	4,113,715
	WMA(TR)_Adv	276,485	1,851,784
	WMA(TR)_Sas	354,690	4,052,364

Table 23: Experimental Program to Evaluate the Impact of Residual Moisture – Phase II

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	Residual Moisture	Dynamic Modulus, |E*|, Master Curve		
				$\|E^*\|_{dry}$ After 0 F-T*	$\|E^*\|_{Moist}$ after 1 F-T	$\|E^*\|_{Moist}$ after 6 F-T
PG64-22	Untreated	None	No	X	X	X
		None (2h Curing @ WMA Comp Temp)	No and Yes	X	X	X
		Evotherm	No and Yes	X	X	X
PG64-28NV/PM	Untreated	None	No	X	X	X
		None (2h Curing @ WMA Comp Temp)	No and Yes	X	X	X
		Evotherm	No and Yes	X	X	X
PG64-28NV/TR	Untreated	None	No	X	X	X
		None (2h Curing @ WMA Comp Temp)	No and Yes	X	X	X
		Evotherm	No and Yes	X	X	X

* F-T denotes “Freeze-Thaw”

Table 24: Experimental Program to Evaluate the Impact of Anti-strip Additives – Phase II

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	Residual Moisture	$\|E^*\|_{dry}$ Master Curve after 0 F-T*	$\|E^*\|_{Moist}$ Master Curve after 6 F-T
PG64-22	Untreated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm			
	Lime-treated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm	Yes	X	X
	Liquid-treated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm	Yes	X	X
PG64-28NV/PM	Untreated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm			
	Lime-treated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm	Yes	X	X
	Liquid-treated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm	Yes	X	X
PG64-28NV/TR	Untreated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm			
	Lime-treated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm	Yes	X	X
	Liquid-treated	None	No	X	X
		None (2h Curing @ WMA Comp Temp)	No	X	X
		Evotherm	Yes	X	X

* F-T denotes “Freeze-Thaw”

Table 25: Experimental Program to Evaluate the FN - Phase II

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	Residual Moisture	FN
PG64-22	Untreated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X
	Lime-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X
	Liquid-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X
PG64-28NV/PM	Untreated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X
	Lime-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X
	Liquid-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X
PG64-28NV/TR	Untreated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X
	Lime-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X
	Liquid-treated	None	No	X
		None (2h Curing @ WMA Comp Temp)	No	X
		Evotherm	No	X

Table 26: Summary Table of the FN - Phase II

SUMMARY TABLE				
Binder	**Mix**	**FN untreated**	**FN Lime treated**	**FN Liquid treated**
PG64-22	HMA(22)	88	84	71
	WMA(22)_Evo	39	27	37
	HMA(22)-Cured 2h@ WMA Comp Temp	47	56	62
PG64-28NV	HMA(NV)	137	164	155
	WMA(NV)_Evo	83	106	97
	HMA(NV)_Cured 2h@ WMA Comp Temp	64	174	72
PG64-28TR	HMA(TR)	109	126	160
	WMA(TR)_Evo	95	118	84
	HMA(TR)-Cured 2h@ WMA Comp Temp	43	332	128

Table 27: Lockwood Stockpile / Aggregate Blend Gradation – Phase II

Aggregate Properties					
Nominal Maximum Aggregate Size, mm					19.5
Sieve Size	**%Passing**	**Control Points (NDOT T2C)**		**Control Points (CT Type A)**	
		Min	**Max**	**Min**	**Max**
37.5 mm (1 1/2")	100.0	--	--	--	--
25.0 mm (1")	100.0	100	100	100	100
19.0 mm (3/4")	91.0	88	95	90	100
12.5 mm (1/2")	77.5	70	85	70	90
9.5 mm (3/8")	67.7	60	78		
4.75 mm (No. 4)	52.0	43	60	45	55
2.36 mm (No. 8)	40.0			32	40
2.00 mm (No. 10)	36.2	30	44		
1.18 mm (No. 16)	27.4				
0.6 mm (No. 30)	19.1			12	21
0.425 mm (No. 40)	15.1	12	22		
0.3 mm (No. 50)	11.5				
0.15 mm (No. 100)	7.3				
0.075 mm (No. 200)	5.08	3	8	2	7
Aggregates	**Material Description**			**Bin %**	
Aggr. 1	Lockwood 1 inch			25.0%	
Aggr. 2	Lockwood 1/2 inch			15.0%	
Aggr. 3	Lockwood 3/8 inch			10.0%	
Aggr. 4	Lockwood CF			40.0%	
Aggr. 5	Wade Sand			10.0%	

Table 28: Lockwood Stockpile Gradation – Phase II

Seive Size (in)	Sieve Size (mm)	Lockwood 1"	Lockwood 3/4"	Lockwood 1/2"	Lockwood 3/8"	Lockwood CF	Wade Sand
1-1/2"	37.5	100.0	--	100.0	100.0	100.0	100.0
1"	25.4	100.0	--	100.0	100.0	100.0	100.0
3/4"	19.0	64.0	--	100.0	100.0	100.0	100.0
1/2"	12.5	10.0	--	100.0	100.0	100.0	100.0
3/8"	9.5	1.0	--	50.0	99.0	100.0	100.0
#4	4.75	1.0	--	1.0	25.0	98.0	99.0
#8	2.36	1.0	--	1.0	2.0	74.0	98.0
#10	2.00	1.0	--	1.0	1.0	65.0	97.0
#16	1.18	1.0	--	1.0	1.0	44.0	93.0
#30	0.600	1.0	--	1.0	1.0	28.0	74.0
#40	0.425	1.0	--	1.0	1.0	23.0	54.0
#50	0.300	1.0	--	1.0	1.0	19.0	34.0
#100	0.150	1.0	--	1.0	1.0	14.0	12.0
#200	0.075	0.4	--	0.6	0.5	11.0	4.4

Table 29: Lockwood Aggregate Properties – Phase II

Property	Test Results	NDOT Specification	NDOT Test Method	CT Specification	CT Test Method
Aggregate Blend Tests					
Percent Crushed (Coarse Agg.) - 1 Fractured Face	99	--	Nev. T230	90% Min	CTM 205
Percent Crushed (Coarse Agg.) - 2 Fractured Faces	96	80% Min	Nev. T230	75% Min	CTM 205
Percent Crushed (No. 4 to No. 8) - 1 Fractured Face	99	--	--	70% Min	CTM 205
Fine Aggregate Angularity	47.7	--	--	45% Min	AASHTO T304 (A)
Sand Equivalent	71	--	--	47 Min	CTM 217
Flat and Elongated Particles (by wt @ 5:1)	0.9	--	--	10% Min	ASTM D4791
Aggregate Source Tests					
Absorption of Coarse Aggregate	1.5	4% Max	AASHTO T85	--	CTM 206
Absorption of Fine Aggregate	2.4	4% Max	AASHTO T85	--	CTM 207
Specific Gravity of Fine Aggregate	2.57	2.85 Max	AASHTO T84	--	--
Specific Gravity of Coarse Aggregate	2.619	2.85 Max	AASHTO T84	--	--

Table 30: PG64-22 Specifications and Test Results – Phase II

Property	Test Results	NDOT Specification	NDOT Test Method	CT Specification	CT Test Method
Tests on Original Binder					
Flash Point, ^{0}C	274	--	--	230 Min	AASHTO T48
Solubility	NT	--	--	99% Min	AASHTO T44
Rotational viscosity at 135^{0}C, Pa·s	0.38	--	--	3.0 Max	AASHTO T316
Dynamic shear, G*/sin□ at 64^{0}C (10 rad/s), kPa	1.19	--	--	1.00 Min	AASHTO T315
Tests on Residue from RTFO, Nev. T728 (NDOT) / AASHTO T240 (CT)					
Mass loss, %	0.32	--	--	1.00% Max	AASHTO T240
Dynamic shear, G*/sin□ at 64^{0}C (10 rad/s), kPa	2.63	--	--	2.20 Min	AASHTO T315
Ductility at 25^{0}C, cm	NT	--	--	75 Min	AASHTO T51
Tests on Residue from Pressure Aging Vessel, AASHTO R28 @ 100^{0}C					
Dynamic shear, G*sin□ at 28^{0}C (10 rad/s), kPa	2740	--	--	5000 Max	AASHTO T315
Creep Stiffness at -6^{0}C S-value, MPa m-value	 58 0.350	--	--	 300 Max 0.300 Min	AASHTO T313

* NT denotes "Not Tested"

True Grade	High	Intermediate	Low
	65.4	23.25	-21

Table 31: PG64-28NV/PM Specifications and Test Results – Phase II

Property	Test Results	NDOT Specification	NDOT Test Method	CT Specification	CT Test Method
Tests on Original Binder					
Flash Point, ^{0}C	298	230 Min	AASHTO T48	230 Min	AASHTO T48
Solubility	NT	99.0 Min	AASHTO T44	98.5% Min	AASHTO T44
Rotational viscosity at 135^{0}C, Pa·s	0.715	3.0 Max	AASHTO T316	3.0 Max	AASHTO T316
Dynamic shear, G*/sin□ at 64^{0}C (10 rad/s), kPa	1.63	1.0 Min	AASHTO T315	1.00 Min	AASHTO T315
Ductility at 4^{0}C (5 cm/min), cm	NT	50 min.	Nev. T746	--	--
Sieve particulates retained	NT	0	Nev. T730	--	--
Toughness at 25^{0}C, in-lbs	NT	110 Min	Nev. T745	--	--
Tenacity at 25^{0}C, in-lbs	NT	75 Min	Nev. T745	--	--
Tests on Residue from RTFO, Nev. T728 (NDOT) / AASHTO T240 (CT)					
Mass loss, %	0.46	1.0% Max	Nev. T728	1.00% Max	AASHTO T240
Dynamic shear, G*/sin□ at 64^{0}C (10 rad/s), kPa	3.43	2.20 Min	AASHTO T315	2.20 Min	AASHTO T315
Dynamic shear, □ at 64^{0}C (10 rad/s), kPa	65.2	--	--	80% Max	AASHTO T315
Ductility at 4^{0}C (5 cm/min), cm	NT	25 Min	Nev. T746	--	--
Elastic Recovery at 25^{0}C, cm	NT	--	--	75% Min	AASHTO T301
Tests on Residue from Pressure Aging Vessel, AASHTO R28 @ 100^{0}C					
Dynamic shear, G*sin□ at 16^{0}C (10 rad/s), kPa	3594	5000 Max	AASHTO T315	5000 Max	AASHTO T315
Creep Stiffness at -18^{0}C S-value, MPa m-value	140 0.33	300 Max 0.300 Min	AASHTO T313	300 Max 0.300 Min	AASHTO T313

* NT denotes "Not Tested"

True Grade	High	Intermediate	Low
	68.8	**13.2**	**-31.5**

Table 32: PG64-28NV/TR Specifications and Test Results – Phase II

Property	Test Results	NDOT Specification	NDOT Test Method	CT Specification	CT Test Method
Tests on Original Binder					
Flash Point, ^{0}C	289	230 Min	AASHTO T48	230 Min	AASHTO T48
Solubility	NT	99.0 Min	AASHTO T44	98.5% Min	AASHTO T44
Rotational viscosity at 135^{0}C, Pa·s	0.99	3.0 Max	AASHTO T316	3.0 Max	AASHTO T316
Dynamic shear, G*/sin□ at 64^{0}C (10 rad/s), kPa	2.06	1.0 Min	AASHTO T315	1.00 Min	AASHTO T315
Ductility at 4^{0}C (5 cm/min), cm	NT	50 min.	Nev. T746	--	--
Sieve particulates retained	NT	0	Nev. T730	--	--
Toughness at 25^{0}C, in-lbs	NT	110 Min	Nev. T745	--	--
Tenacity at 25^{0}C, in-lbs	NT	75 Min	Nev. T745	--	--
Tests on Residue from RTFO, Nev. T728 (NDOT) / AASHTO T240 (CT)					
Mass loss, %	0.39	1.0% Max	Nev. T728	1.00% Max	AASHTO T240
Dynamic shear, G*/sin□ at 64^{0}C (10 rad/s), kPa	3.84	2.20 Min	AASHTO T315	2.20 Min	AASHTO T315
Dynamic shear, □ at 64^{0}C (10 rad/s), kPa	64.6	--	--	80% Max	AASHTO T315
Ductility at 4^{0}C (5 cm/min), cm	NT	25 Min	Nev. T746	--	--
Elastic Recovery at 25^{0}C, cm	NT	--	--	75% Min	AASHTO T301
Tests on Residue from Pressure Aging Vessel, AASHTO R28 @ 100^{0}C					
Dynamic shear, G*sin□ at 22^{0}C (10 rad/s), kPa	2708	5000 Max	AASHTO T315	5000 Max	AASHTO T315
Creep Stiffness at -18^{0}C S-value, MPa m-value	 170 0.309	 300 Max 0.300 Min	AASHTO T313	 300 Max 0.300 Min	AASHTO T313

* NT denotes "Not Tested"

True Grade	High	Intermediate	Low
	70.25	17.45	-30

Table 33: Summary of Mixture Optimum Binder Contents – Phase II

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	% Evotherm	Optimum Binder Content (% by TWA)
PG64-22	Untreated	None	--	5.70%
		Evotherm	0.40%	5.40%
	Lime-treated	None	--	5.70%
		Evotherm	0.40%	5.20%
	Liquid-treated	None	--	5.60%
		Evotherm	0.40%	5.50%
PG64-28NV/PM	Untreated	None	--	5.80%
		Evotherm	0.40%	5.80%
	Lime-treated	None	--	5.50%
		Evotherm	0.40%	5.40%
	Liquid-treated	None	--	5.50%
		Evotherm	0.40%	5.40%
PG64-28NV/TR	Untreated	None	--	5.80%
		Evotherm	0.30%	5.60%
	Lime-treated	None	--	5.55%
		Evotherm	0.30%	5.00%
	Liquid-treated	None	--	5.70%
		Evotherm	0.30%	5.30%

Table 34: Recommended Production Temperatures below Which the High Temperature Grade should be Increased One Grade

PG High Temperature Grade	Aging Index (AI)[1]											
	1.4	1.6	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	3.4	3.6
	Minimum WMA Mixing Temperature Not Requiring PG Grade Increase, °F											
52	<215	<215	<215	<215	<215	<215	220	220	225	225	230	230
58	<215	<215	<215	220	225	230	235	235	240	240	245	245
64	<215	<215	220	230	235	235	240	245	245	250	250	250
67	<215	220	230	235	240	245	250	255	255	255	260	260
70	<215	220	230	240	245	245	250	255	255	260	260	260
76	<215	225	235	245	250	255	260	260	265	265	265	270
82	<215	235	245	250	255	260	265	265	270	270	275	275

1. $AI = \frac{(G^*/\sin\delta)_{RTFOT}}{(G^*/\sin\delta)_{Tank}}$ at the high temperature performance grade temperature.

Table 35: Gyratory Compaction Effort – Phase II

Design ESALs[a]	Compaction Parameters			Typical Roadway Application[b]
(millions)	N initial	N design	N max	
< 0.3	8	50	75	Applications include roadways with very light traffic volumes such as local roads, country roads, and city streets where truck traffic is prohibited or at a very minimal level. Traffic on these roadways would be considered local in nature, not regional, intrastate, or interstate. Special purpose roadways serving recreational sites or areas may also be applicable to this level.
0.3 to < 3	7	75	115	Applications include many collector roads or access streets. Medium-trafficked city streets and the majority of country roadways may be applicable to this level.
3 to < 30	8	100	160	Applications include many two-lane, multilane, divided, and partially or completely controlled access roadways. Among these are medium to highly trafficked city streets, many state routes, U.S. highways, and some rural Interstates.
≥ 30	9	125	205	Applications include the vast majority of the U.S. Interstate System, both rural and urban in nature. Special applications such as truck-weighing stations or truck-climbing lanes on two-lane roadways may also be applicable to this level.

[a] The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design the ESALs for 20 years.

[b] As defined by A Policy on Geometric Design of Highways and Stress, 1994, AASHTO.

Note 1 – When specified by the Agency and the top of the design layer is ≥ 100 mm from the pavement surface and the estimated design traffic level is ≥ 0.3 million ESALs, decrease the estimated design traffic level by one, unless the mixture will be exposed to significant mainline construction traffic prior to being overlaid. If less than 25 percent of a construction lift is within 100 mm of the surface, the lift may be considered to be below 100 mm for the mixture design purposes.

Note 2 – When it is estimated that the design traffic level is between 3 and <10 million ESALs, the Agency may, at its discretion, specify $N_{initial}$ at 10 N_{design} at 75, and N_{max} at 115.

Table 36: Degree of Aggregate Coating and Compactability Requirements – Phase II

Property	**Criteria**
Degree of Aggregate Coating	100% of Particles
Compactability @ Compaction Temp.	$N92 < 0.35N_{design}$
Compactability @ Compaction Temp. minus 55°F (30°C)	N92 @ Compaction Temp. minus 55°F (30°C) < 1.25N92 @ Compaction Temp.

Table 37: Degree of Aggregate Coating of Lockwood Asphalt Mixture at Various Mixing Temperatures – Phase II

Asphalt Binder Type	Mixture Type	WMA Additives/ Techniques	Mixing Temp, ^{0}F	% Aggregate Coated
PG64-22	Untreated	None	308	100%
		Evotherm	255	100%
	Lime-treated	None	308	100%
		Evotherm	265	100%
	Liquid-treated	None	308	100%
		Evotherm	255	100%
PG64-28NV/PM	Untreated	None	320	100%
		Evotherm	275	100%
	Lime-treated	None	320	100%
		Evotherm	275	100%
	Liquid-treated	None	320	100%
		Evotherm	275	100%
PG64-28NV/TR	Untreated	None	320	100%
		Evotherm	275	100%
	Lime-treated	None	320	100%
		Evotherm	275	100%
	Liquid-treated	None	320	100%
		Evotherm	275	100%

Table 38: Compactability of WMA Mixtures with PG 64-22, PG 64-28 NV/PM, and PG 64-28 NVTR/TR binder – Phase II

Asphalt Binder	WMA Additive	Mix Type	Compaction Temp. (°C)	Average Number of Gyration at		Compactability Ratio	Criterion (Ratio < 1.25)
				Compaction Temp.	Compaction Temp. minus 30°C		
PG64-22	Evotherm	Untreated	230	22.0	24.5	1.11	Pass
		Lime-treated	245	21.5	22.5	1.05	Pass
		Liquid-treated	230	31.5	34.5	1.10	Pass
PG64-28NV	Evotherm	Untreated	250	8.0	9.5	1.19	Pass
		Lime-treated	250	19.0	23.0	1.21	Pass
		Liquid-treated	250	15.5	16.0	1.03	Pass
PG64-28TR	Evotherm	Untreated	250	18.0	22.0	1.22	Pass
		Lime-treated	250	22.5	25.0	1.11	Pass
		Liquid-treated	250	28.5	31.5	1.11	Pass

Table 39: Measured Residual Moisture Content of Dynamic Modulus Samples – Phase II

Asphalt Binder Type	Mixture	WMA Additives/ Techniques	% Residual Moisture
PG64-22	Untreated	Evotherm	0.54%
	Lime-treated	Evotherm	0.36%
	Liquid-treated	Evotherm	0.68%
PG64-28NV/PM	Untreated	Evotherm	0.88%
	Lime-treated	Evotherm	0.75%
	Liquid-treated	Evotherm	0.46%
PG64-28NV/TR	Untreated	Evotherm	0.78%
	Lime-treated	Evotherm	0.68%
	Liquid-treated	Evotherm	0.27%

FIGURES

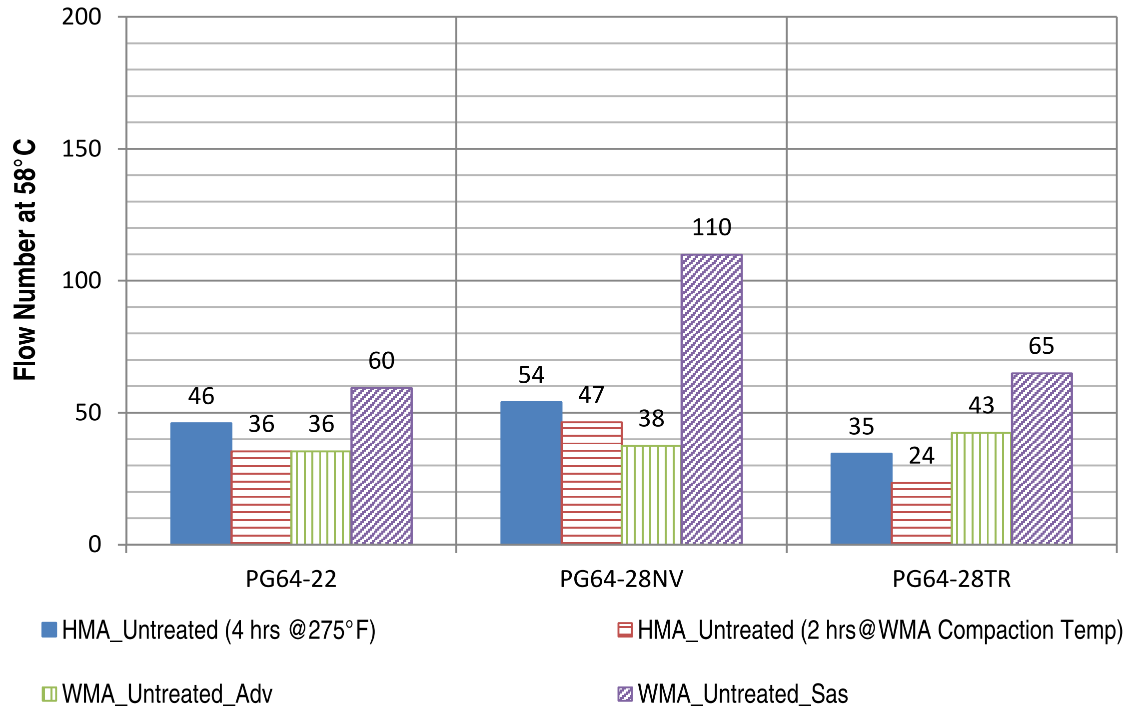


Figure 1: FN Untreated HMA Vs WMA - Phase I

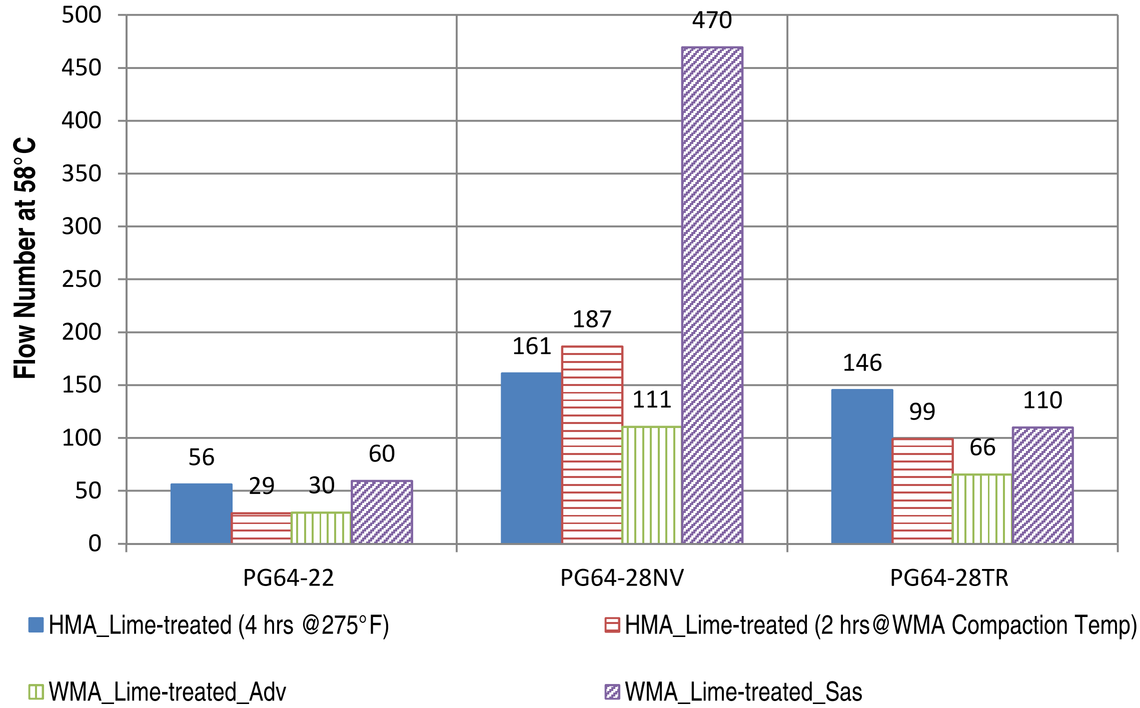


Figure 2: FN Lime-treated HMA Vs WMA - Phase I

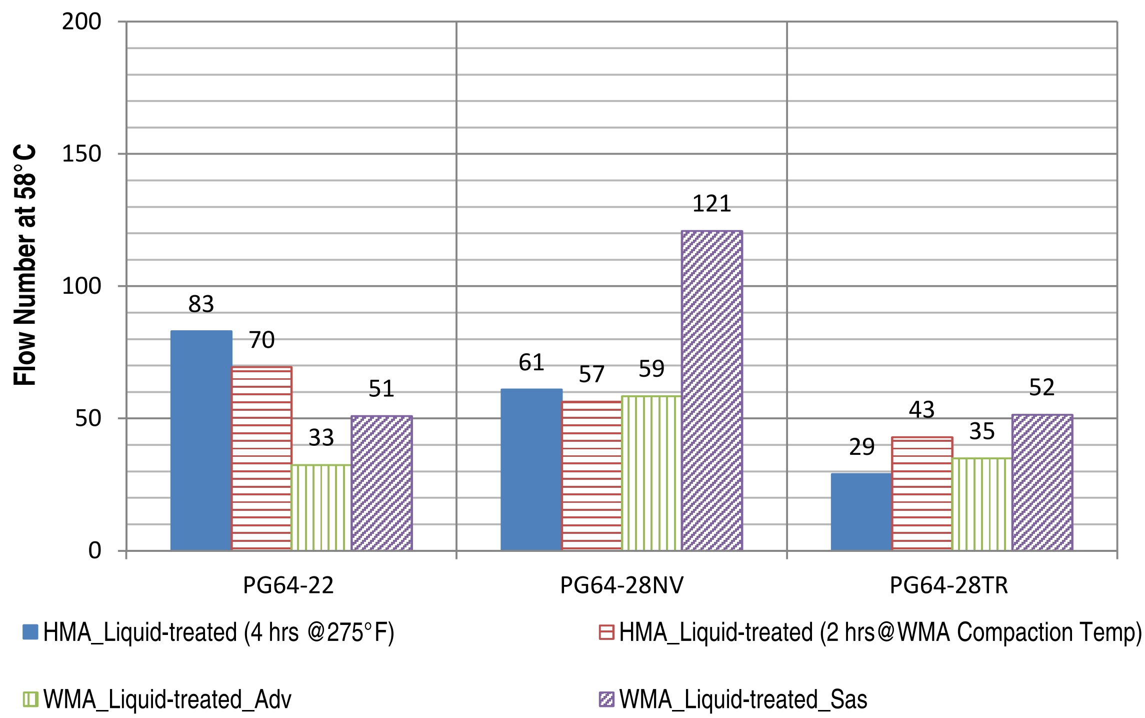


Figure 3: FN Liquid-treated HMA Vs WMA - Phase I

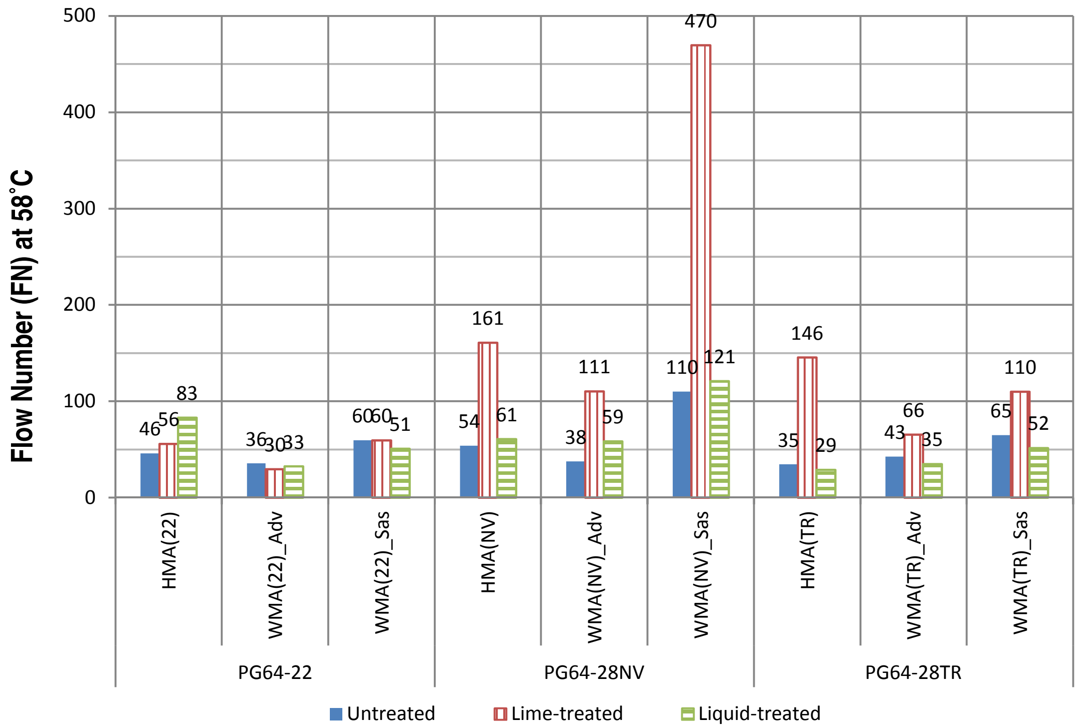


Figure 4: FN Summary - Phase I

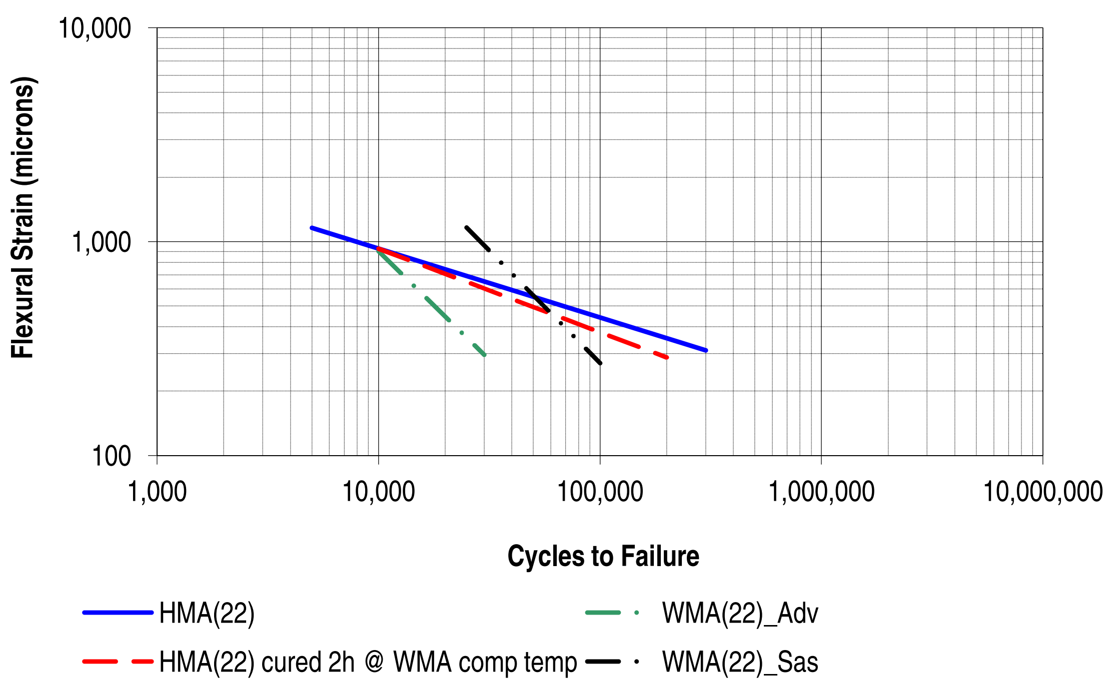


Figure 5: Beam Fatigue Model Comparison for Mixtures with PG64-22 - Phase I

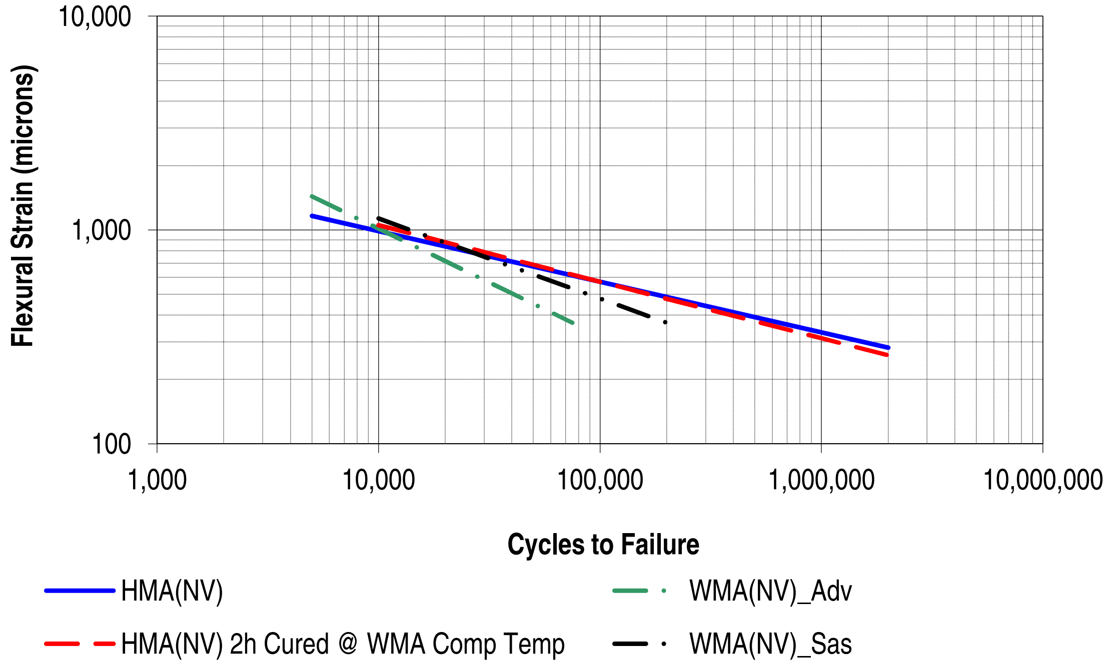


Figure 6: Beam Fatigue Model Comparison for Mixtures with PG64-28NV - Phase I

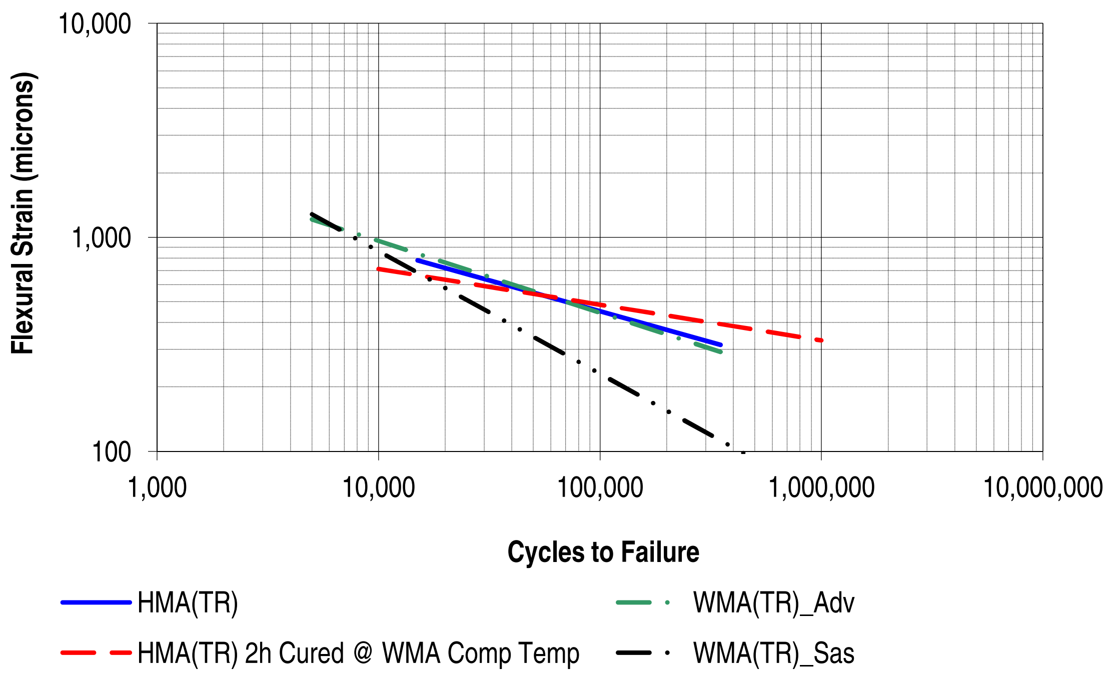


Figure 7: Beam Fatigue Model Comparison for Mixtures with PG64-28TR - Phase I

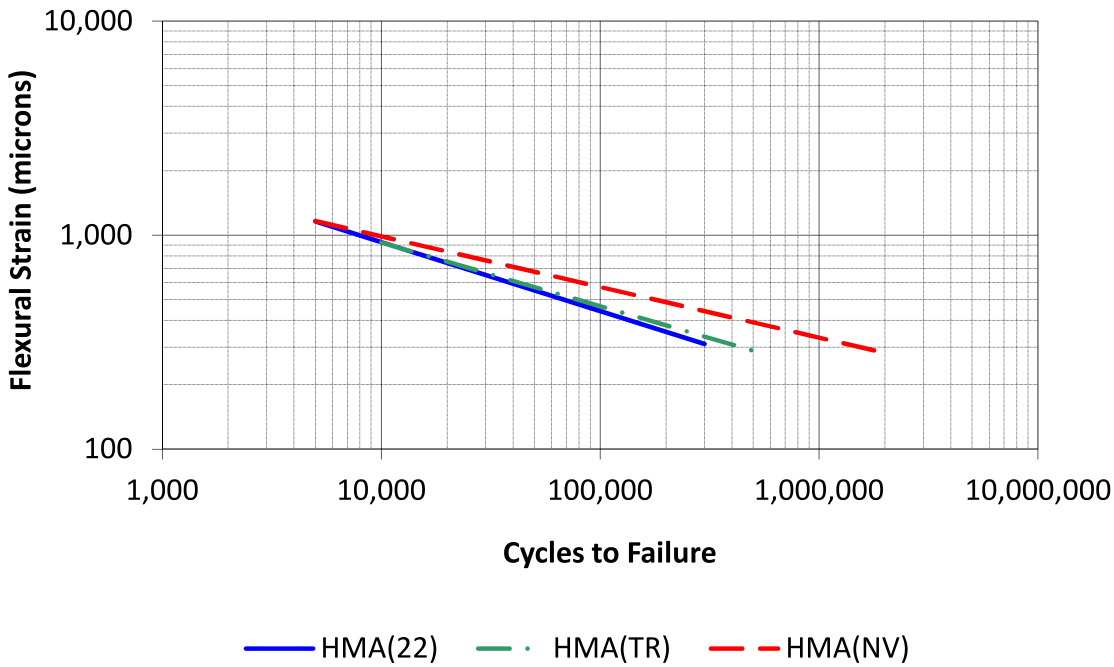


Figure 8: Beam Fatigue Model Comparison for HMA Mixtures - Phase I

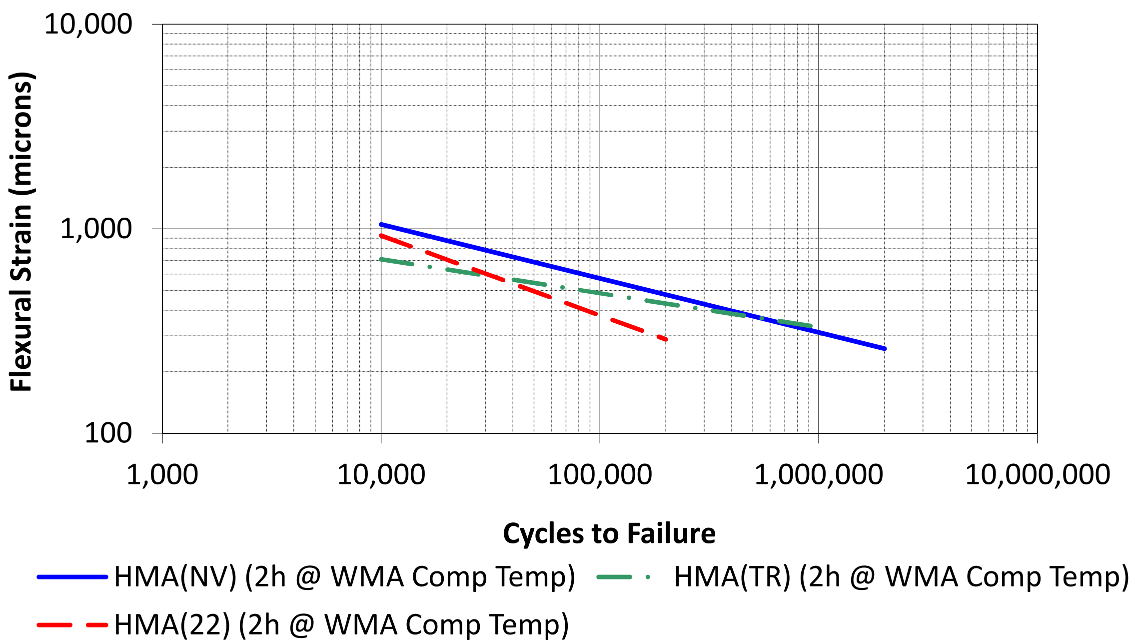


Figure 9: Beam Fatigue Model Comparison for HMA Mixtures Cured for 2h @ WMA Compaction Temperature - Phase I

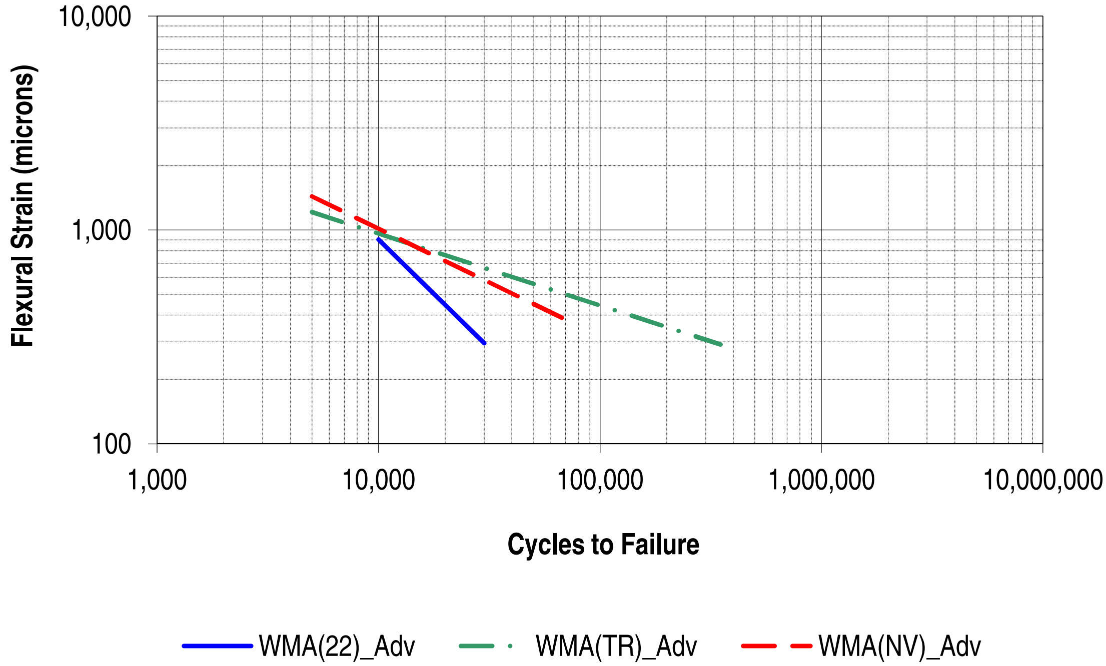


Figure 10: Beam Fatigue Model Comparison for WMA Mixtures with Advera - Phase I

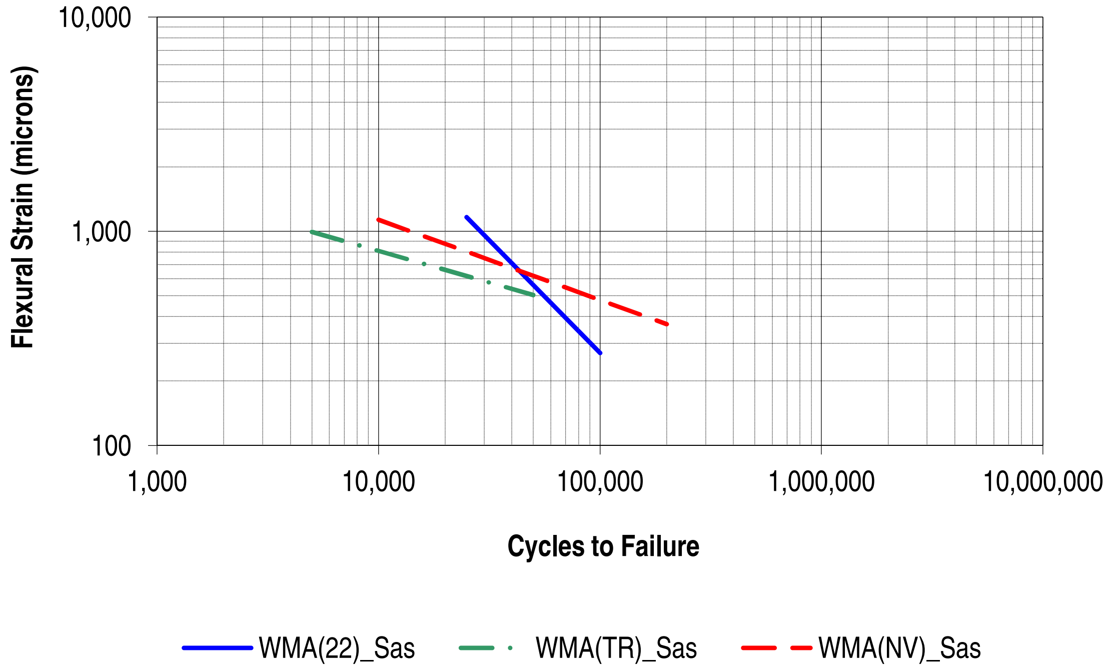


Figure 11: Beam Fatigue Model Comparison for WMA Mixtures with Sasobit - Phase I

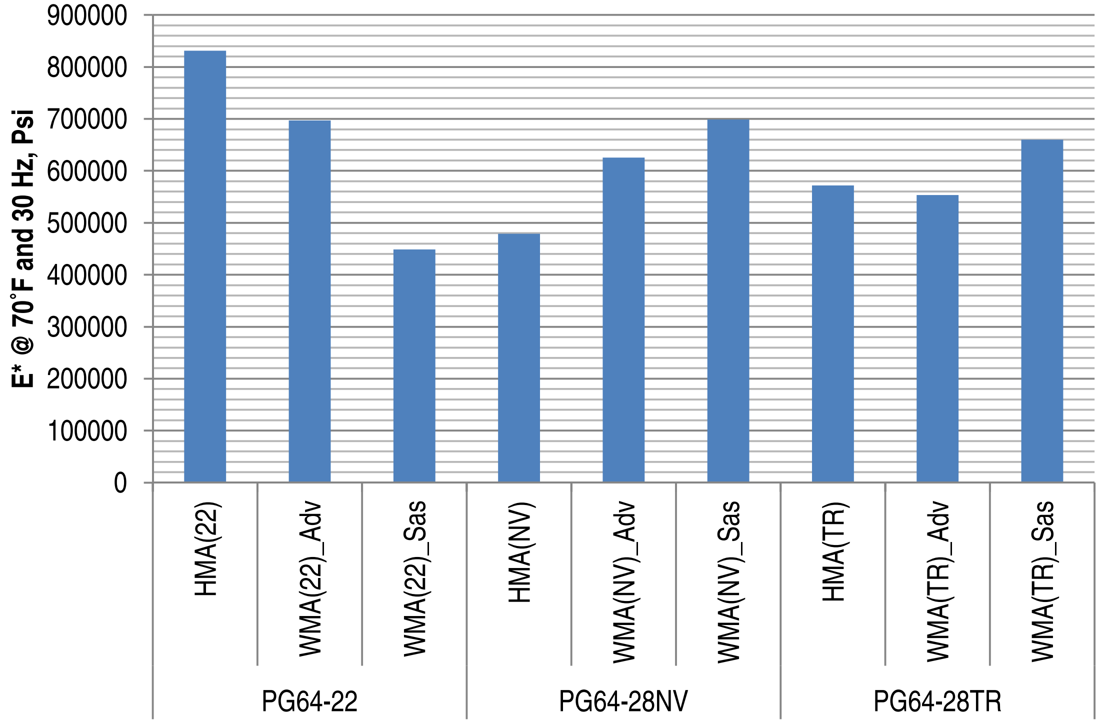


Figure 12: Dynamic Modulus E* of All Mixtures Used for 3D-Move Static Analysis for Thin Pavement - Phase I

