University of Nevada, Reno

Evaluation of Warm Mix Additives for Use in Modified Asphalt Mixtures: Phase I

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by

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ABSTRACT

The intention of this research effort is to evaluate the use of warm mix additives with typical polymer-modified and terminal blend tire rubber asphalt mixtures from Nevada and California. The research effort is broken into three phases that are intended to evaluate the impacts of warm mix additives with typical polymer-modified and terminal blend tire rubber asphalt mixtures from Nevada and California: moisture damage, performance characteristics, and mechanistic analysis.

In Phase I of this research effort, mixture resistance to moisture damage was evaluated using the indirect tensile test and the dynamic modulus at multiple freeze-thaw cycles. Laboratory testing was conducted to address the following: (1) the impact of warm mix additive and reduced production temperatures on the moisture damage resistance of asphalt mixtures, (2) the impact of residual aggregate moisture on the moisture damage resistance of WMA mixtures, (3) the impact of warm mix additives on the moisture damage resistance of anti-strip treated WMA mixtures, and (3) the impact of long-term aging on strength gain and the moisture damage resistance of WMA mixtures.

A total of one aggregate source, four warm mix asphalt technologies (Advera, Sasobit, Revix and Foaming) and three asphalt binder types (neat, polymer-modified and terminal blend tire rubber modified asphalt binders) typically used in both Nevada and California are being evaluated in this study. This thesis will only summarize the test results and findings of the Phase I of the study for two warm-mix additives: Advera and Sasobit. The evaluation of the other two technologies (i.e. Revix and Foaming) as well as the Phase II testing are still in progress and have not been completed.

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CHAPTER 1 INTRODUCTION

In an effort to conserve energy, reduce emissions and extend paving seasons, warm mix technologies are increasingly being investigated for their impact on asphalt mixture performance. Warm mix technologies allow asphalt mixtures to be produced and placed at temperatures lower than the temperatures used for conventional asphalt mixtures produced without warm mix additives. In general, warm mix additives improve workability and compactability of mixtures to the point that the asphalt mixtures can be produced at lower temperatures. Major concerns are that the reduced production temperatures may: (a) impair the hardening of the asphalt binder and (b) hinder the evaporation of moisture from hot mix aggregates leading to an increased incidence of moisture damage in asphalt concrete pavements. There may also be further asphalt mixture interactions with the warm mix additives that affect other performance properties of an asphalt concrete pavement depending on the warm mix technology.

Most of the laboratory research conducted to date on warm mix technologies has been concentrated on studying the impacts of warm mix technologies without regard to the impact of potential binder modification used in the asphalt mixture on pavement performance. And most of warm mix asphalt (WMA) research in the United States has studied asphalt mixtures developed utilizing the Superpave mix design method. The Superpave mix design method uses the volumetric properties to determine the optimum binder content of a given asphalt mixture. The Superpave mix design method is currently the most commonly used mix design method in the United States.

1.1. Objective

The intention of this research effort is to evaluate the use of warm mix additives with typical polymer-modified and terminal blend tire rubber asphalt mixtures from Nevada and California.

The research effort is broken into three phases that are intended to evaluate the impacts of warm mix additives with typical polymer-modified and terminal blend tire rubber asphalt mixtures from Nevada and California: moisture damage, performance characteristics, and mechanistic analysis. In phase I of this research effort, materials were identified, mix designs were conducted and the warm mix additives were evaluated for their impact on the resistance of the asphalt mixtures to moisture damage.

Since this research effort focuses on WMA mixtures typically used in Nevada and California, states which utilize the Hveem mix design method, previous research efforts were drawn upon to analyze WMA mixtures designed utilizing the Hveem mix design method. The Hveem mix design procedure used in this research effort complies with the specifications of both the Nevada Department of Transportation (NDOT) and the California Department of Transportation (Caltrans).

1.2. Scope

A total of one aggregate source, two warm mix asphalt technologies (Advera, Sasobit) and two asphalt binder types (terminal blend tire rubber modified and polymer-modified asphalt binders) typically used in both Nevada and California are being evaluated as part of this research effort. Laboratory hot mix asphalt (HMA) mixtures were designed to comply with both NDOT and Caltrans specifications and used as control mixtures. Laboratory WMA mixtures were verified utilizing the mixing temperatures developed utilizing the procedure in the draft Proposed Standard Practice for Design of WMA dated October 31, 2008 that is being developed by the National Cooperative Highway Research Program (NCHRP) Project NCHRP 9-43 (1).

To address the impact of moisture susceptibility, the research effort focused on several factors related to the resistance of asphalt mixtures to moisture damage. Laboratory testing was conducted to address the following questions related to asphalt mixture moisture damage susceptibility:

- the impact of warm mix additive and reduced production temperatures on the resistance of asphalt mixtures to moisture damage,
- the impact of residual aggregate moisture on the resistance of WMA mixtures to moisture damage,
- the impact of warm mix additives on the resistance to moisture damage of anti-strip treated WMA mixtures and,
- the impact of long-term aging on the resistance to moisture damage of WMA mixtures.

All mixtures were subjected to moisture damage through freeze-thaw (F-T) cycling. Their resistance to moisture damage was then evaluated utilizing the indirect tensile strength (ITS), tensile strength ratio (TSR), dynamic modulus (|E*|), and dynamic modulus (|E*|) ratio at various F-T cycles.