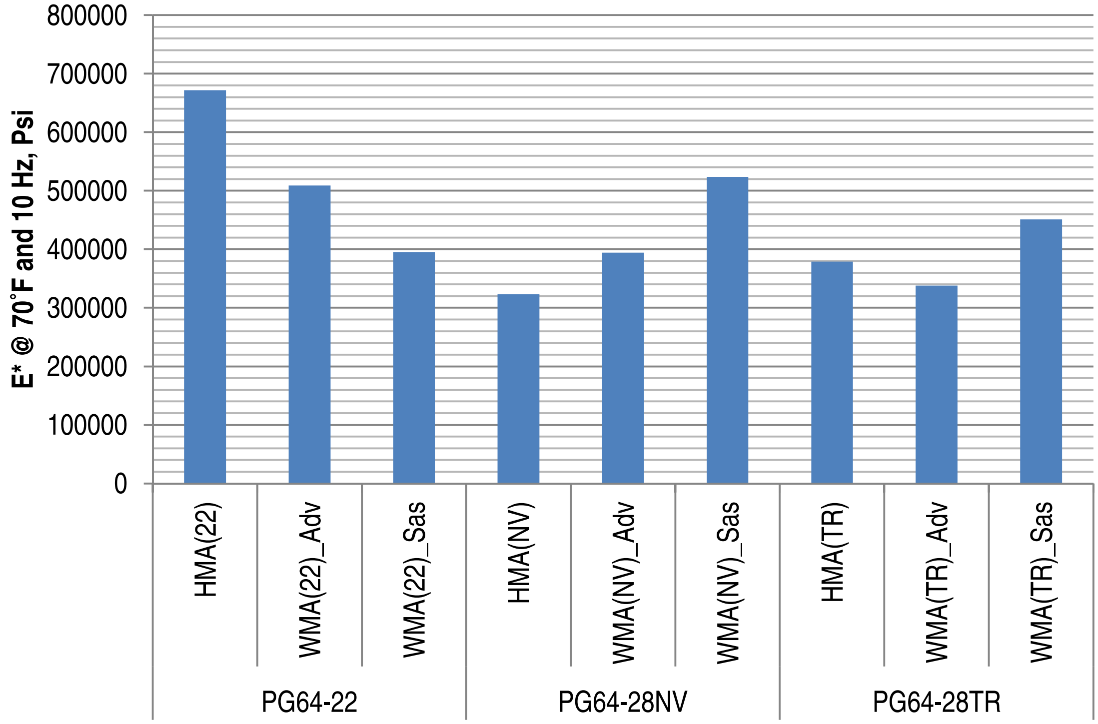


Figure 13: Dynamic Modulus E* of all Mixtures Used for 3D-Move Static Analysis for Thick Pavement - Phase I

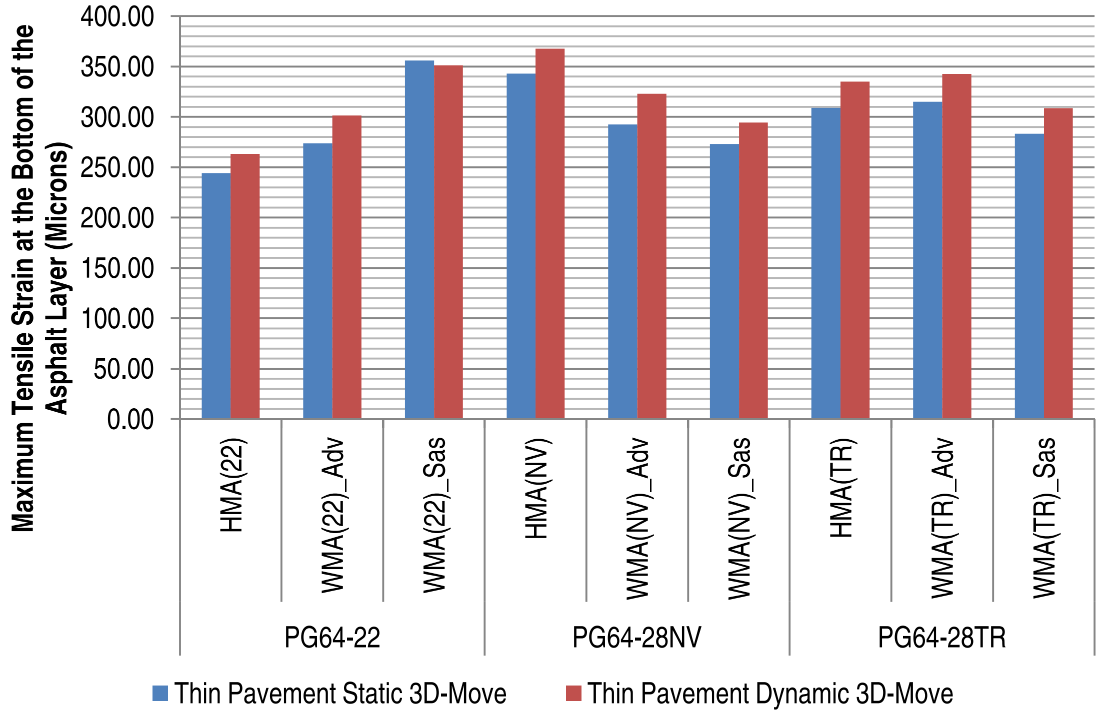


Figure 14: 3D-Move Analysis of the Max Tensile at Bottom of Asphalt layer for Thin Pavement - Phase I

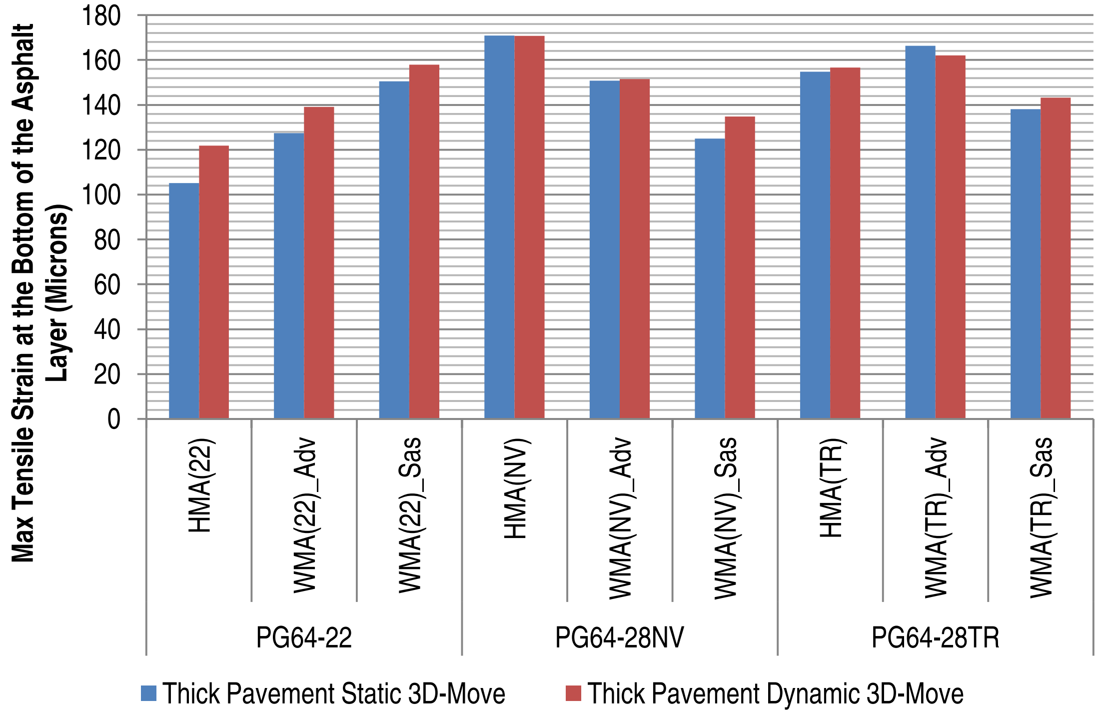


Figure 15: 3D-Move Analysis of the Max Tensile at Bottom of Asphalt layer for Thick Pavement - Phase I

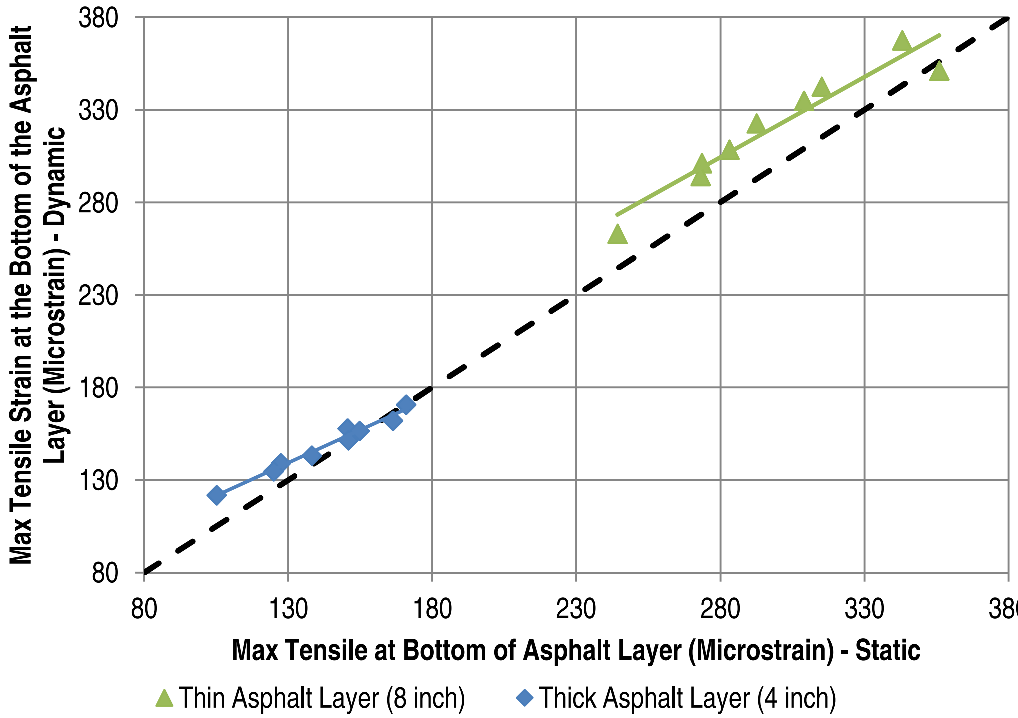


Figure 16: Max Tensile at Bottom of Asphalt layer Static Vs Dynamic - Phase I

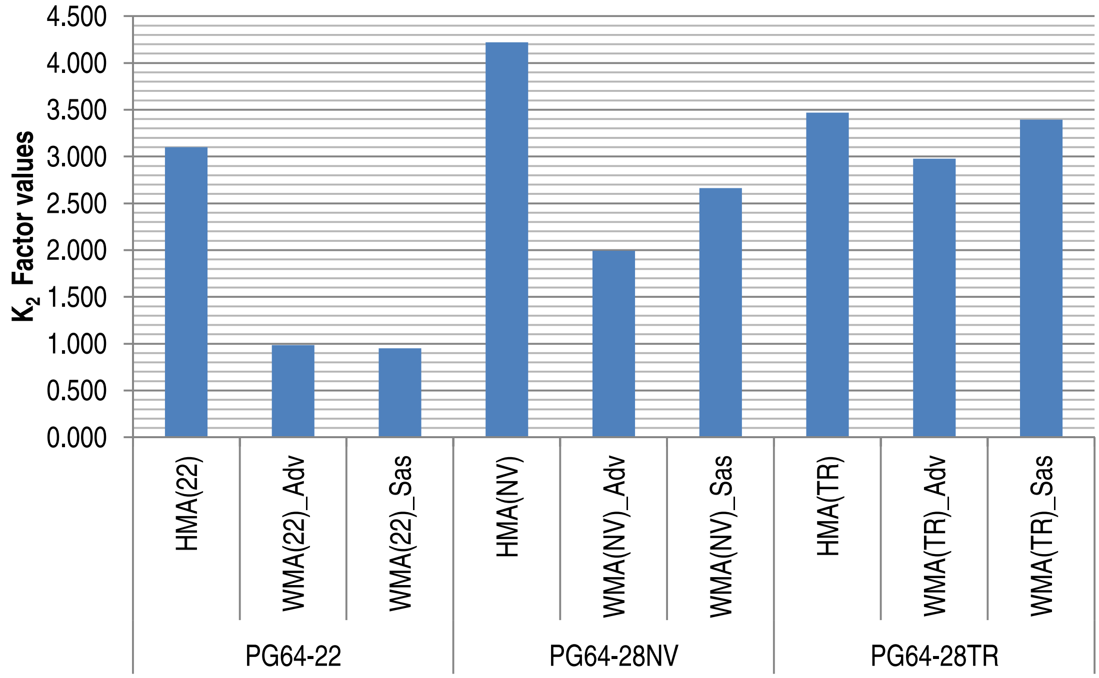


Figure 17: K_2 factors for Different Mixtures from the Fatigue Relation Developped in the Lab - Phase I

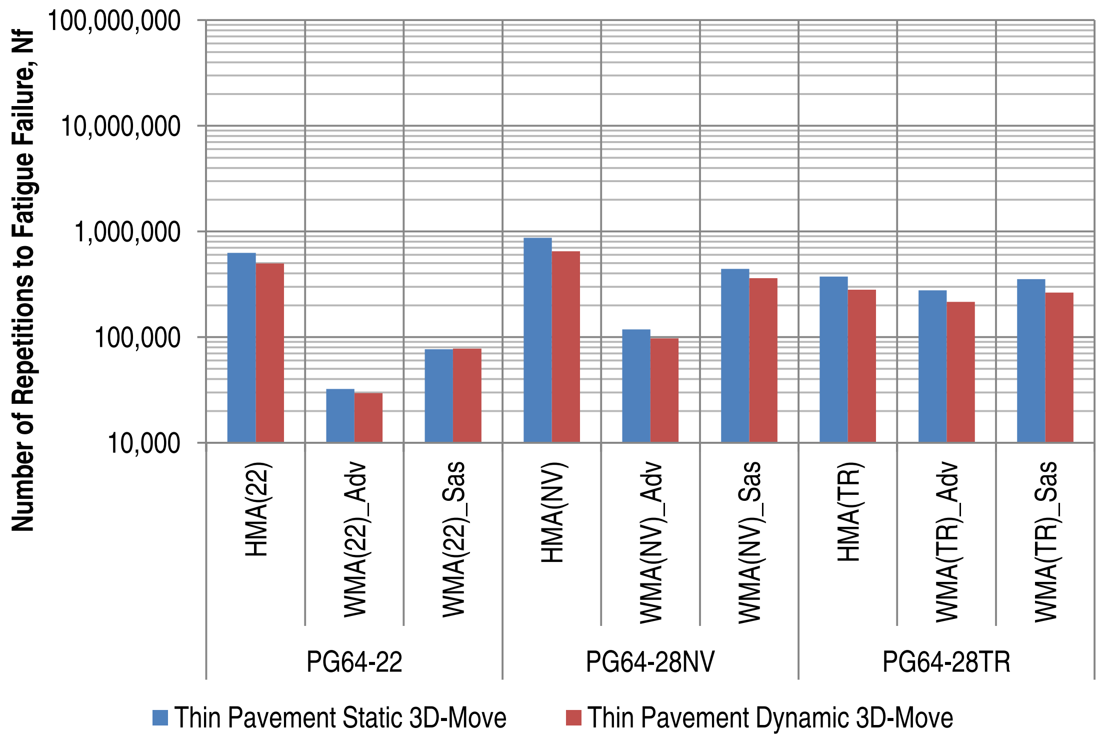


Figure 18: N_f Comparison of All Mixtures Using 3D-Move Static and Dynamic Analysis for Thin Pavement - Phase I

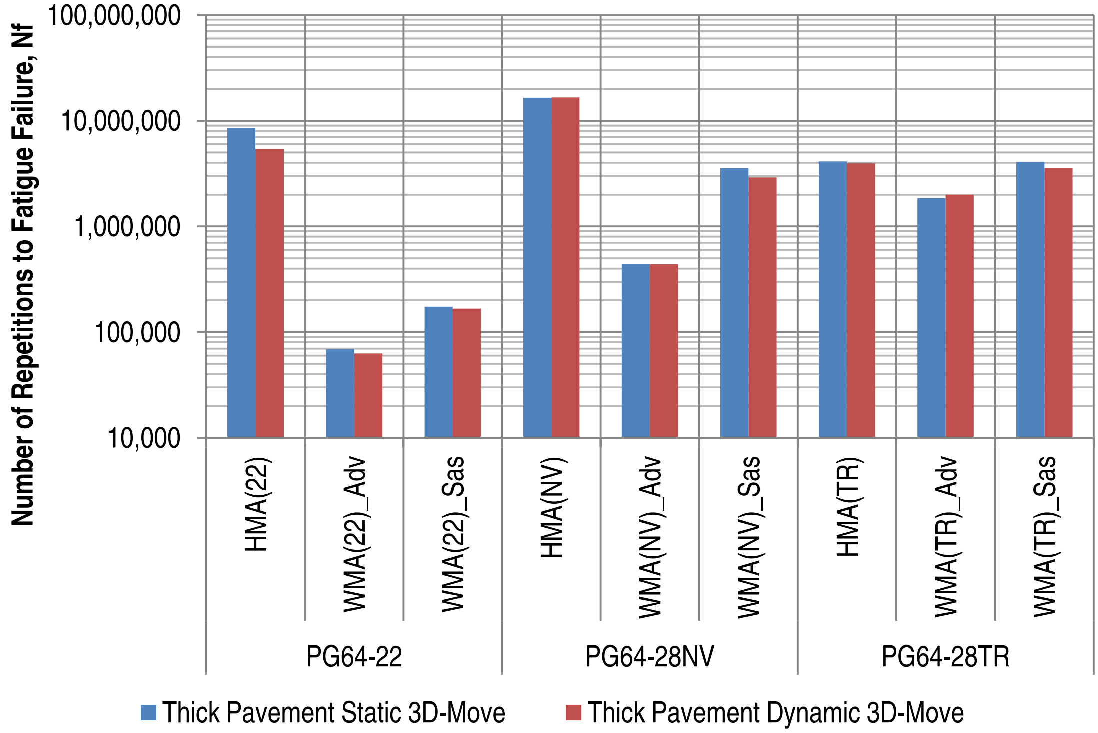


Figure 19: N_f Comparison of All Mixtures Using 3D-Move Static and Dynamic Analysis for Thick Pavement - Phase I

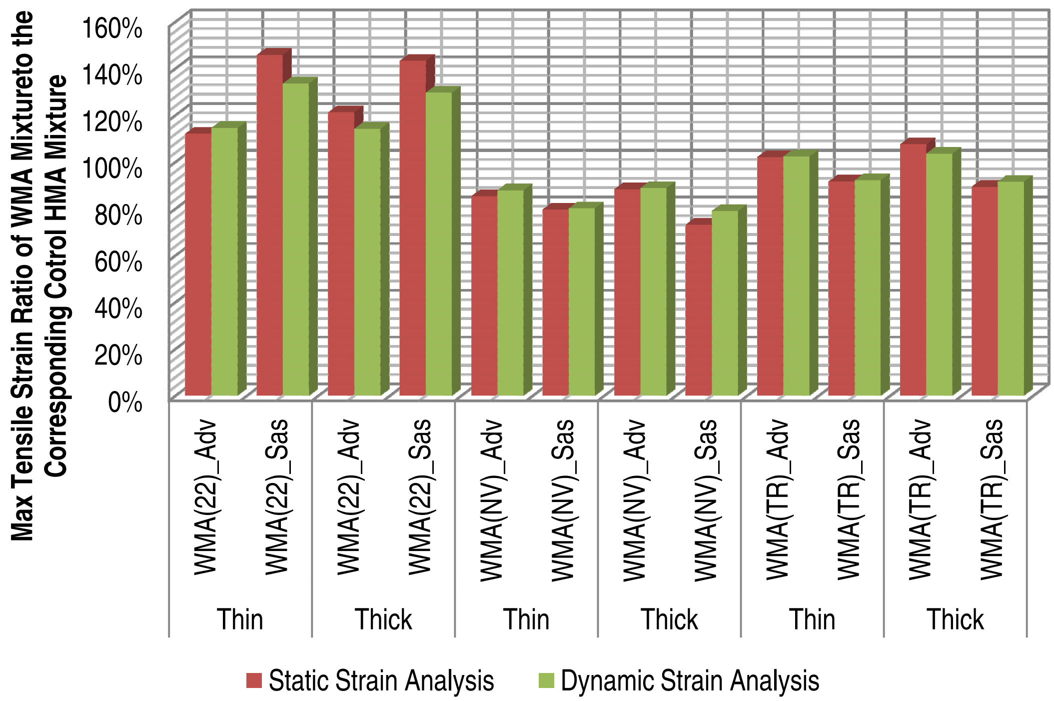


Figure 20: Strain Ratio of all Mixtures to the Corresponding HMA Control Mixture - Phase I

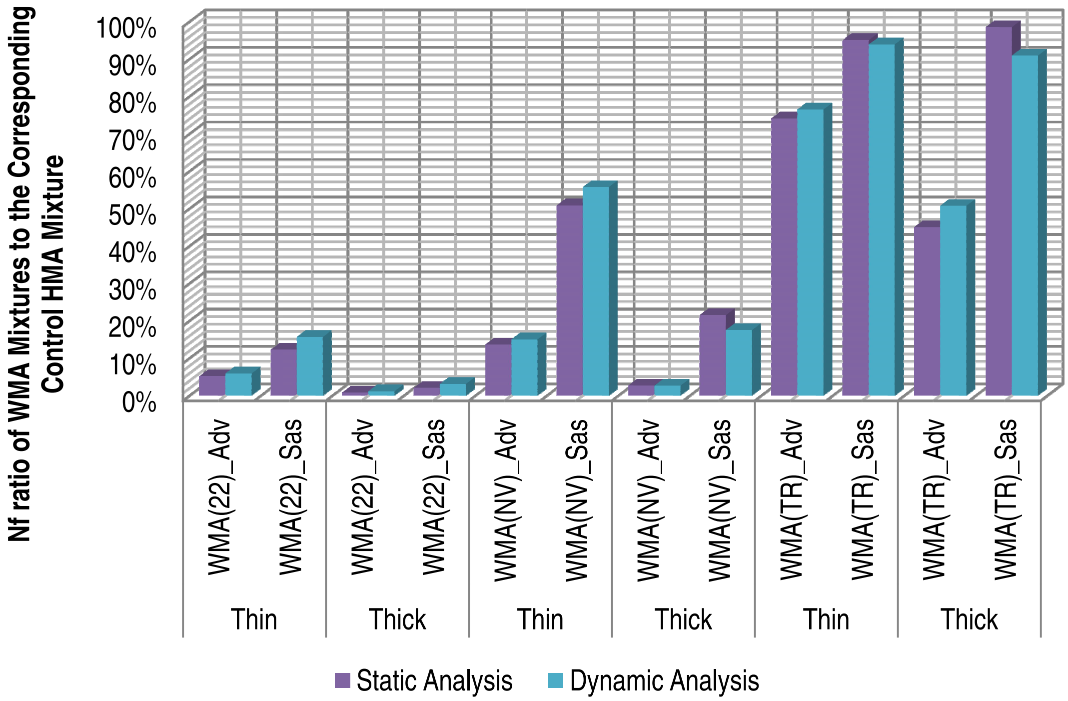
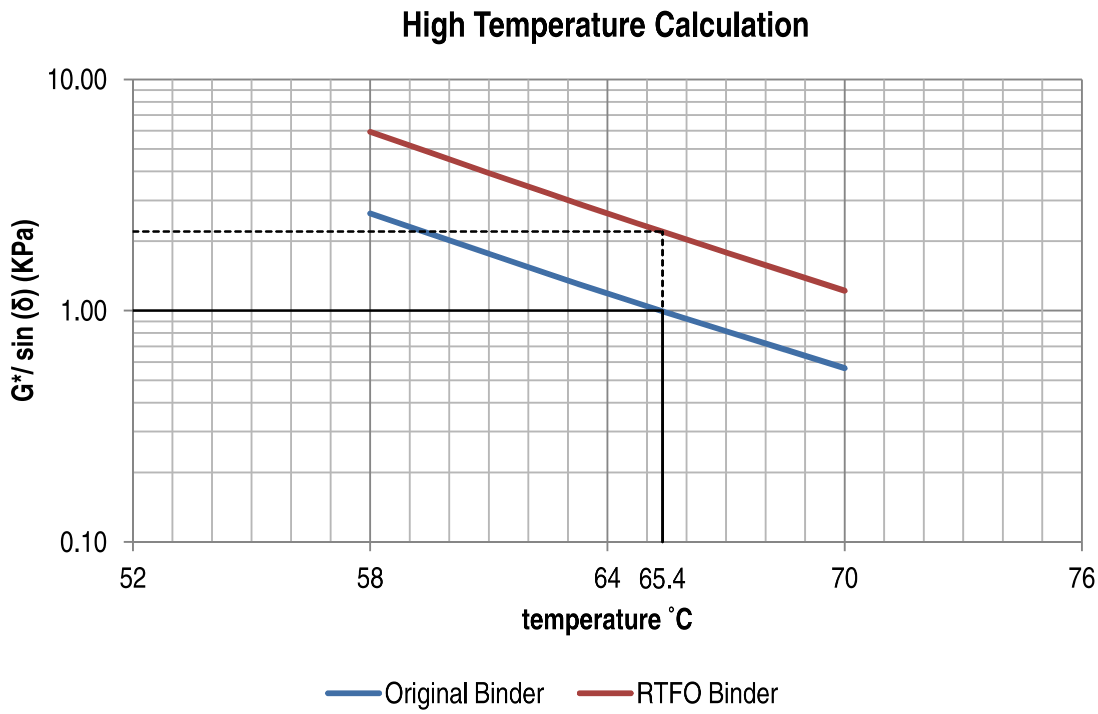


Figure 21: Number of Repetition to Fatigue Failure Ratio of all Mixtures to the Corresponding HMA Control Mixture - Phase I



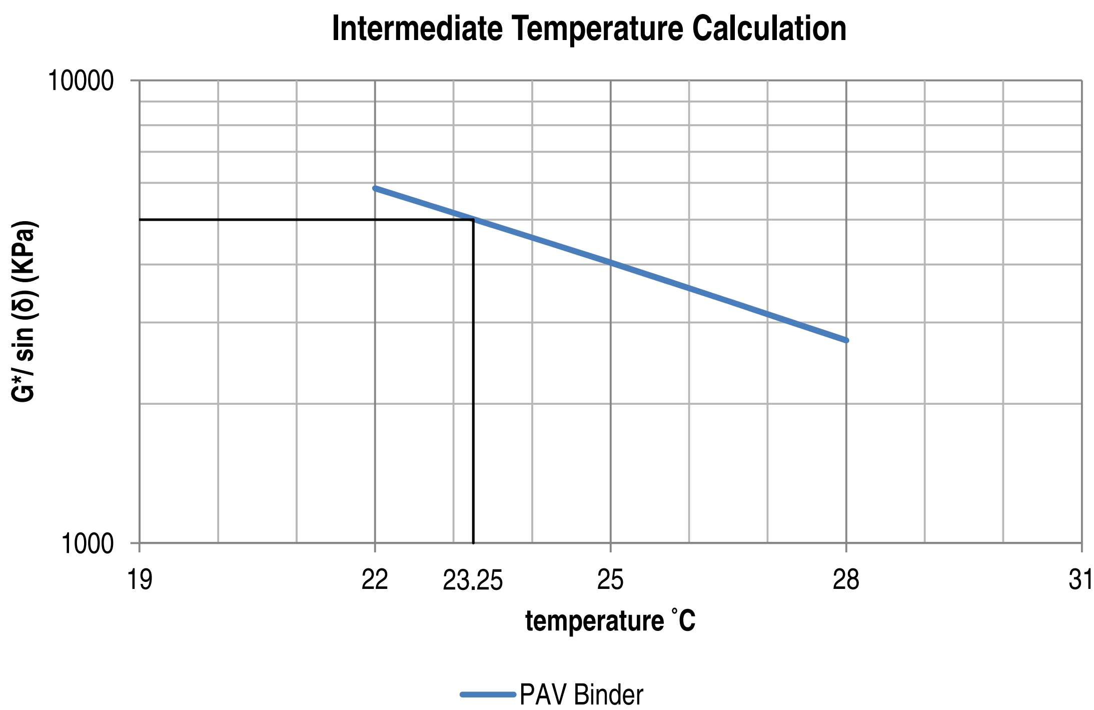


Figure 22: DSR Data Analysis for PG64-22 - Phase II

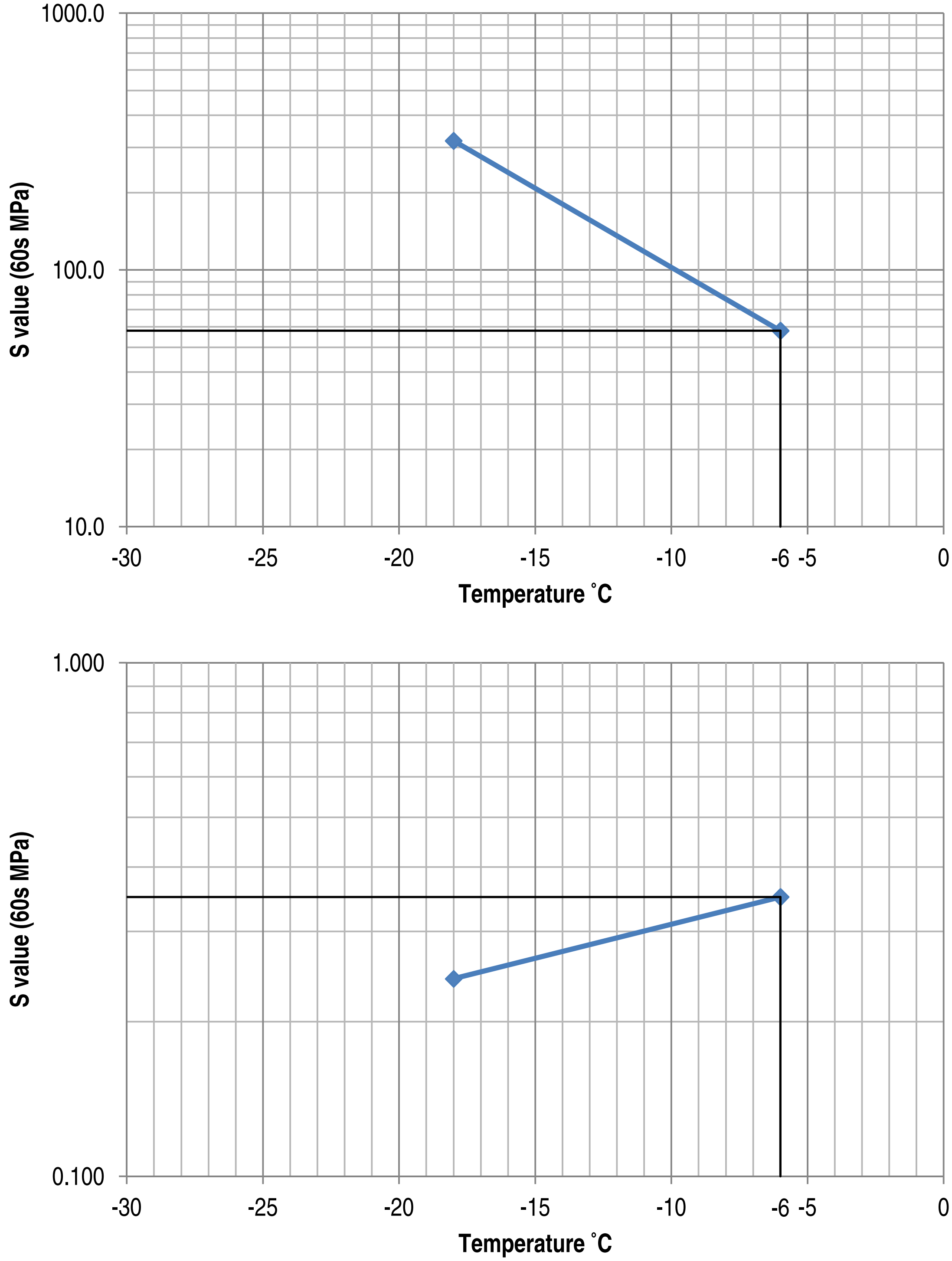
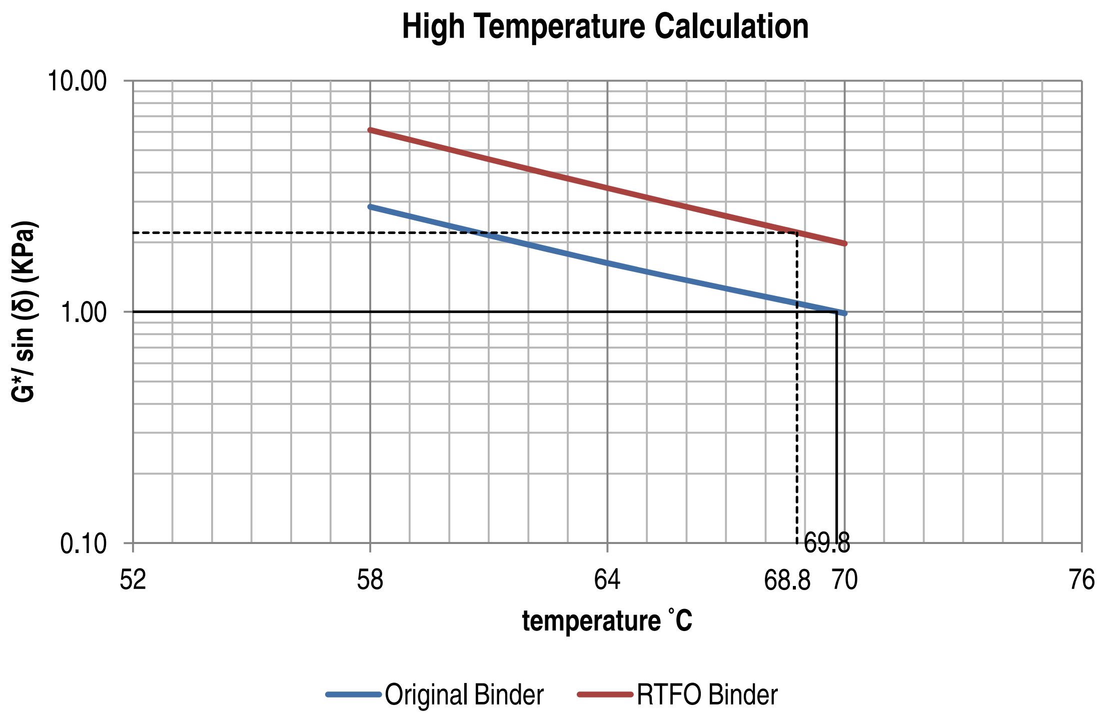


Figure 23: BBR Data Analysis for PG64-22 - Phase II



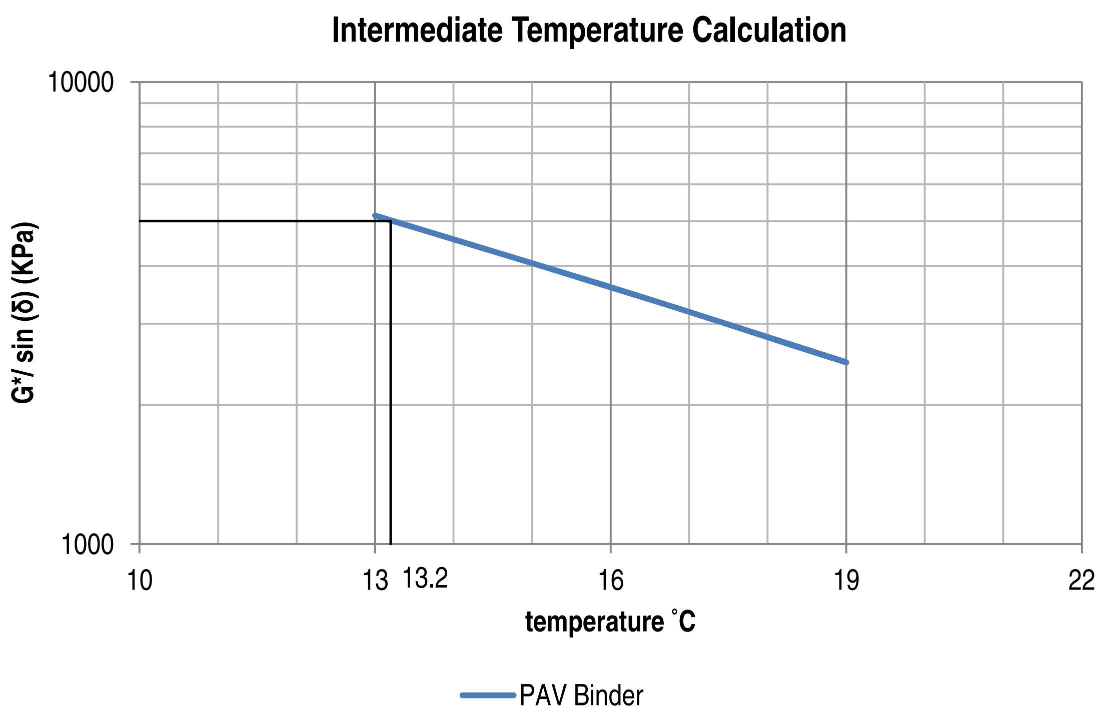
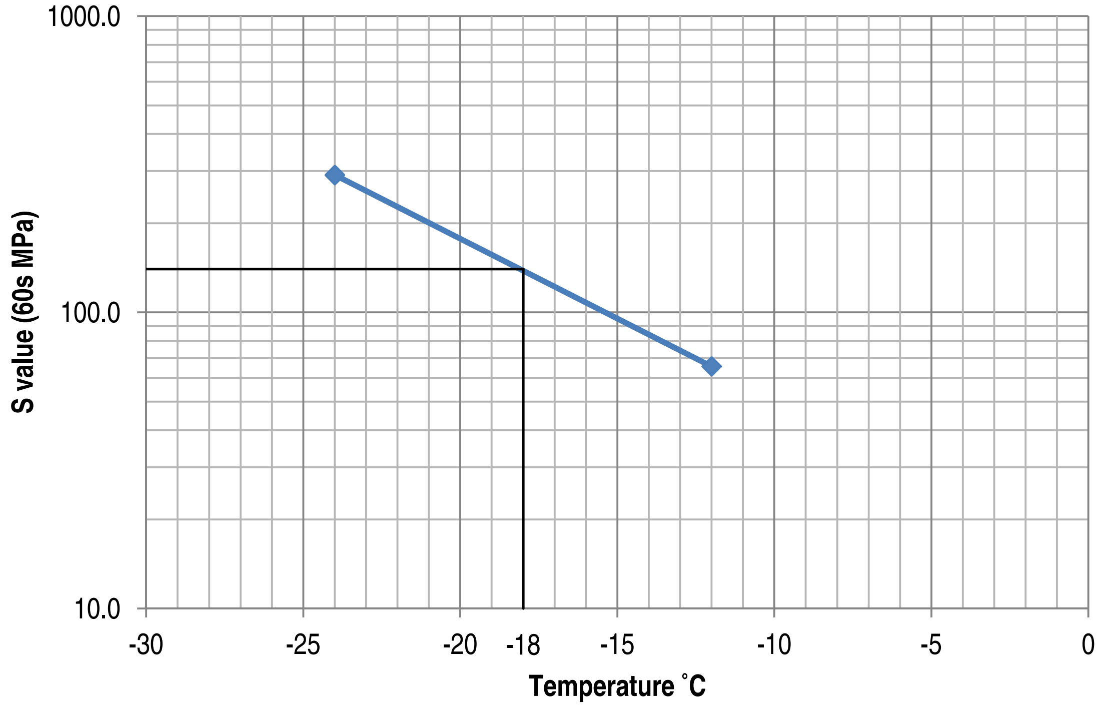


Figure 24: DSR Data Analysis for PG64-28NV - Phase II



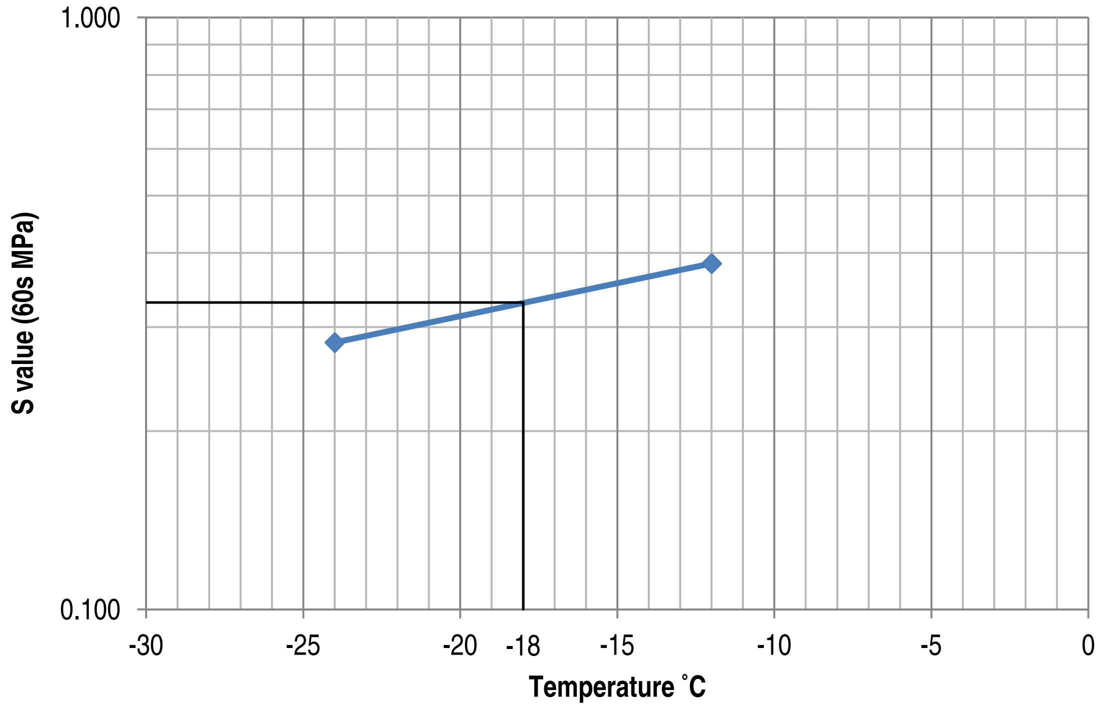


Figure 25: BBR Data Analysis for PG64-28NV - Phase II

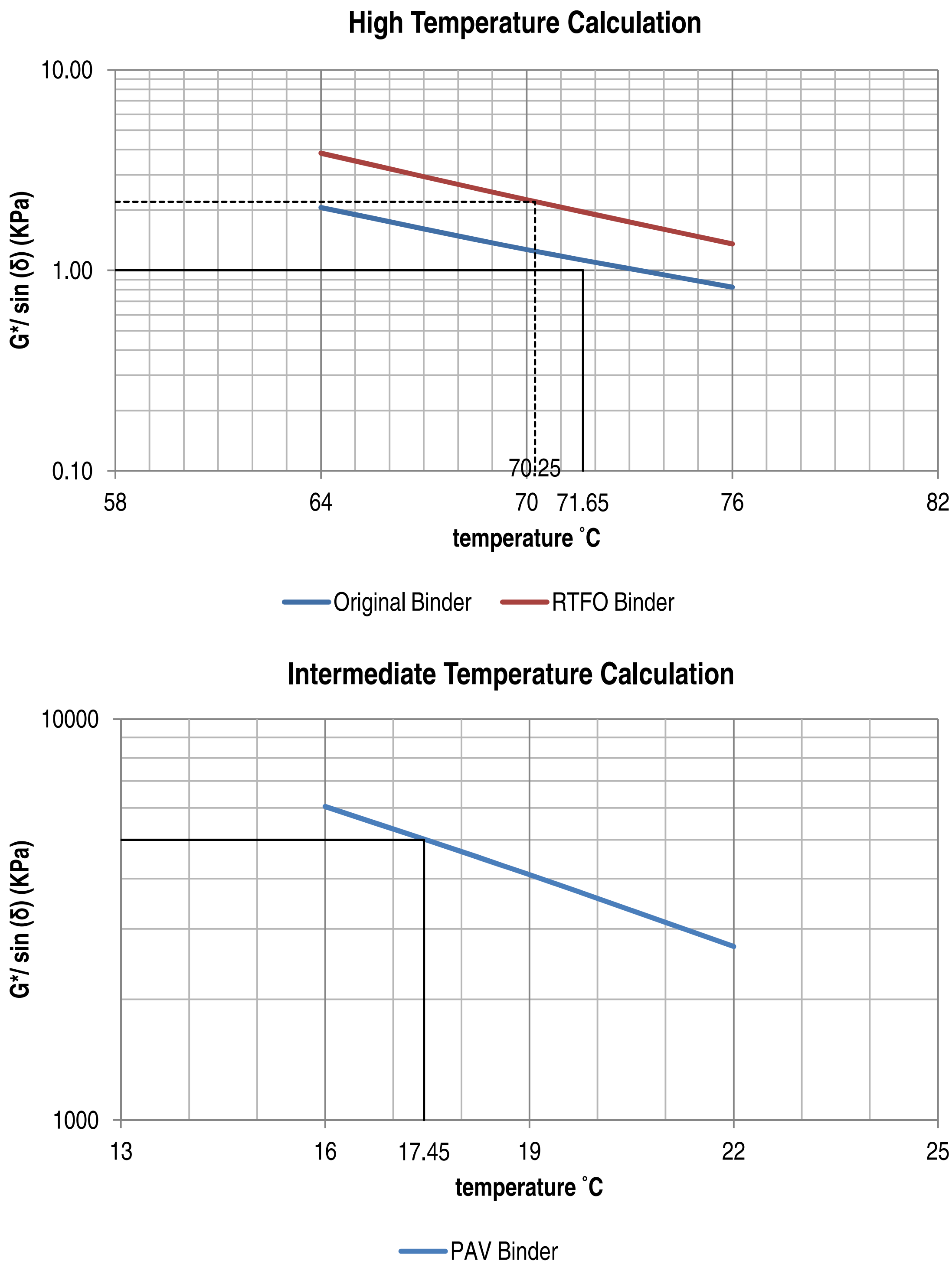
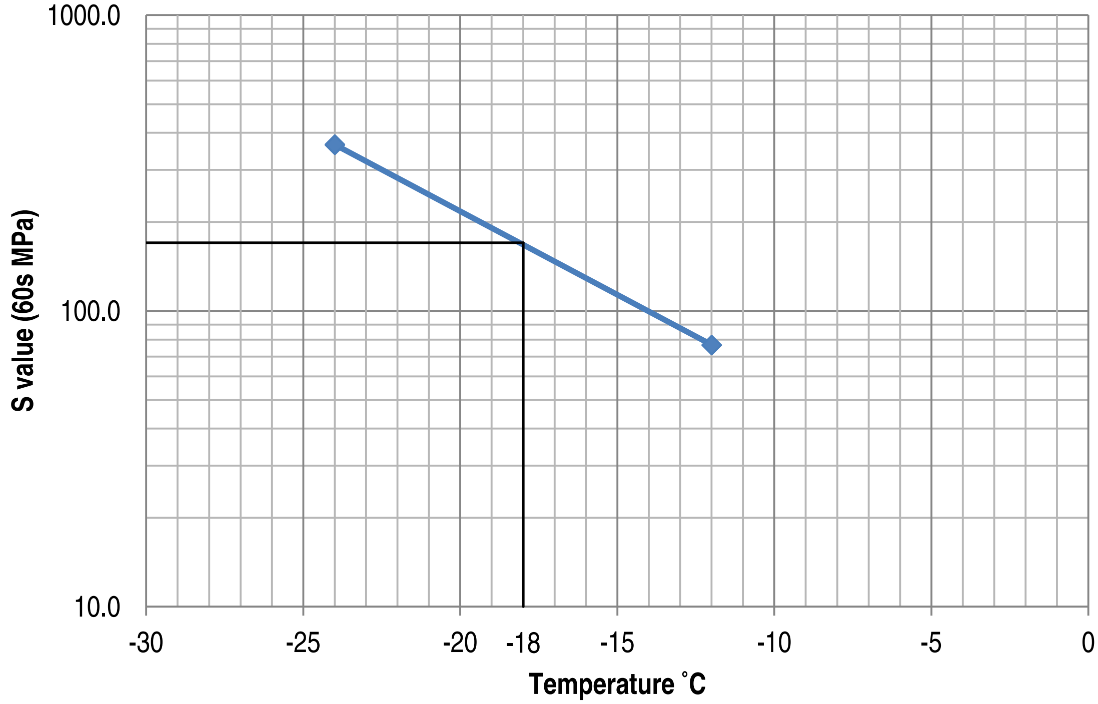


Figure 26: DSR Data Analysis for PG64-28TR - Phase II



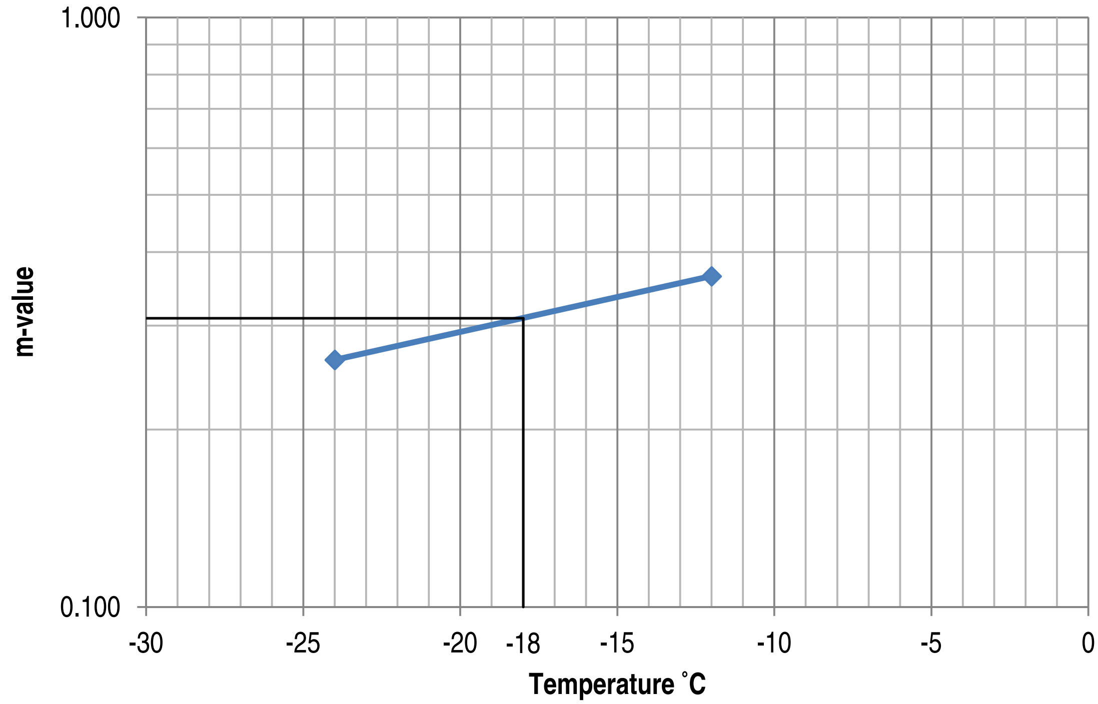


Figure 27: BBR Data Analysis for PG64-28TR - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	308	303-313
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.639	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.29	4-7 / 4.0
VMA, % (NDOT / CT)	15.00 / 15.02	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.28/ 71.41	70-80% / 65-75%
Film Thickness, μm	9.33	8 Min.
Hveem Stability, lbs	41	37 Min.
Max. specific gravity at OBC, G_{mm}	2.434	--
Unconditioned Tensile Strength, psi	85	65 Min.
Tensile Strength Ratio, %	64	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

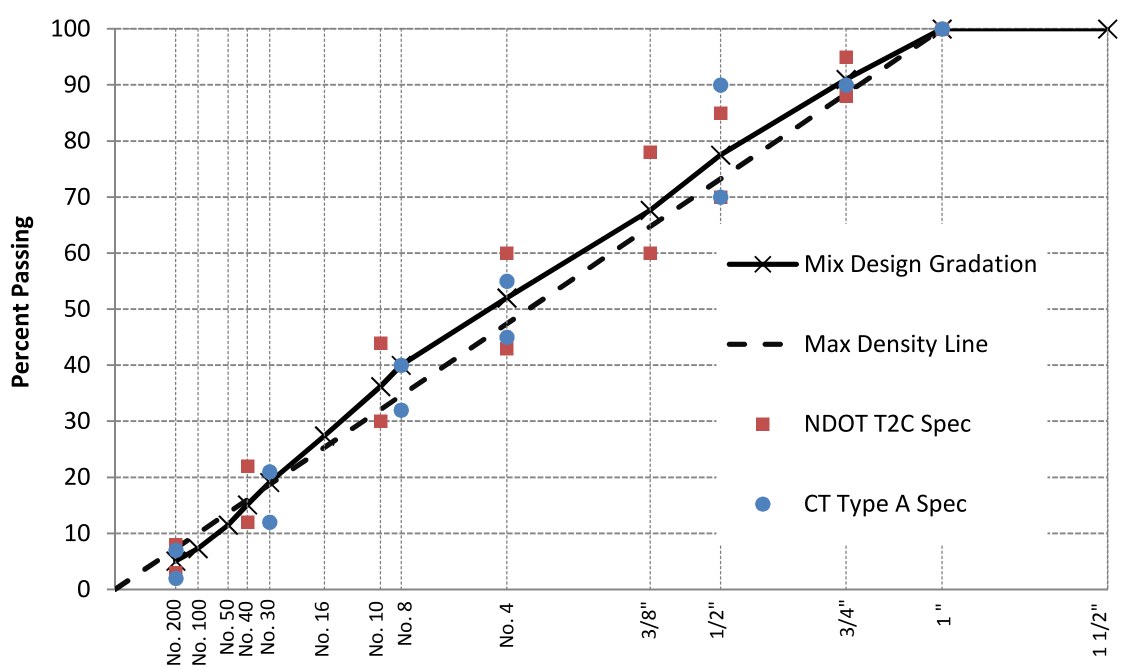


Figure 28: Lockwood untreated mix design and aggregate properties w/Paramount PG 64-22 - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	1	1.5
Mixing Temperature, °F	308	303-313
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.646	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.85	4-7 / 4.0
VMA, % (NDOT / CT)	15.45 / 15.46	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.66/ 69.00	70-80% / 65-75%
Film Thickness, μm	8.52	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.436	--
Unconditioned Tensile Strength, psi	75	65 Min.
Tensile Strength Ratio, %	94	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

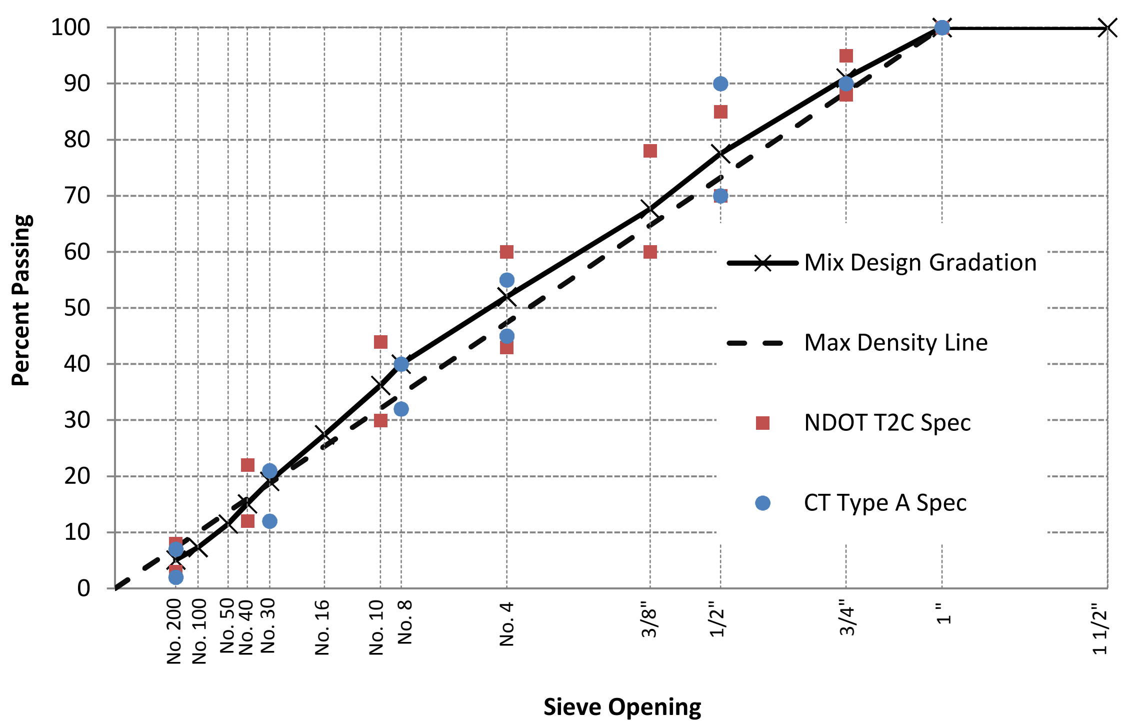


Figure 29: Lockwood Lime-treated mix design and aggregate properties w/Paramount PG 64-22 - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	308	303-313
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.672	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	4.71	4-7 / 4.0
VMA, % (NDOT / CT)	14.40/14.41	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.00/67.40	70-80% / 65-75%
Film Thickness, µm	8.39	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.460	--
Unconditioned Tensile Strength, psi	80	65 Min.
Tensile Strength Ratio, %	93	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

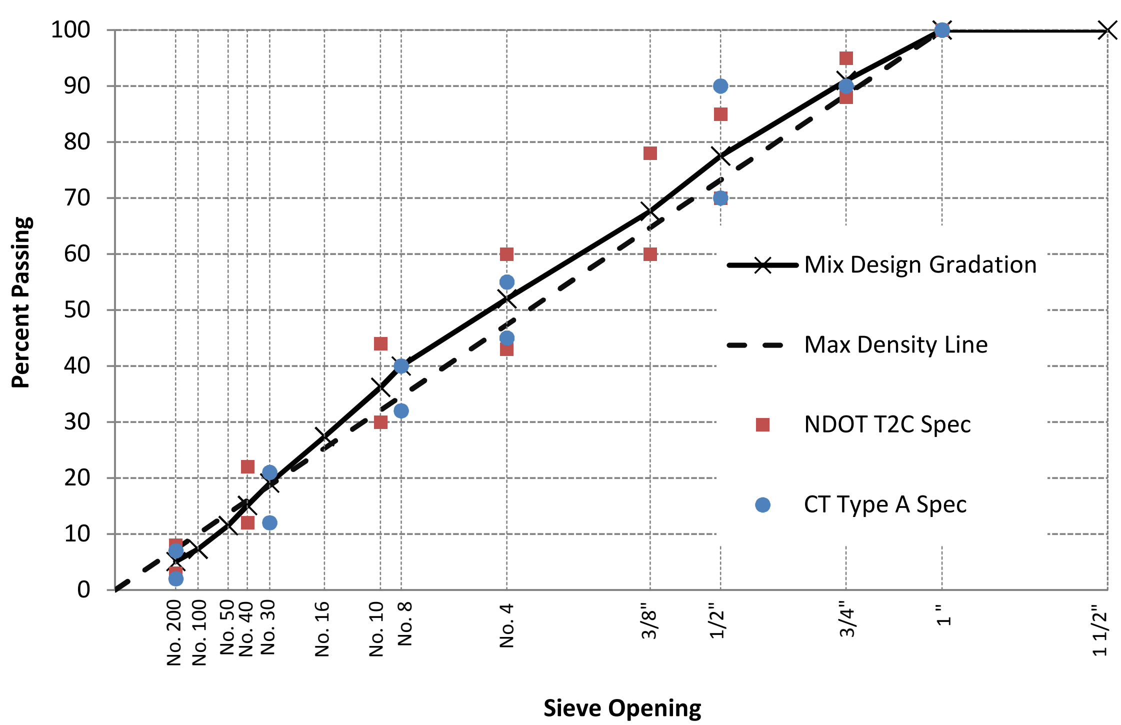


Figure 30: Lockwood Liquid-treated mix design and aggregate properties w/Paramount PG 64-22 - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	255	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.648	--
Optimum Binder (OBC), % DWA	5.40	--
Air Voids, % TMW (NDOT / CT)	4.30	4-7 / 4.0
VMA, % (NDOT / CT)	14.30 / 14.40	12-22 / 13 Min.
VFA, % (NDOT / CT)	71.90/ 70.30	70-80% / 65-75%
Film Thickness, μm	8.7	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.445	--
Unconditioned Tensile Strength, psi	86	65 Min.
Tensile Strength Ratio, %	77	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

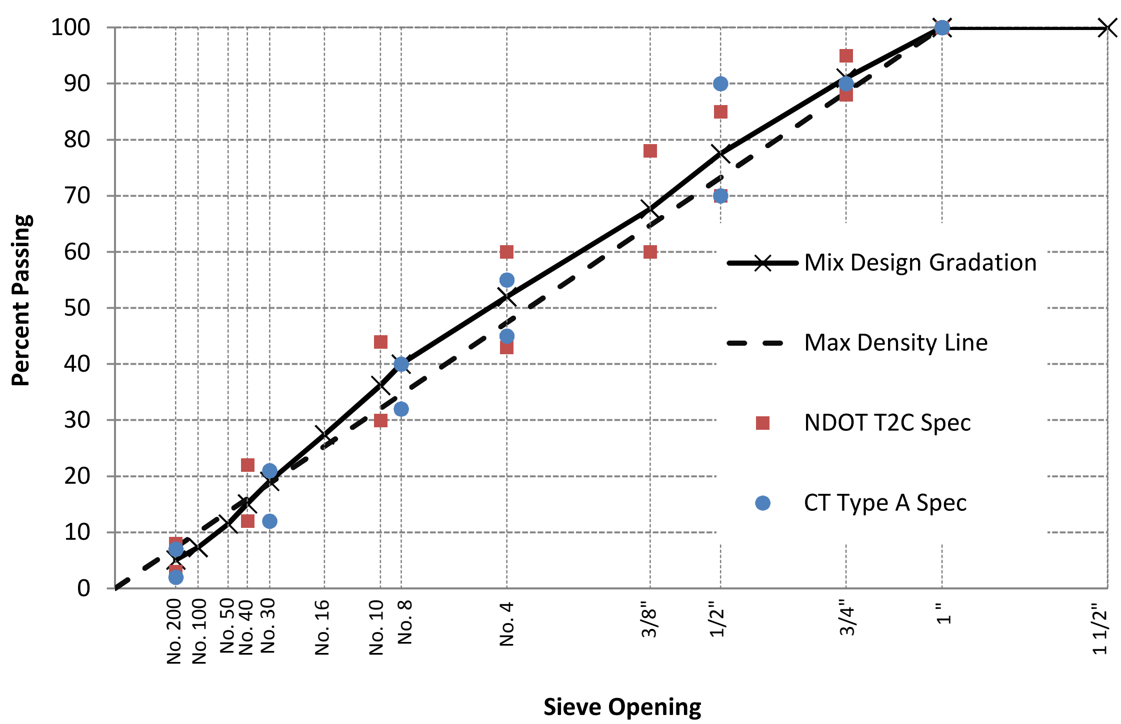


Figure 31: Lockwood Untreated mix design and aggregate properties w/Paramount PG 64-22 with 0.4% Evotherm - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	265	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.640	--
Optimum Binder (OBC), % DWA	5.20	--
Air Voids, % TMW (NDOT / CT)	4.47	4-7 / 4.0
VMA, % (NDOT / CT)	14.57/14.58	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.49/69.40	70-80% / 65-75%
Film Thickness, μm	8.76	8 Min.
Hveem Stability, lbs	32	37 Min.
Max. specific gravity at OBC, G_{mm}	2.439	--
Unconditioned Tensile Strength, psi	90	65 Min.
Tensile Strength Ratio, %	74	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

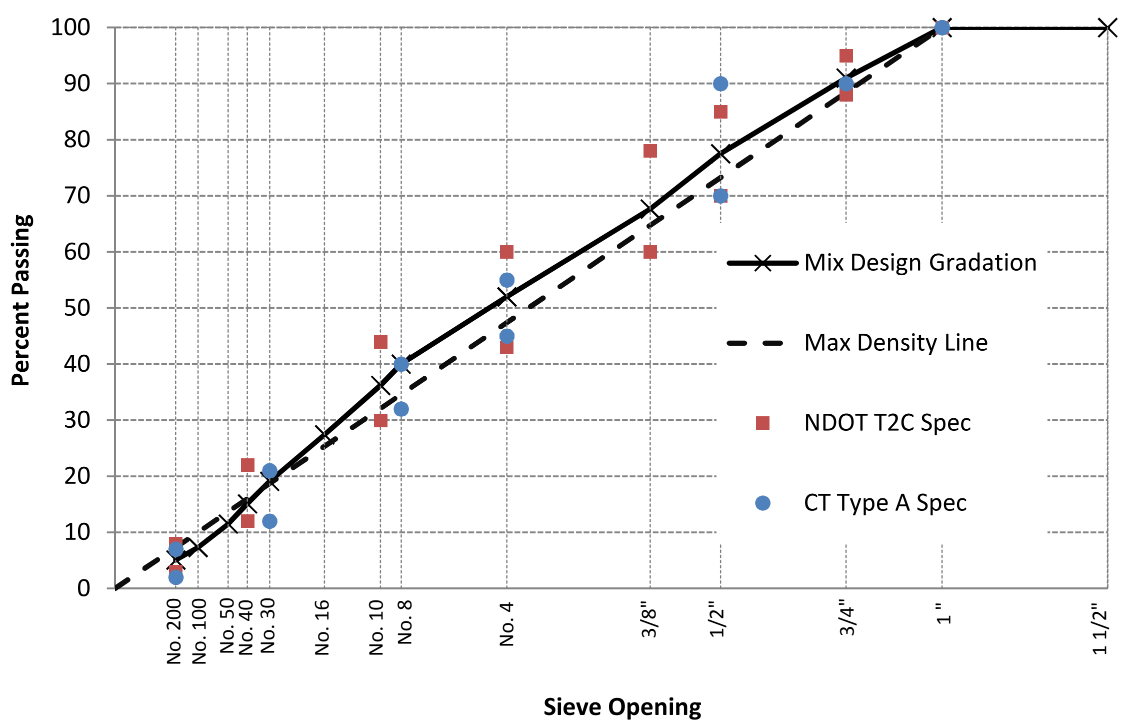


Figure 32: Lockwood Lime-treated mix design and aggregate properties w/Paramount PG 64-22 with 0.4% Evotherm - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	255	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.648	--
Optimum Binder (OBC), % DWA	5.50	--
Air Voids, % TMW (NDOT / CT)	4.03	4-7 / 4.0
VMA, % (NDOT / CT)	14.29 / 14.31	12-22 / 13 Min.
VFA, % (NDOT / CT)	72.89/ 71.51	70-80% / 65-75%
Film Thickness, μm	8.87	8 Min.
Hveem Stability, lbs	40	37 Min.
Max. specific gravity at OBC, G_{mm}	2.443	--
Unconditioned Tensile Strength, psi	89	65 Min.
Tensile Strength Ratio, %	76	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

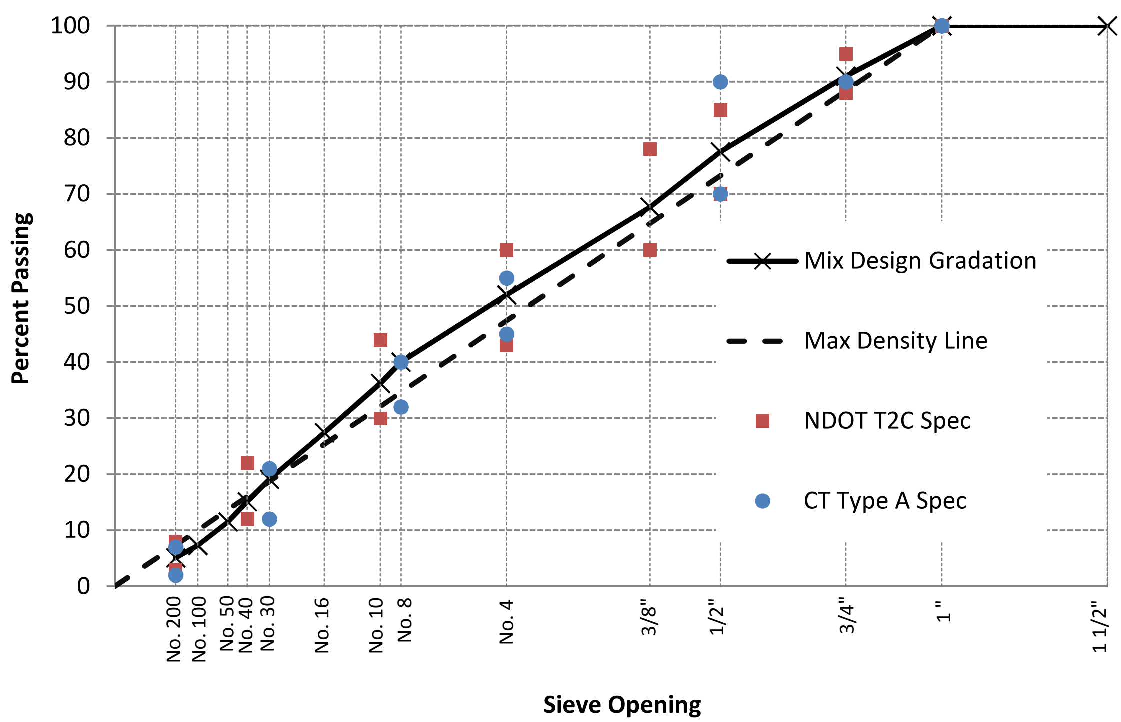


Figure 33: Lockwood Liquid-treated mix design and aggregate properties w/Paramount PG 64-22 with 0.4% Evotherm - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.647	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	4.67	4-7 / 4.0
VMA, % (NDOT / CT)	15.32 / 15.33	12-22 / 13 Min.
VFA, % (NDOT / CT)	72.73/ 69.61	70-80% / 65-75%
Film Thickness, µm	9.32	8 Min.
Hveem Stability, lbs	42	37 Min.
Max. specific gravity at OBC, G_{mm}	2.437	--
Unconditioned Tensile Strength, psi	66	65 Min.
Tensile Strength Ratio, %	79	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

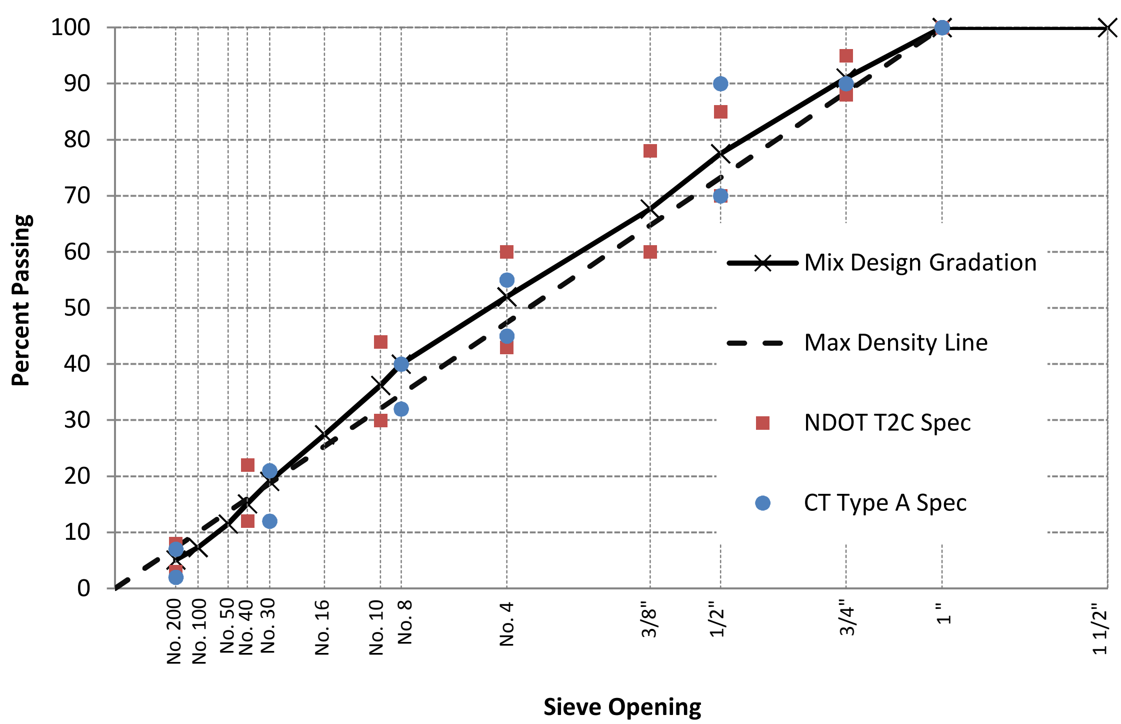


Figure 34: Lockwood Untreated mix design and aggregate properties w/Paramount PG 64-28NV - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	1	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.638	--
Optimum Binder (OBC), % DWA	5.50	--
Air Voids, % TMW (NDOT / CT)	4.86	4-7 / 4.0
VMA, % (NDOT / CT)	14.88/ 14.90	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.00/67.6 0	70-80% / 65-75%
Film Thickness, µm	8.01	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.447	--
Unconditioned Tensile Strength, psi	71	65 Min.
Tensile Strength Ratio, %	89	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

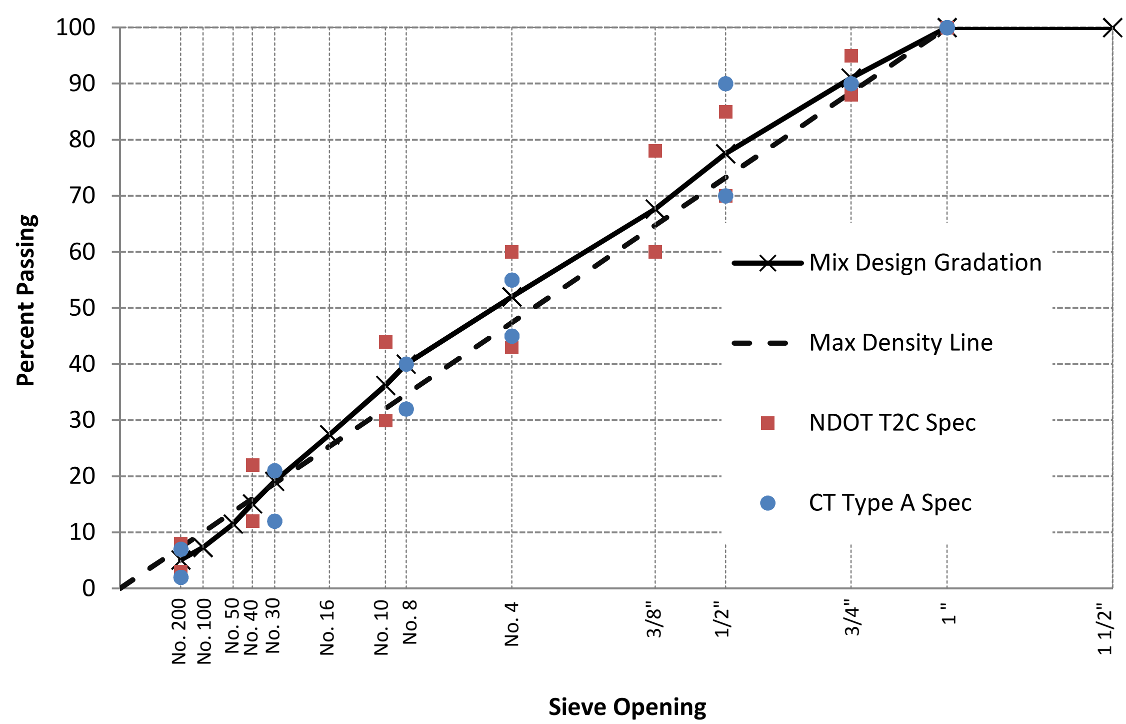


Figure 35: Lockwood Lime-treated mix design and aggregate properties w/Paramount PG 64-28NV - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.647	--
Optimum Binder (OBC), % DWA	5.50	--
Air Voids, % TMW (NDOT / CT)	4.80	4-7 / 4.0
VMA, % (NDOT / CT)	14.89/14.91	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.00/67.71	70-80% / 65-75%
Film Thickness, µm	8.06	8 Min.
Hveem Stability, lbs	35	37 Min.
Max. specific gravity at OBC, G_{mm}	2.446	--
Unconditioned Tensile Strength, psi	76	65 Min.
Tensile Strength Ratio, %	88	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

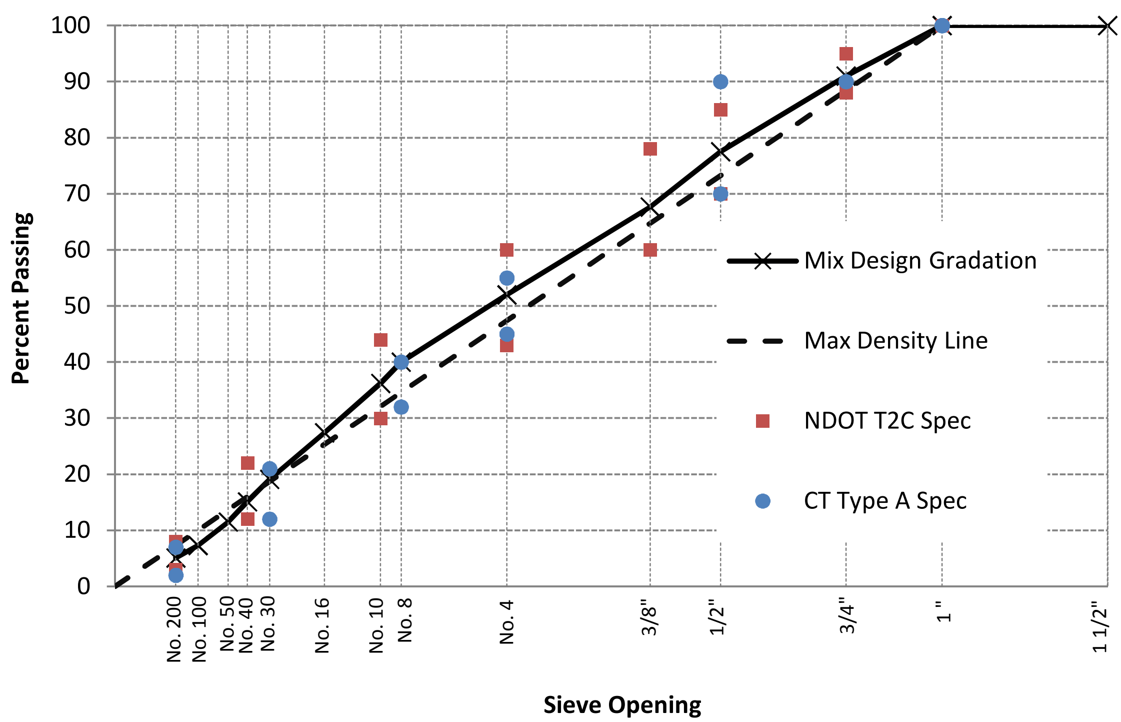


Figure 36: Lockwood Liquid-treated mix design and aggregate properties w/Paramount PG 64-28NV - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.638	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	3.80	4-7 / 4.0
VMA, % (NDOT / CT)	14.80/ 14.90	12-22 / 13 Min.
VFA, % (NDOT / CT)	76.50/ 74.30	70-80% / 65-75%
Film Thickness, µm	9.60	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.429	--
Unconditioned Tensile Strength, psi	65	65 Min.
Tensile Strength Ratio, %	83	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

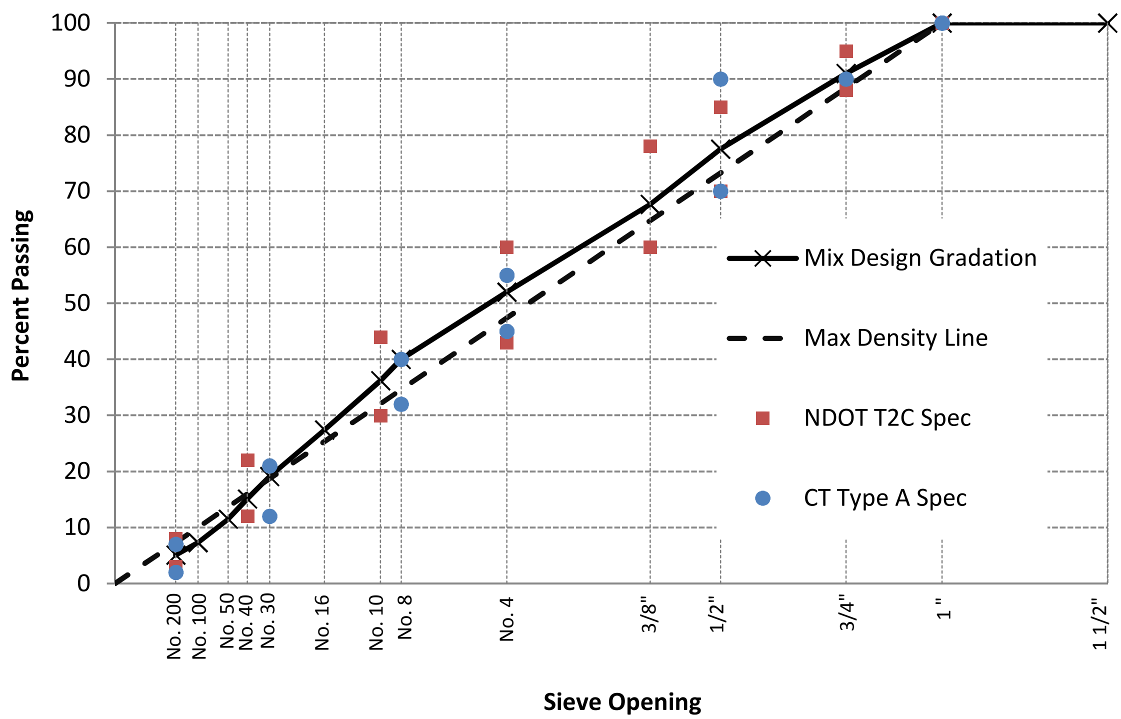


Figure 37: Lockwood Untreated mix design and aggregate properties w/Paramount PG 64-28NV with 0.4% Evotherm - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	1	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.636	--
Optimum Binder (OBC), % DWA	5.40	--
Air Voids, % TMW (NDOT / CT)	4.23	4-7 / 4.0
VMA, % (NDOT / CT)	14.51/14.52	12-22 / 13 Min.
VFA, % (NDOT / CT)	71.95/70.92	70-80% / 65-75%
Film Thickness, µm	8.91	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.440	--
Unconditioned Tensile Strength, psi	88	65 Min.
Tensile Strength Ratio, %	74	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

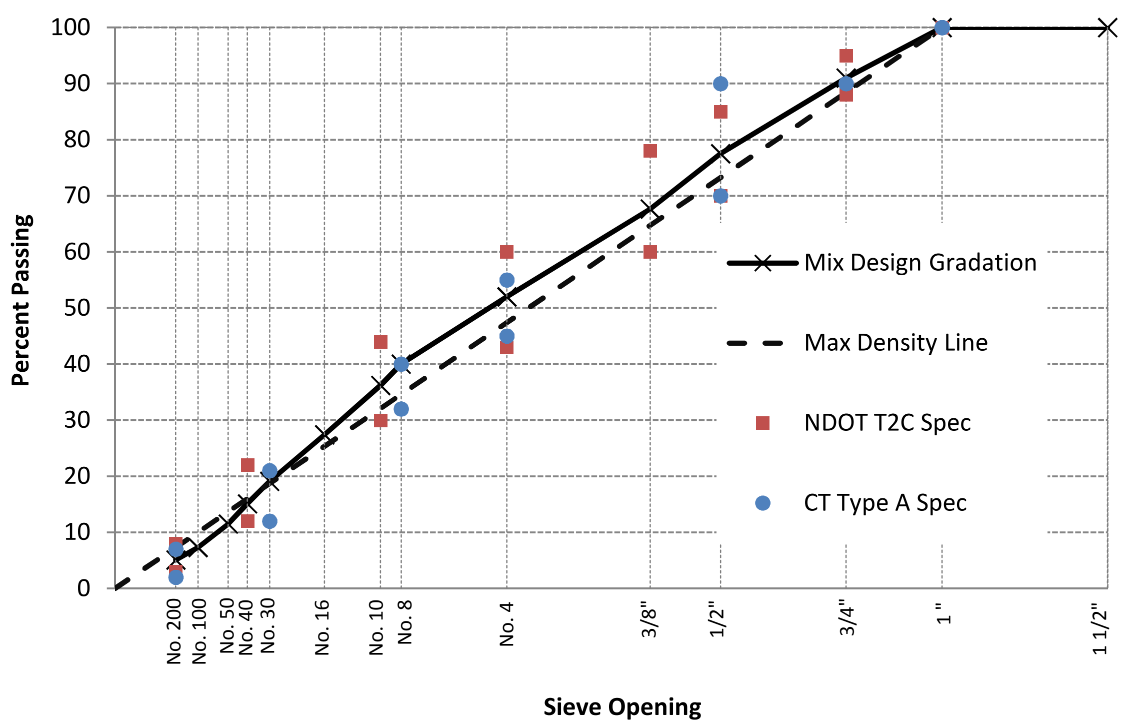


Figure 38: Lockwood Lime-treated mix design and aggregate properties w/Paramount PG 64-28NV with 0.4% Evotherm - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.644	--
Optimum Binder (OBC), % DWA	5.40	--
Air Voids, % TMW (NDOT / CT)	4.24	4-7 / 4.0
VMA, % (NDOT / CT)	14.26 / 14.28	12-22 / 13 Min.
VFA, % (NDOT / CT)	71.73/ 70.47	70-80% / 65-75%
Film Thickness, µm	8.66	8 Min.
Hveem Stability, lbs	39	37 Min.
Max. specific gravity at OBC, G_{mm}	2.447	--
Unconditioned Tensile Strength, psi	84	65 Min.
Tensile Strength Ratio, %	72	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

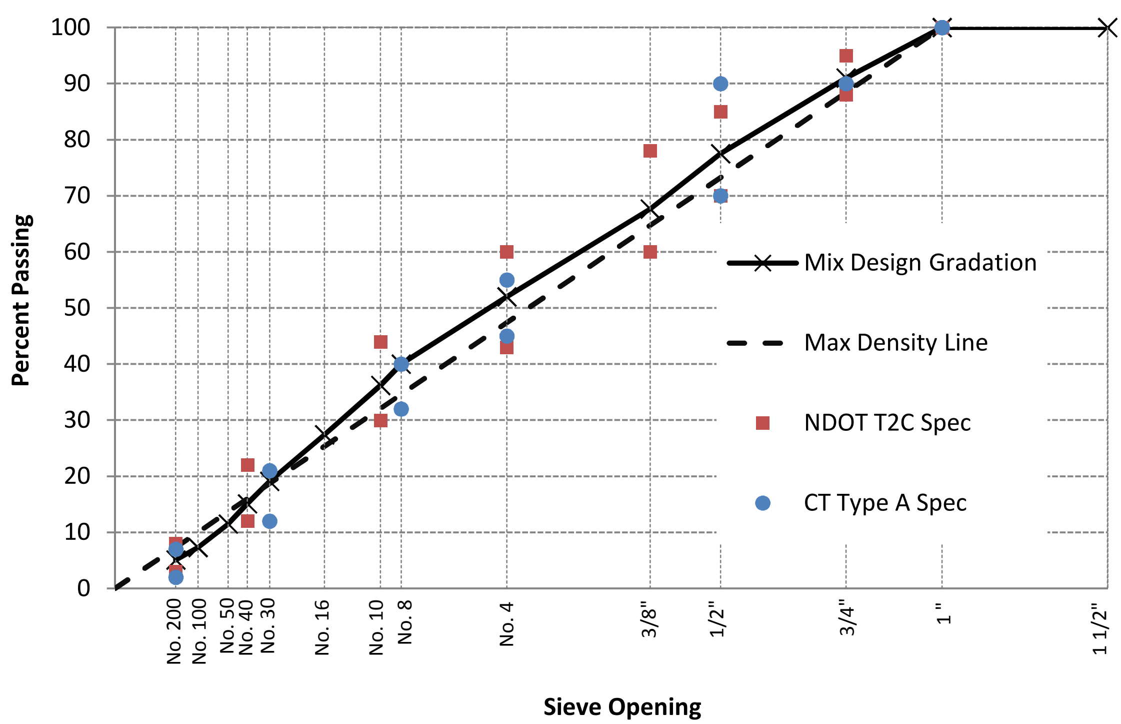


Figure 39: Lockwood Liquid-treated mix design and aggregate properties w/Paramount PG 64-28NV with 0.4% Evotherm - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.659	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	4.86	4-7 / 4.0
VMA, % (NDOT / CT)	15.15/15.16	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.64/ 67.94	70-80% / 65-75%
Film Thickness, µm	8.98	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.447	--
Unconditioned Tensile Strength, psi	86	65 Min.
Tensile Strength Ratio, %	60	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

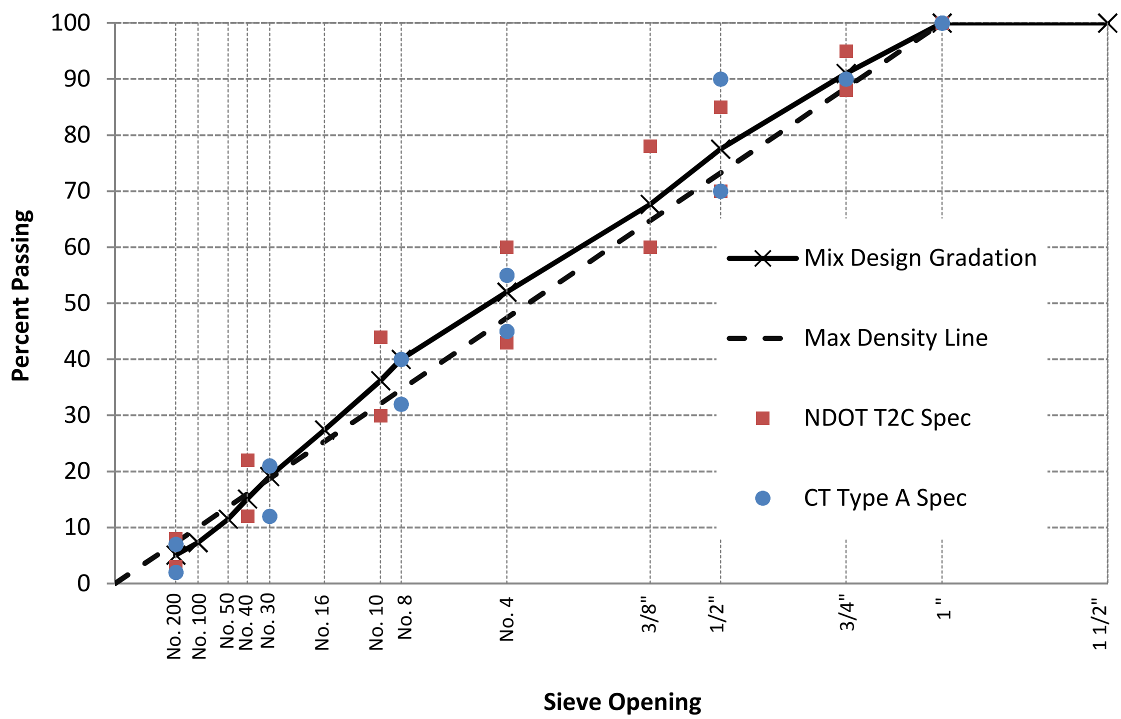


Figure 40: Lockwood Untreated mix design and aggregate properties w/Paramount PG 64-28TR - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	1	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.643	--
Optimum Binder (OBC), % DWA	5.55	--
Air Voids, % TMW (NDOT / CT)	4.67	4-7 / 4.0
VMA, % (NDOT / CT)	14.99/15.00	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.30/ 68.97	70-80% / 65-75%
Film Thickness, µm	8.99	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.441	--
Unconditioned Tensile Strength, psi	73	65 Min.
Tensile Strength Ratio, %	84	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

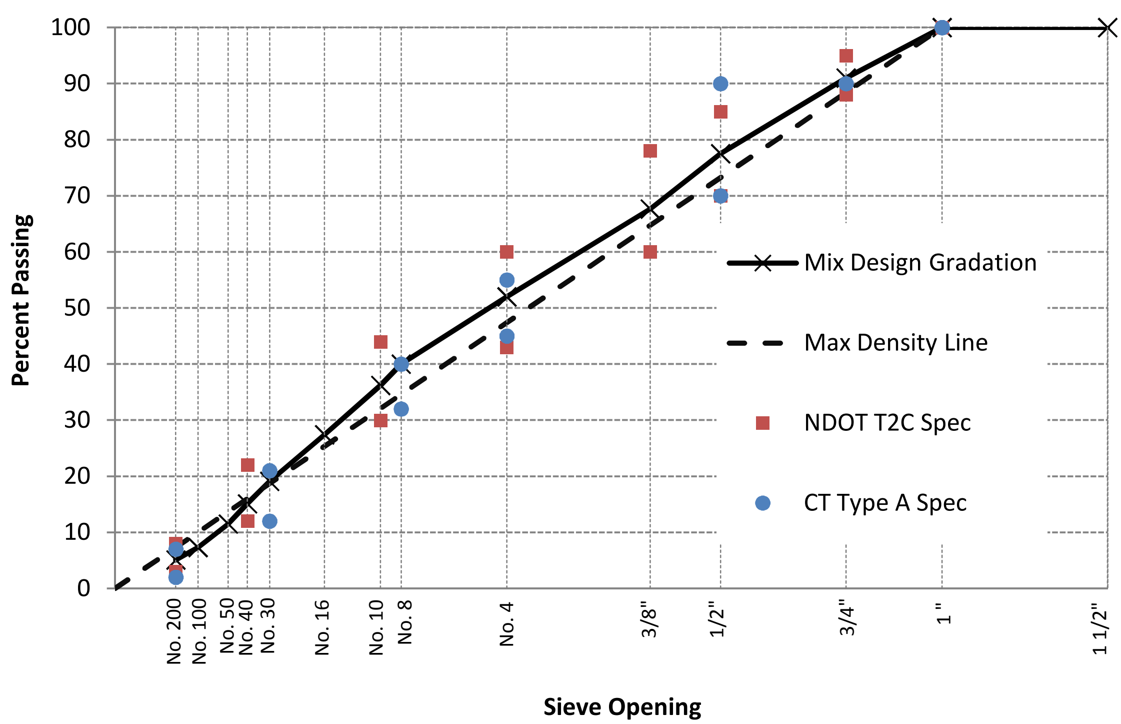


Figure 41: Lockwood Lime-treated mix design and aggregate properties w/Paramount PG 64-28TR - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.648	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.70	4-7 / 4.0
VMA, % (NDOT / CT)	15.04/15.06	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.62/68.61	70-80% / 65-75%
Film Thickness, µm	9	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.444	--
Unconditioned Tensile Strength, psi	79	65 Min.
Tensile Strength Ratio, %	78	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

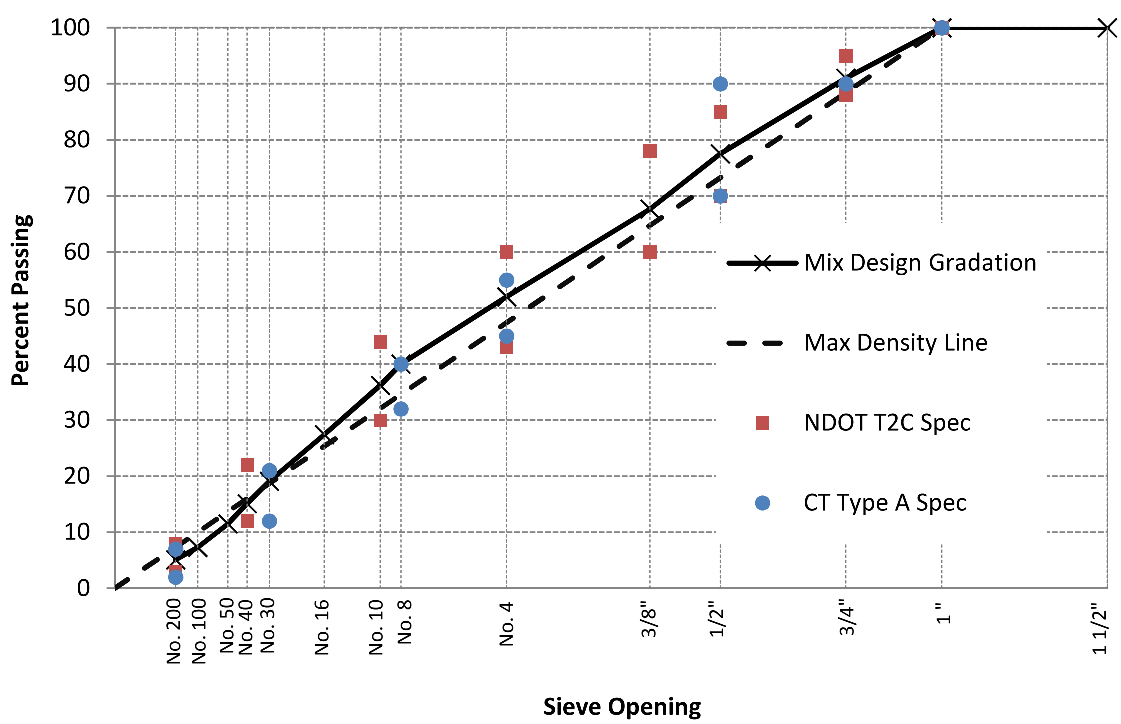


Figure 42: Lockwood Liquid-treated mix design and aggregate properties w/Paramount PG 64-28TR - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.658	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	4.60	4-7 / 4.0
VMA, % (NDOT / CT)	14.70/14.69	12-22 / 13 Min.
VFA, % (NDOT / CT)	70.30/ 68.40	70-80% / 65-75%
Film Thickness, µm	8.70	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.450	--
Unconditioned Tensile Strength, psi	96	65 Min.
Tensile Strength Ratio, %	73	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

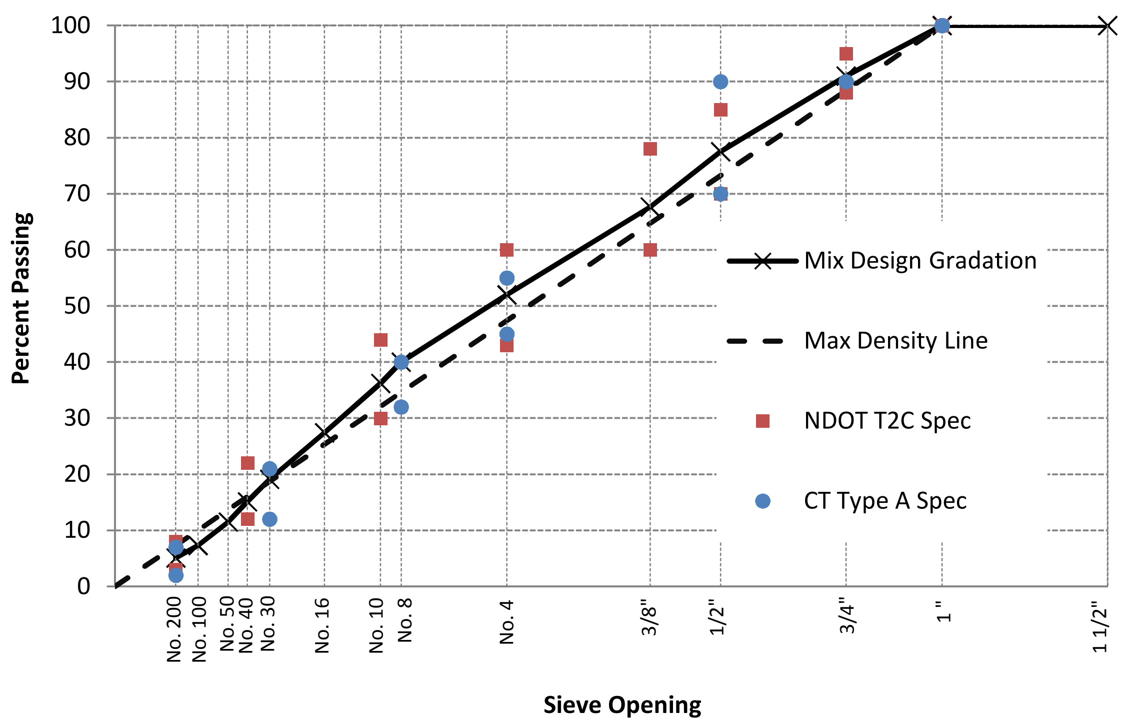


Figure 43: Lockwood Untreated mix design and aggregate properties w/Paramount PG 64-28TR + 0.3% Evotherm - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.643	--
Optimum Binder (OBC), % DWA	5.00	--
Air Voids, % TMW (NDOT / CT)	4.07	4-7 / 4.0
VMA, % (NDOT / CT)	13.76/13.77	12-22 / 13 Min.
VFA, % (NDOT / CT)	72.07/70.73	70-80% / 65-75%
Film Thickness, µm	8.32	8 Min.
Hveem Stability, lbs	39	37 Min.
Max. specific gravity at OBC, G_{mm}	2.448	--
Unconditioned Tensile Strength, psi	95	65 Min.
Tensile Strength Ratio, %	84	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

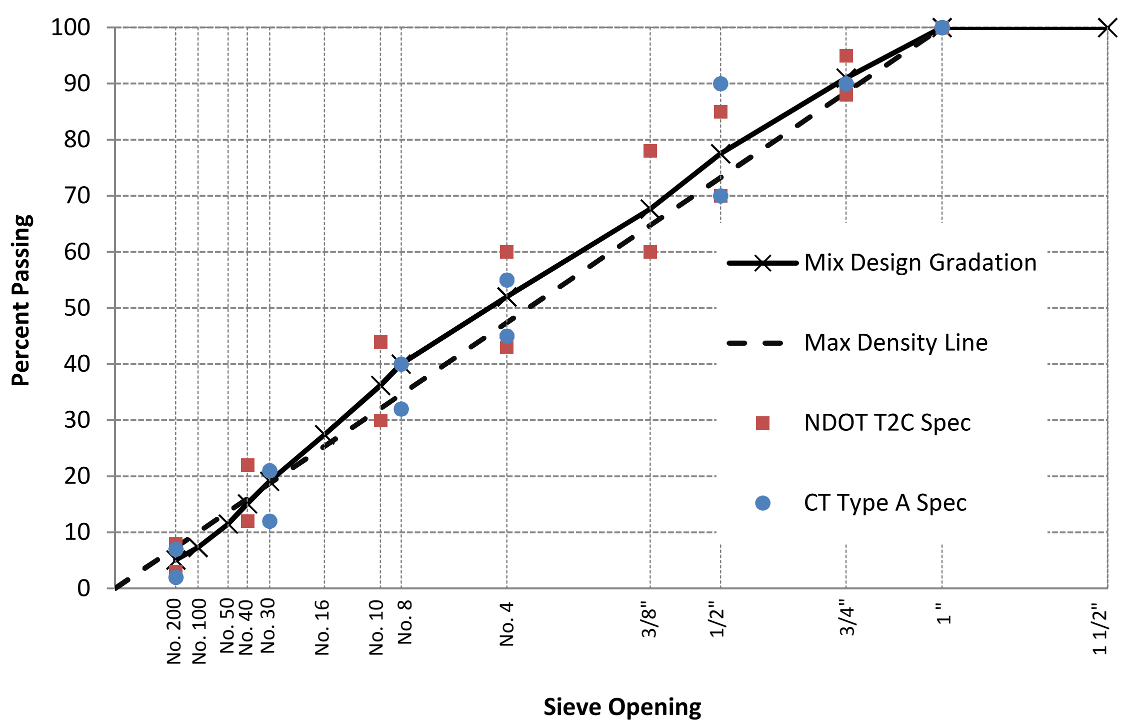


Figure 44: Lockwood Lime-treated mix design and aggregate properties w/Paramount PG 64-28TR + 0.3% Evotherm - Phase II

Mix Design (NDOT T2C & CT Type A)		
Nominal Maximum Aggregate Size, mm		19.0
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.619	--
Fine Aggr. Apparent Gravity, G_{sa}	2.739	--
Aggregate Effective Gravity, G_{se}	2.632	--
Optimum Binder (OBC), % DWA	5.30	--
Air Voids, % TMW (NDOT / CT)	4.20	4-7 / 4.0
VMA, % (NDOT / CT)	14.39/14.4	12-22 / 13 Min.
VFA, % (NDOT / CT)	72.00/ 71.03	70-80% / 65-75%
Film Thickness, μm	8.83	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.440	--
Unconditioned Tensile Strength, psi	93	65 Min.
Tensile Strength Ratio, %	70	70 Min.

Aggregate Gradation (NDOT T2C & CT Type A)			
Sieve Size	**%Passing**	**Control Points**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	91	90	95
12.5 mm (1/2")	77.5	70	85
9.5 mm (3/8")	67.7	60	78
4.75 mm (No. 4)	52	45	55
2.36 mm (No. 8)	40	32	40
2.00 mm (No. 10)	36.2	30	44
1.18 mm (No. 16)	27.4		
0.6 mm (No. 30)	19.1	12	21
0.425 mm (No. 40)	15.1	12	22
0.3 mm (No. 50)	11.5		
0.15 mm (No. 100)	7.3		
0.075 mm (No. 200)	5.1	3	7

Aggregates	AGG. 1	AGG. 2	AGG. 3	AGG. 4	AGG. 5	AGG. 6
Material Description	1" AGG	1/2" AGG	3/8" AGG	Cr. Fines	Wade Sand	
Bin Proportions	25%	15%	10%	40%	10%	

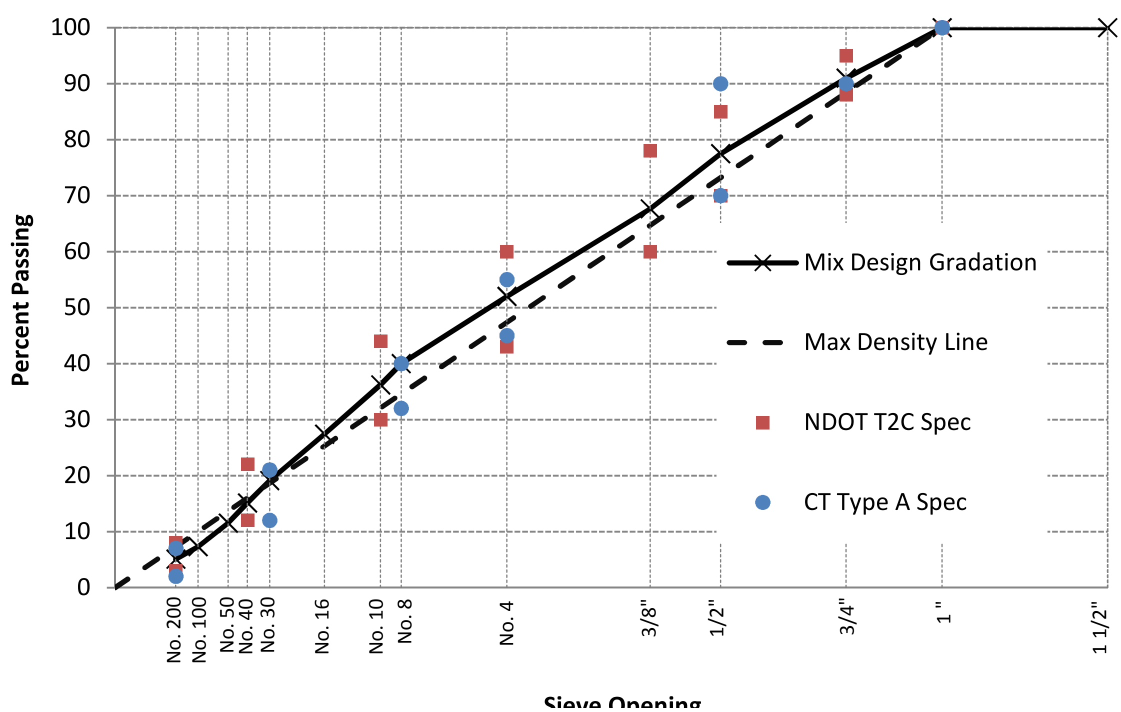


Figure 45: Lockwood Liquid-treated mix design and aggregate properties w/Paramount PG 64-28TR + 0.3% Evotherm - Phase II

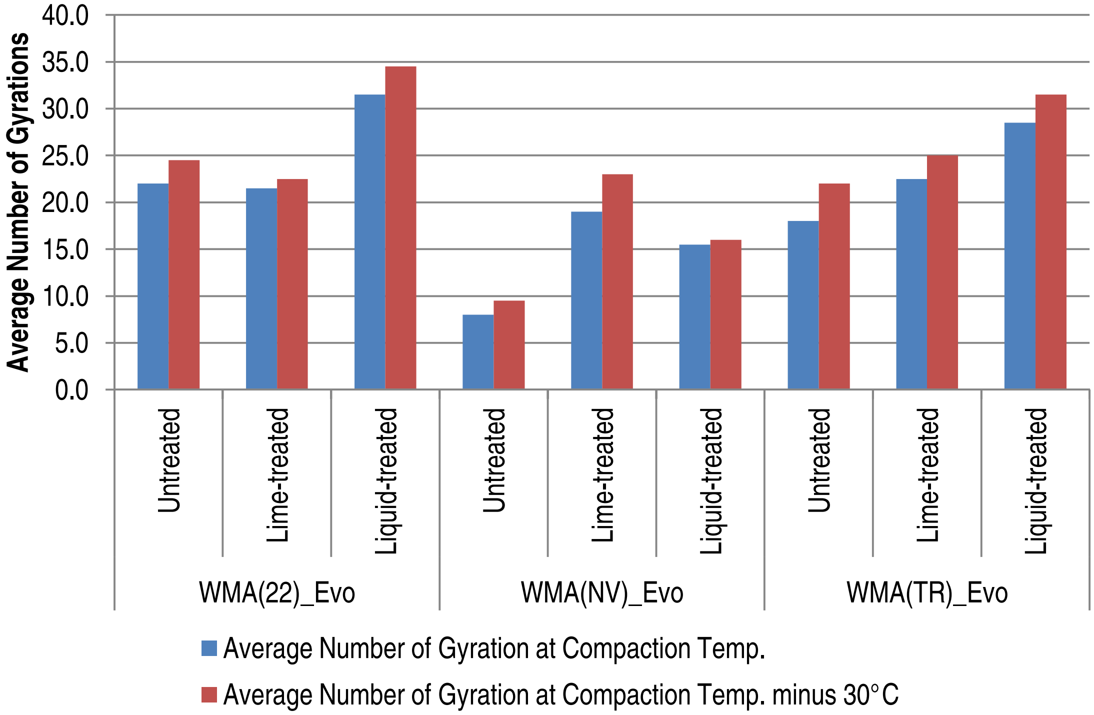


Figure 46: Compactibility of WMA Mixtures with PG64-22, PG64-28NV and PG64-28TR - Phase II

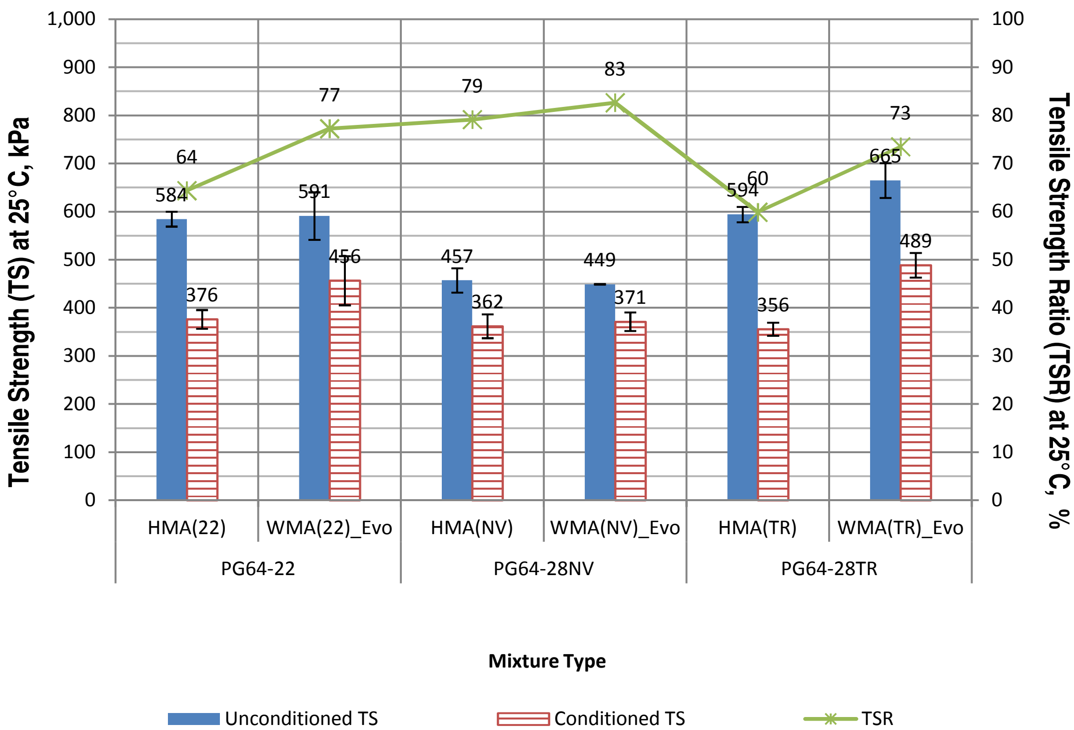


Figure 47: TS and TSR of Untreated Mixtures - Phase II

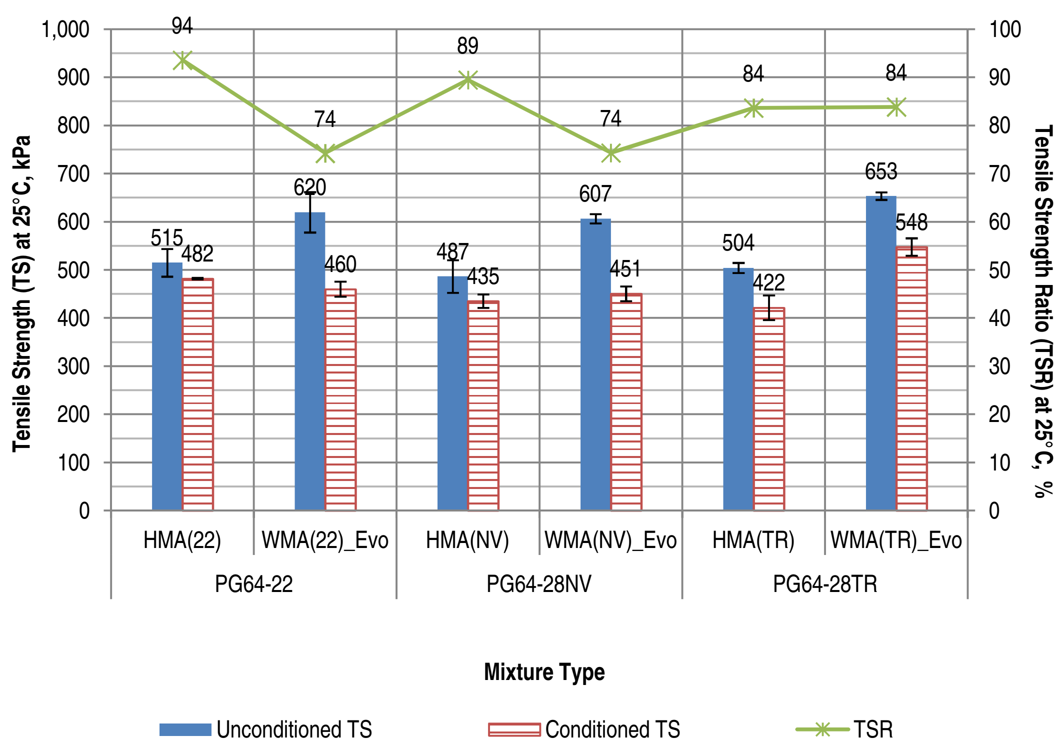


Figure 48: TS and TSR of Lime-treated Mixtures - Phase II

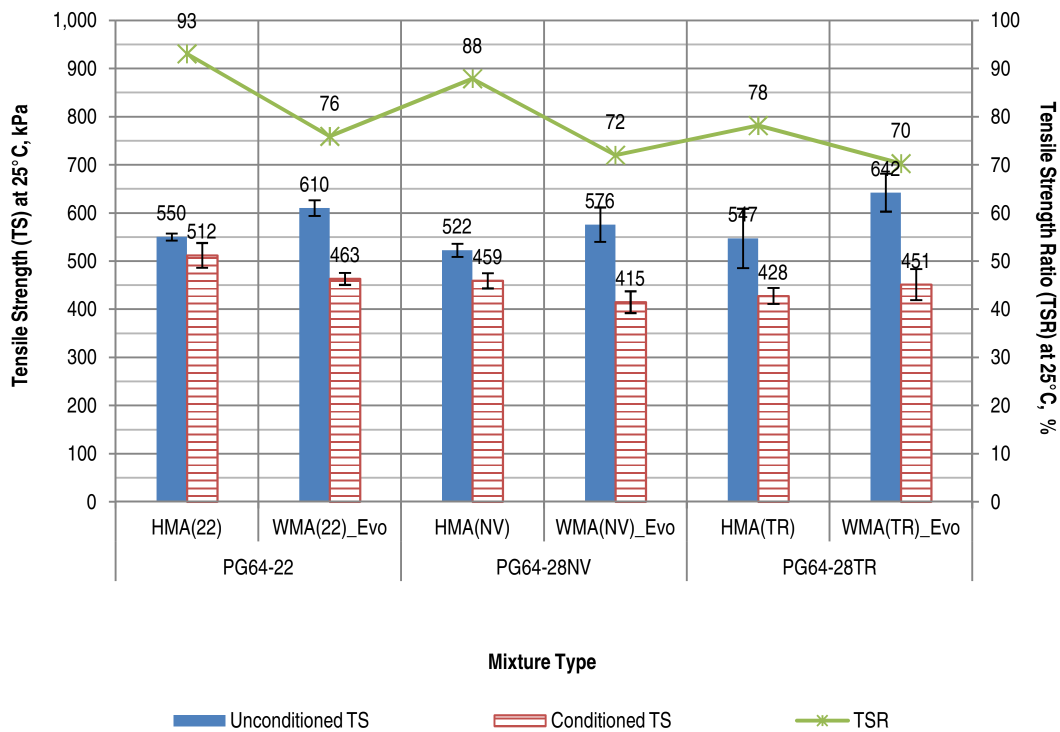


Figure 49: TS and TSR of Liquid-treated Mixtures - Phase II

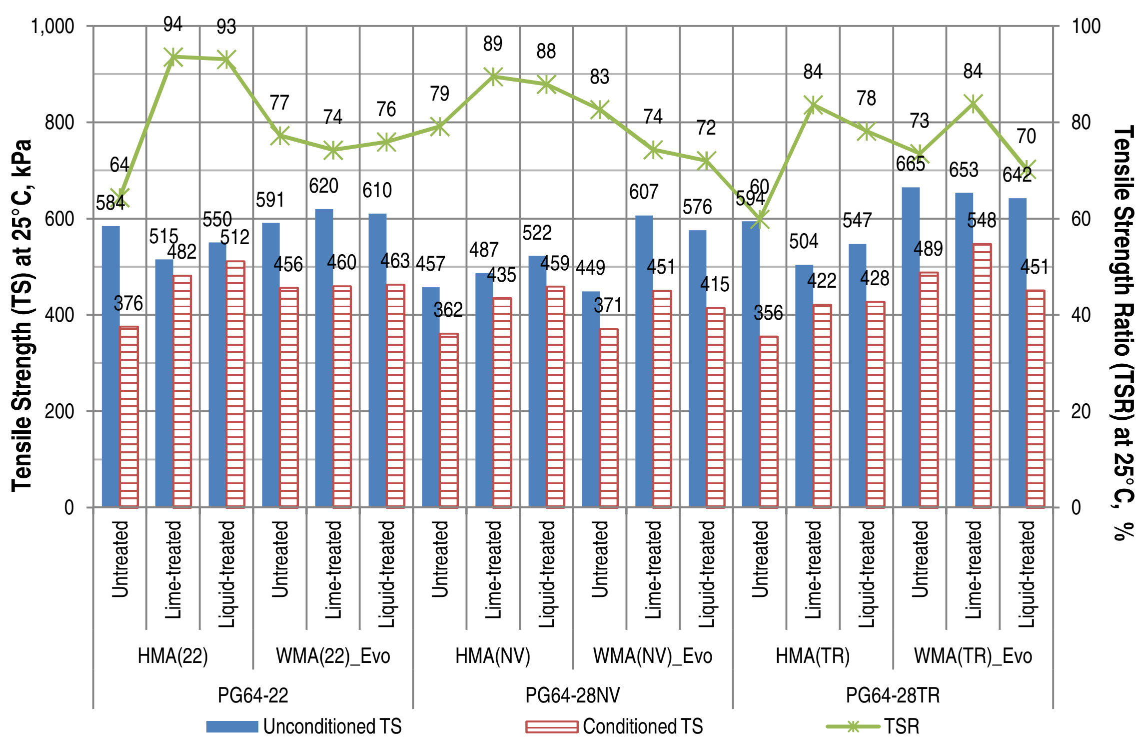


Figure 50: TS and TSR of All Mixtures - Phase II

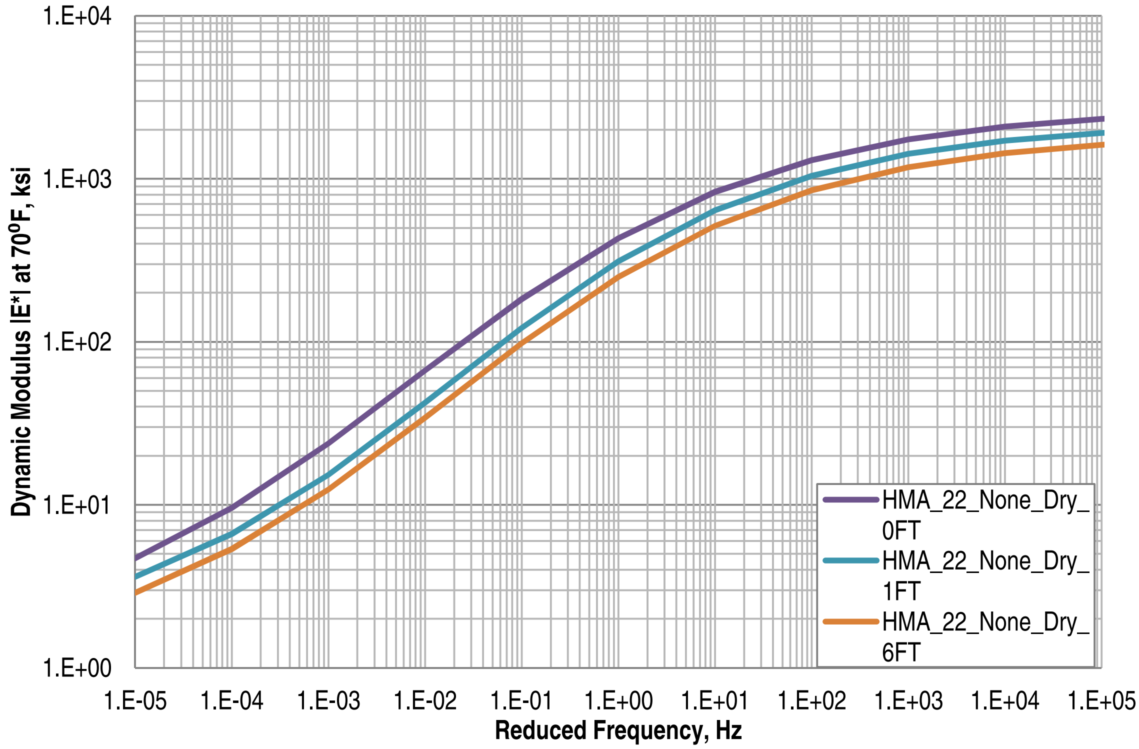


Figure 51: Dynamic Modulus (E*) Mater Curves for Untreated HMA Mixtures with PG64-22 - Phase II

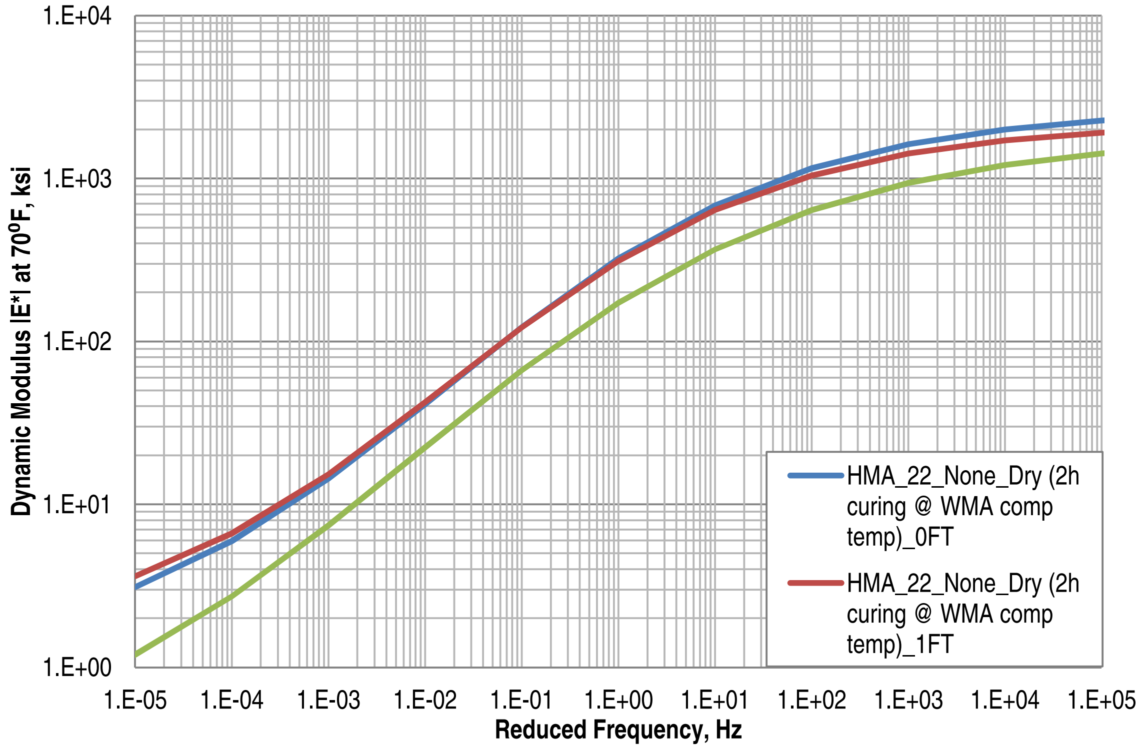


Figure 52: Dynamic Modulus (E*) Master Curves for Untreated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-22 - Phase II

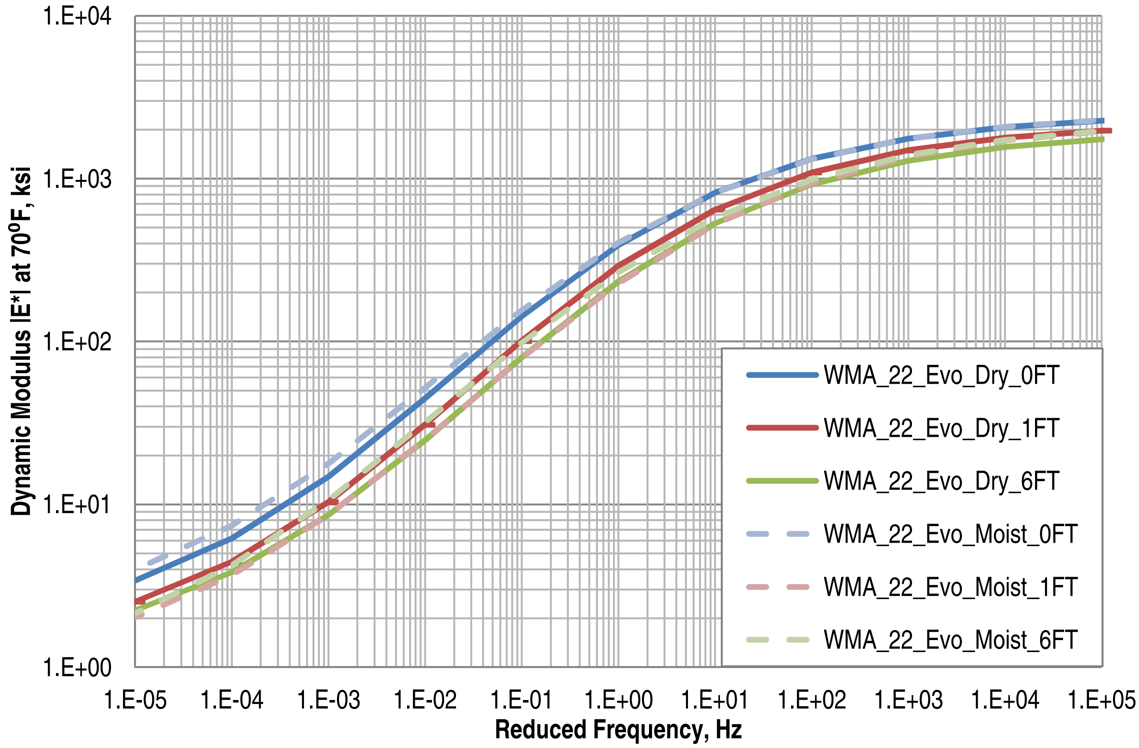


Figure 53: Dynamic Modulus (E*) Mater Curves for Untreated WMA_Evo Mixtures with PG64-22 - Phase II

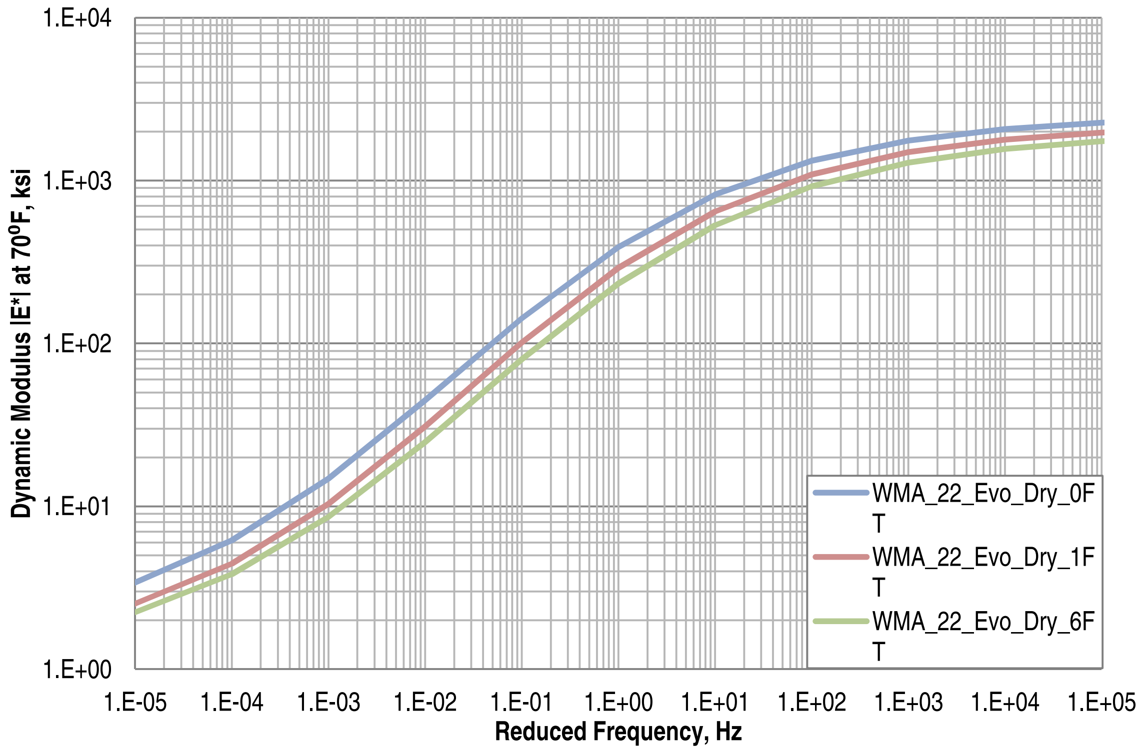


Figure 54: Dynamic Modulus (E*) Master Curves for Untreated WMA_Evo Dry Mixtures with PG64-22 - Phase II

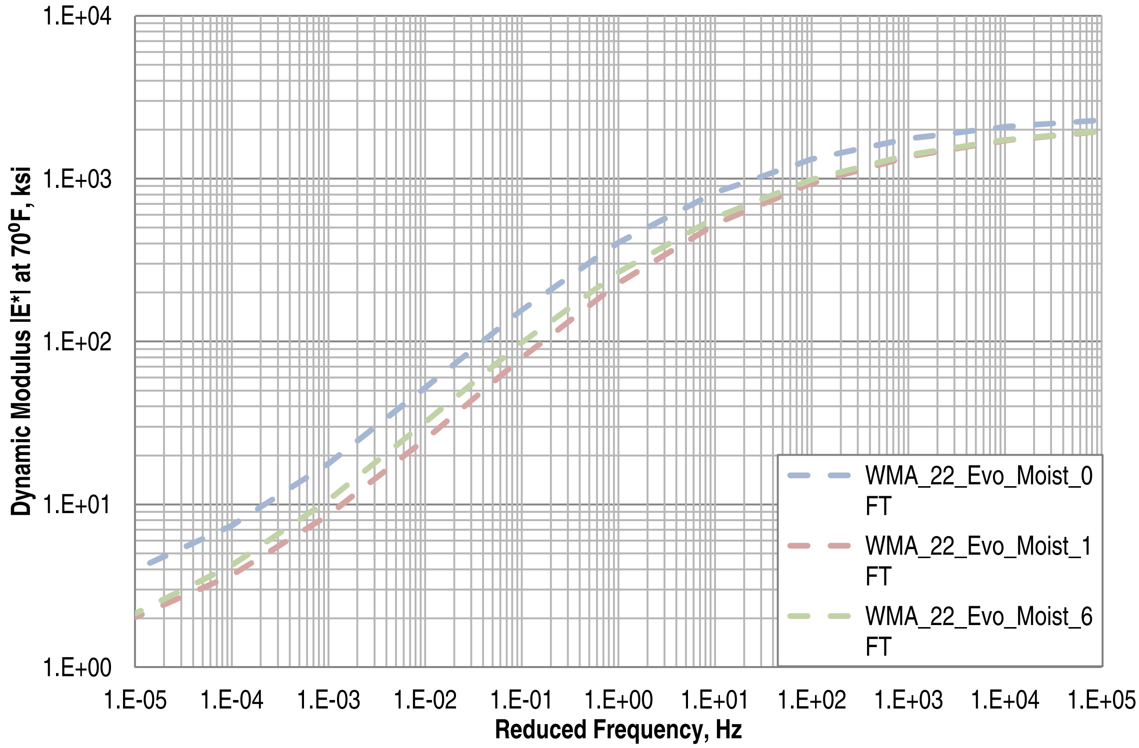


Figure 55: Dynamic Modulus (E*) Master Curves for Untreated WMA_Evo Moist Mixtures with PG64-22 - Phase II

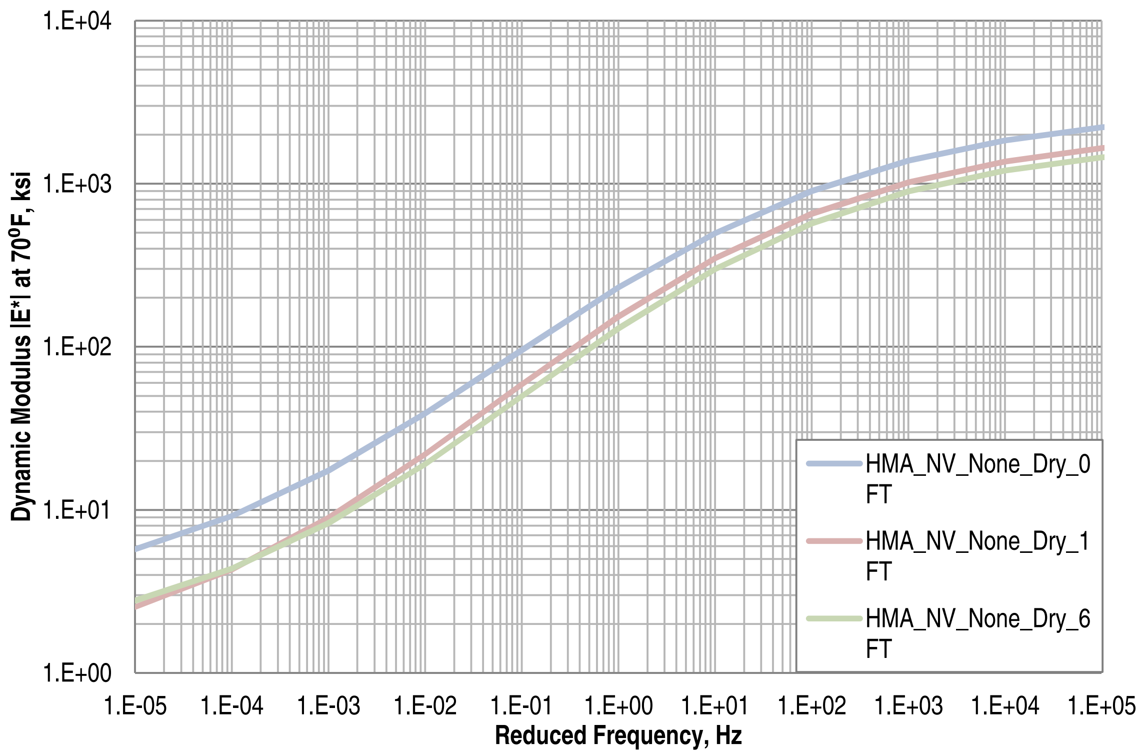


Figure 56: Dynamic Modulus (E*) Master Curves for Untreated HMA Mixtures with PG64-28NV - Phase II

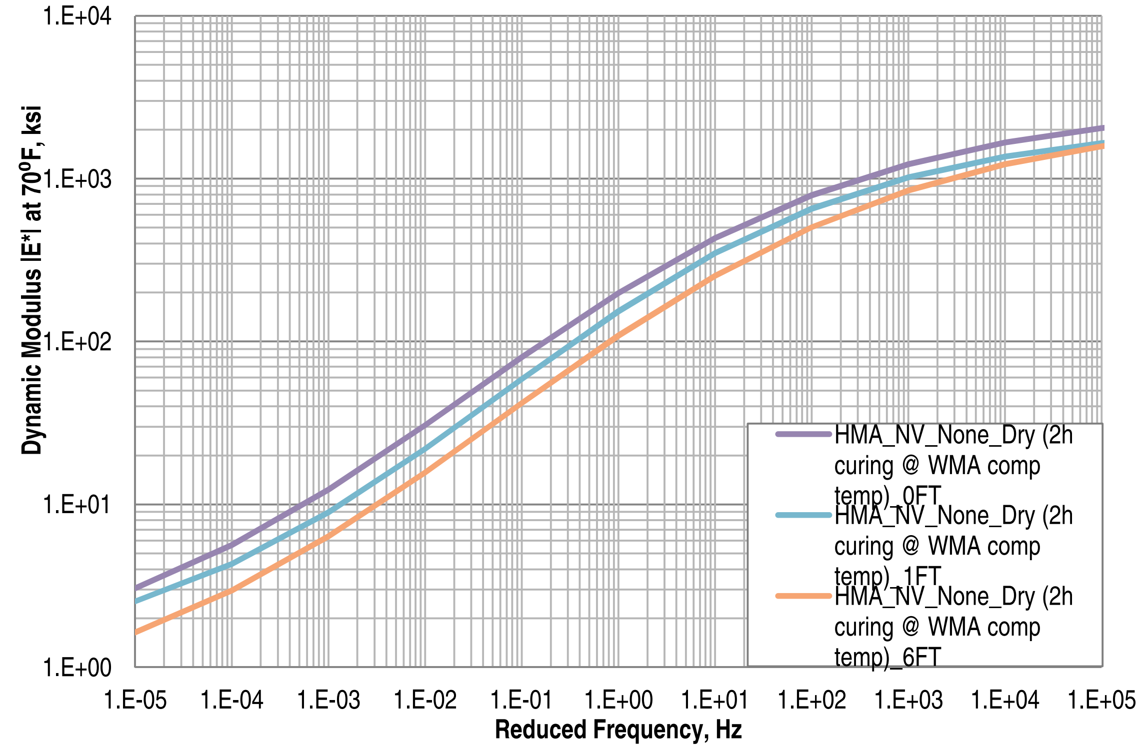


Figure 57: Dynamic Modulus (E*) Master Curves for Untreated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-28NV - Phase II

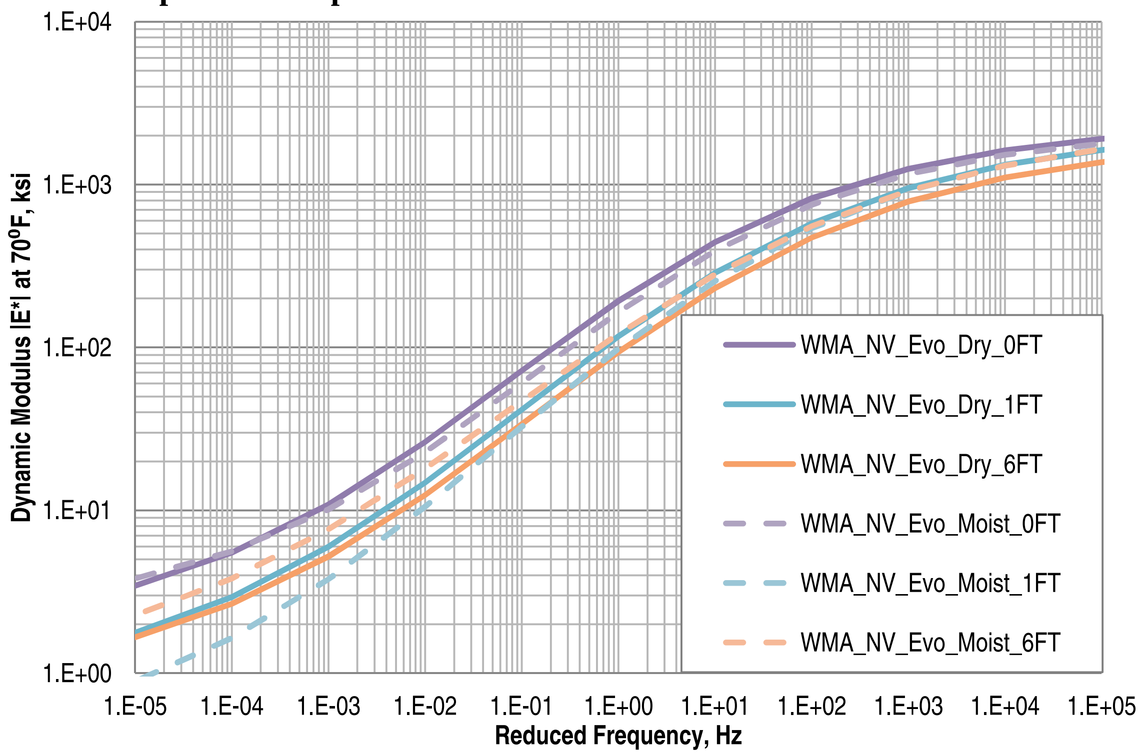


Figure 58: Dynamic Modulus (E*) Mater Curves for Untreated WMA_Evo Mixtures with PG64-28NV - Phase II

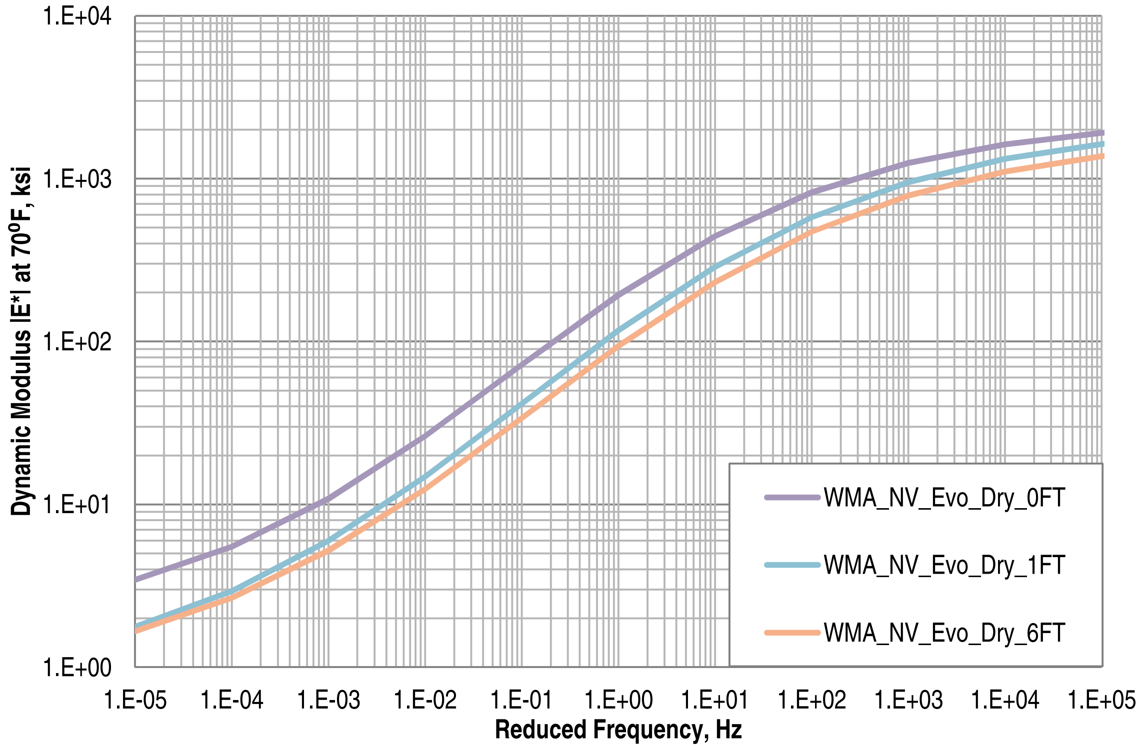


Figure 59: Dynamic Modulus (E*) Mater Curves for Untreated WMA_Evo Dry Mixtures with PG64-28NV - Phase II

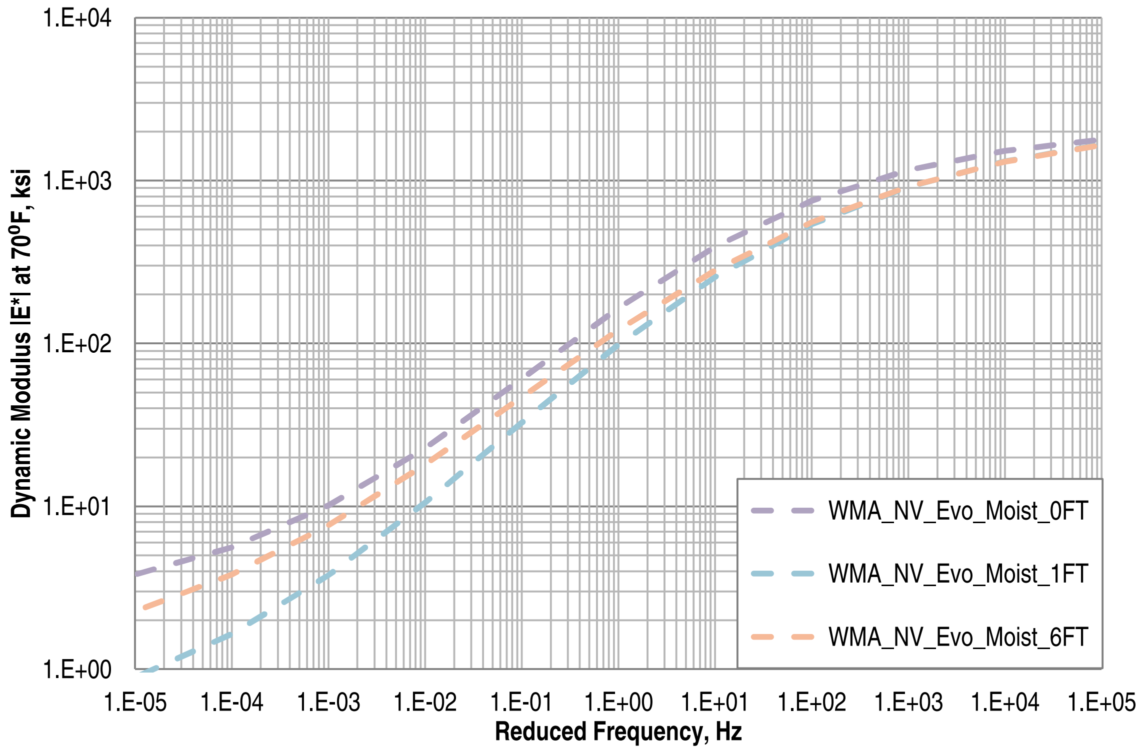


Figure 60: Dynamic Modulus (E*) Dynamic Modulus (E*) Mater Curves for Untreated WMA_Evo Moist Mixtures with PG64-28NV - Phase II

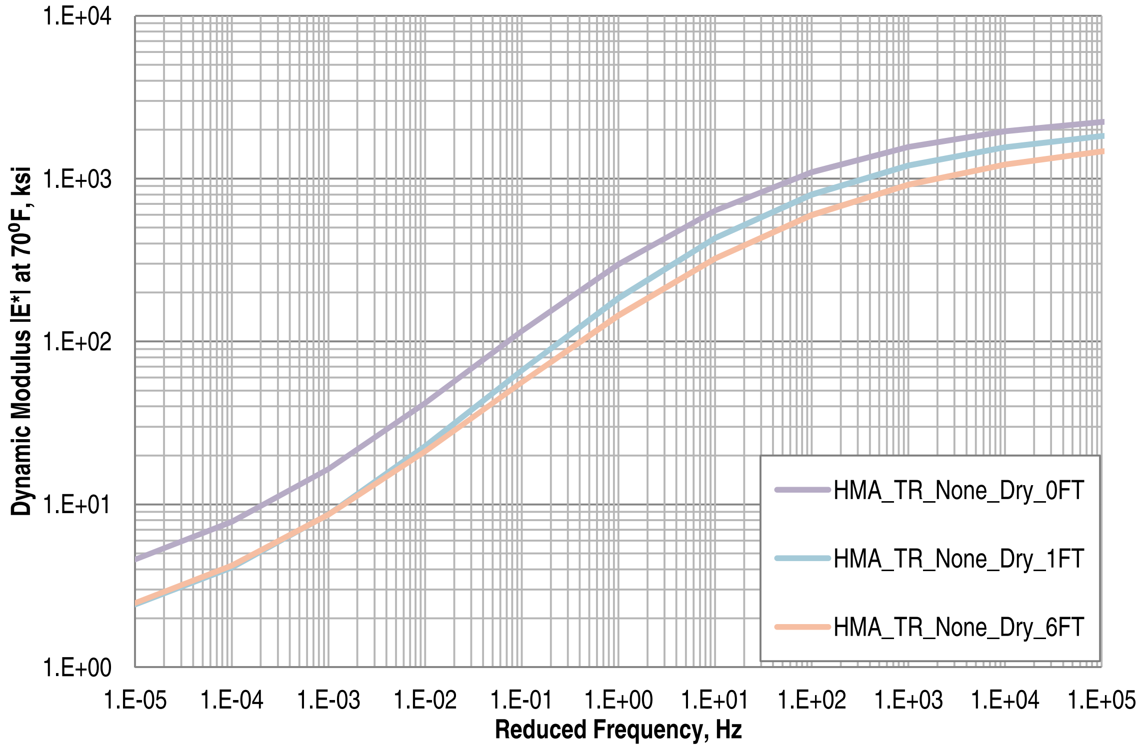


Figure 61: Dynamic Modulus (E*) Mater Curves for Untreated HMA Mixtures with PG64-28TR - Phase II

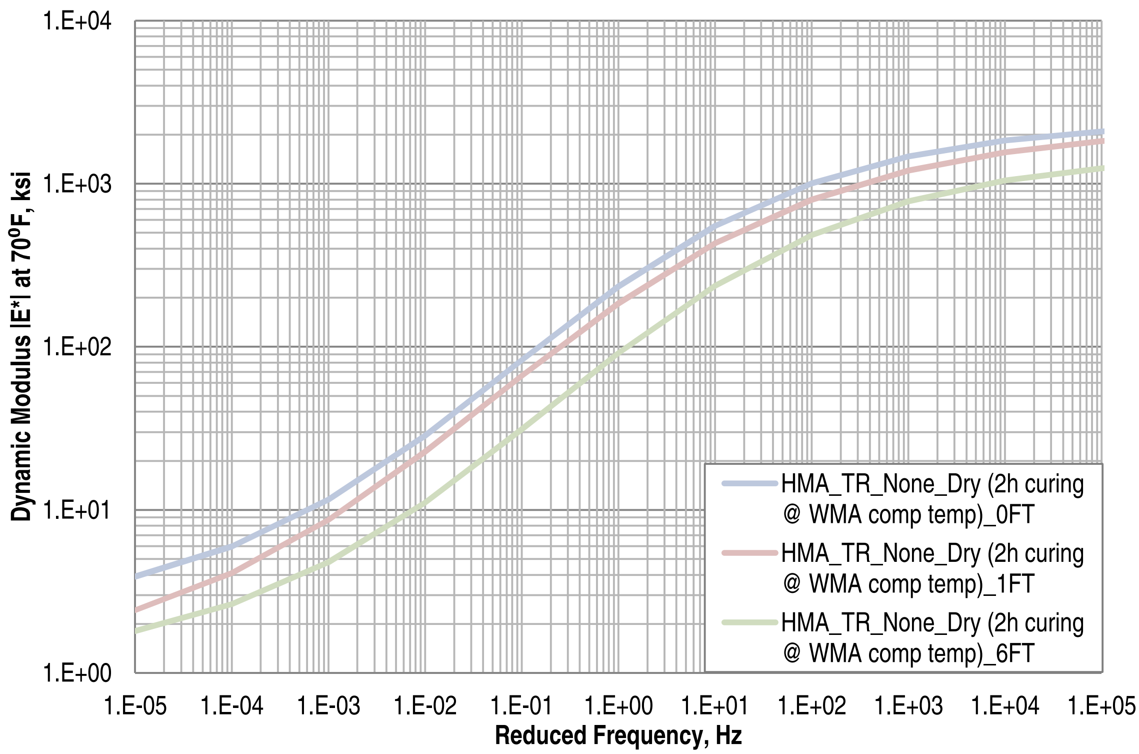


Figure 62: Dynamic Modulus (E*) Mater Curves for Untreated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-28TR - Phase II

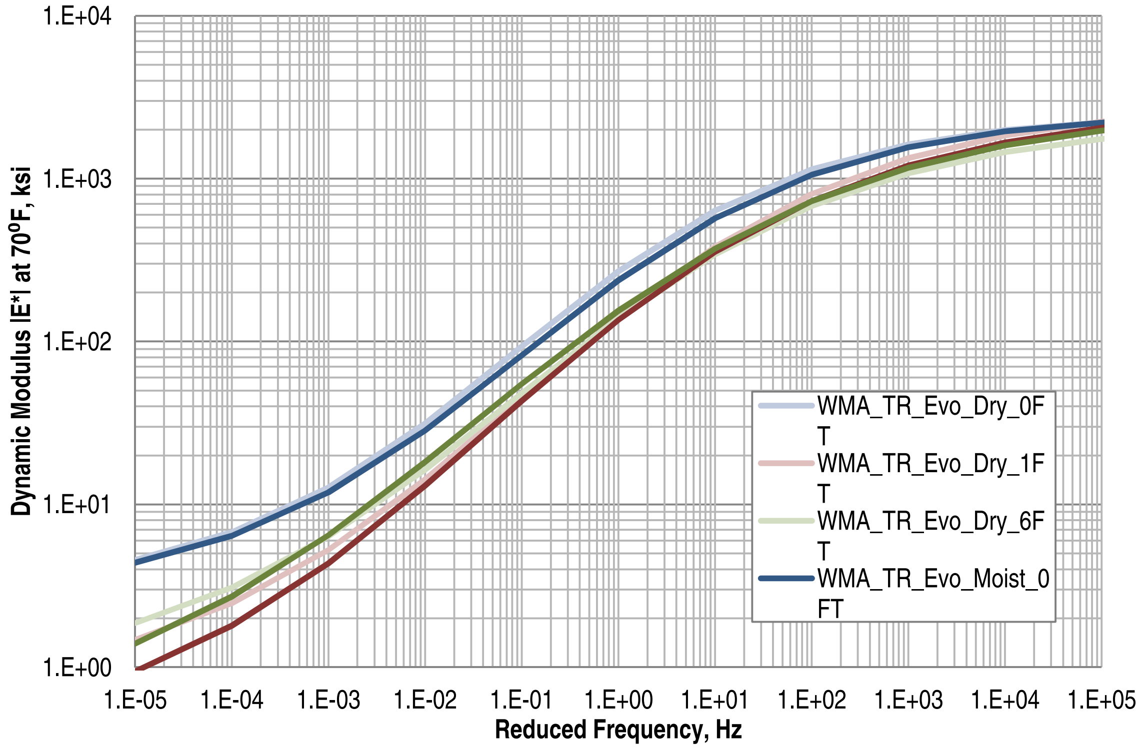


Figure 63: Dynamic Modulus (E*) Mater Curves for Untreated WMA_Evo Mixtures with PG64-28TR - Phase II

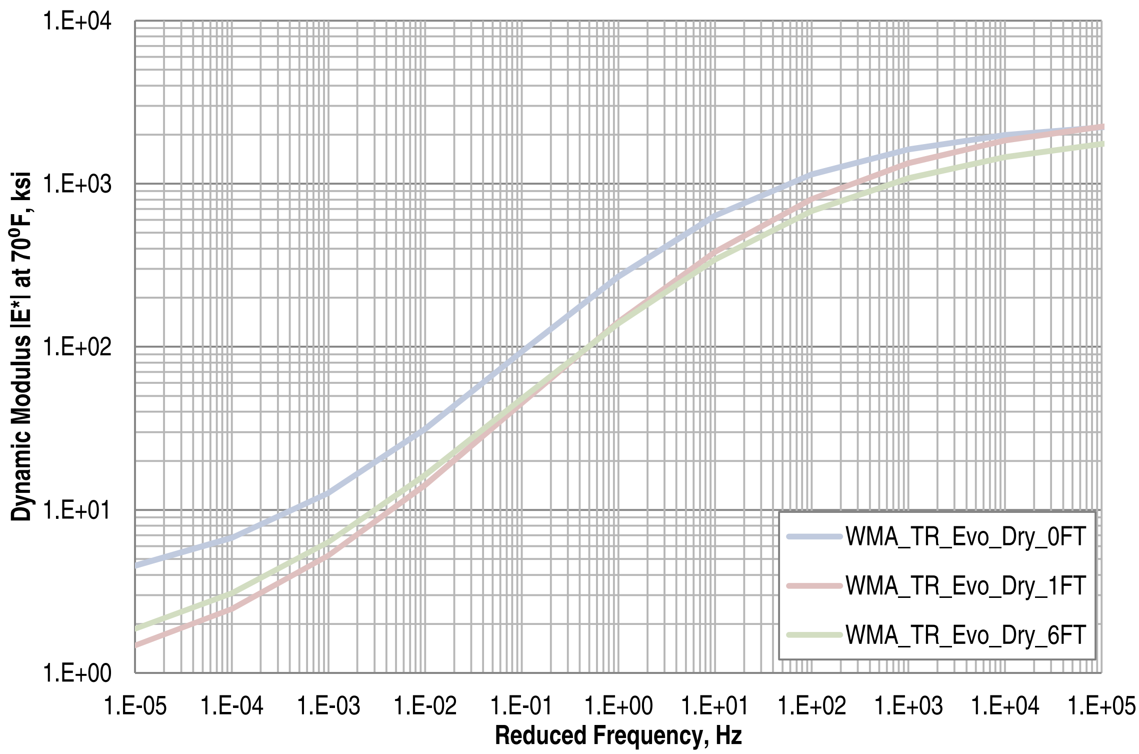


Figure 64: Dynamic Modulus (E*) Mater Curves for Untreated WMA_Evo Dry Mixtures with PG64-28TR - Phase II

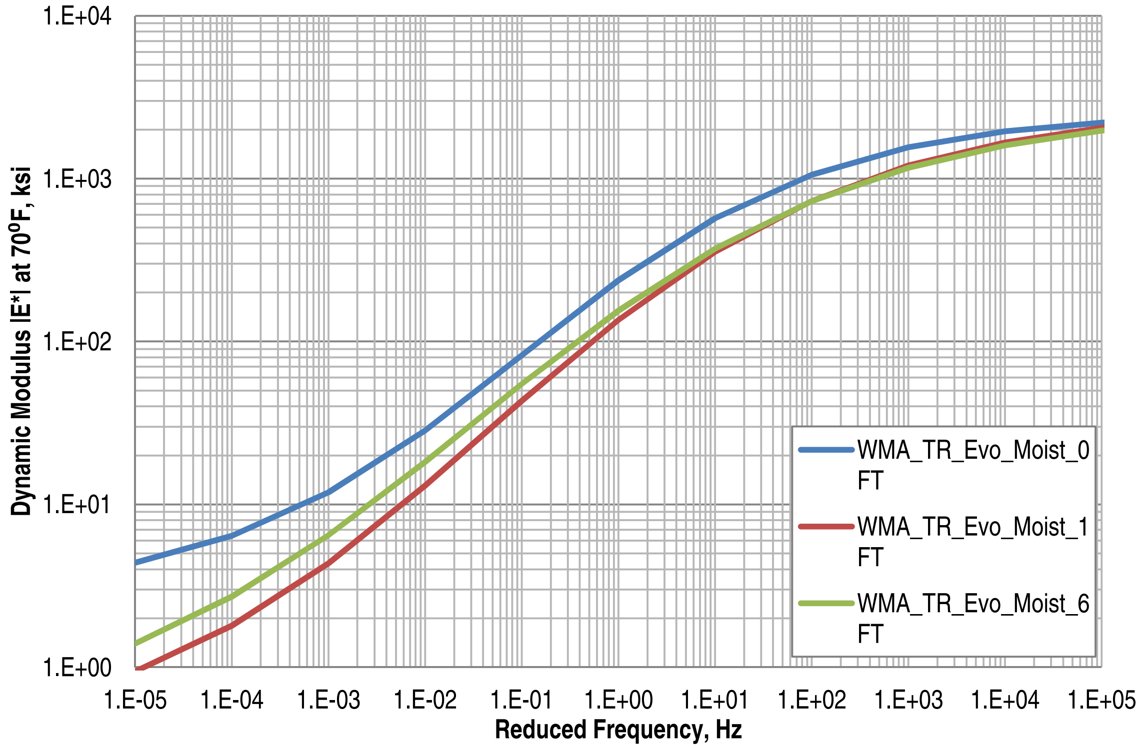


Figure 65: Dynamic Modulus (E*) Mater Curves for Untreated WMA_Evo Moist Mixtures with PG64-28TR - Phase II

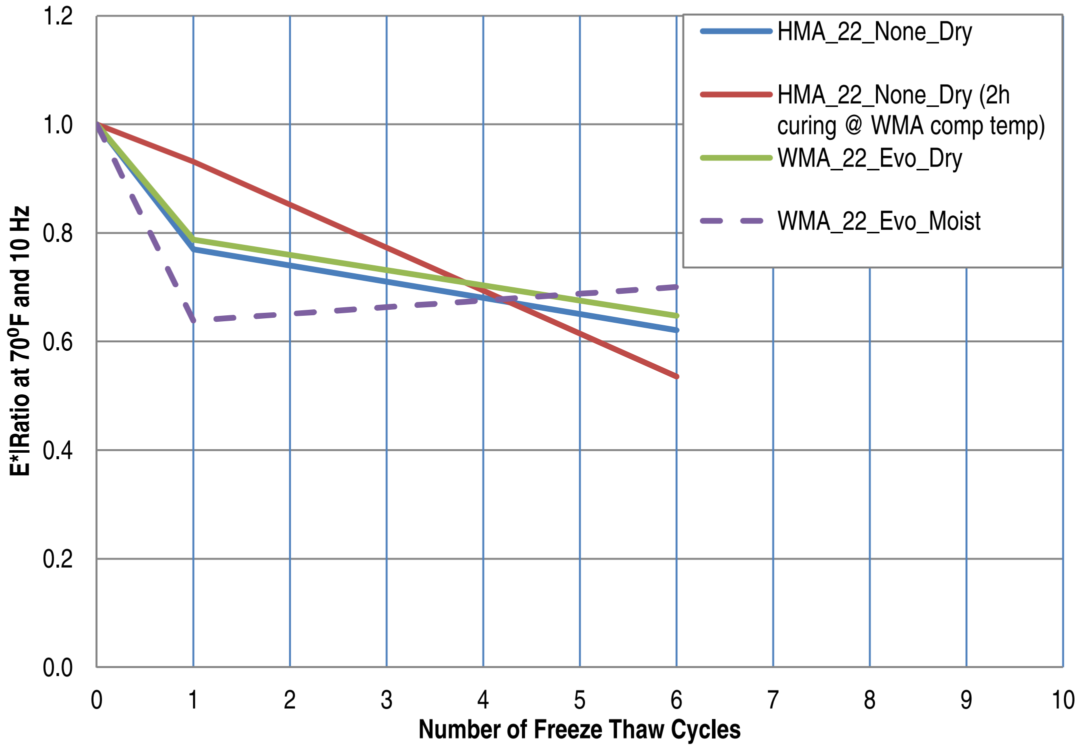


Figure 66: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-22 - Phase II

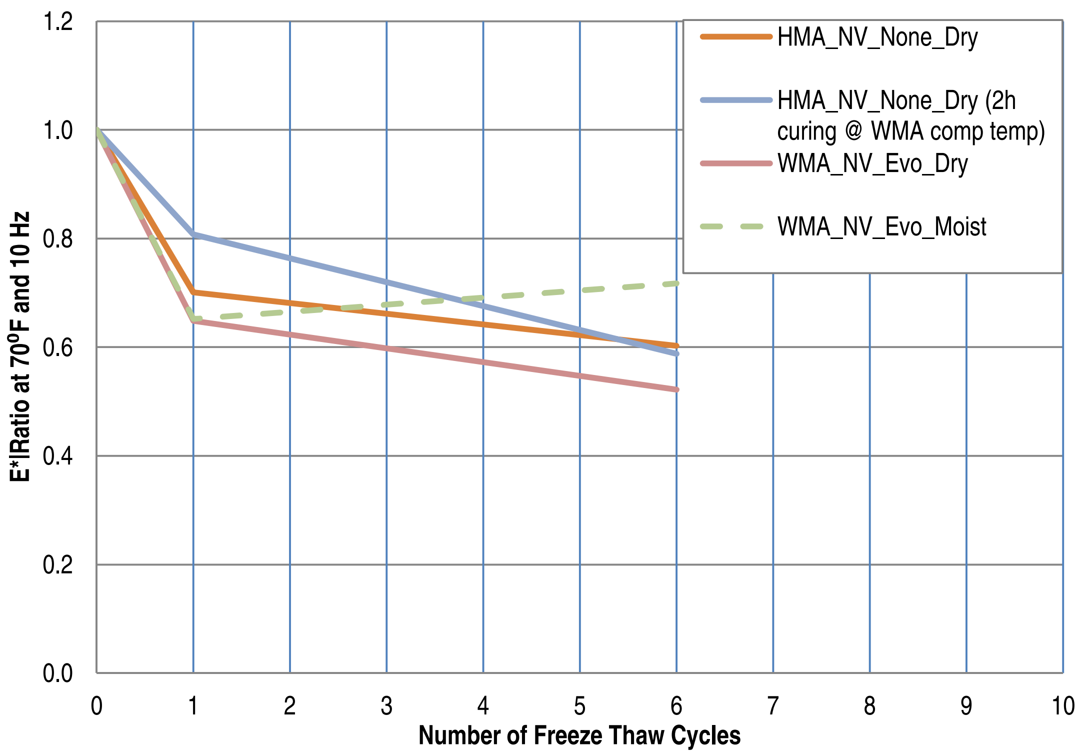


Figure 67: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-28NV - Phase II

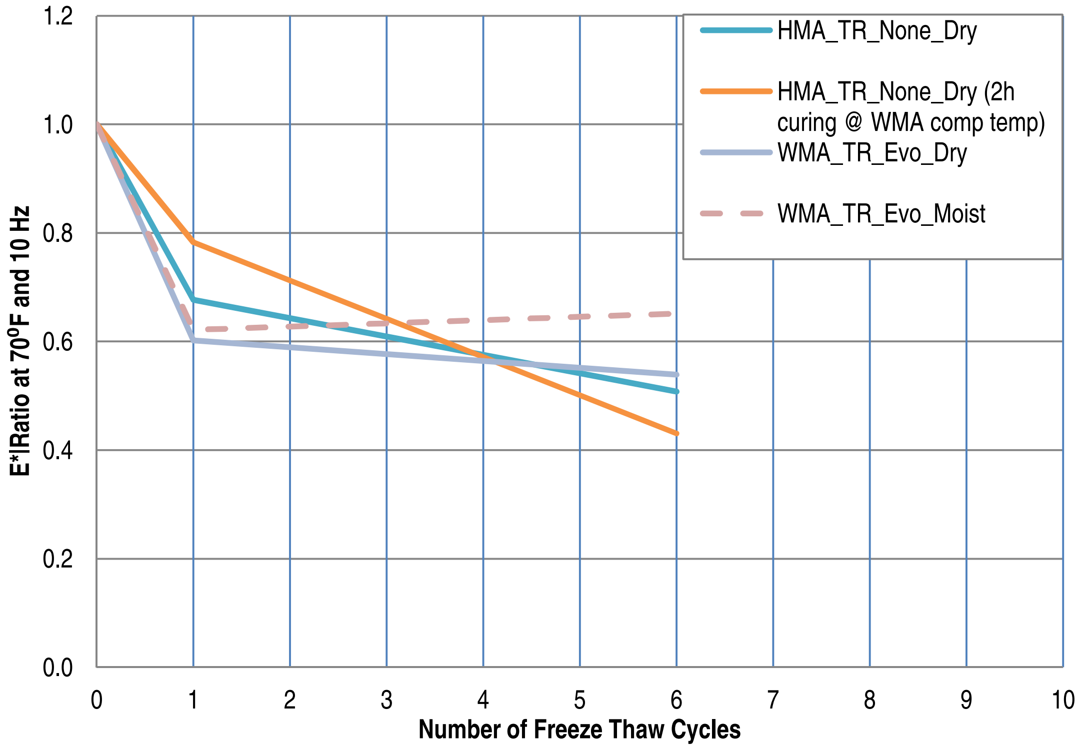


Figure 68: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-28TR - Phase II

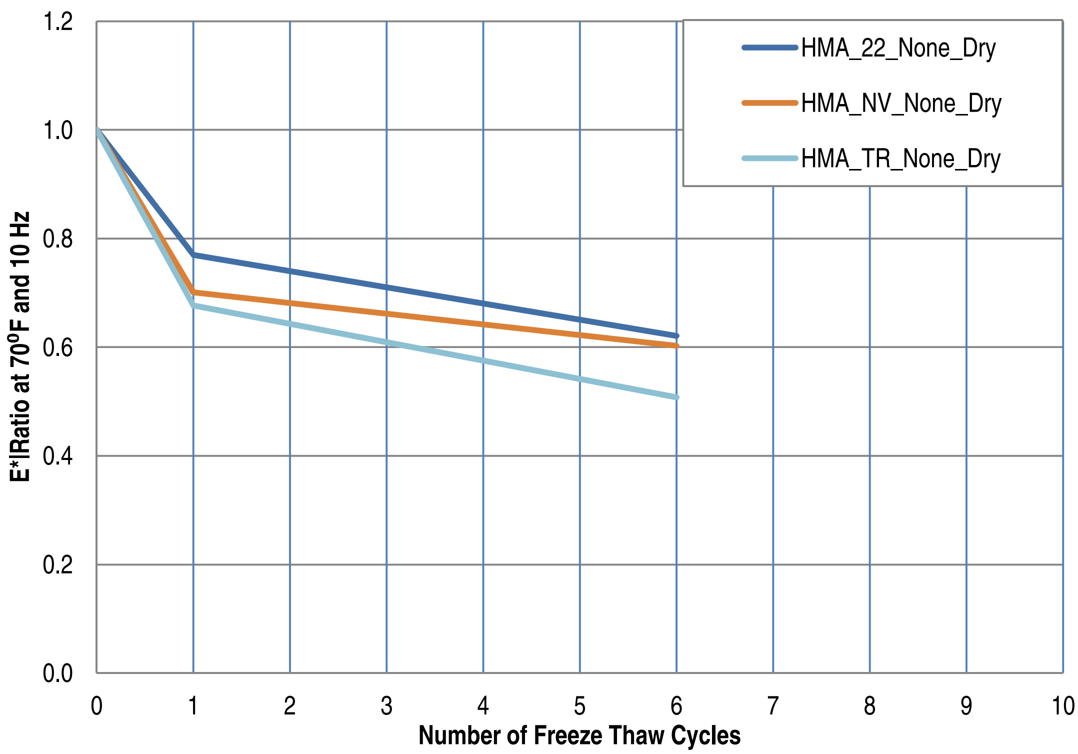


Figure 69: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated HMA Mixtures - Phase II

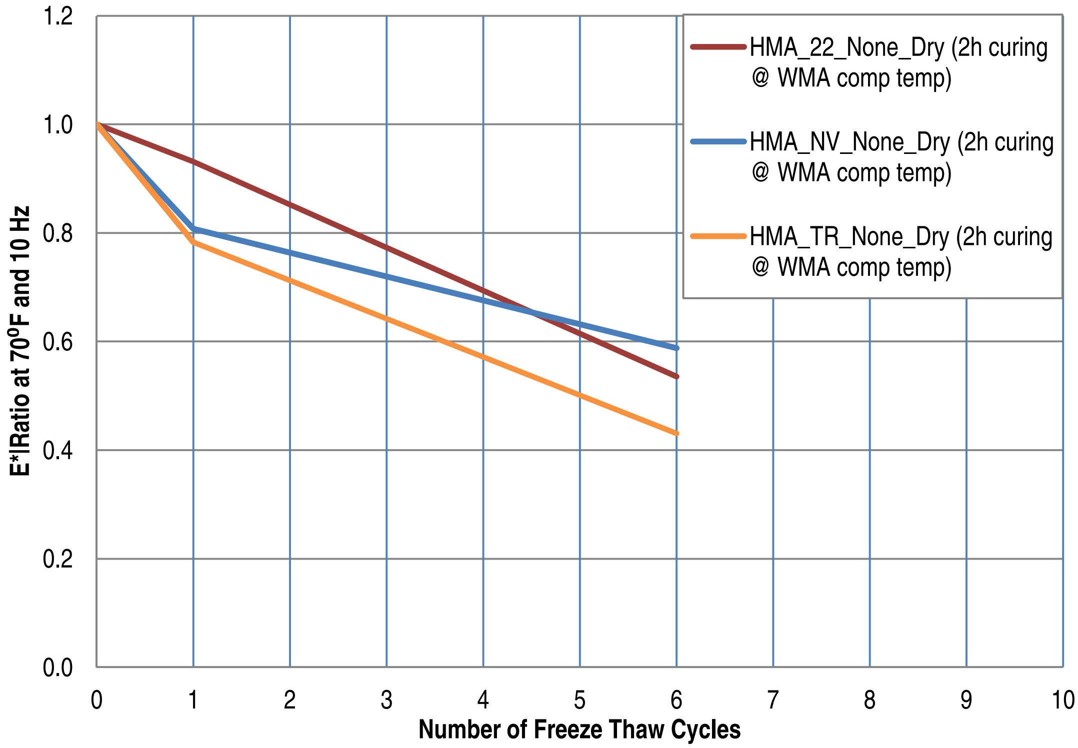


Figure 70: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated HMA 2h Cured @ WMA Compaction Temperature Mixtures - Phase II

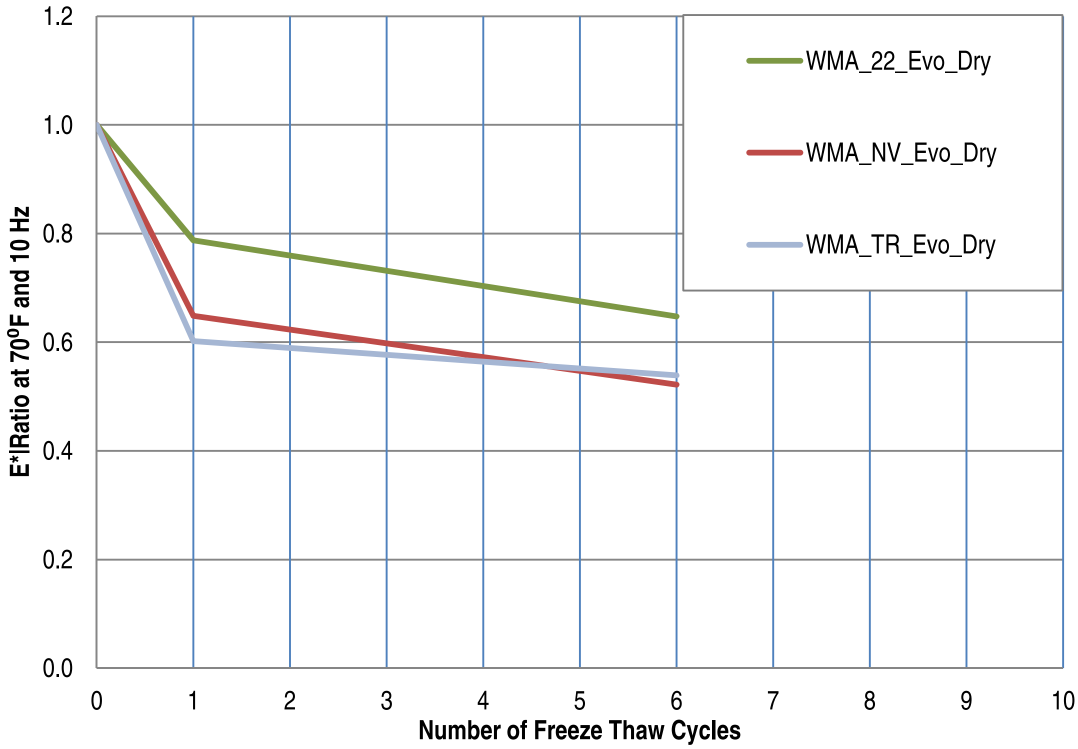


Figure 71: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated WMA_Evo Dry Mixtures - Phase II

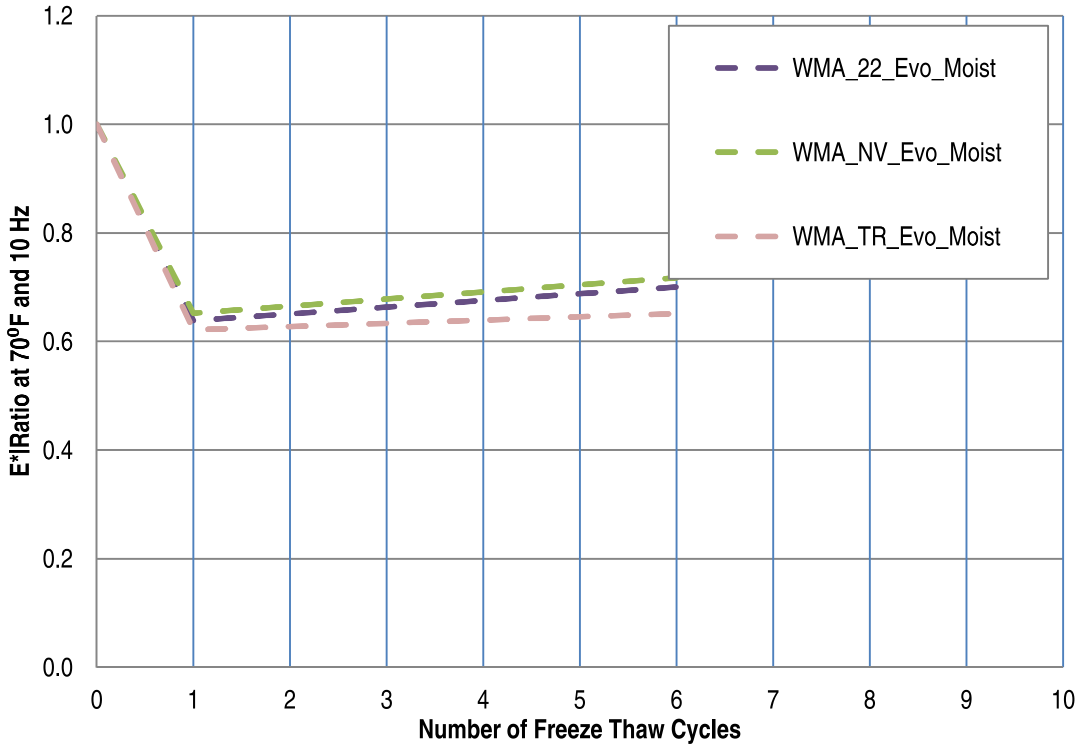


Figure 72: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated WMA_Evo Moist Mixtures - Phase II

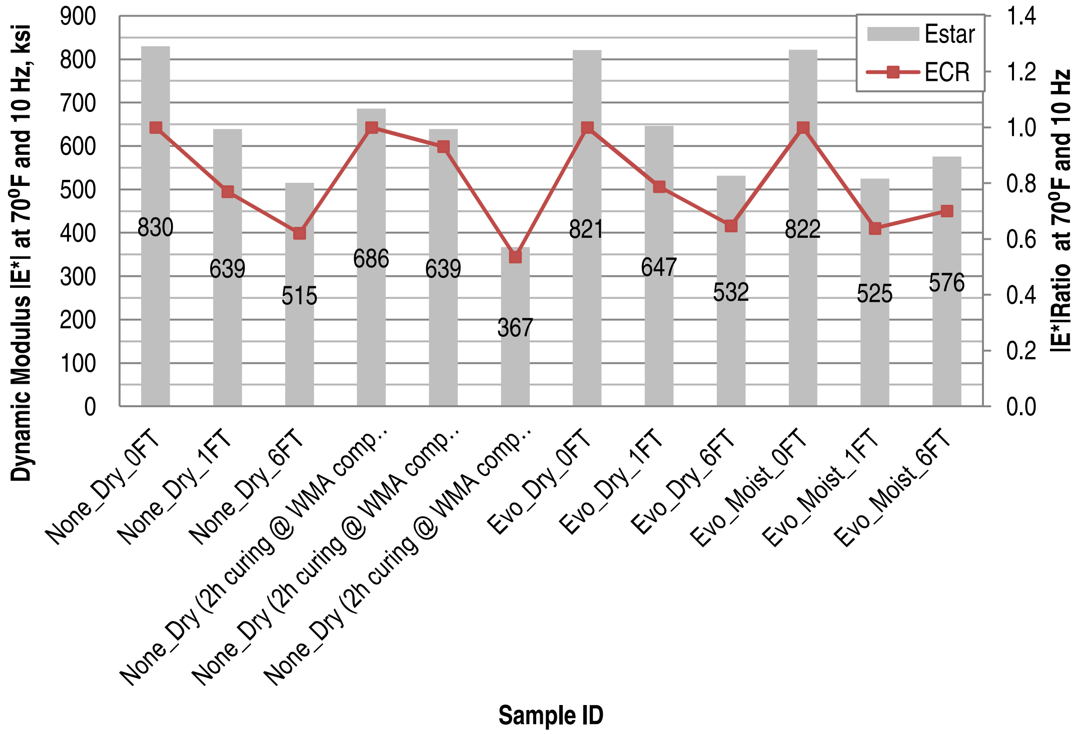


Figure 73: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^0F and 10 Hz for Untreated Mixtures with PG64-22 - Phase II

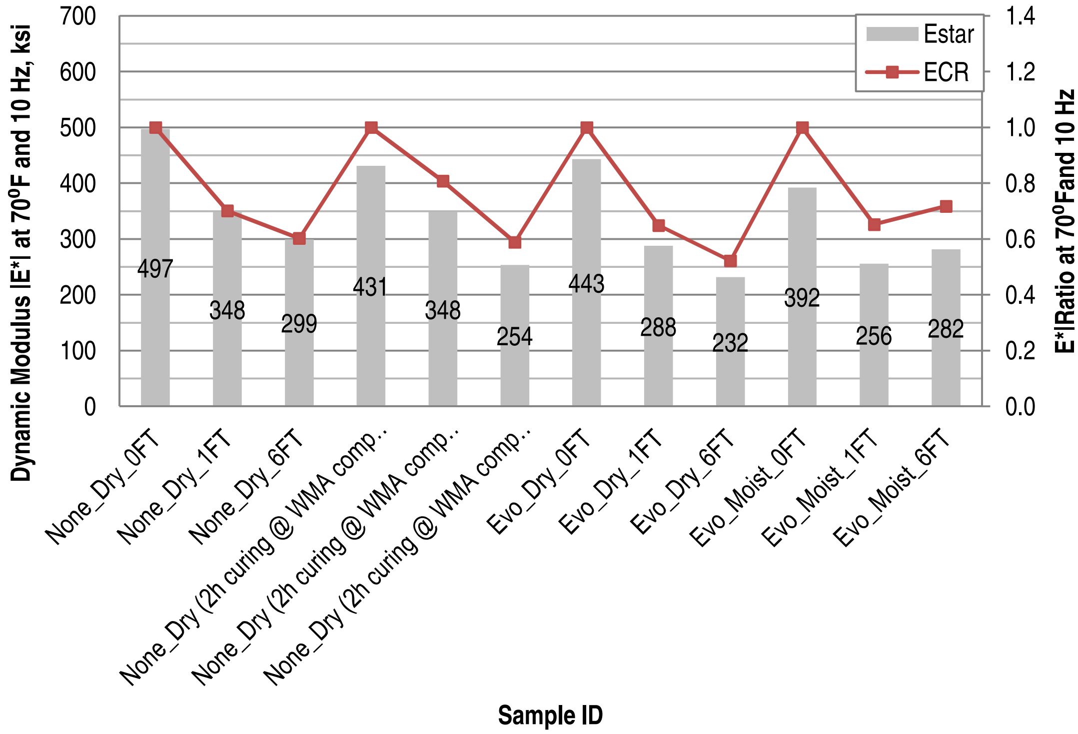


Figure 74: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-28NV - Phase II

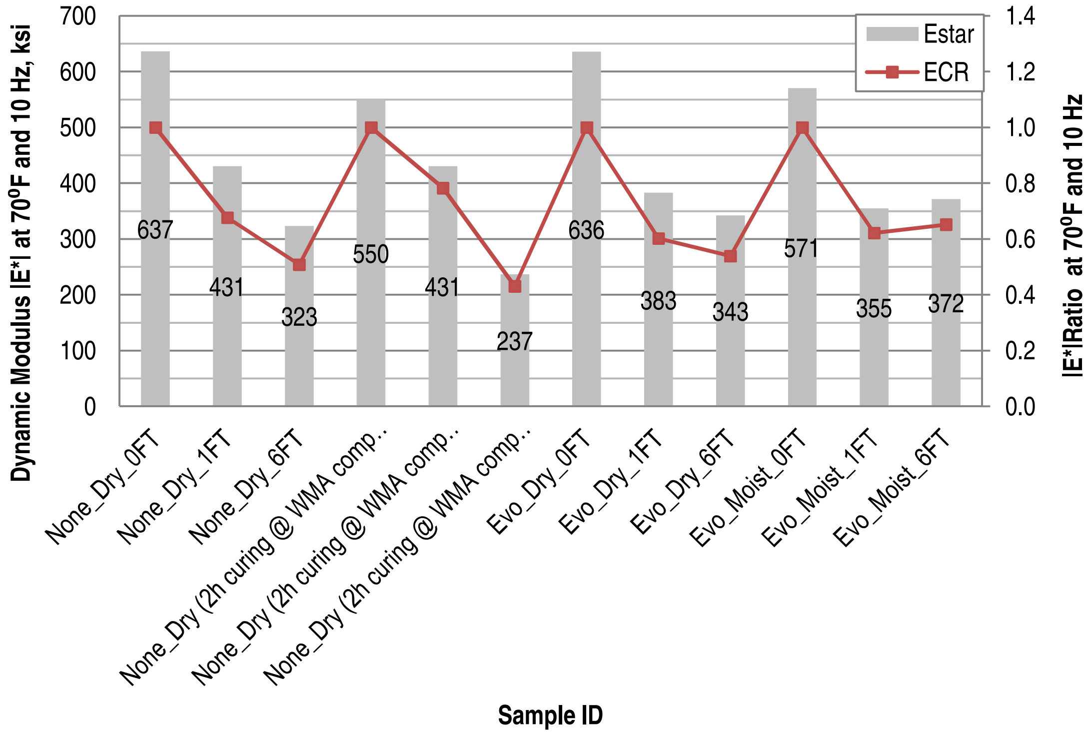


Figure 75: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-28TR - Phase II

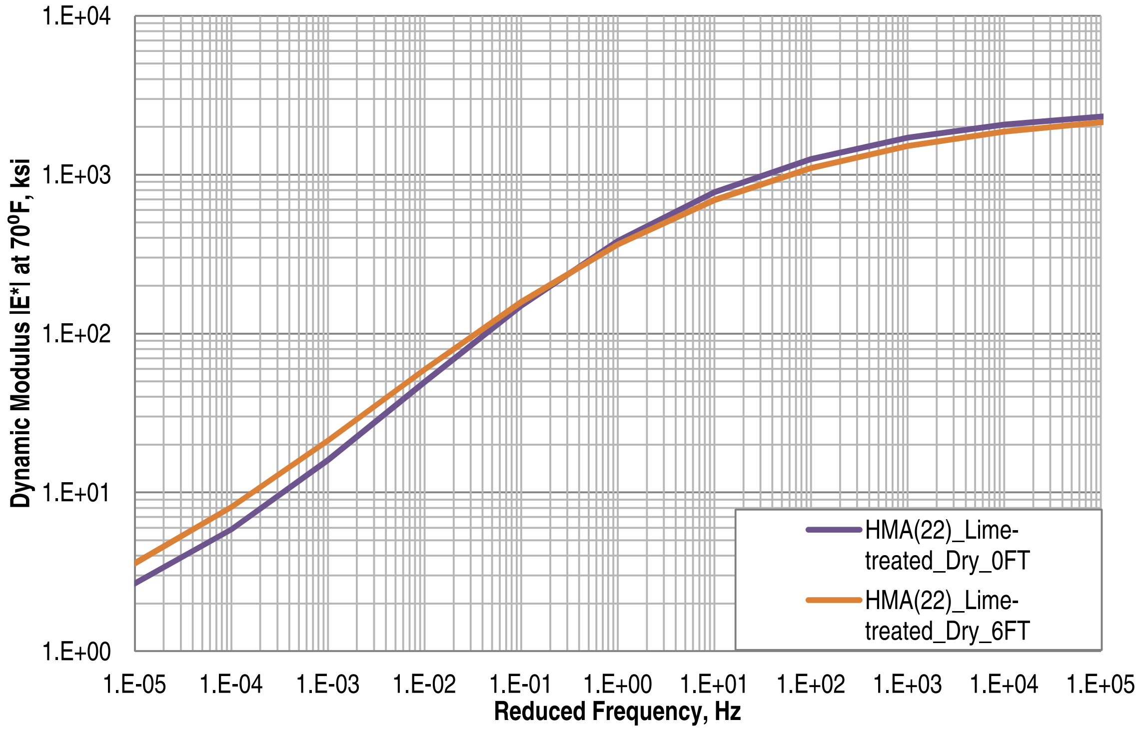


Figure 76: Dynamic Modulus (E*) Mater Curves for Lime-treated HMA Mixtures with PG64-22 - Phase II

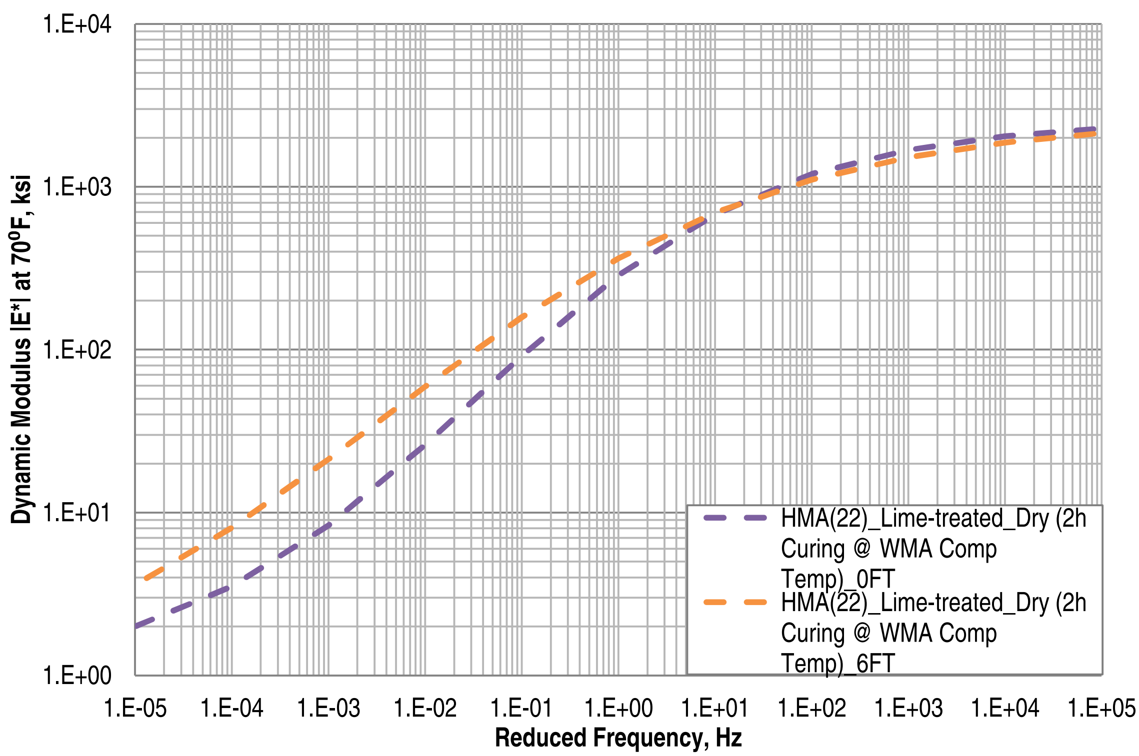


Figure 77: Dynamic Modulus (E*) Master Curves for Lime-treated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-22 - Phase II

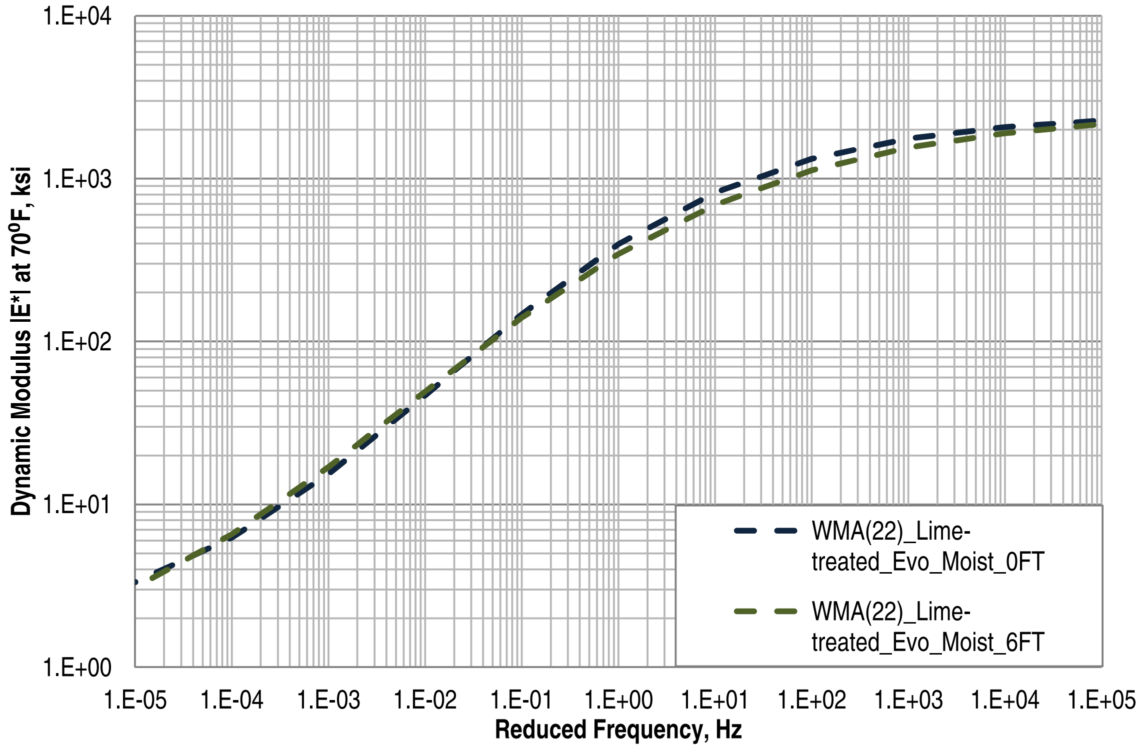


Figure 78: Dynamic Modulus (E*) Mater Curves for Lime-treated WMA_Evo Moist Mixtures with PG64-22 - Phase II

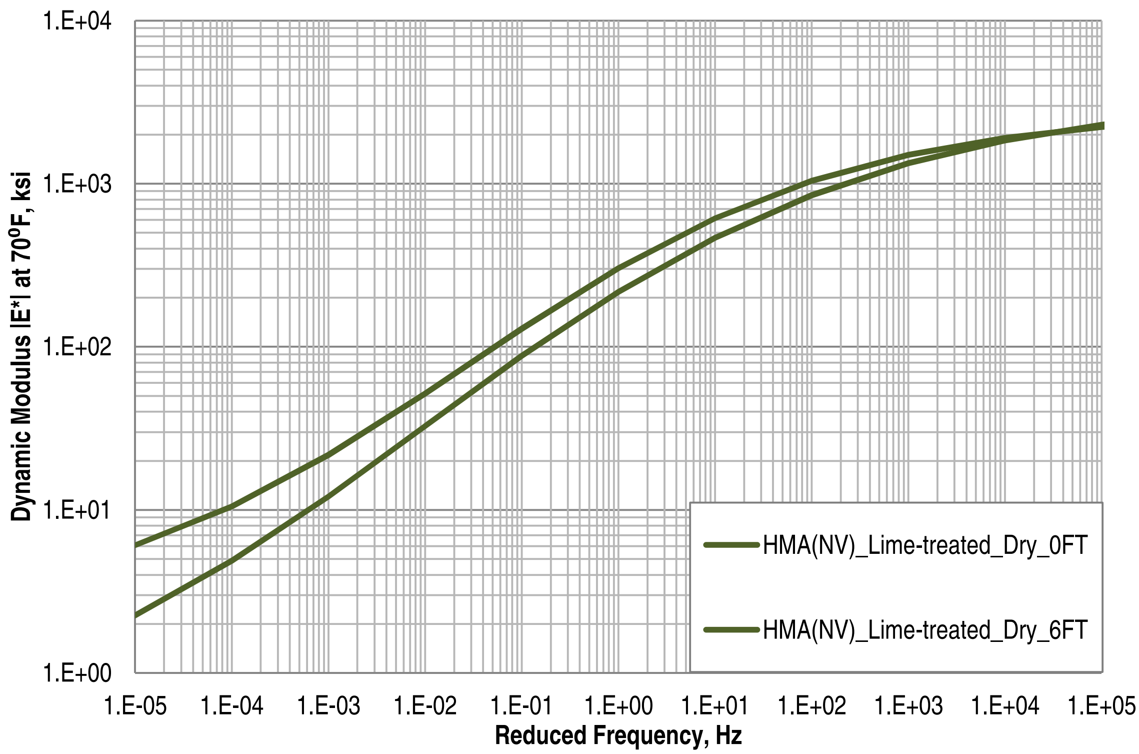


Figure 79: Dynamic Modulus (E*) Master Curves for Lime-treated HMA Mixtures with PG64-28NV - Phase II

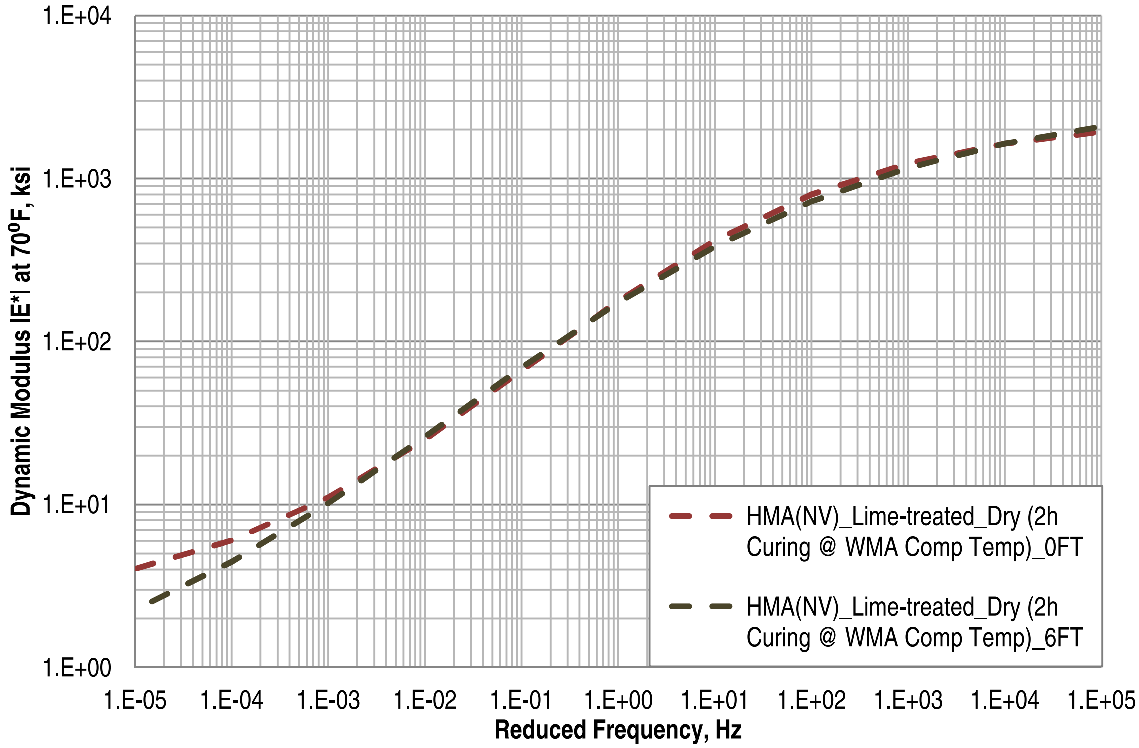


Figure 80: Dynamic Modulus (E*) Master Curves for Lime-treated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-28NV - Phase II

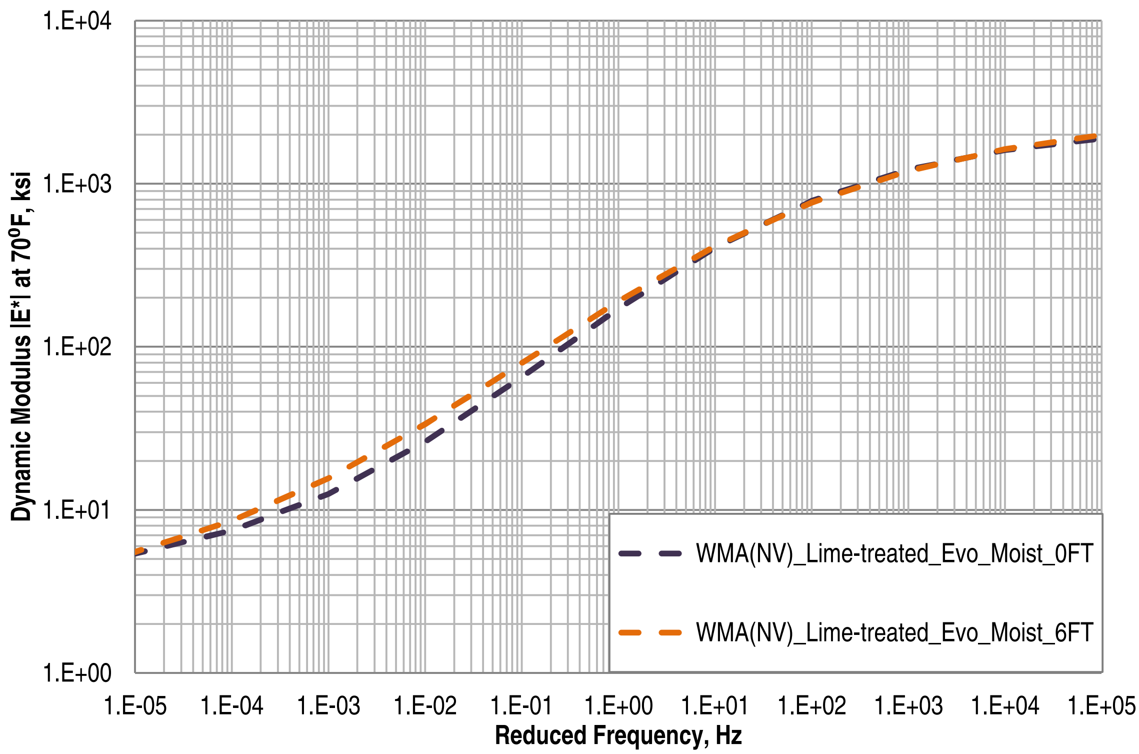


Figure 81: Dynamic Modulus (E*) Mater Curves for Lime-treated WMA_Evo Mixtures with PG64-28NV - Phase II

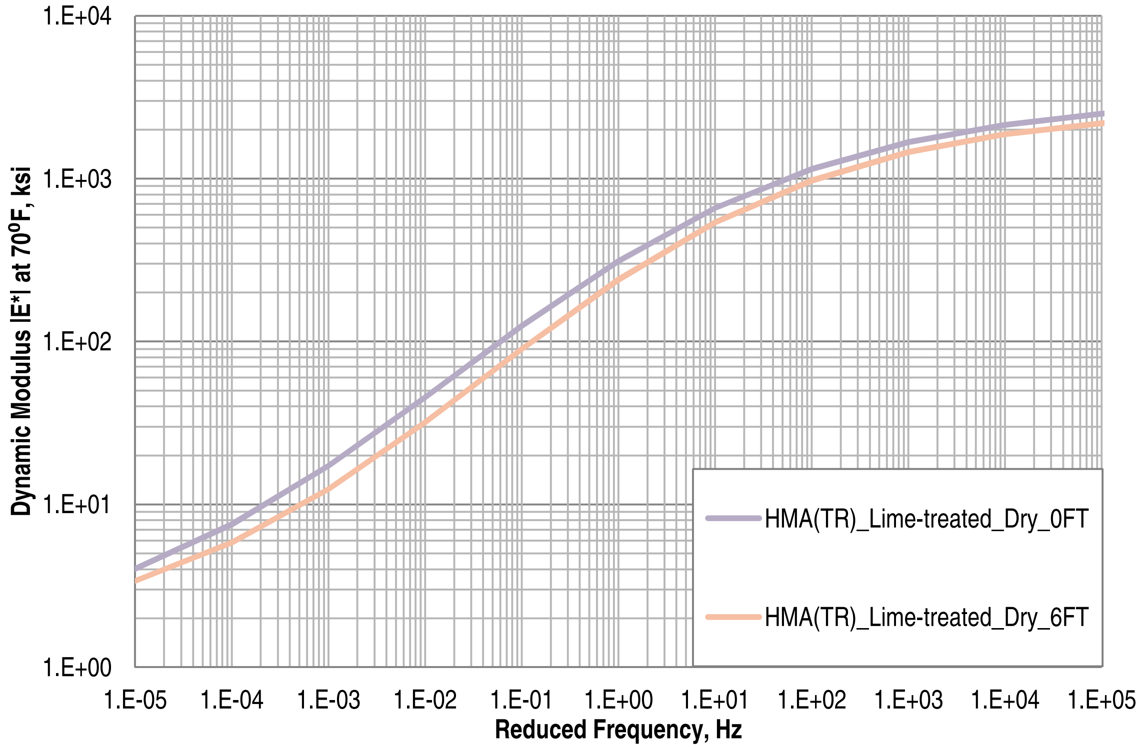


Figure 82: Dynamic Modulus (E*) Mater Curves for Lime-treated HMA Mixtures with PG64-28TR - Phase II

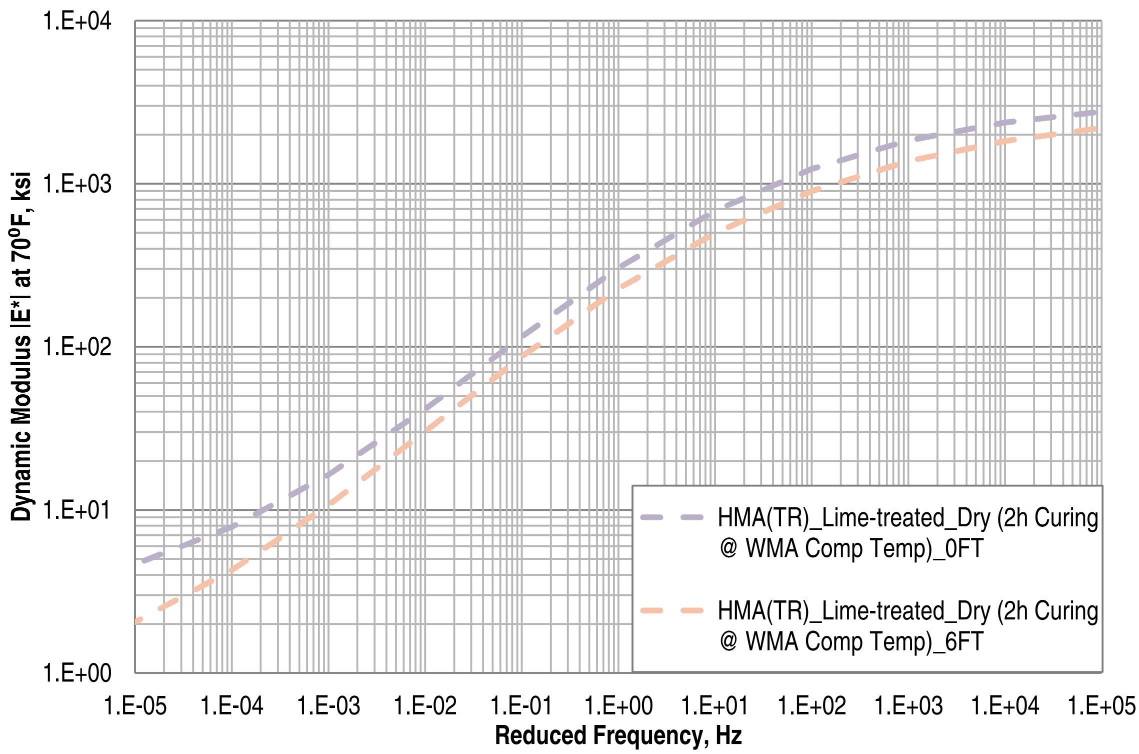


Figure 83: Dynamic Modulus (E*) Mater Curves for Lime-treated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-28TR - Phase II

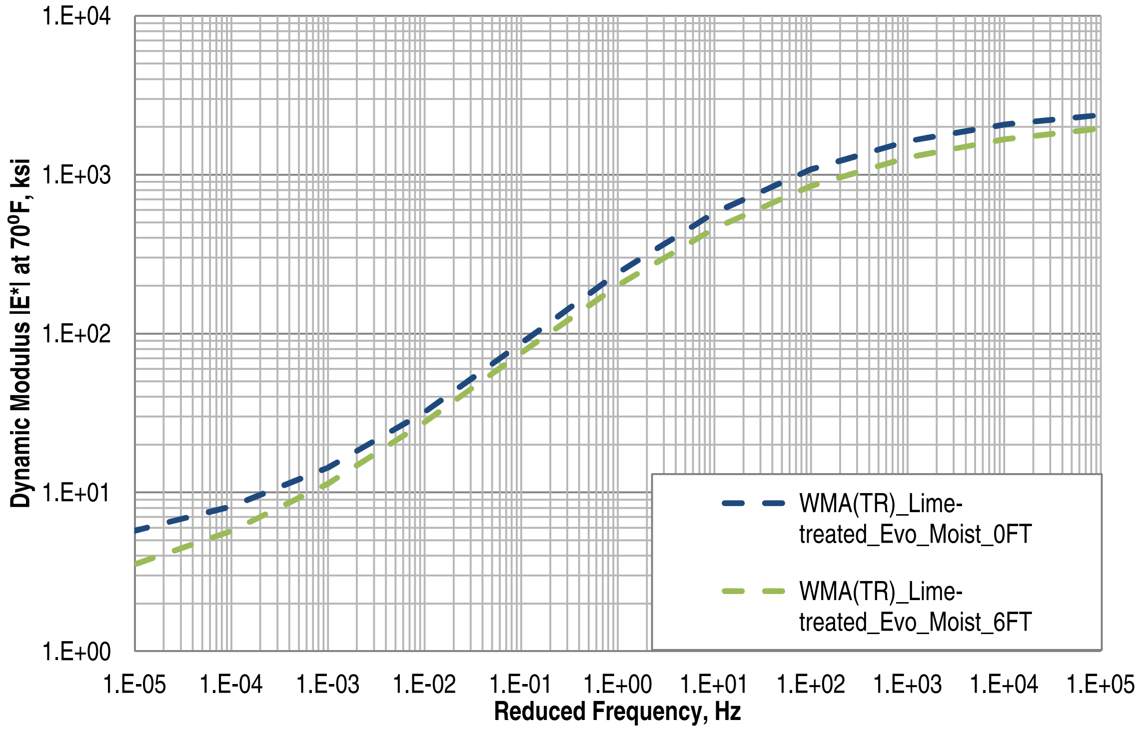


Figure 84: Dynamic Modulus (E*) Mater Curves for Lime-treated WMA_Evo Mixtures with PG64-28TR - Phase II

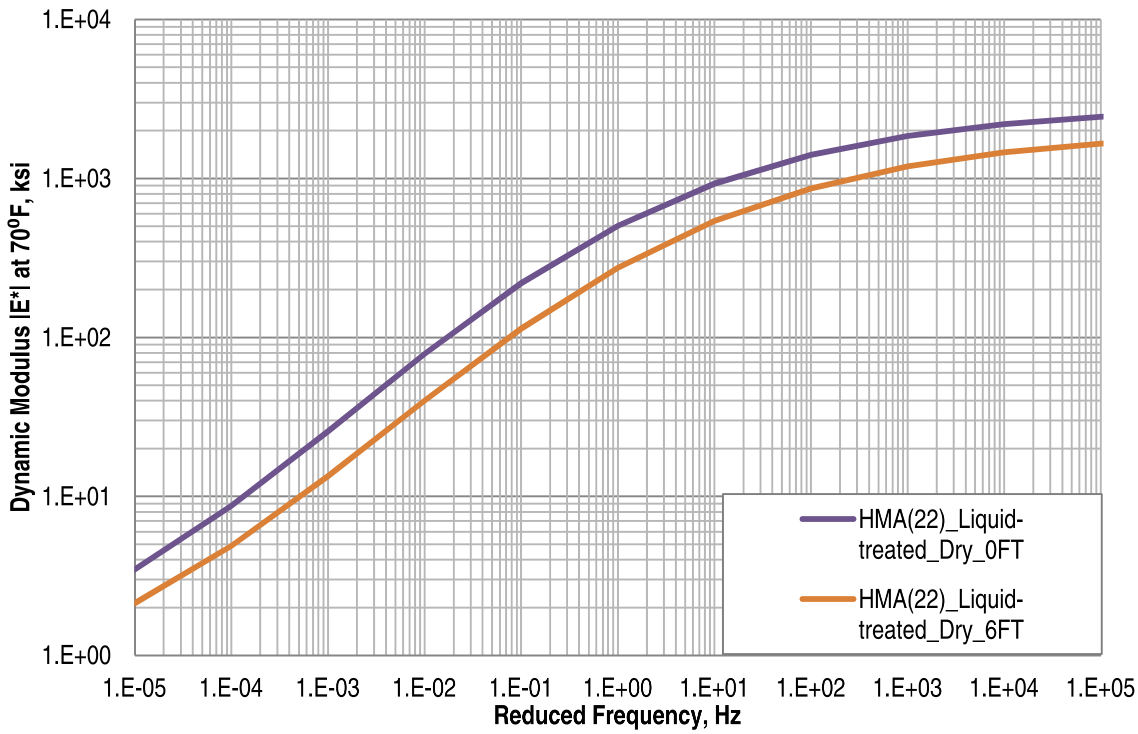


Figure 85: Dynamic Modulus (E*) Mater Curves for Liquid-treated HMA Mixtures with PG64-22 - Phase II

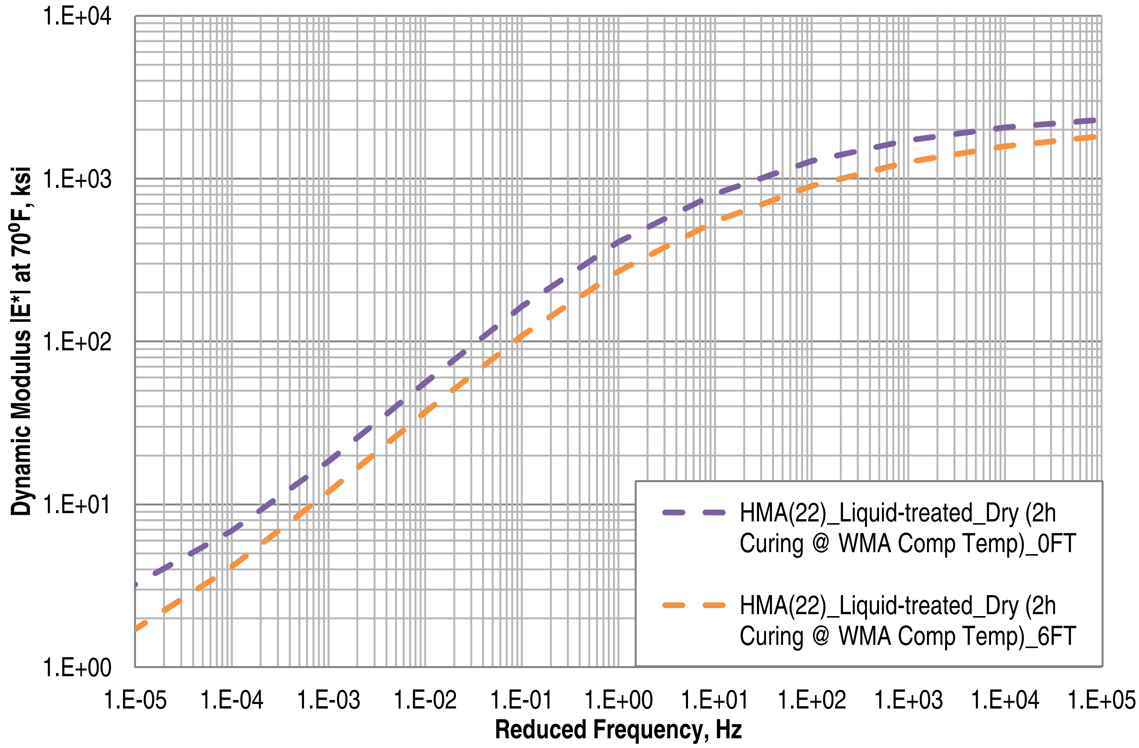


Figure 86: Dynamic Modulus (E*) Master Curves for Liquid-treated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-22 - Phase II

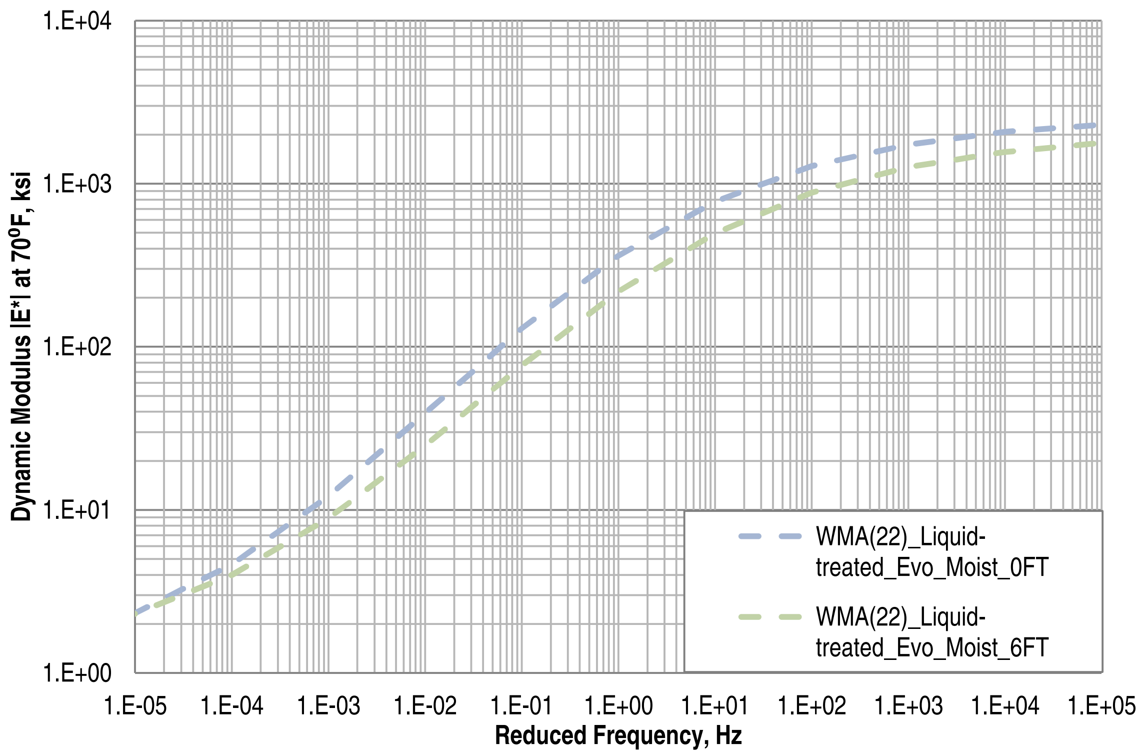


Figure 87: Dynamic Modulus (E*) Mater Curves for Liquid-treated WMA_Evo Moist Mixtures with PG64-22 - Phase II

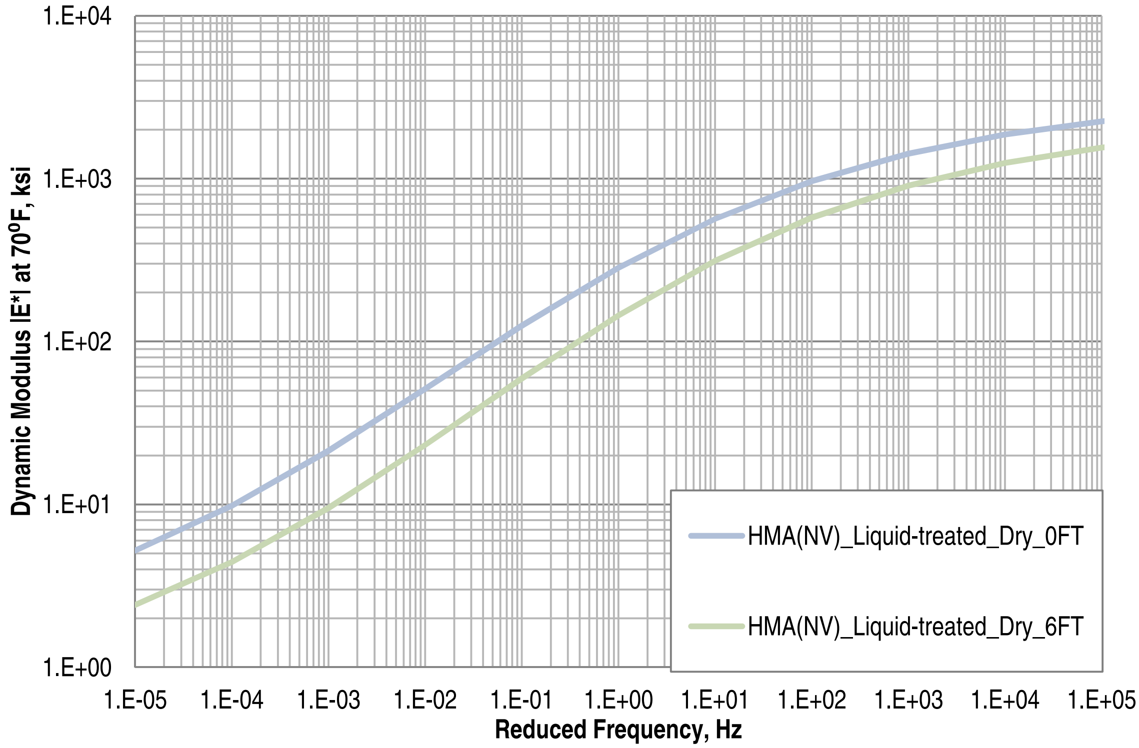


Figure 88: Dynamic Modulus (E*) Master Curves for Liquid-treated HMA Mixtures with PG64-28NV - Phase II

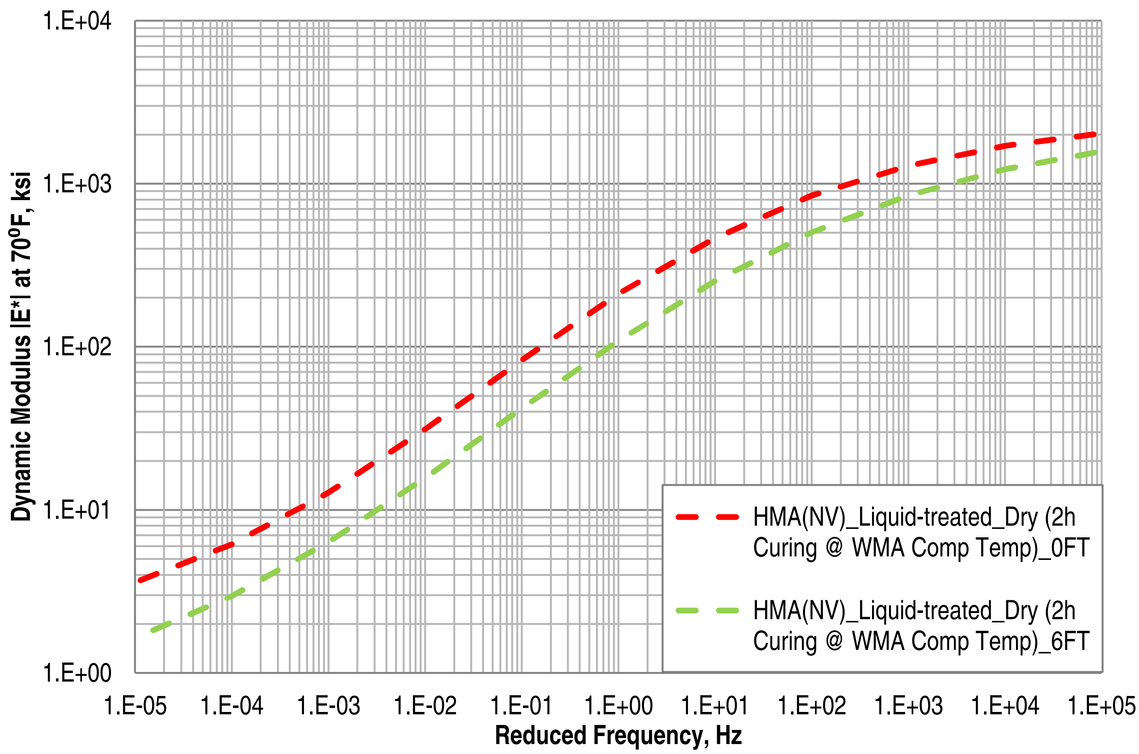


Figure 89: Dynamic Modulus (E*) Master Curves for Liquid-treated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-28NV - Phase II

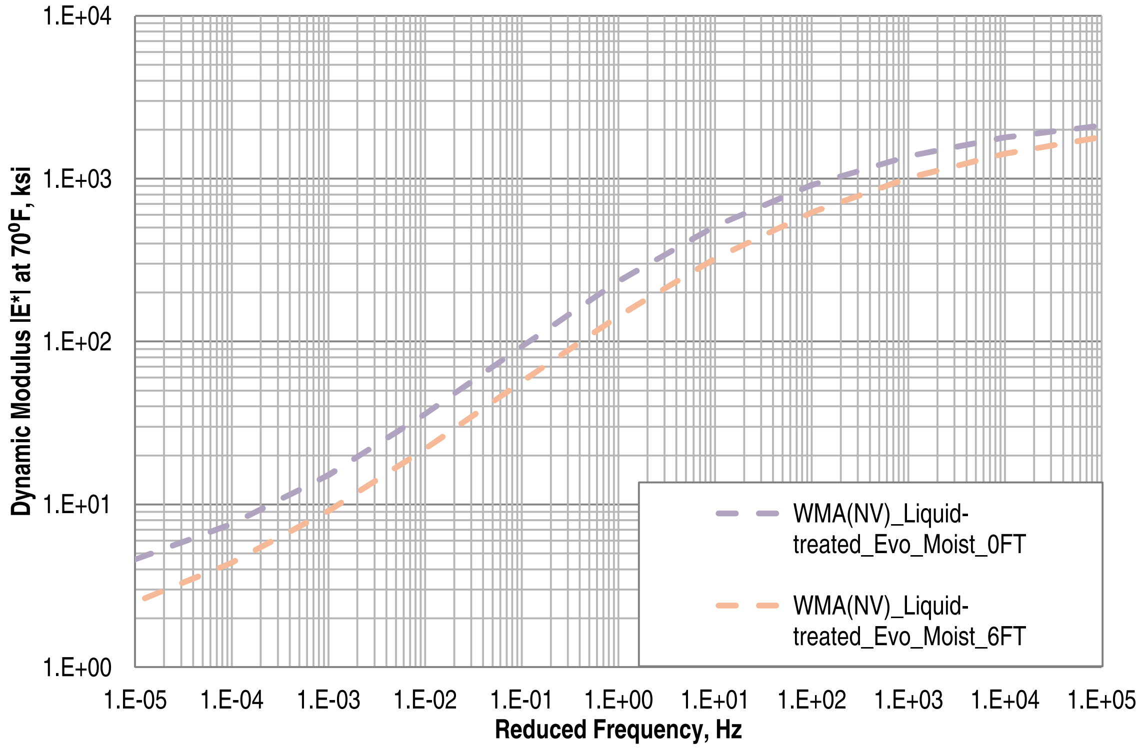


Figure 90: Dynamic Modulus (E*) Mater Curves for Liquid-treated WMA_Evo Mixtures with PG64-28NV - Phase II

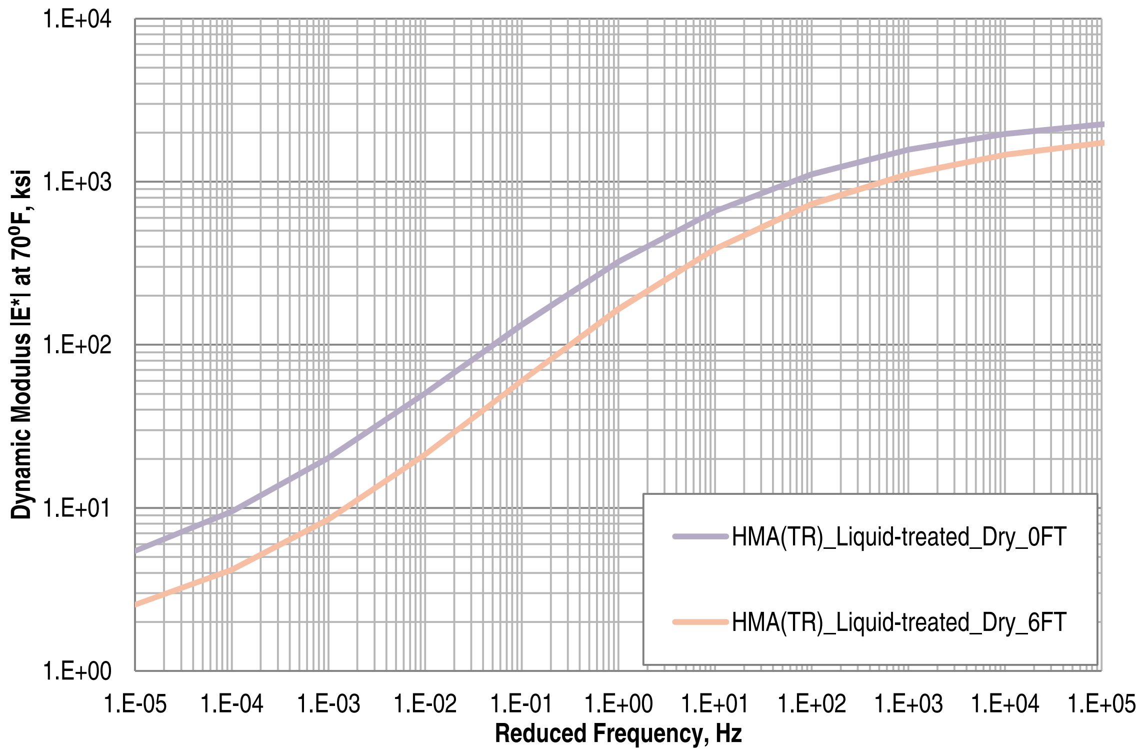


Figure 91: Dynamic Modulus (E*) Mater Curves for Liquid-treated HMA Mixtures with PG64-28TR - Phase II

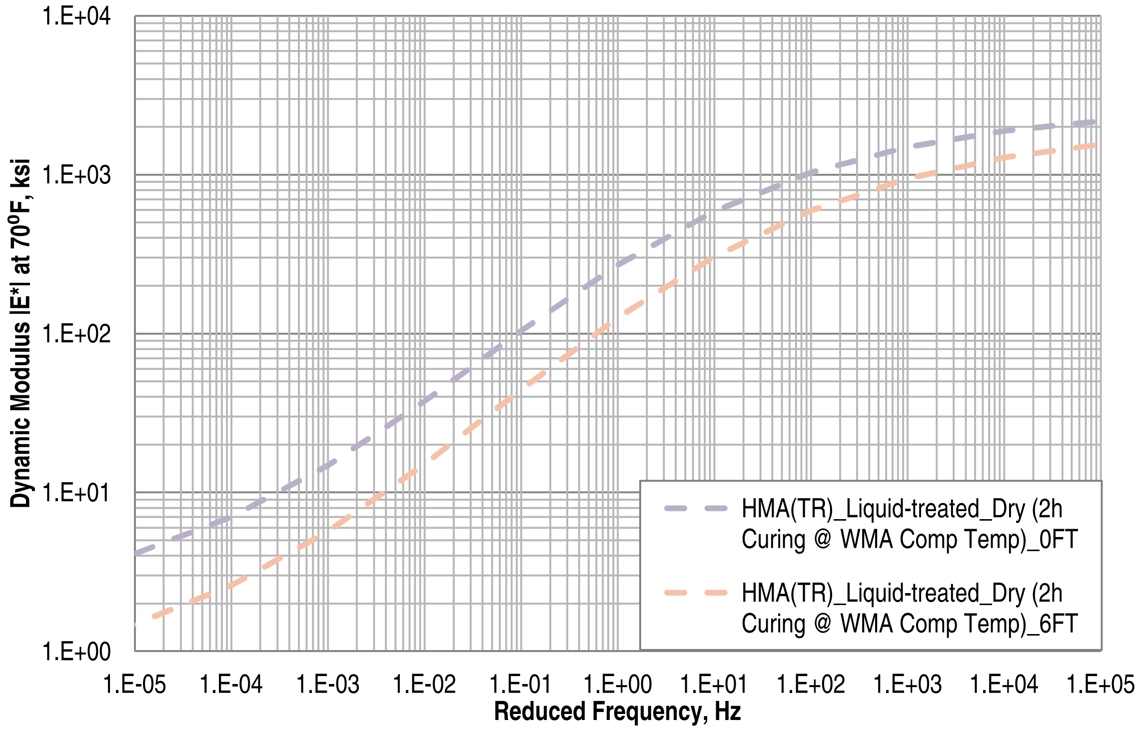


Figure 92: Dynamic Modulus (E*) Mater Curves for Liquid-treated HMA 2h Cured @ WMA Compaction Temperature Mixtures with PG64-28TR - Phase II

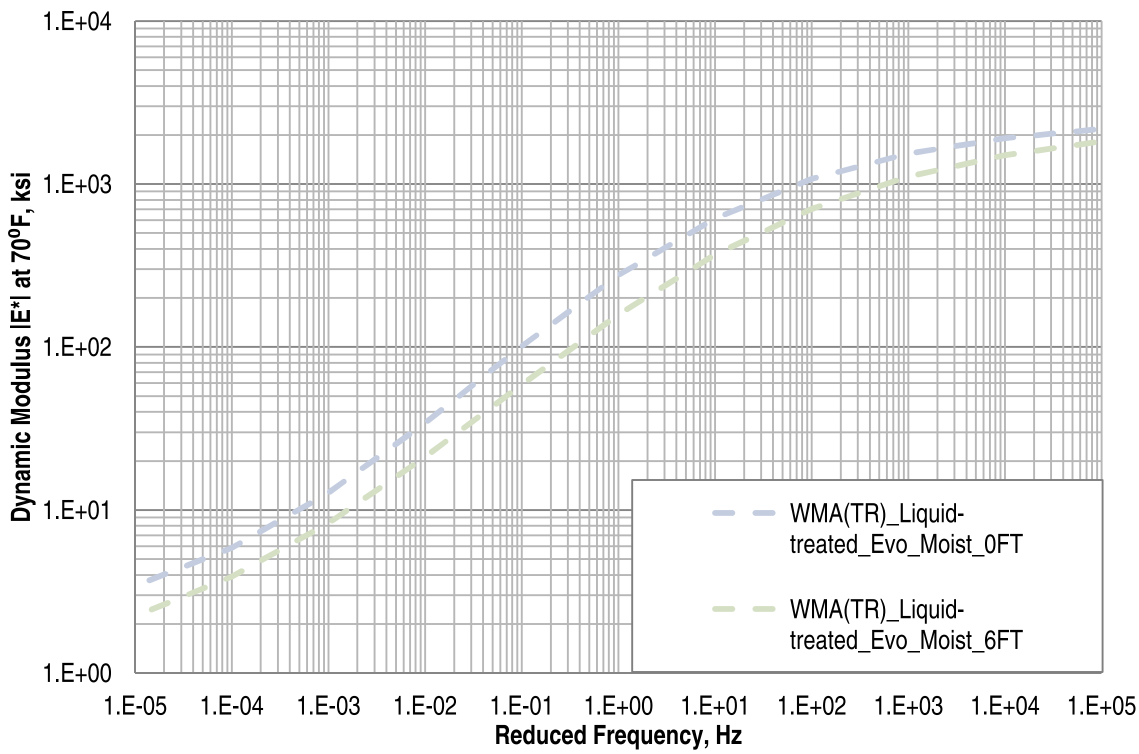


Figure 93: Dynamic Modulus (E*) Mater Curves for Liquid-treated WMA_Evo Mixtures with PG64-28TR - Phase II

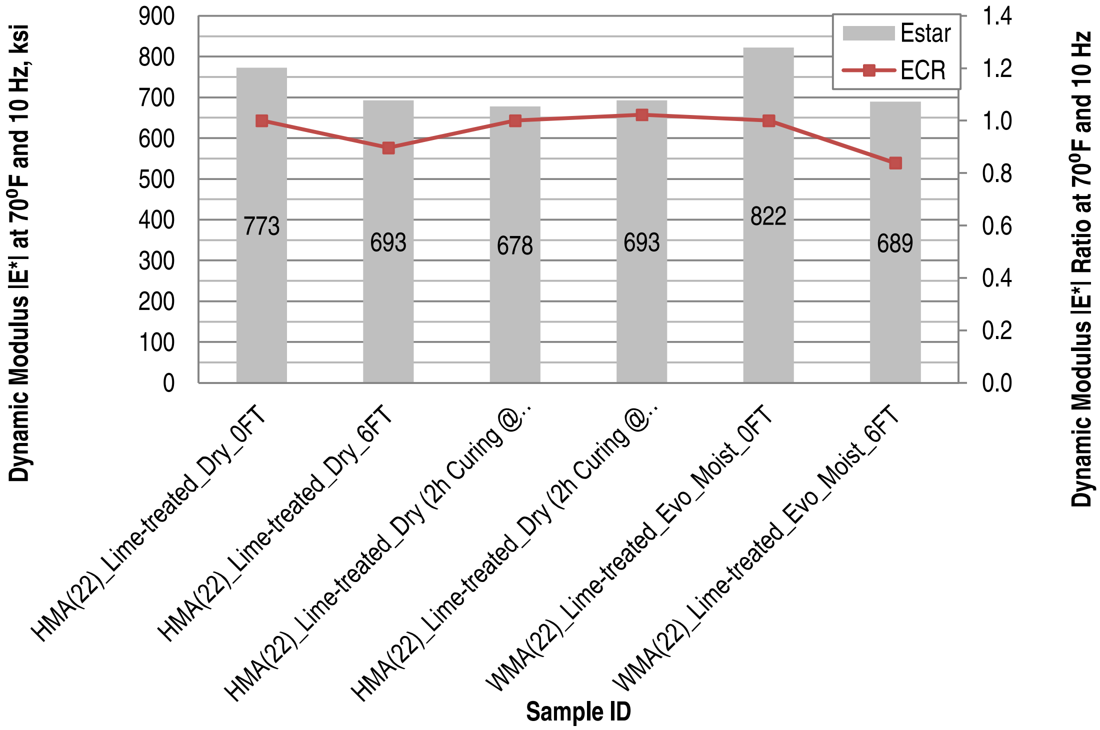


Figure 94: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Lime-treated Mixtures with PG64-22 - Phase II

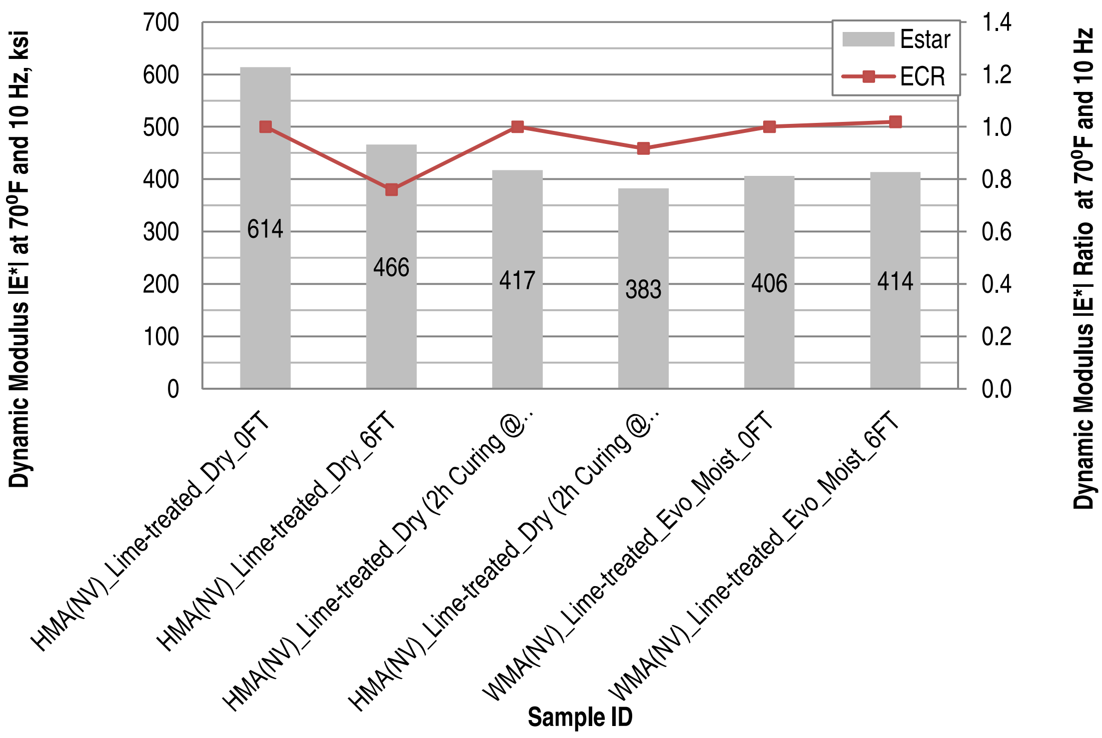


Figure 95: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Lime-treated Mixtures with PG64-28NV - Phase II

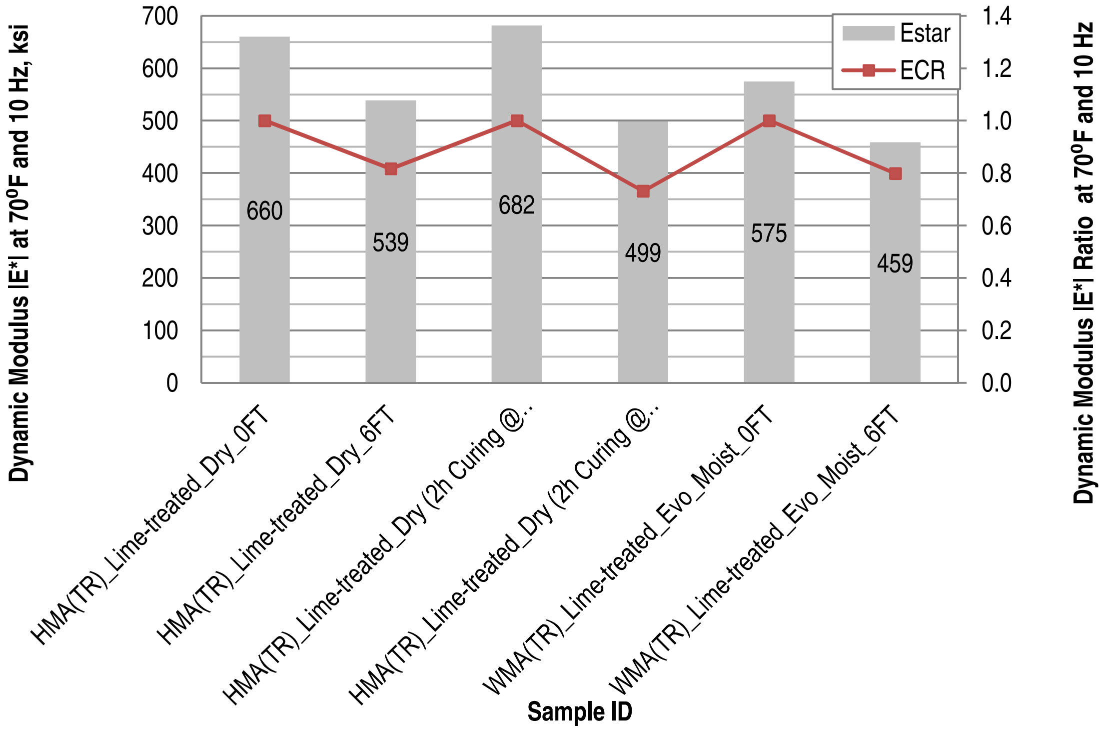


Figure 96: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Lime-treated Mixtures with PG64-28TR - Phase II

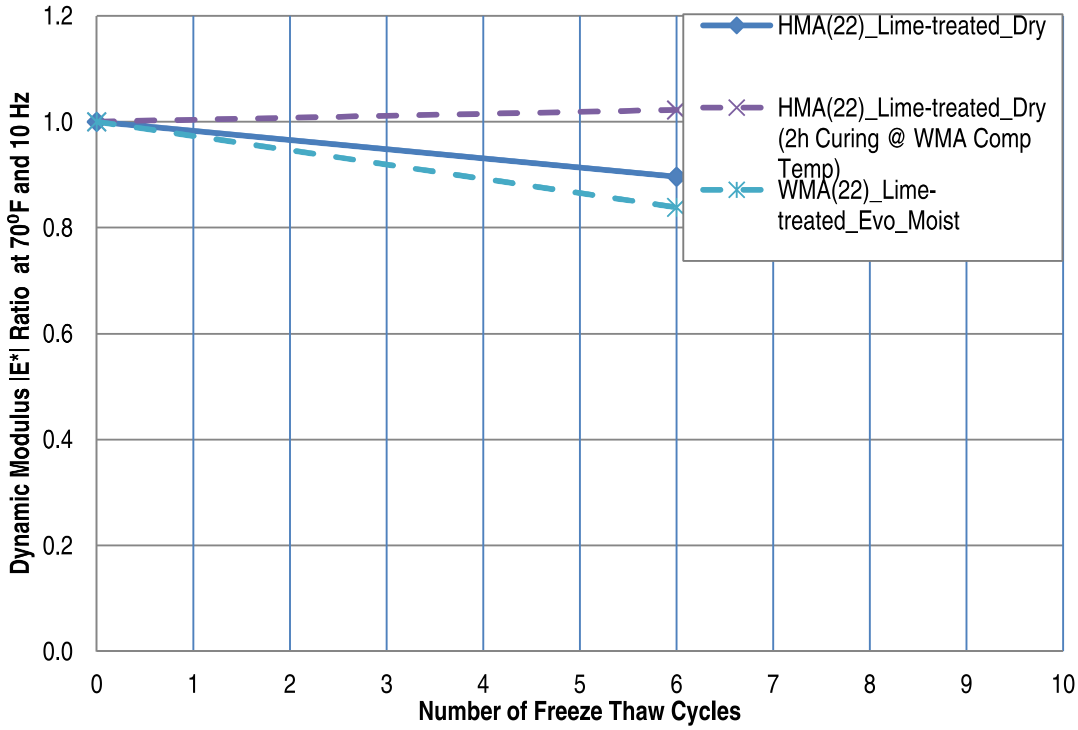


Figure 97: Dynamic Modulus (E*) Ratio Plots at 70⁰F and 10 Hz for Lime-treated Mixtures with PG64-22 - Phase II

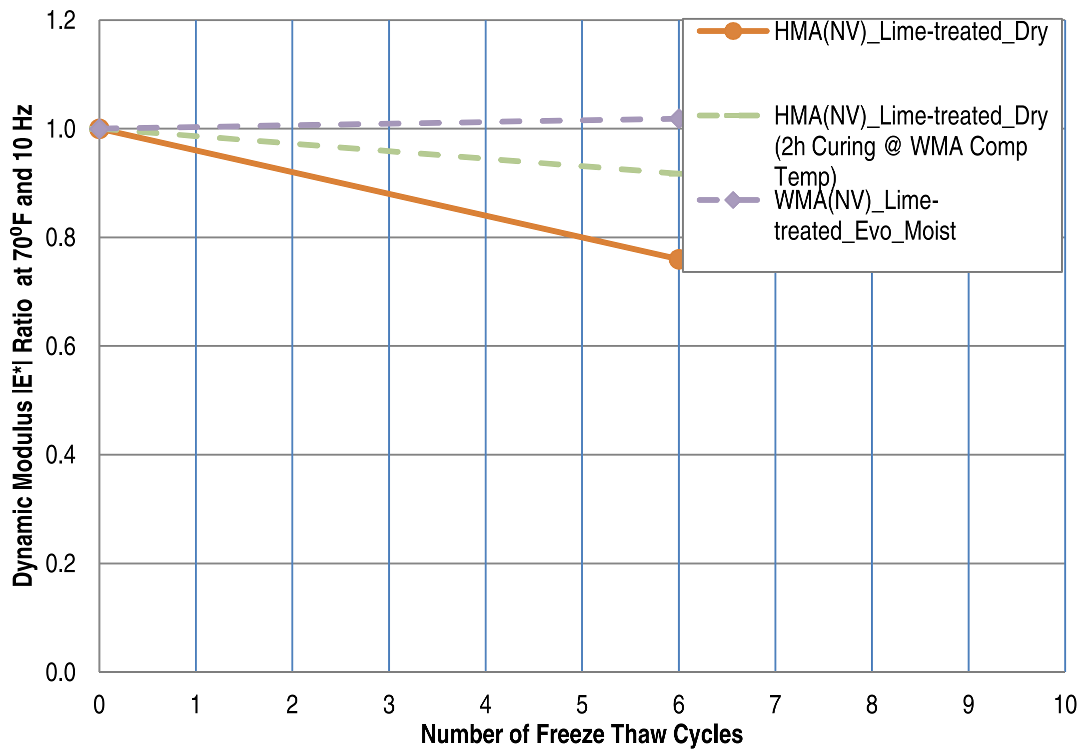


Figure 98: Dynamic Modulus (E*) Ratio Plots at 70⁰F and 10 Hz for Lime-treated Mixtures with PG64-28NV - Phase II

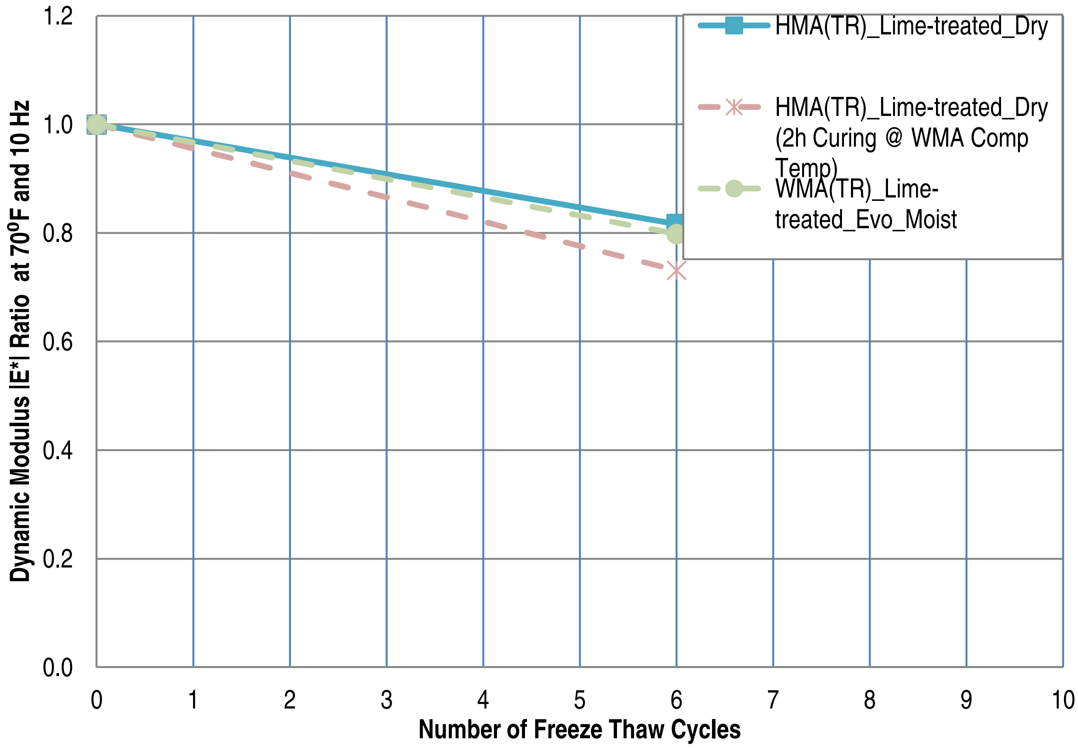


Figure 99: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Lime-treated Mixtures with PG64-28TR - Phase II

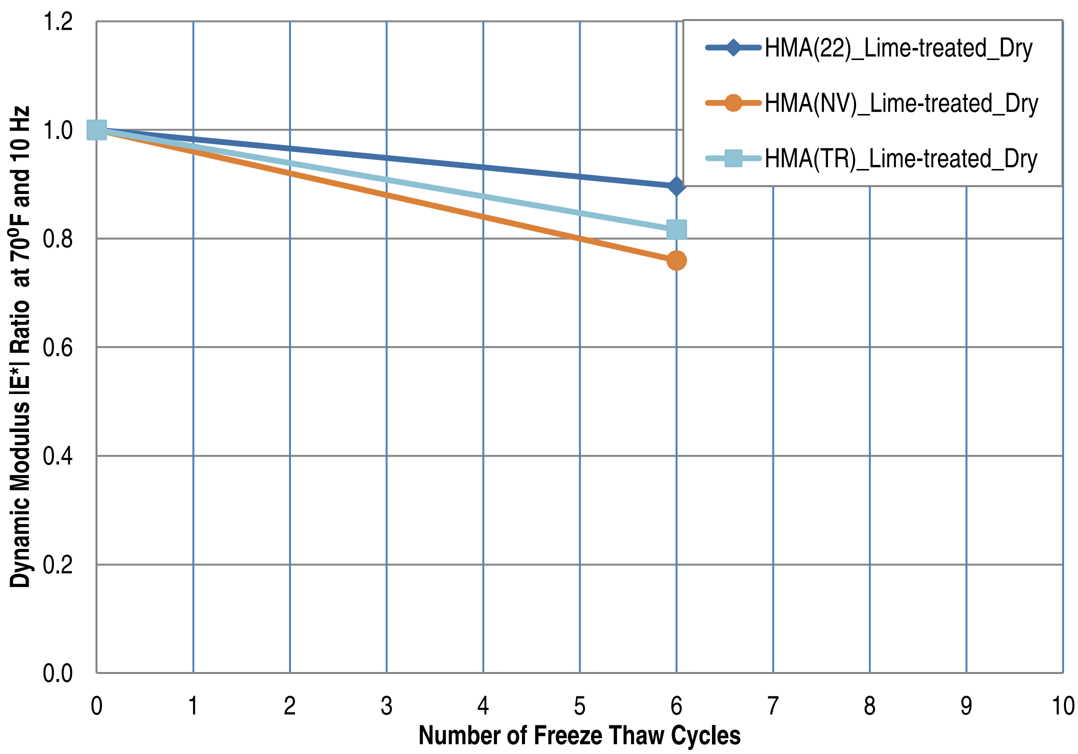


Figure 100: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Lime-treated HMA Mixtures - Phase II

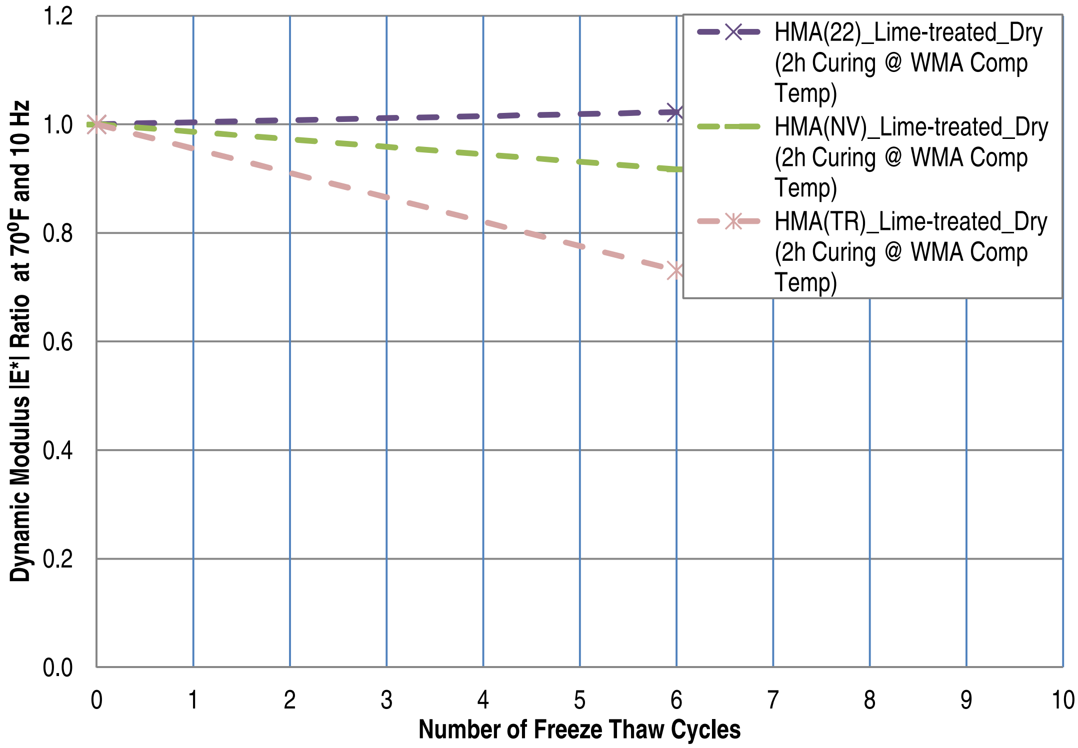


Figure 101: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Lime-treated HMA 2h Cured @ WMA Compaction Temperature Mixtures - Phase II

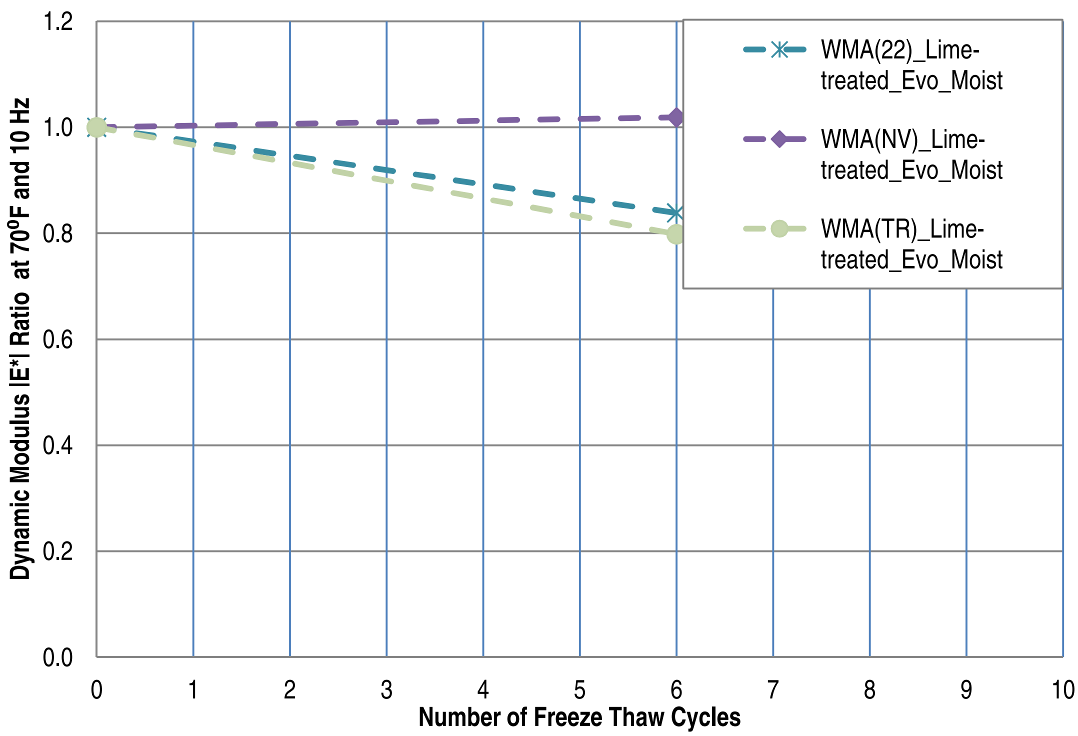


Figure 102: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Lime-treated WMA_Evo Moist Mixtures - Phase II

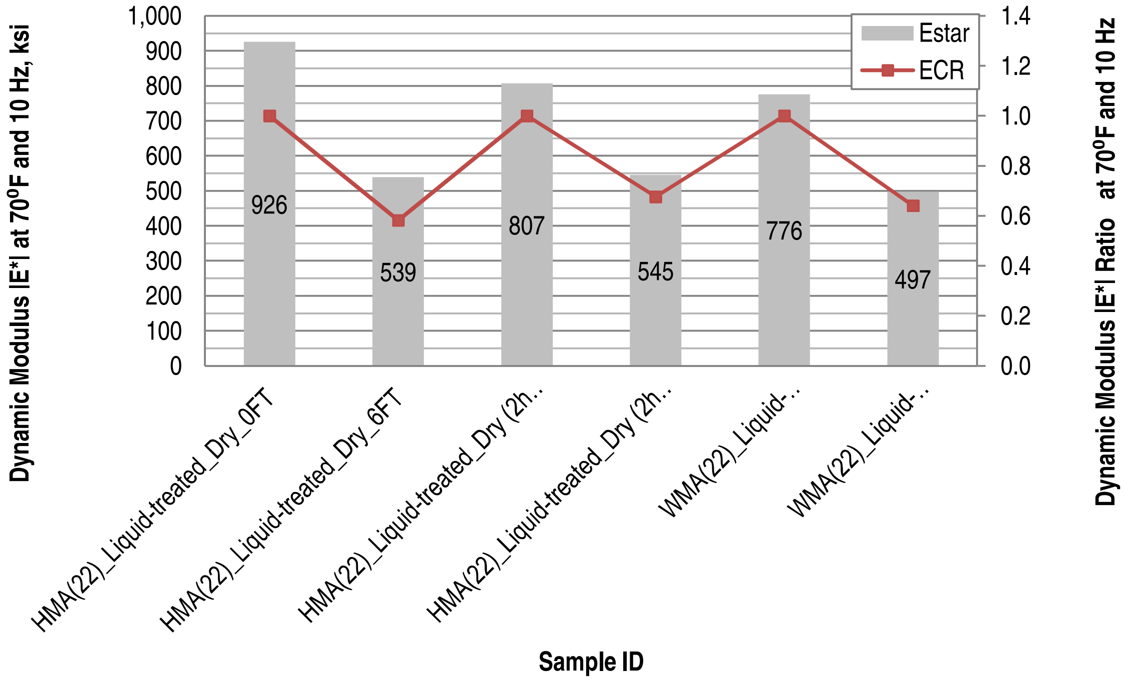


Figure 103: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated Mixtures with PG64-22 - Phase II

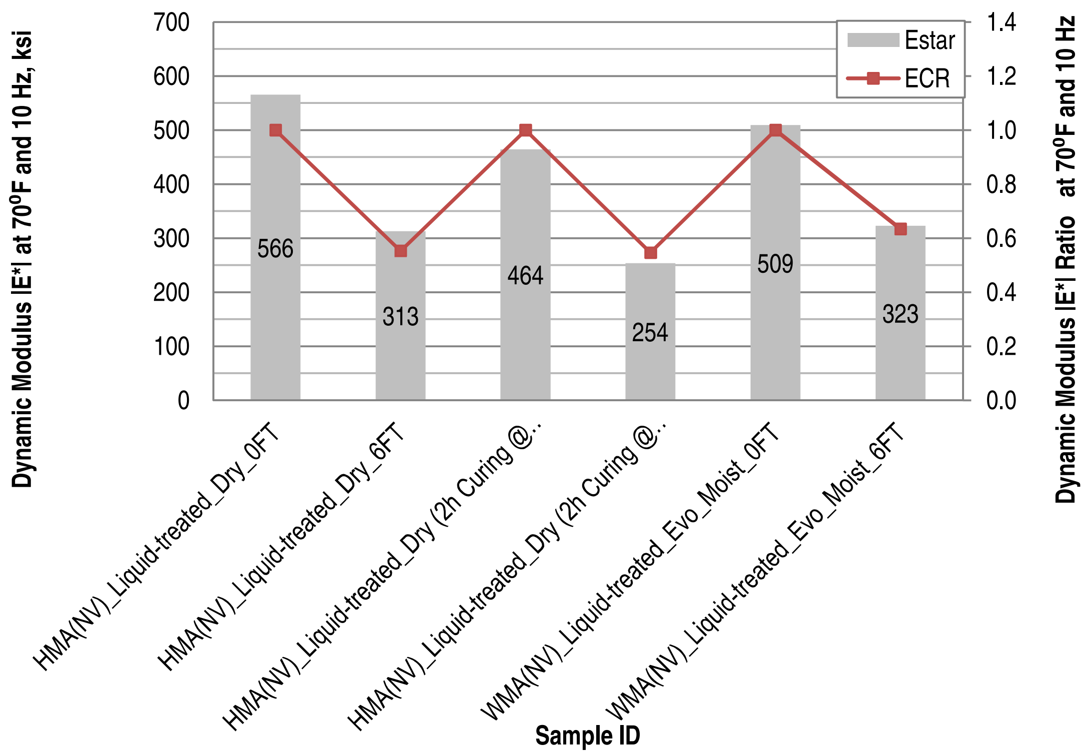


Figure 104: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated Mixtures with PG64-28NV - Phase II

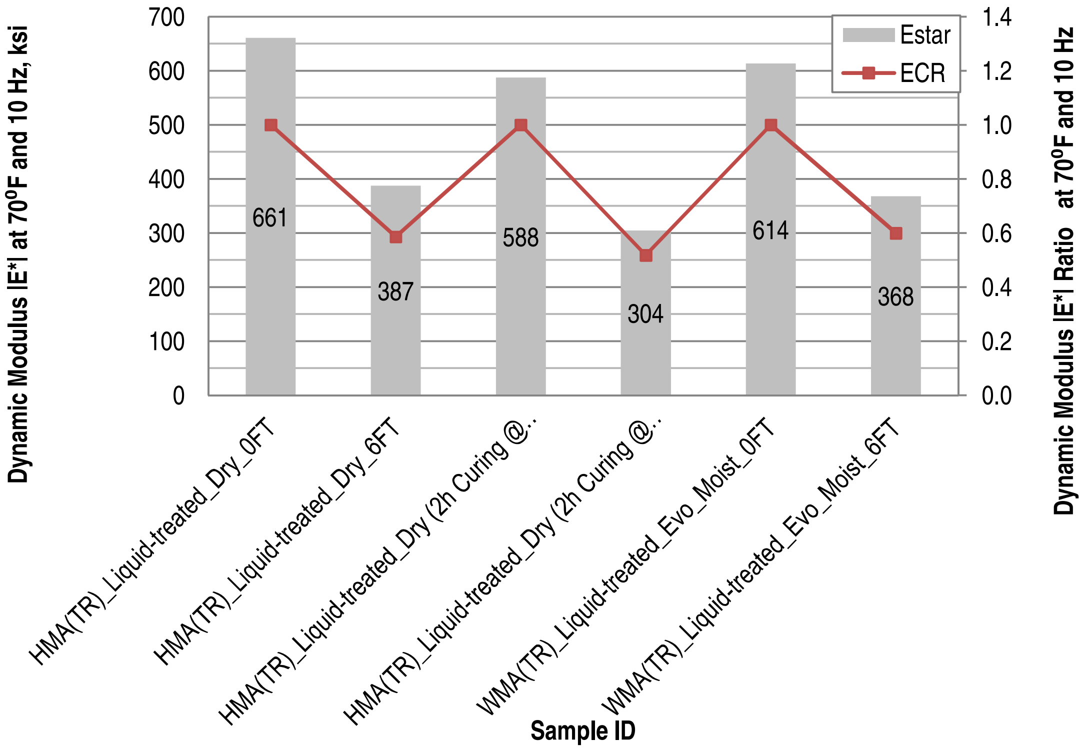


Figure 105: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated Mixtures with PG64-28TR - Phase II

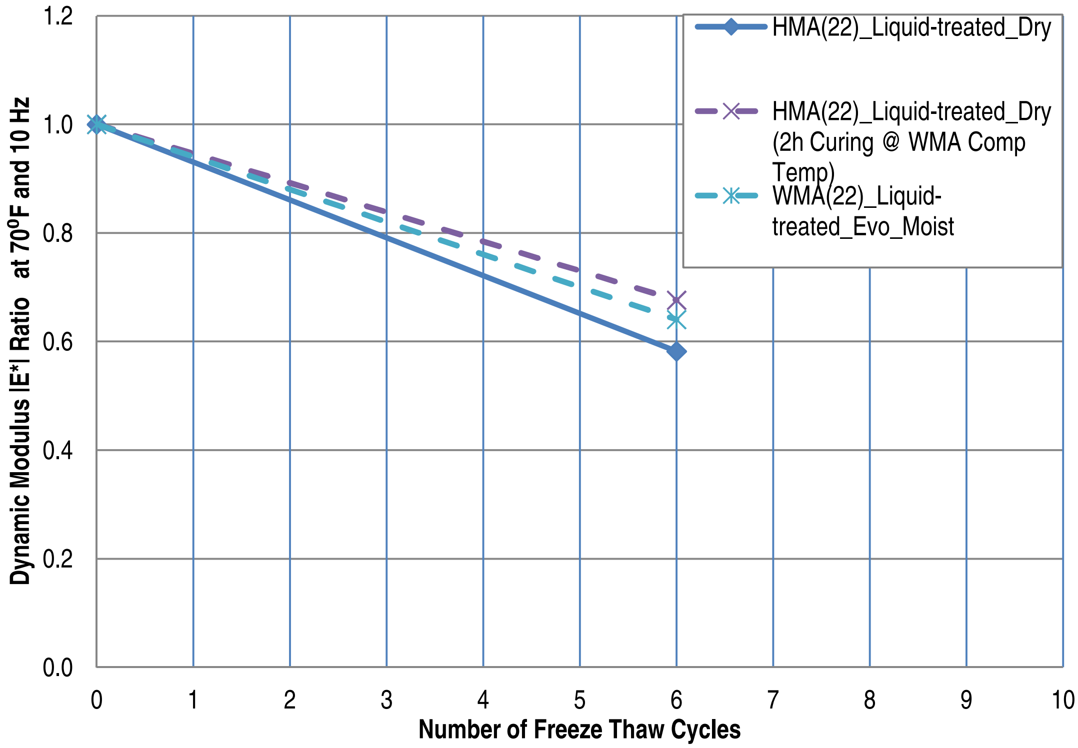


Figure 106: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated Mixtures with PG64-22 - Phase II

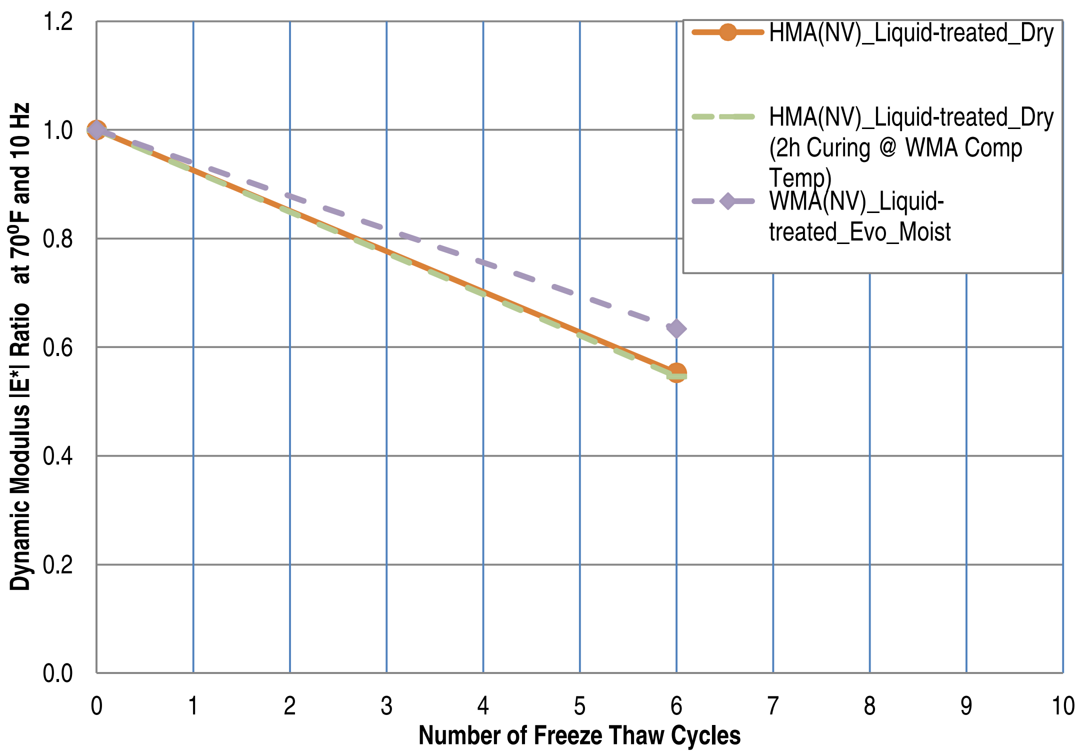


Figure 107: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated Mixtures with PG64-28NV - Phase II

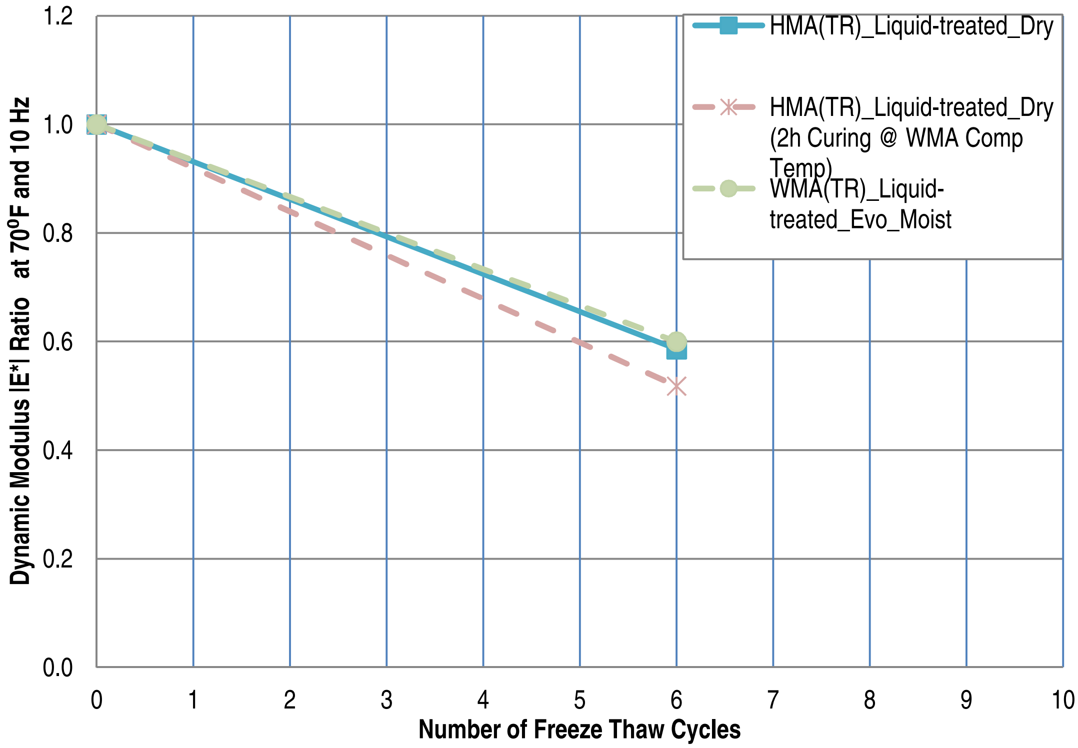


Figure 108: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated Mixtures with PG64-28TR - Phase II

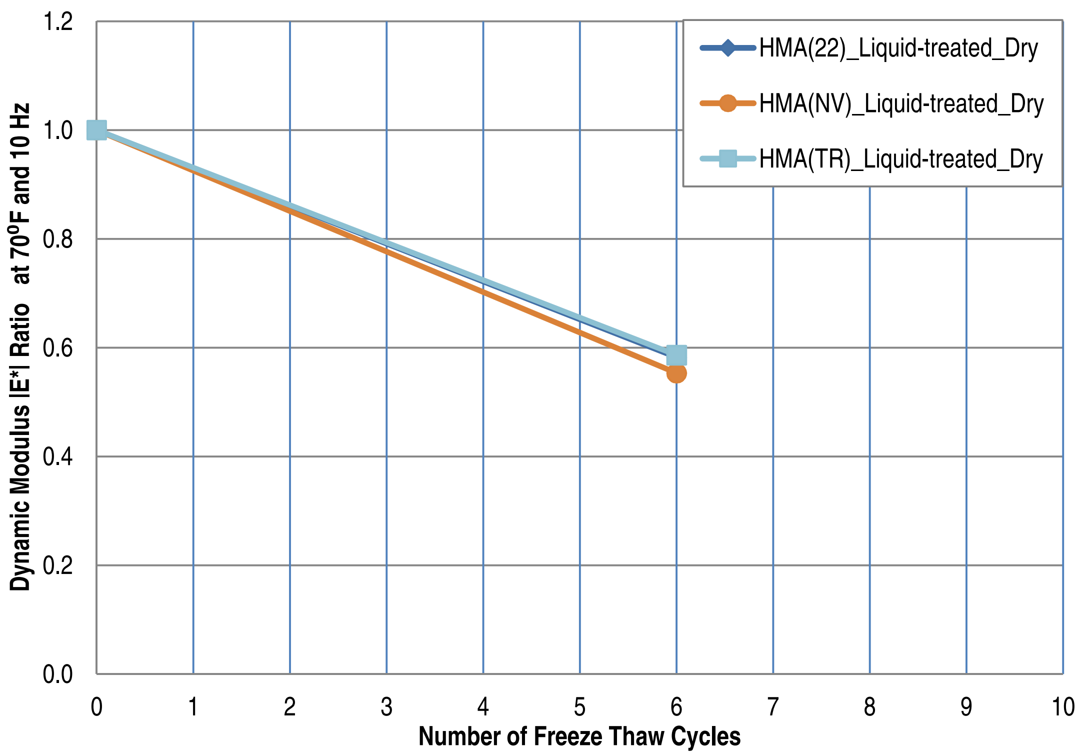


Figure 109: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated HMA Mixtures - Phase II

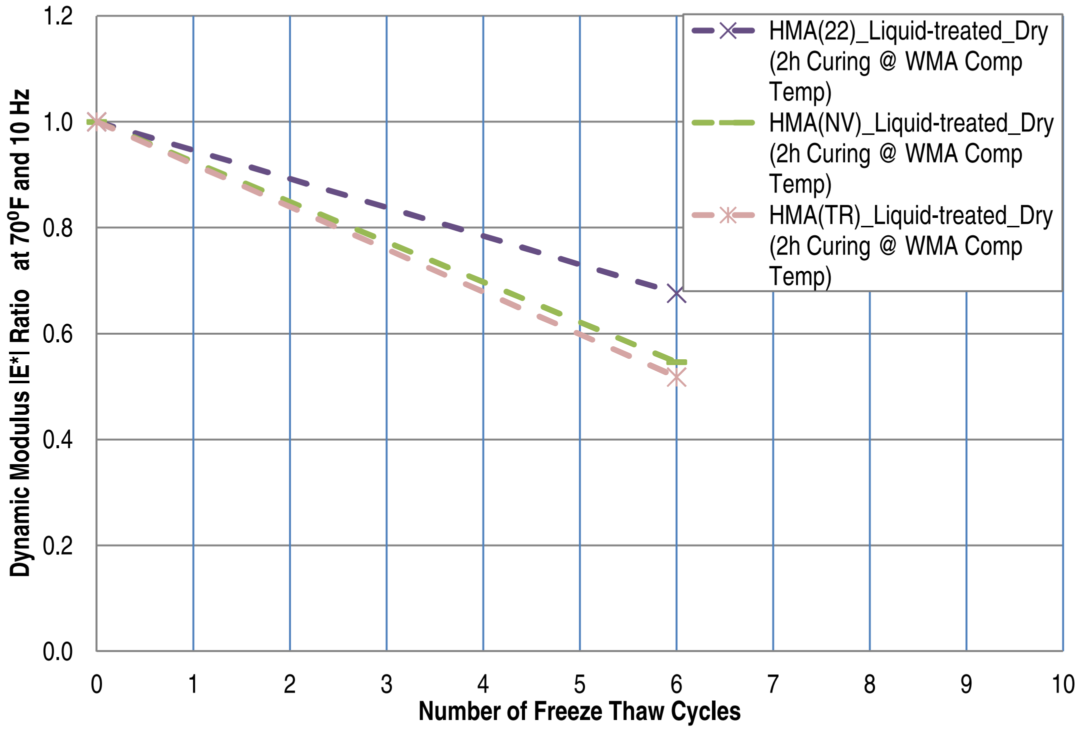


Figure 110: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated HMA 2h Cured @ WMA Compaction Temperature Mixtures - Phase II

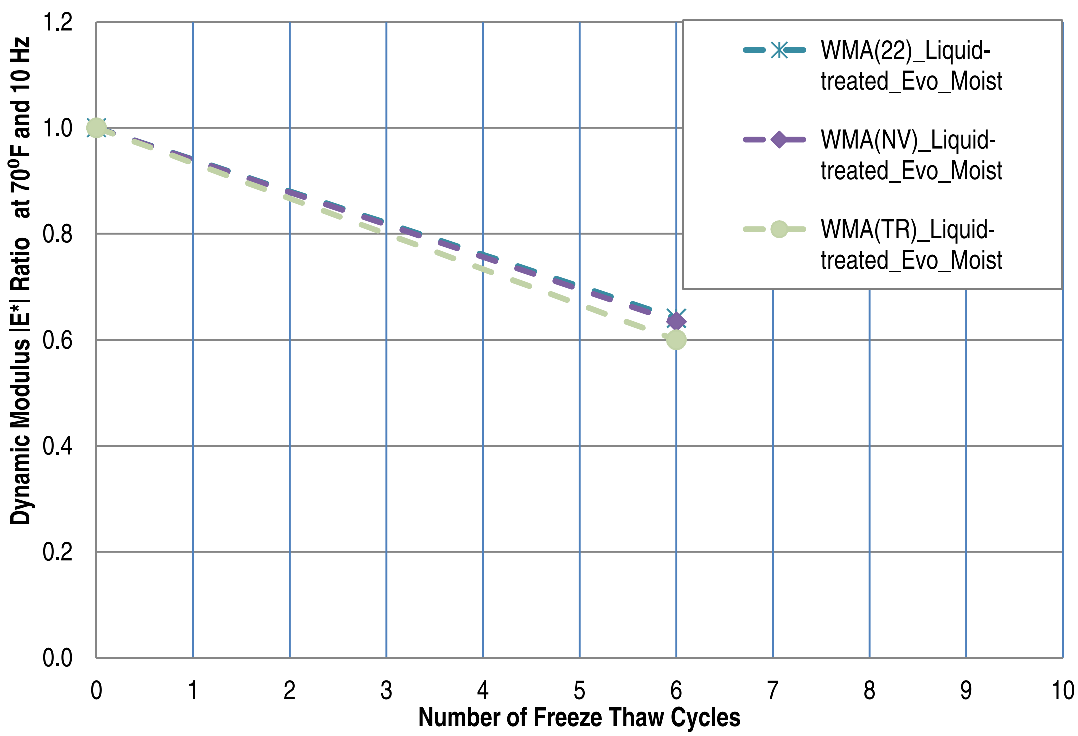


Figure 111: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Liquid-treated WMA_Evo Moist Mixtures - Phase II

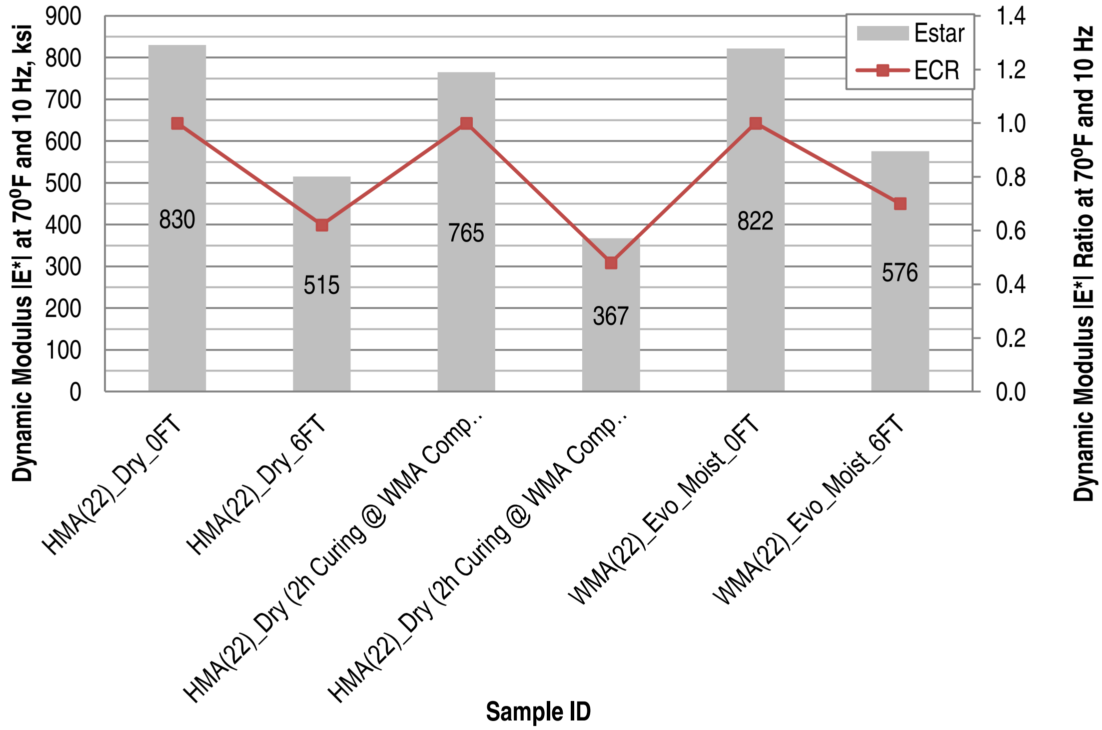


Figure 112: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-22 - Phase II

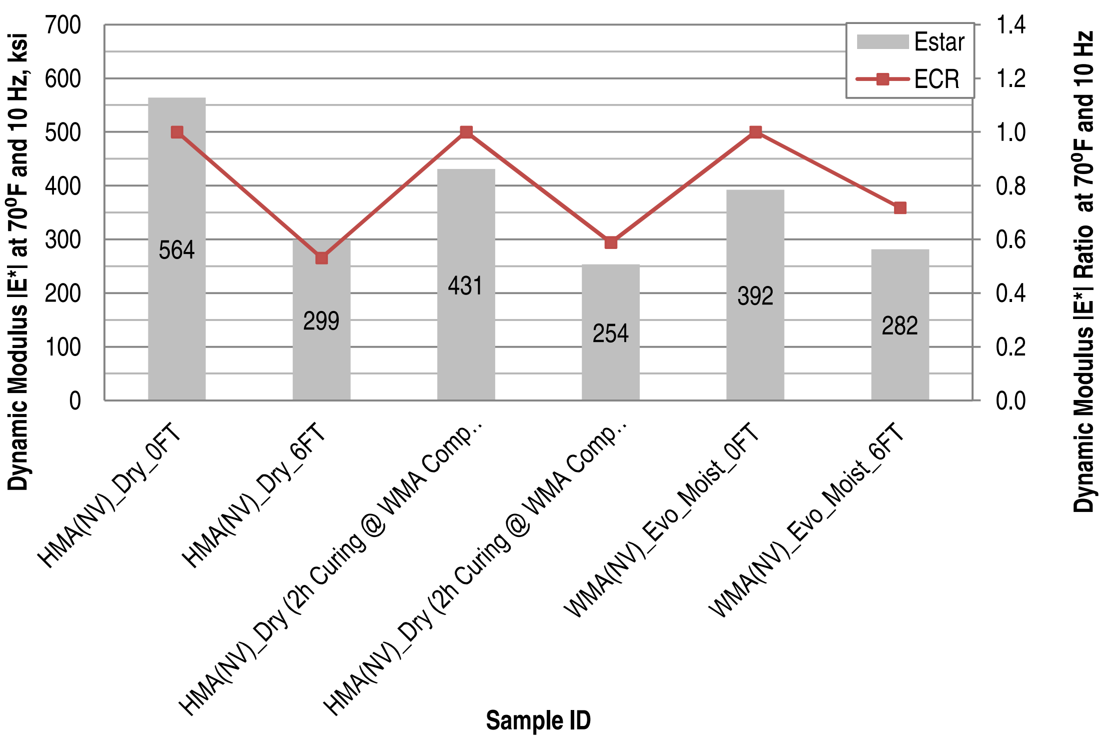


Figure 113: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-28NV - Phase II

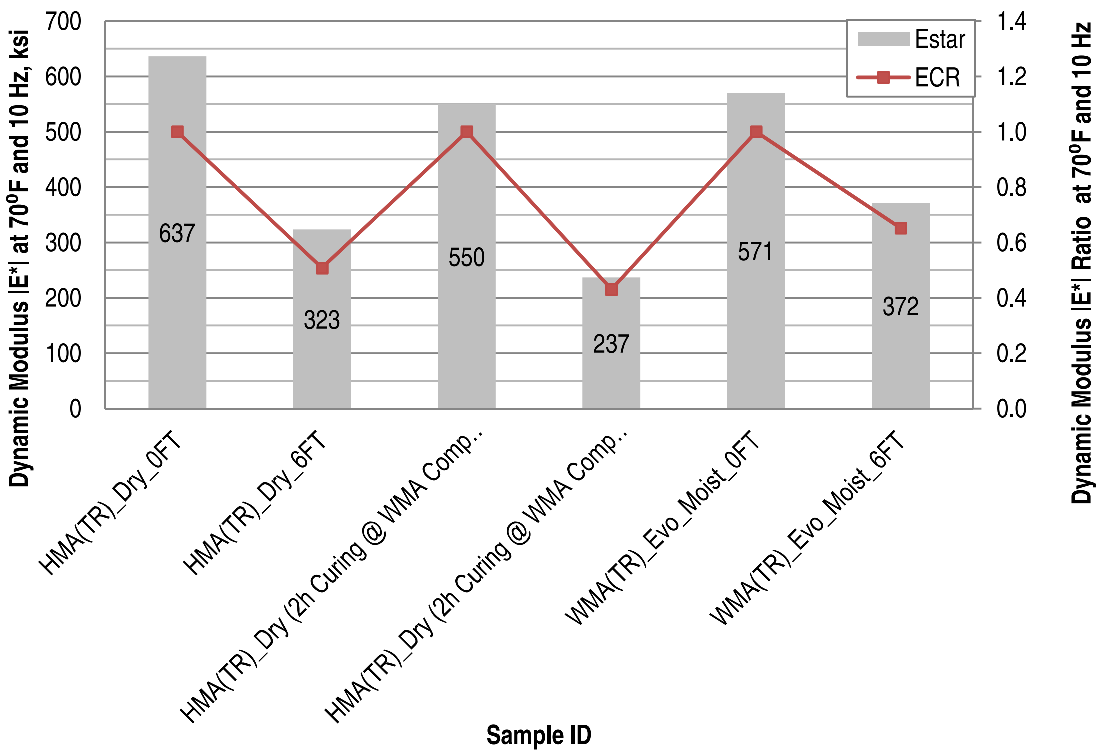


Figure 114: Dynamic modulus (E*) vs Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-28TR - Phase II

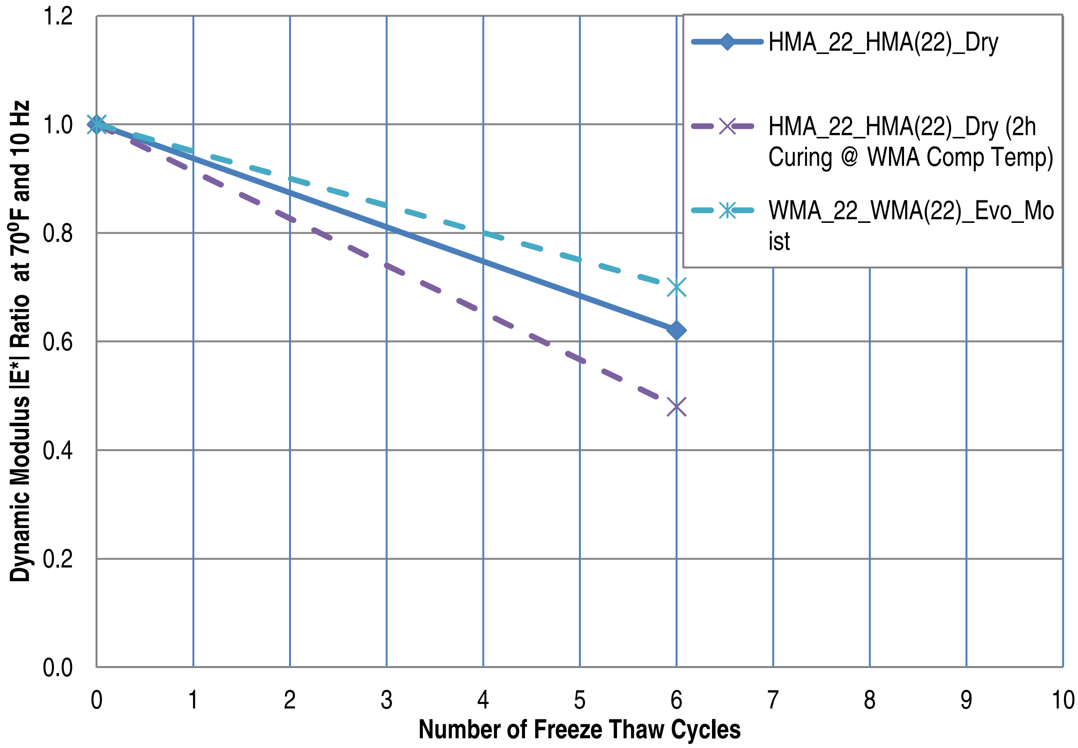


Figure 115: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-22 - Phase II

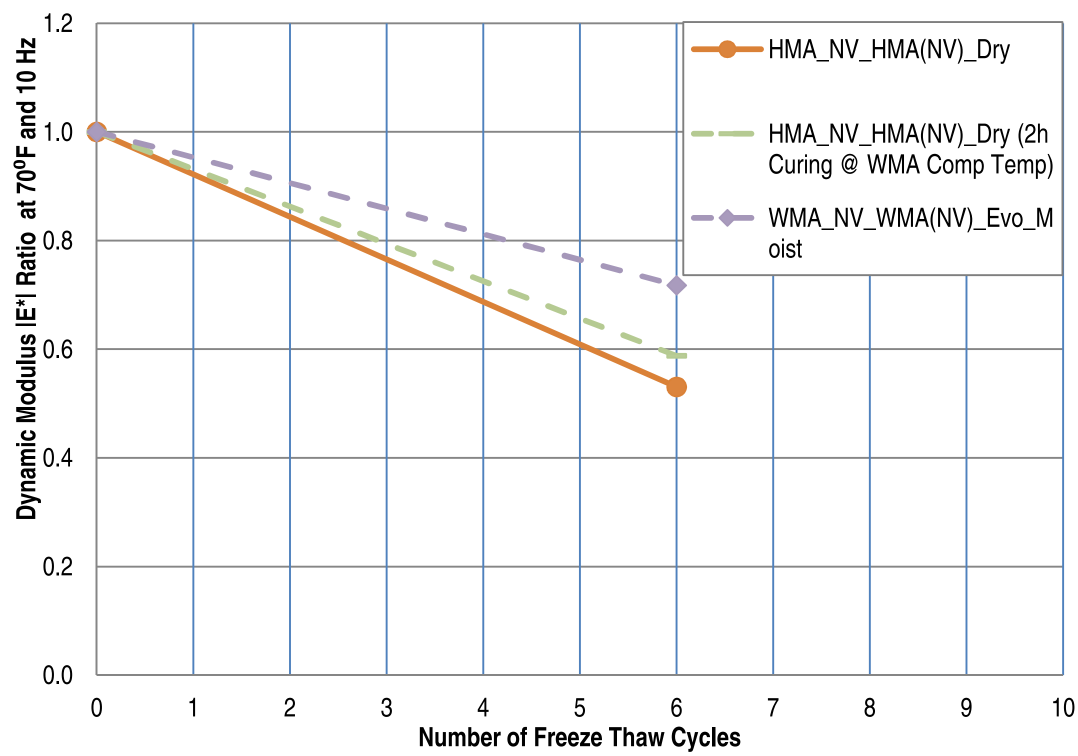


Figure 116: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-28NV - Phase II

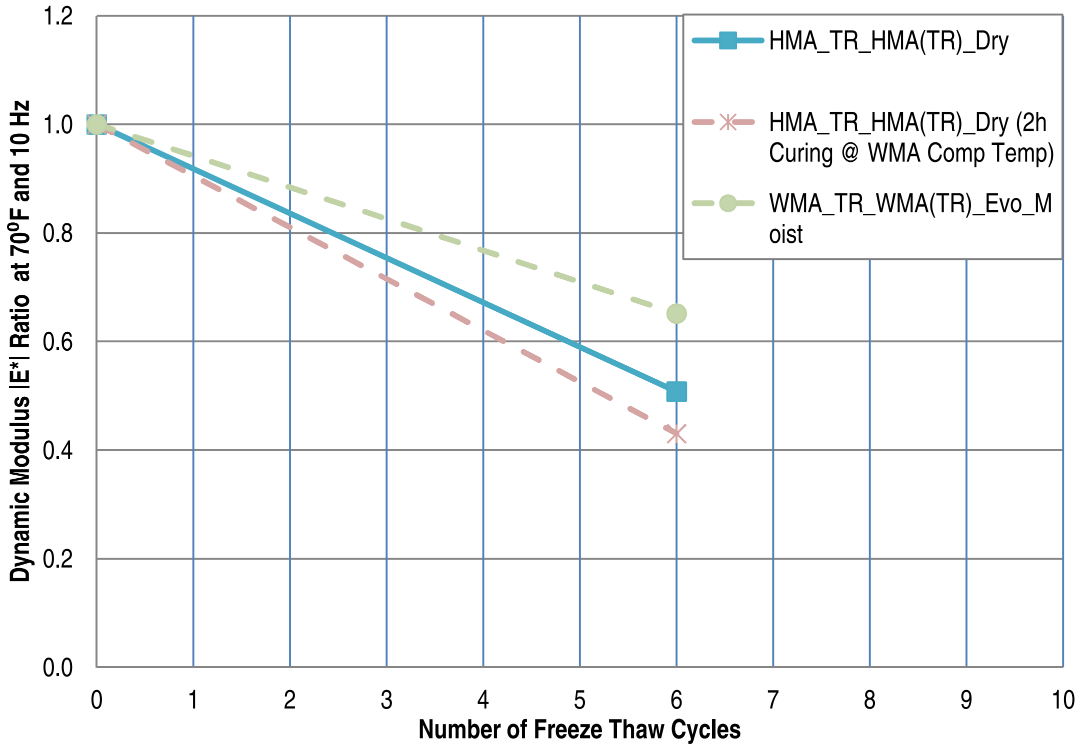


Figure 117: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated Mixtures with PG64-28TR - Phase II

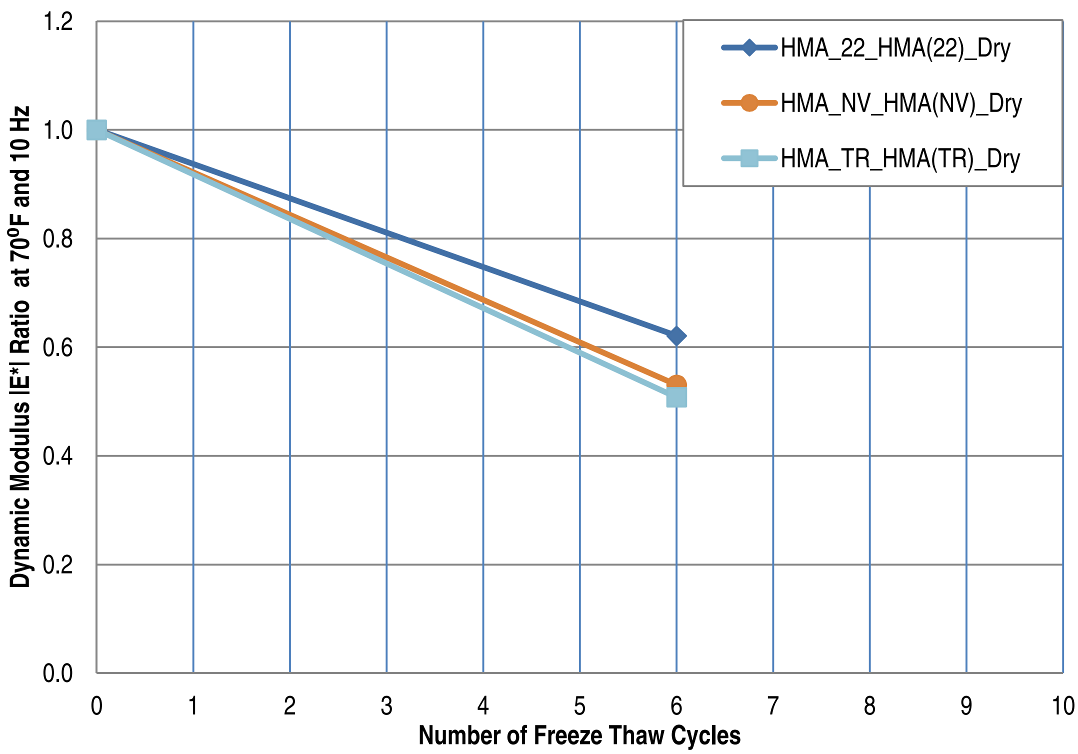


Figure 118: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated HMA Mixtures - Phase II

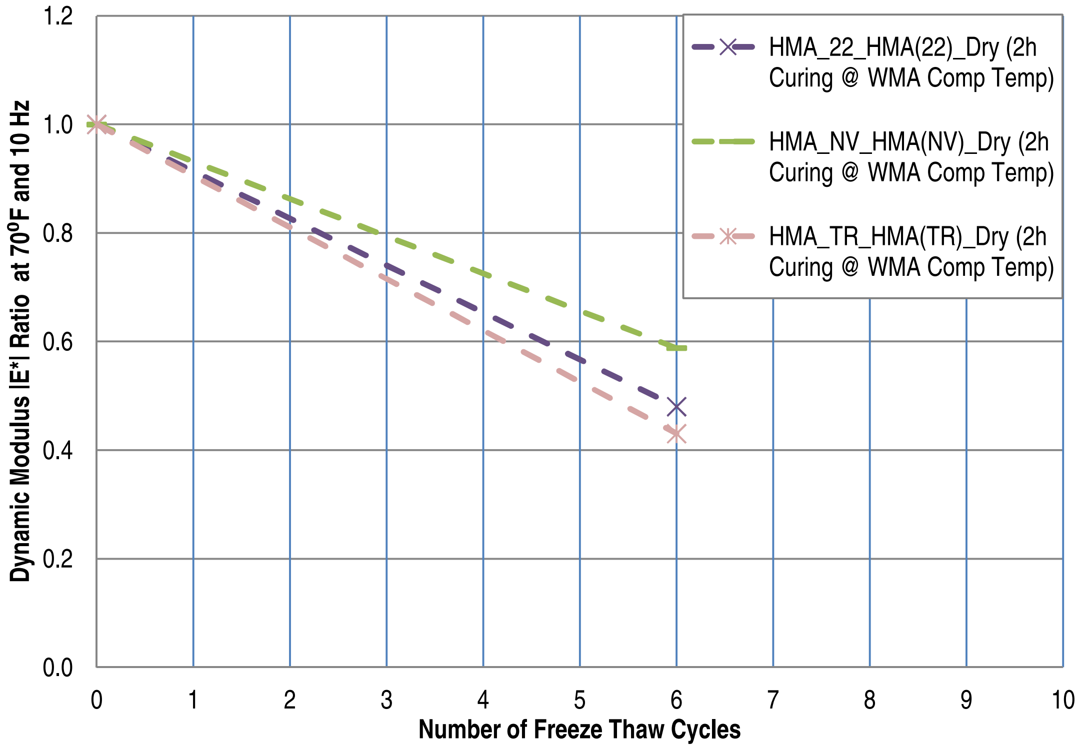


Figure 119: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated HMA 2h Cured @ WMA Compaction Temperature Mixtures - Phase II

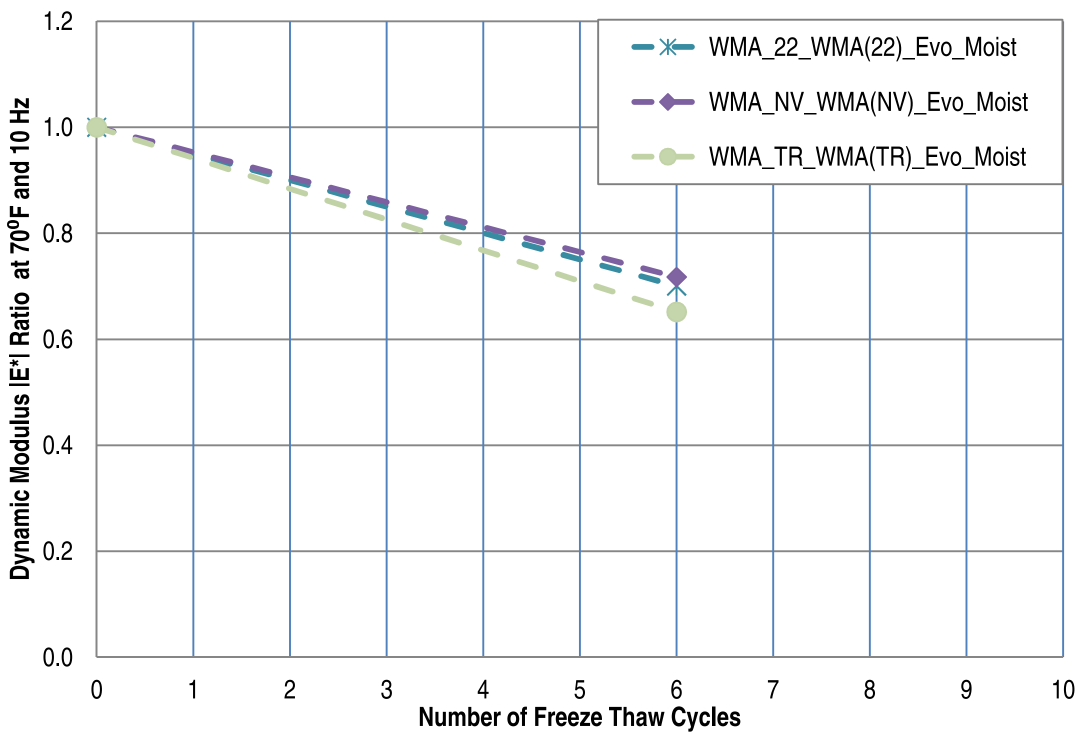


Figure 120: Dynamic Modulus (E*) Ratio Plots at 70^{0}F and 10 Hz for Untreated WMA_Evo Moist Mixtures - Phase II

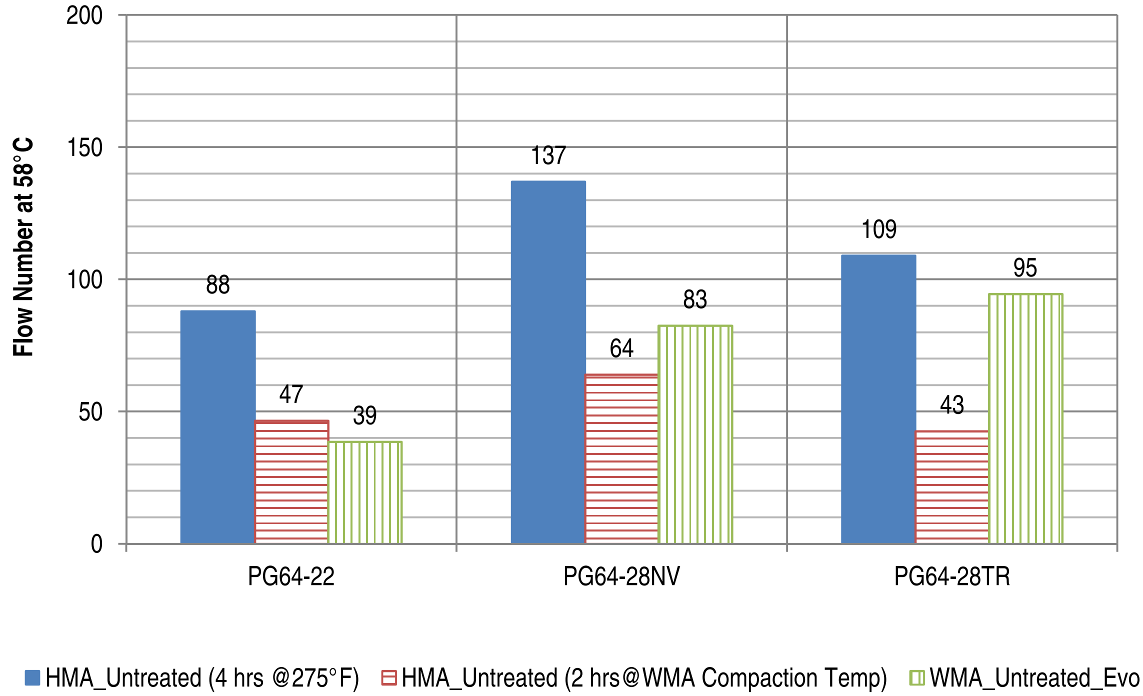


Figure 121: FN Untreated HMA Vs WMA - Phase II

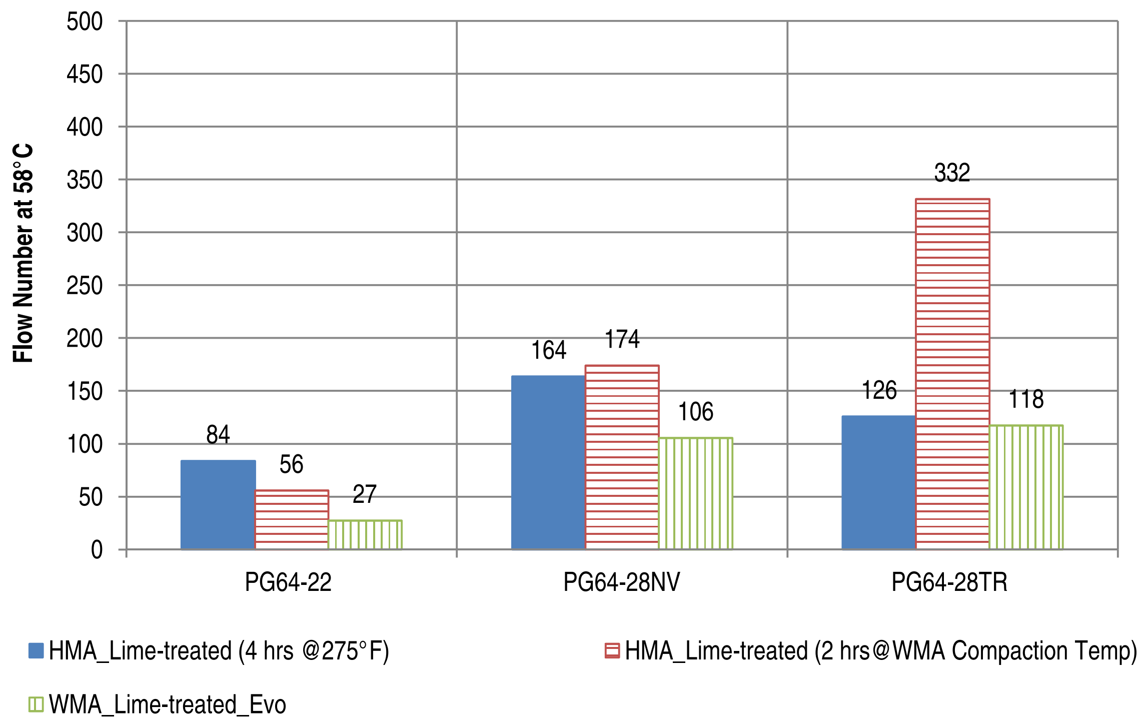


Figure 122: FN Lime-treated HMA Vs WMA - Phase II

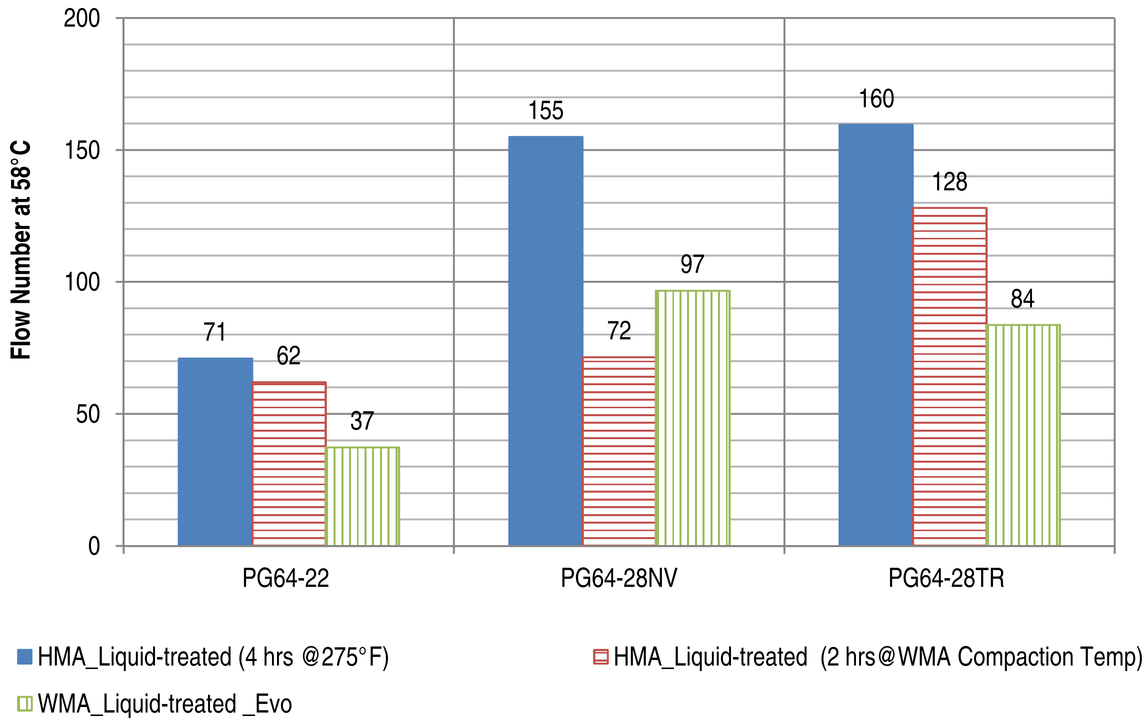


Figure 123: FN Liquid-treated HMA Vs WMA - Phase II

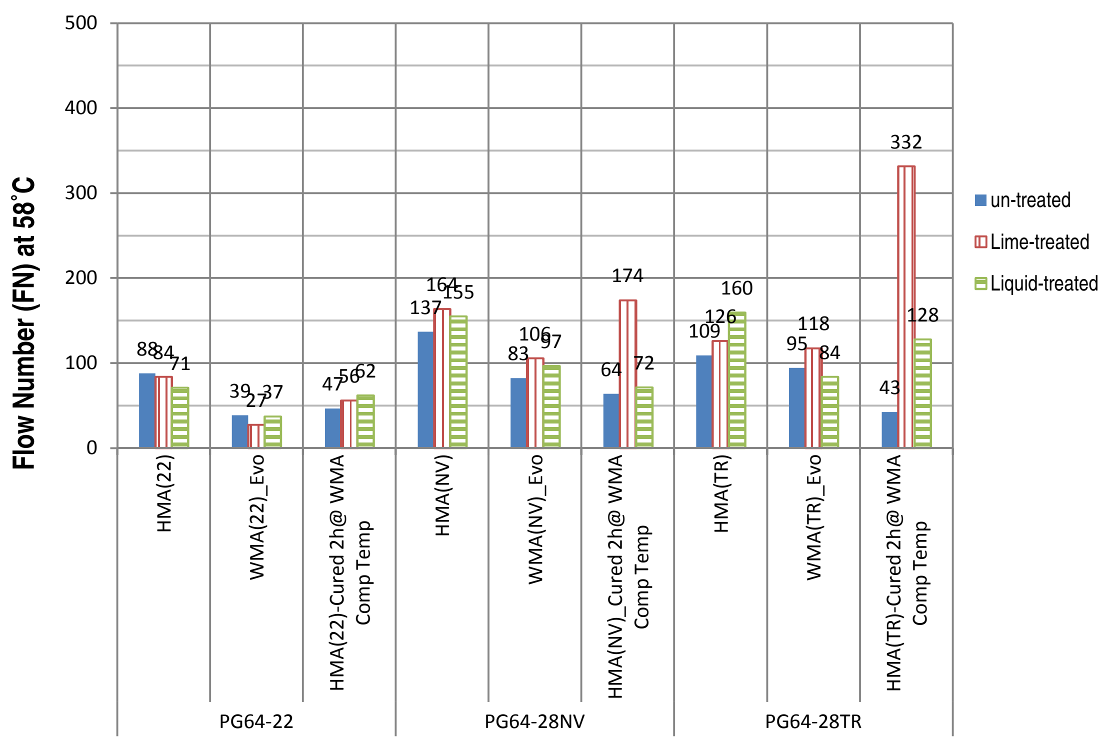


Figure 124: FN Summary - Phase II