1.3. Experimental Program

Phase I of this research effort focuses on the evaluation of the impact of warm mix additives on the resistance of asphalt mixtures to moisture damage.

1.3.1. Mix Designs

HMA mix designs were prepared following the Hveem mix design for heavy traffic as per NDOT and Caltrans specifications. A single aggregate gradation was selected that met both NDOT Type 2C and Caltrans 3/4" Maximum, Type A, specifications. Since the Hveem mix design procedures as prescribed by NDOT and Caltrans do not include methods for designing WMA mixtures, UNR used a modified mix design method to verify the WMA mixtures for compliance to both NDOT and Caltrans specifications. These mix design processes are summarized in Figure 1.

Currently, there are two methods for determining WMA mixing temperature. The first is to ask for recommendations from the warm mix additive supplier and the second is to evaluate the WMA mixing temperature using the procedure in the draft Proposed Standard Practice for Design of WMA (1). This research used the procedure in the draft Proposed Standard Practice for Design of WMA to determine the mixing temperatures for use in the WMA mix design. The proposed procedure for WMA mixing temperature determination requires the use of a Superpave gyratory compactor (SGC) which most likely would not be available to laboratories performing Hveem mix designs. Hveem mix design samples are prepared using a kneading compactor. The mixing and compaction temperatures of WMA mixture were evaluated for asphalt mixtures without anti-strip and assumed to remain constant as anti-strip additives are added to the mixture.

Laboratory WMA mixtures were designed to meet aggregate coating and compactability requirements as per the draft Proposed Standard Practice for Design of WMA. The WMA mixtures were also evaluated for aggregate coating and compactability as part of the determination of WMA mixing and compaction temperatures. The aggregate coating and compactability testing was conducted on asphalt mixtures without anti-strip additives.

As part of the mix design evaluation, all mixtures were subjected to indirect tensile testing to evaluate the resistance of the laboratory compacted mixtures to moisture induced damage (Lottman) as prescribed by Nevada Test Method T341D (13) and Caltrans Test Method 371 (14).

1.3.2. Impact of Residual Moisture on Un-treated Mixtures

One concern regarding WMA is that the moisture from the stockpiled aggregates does not completely evaporate in the drum as WMA mixing temperatures are lower than those used during typical HMA production. The retained moisture, defined as residual moisture, in the asphalt-coated aggregate may result in a moisture susceptible mixture. The objective of this task is to identify the effect of aggregate residual moisture on the resistance of WMA mixtures to moisture damage. To this end, laboratory-produced WMA mixtures will be evaluated with and without residual moisture to study the effects of insufficient aggregate drying during production.

The residual moisture will be determined in the laboratory as the moisture remained in the aggregate after heating the wet aggregate to the WMA mixing temperature for the same time required to totally dry the aggregate when heated to the

HMA mixing temperature. This process involves treating the aggregate blend for 15 to 18 hours with water at 2% above the combined aggregate absorption. Then, the saturated aggregate will be dried for a calibrated time period in an oven set to the WMA mixing temperature before mixing. The calibrated time period is the time for a similarly wet aggregate sample to reach constant dry mass in an oven set at the corresponding HMA mixing temperature. The residual moisture in the aggregate will vary by mixture depending on the WMA mixing temperature. Table 1 lists the anticipated nine mixtures (three mixtures per warm mix additive) that will be evaluated using the dynamic modulus, |E*|, at 0, 1 and 6 freeze-thaw (F-T) cycles with and without residual moisture.

1.3.3. Impact of Anti-strip Additives

The objective of this task is to determine if the use of an anti-stripping agent will improve the moisture resistance of WMA mixtures. Two types of anti-stripping agents will be used; liquid and lime. Aggregate with residual moisture will be used to prepare the various mixtures if found to have the most significant impact on the moisture susceptibility of mixtures. It is anticipated that there will be eighteen mixtures for this task (six mixtures per warm mix additive). Table 2 lists the mixtures that will be evaluated using the dynamic modulus, |E*|, at 0 and 6 F-T cycles.

1.3.4. Impact of Long-term Aging on Moisture Resistance

The objective of this task is to evaluate the effect of long-term aging on the mixtures resistance to moisture damage. This task will look into whether long-term aging will mask the impact of residual moisture on the resistance of the WMA mixtures to moisture damage. Table 3 shows the experimental program for this task (three mixtures per warm mix additive). Only un-treated mixtures (i.e. no anti-stripping additive) will be evaluated in this effort using the dynamic modulus, |E*|, at multiple aging levels and after 6 F-T cycles.

1.4. Background

Moisture damage is a complex failure mode of asphalt mixtures that if properly anticipated can be prevented from occurring during the service life of the pavement. Moisture damage is characteristic of asphalt mixtures that lack sufficient asphalt binder cohesion or adhesion between the asphalt binder and aggregate particles. The presence of moisture and traffic work together to further loosen the weak bonds between the aggregate and asphalt binder leading to structural disintegration of the mixture and premature pavement failure.

The use of warm mix additives are of concern to highway agencies due to their potential to increase the risks of weakened bonds between asphalt and asphalt and aggregate. Typically, as production temperatures decrease, asphalt binder viscosity increases and the ability of an asphalt binder to coat and penetrate into aggregate particles also decreases; thereby, increase moisture damage susceptibility. Warm mix additives reduce the viscosity of an asphalt binder to allow proper aggregate coating and mixture workability at reduced production temperatures which saves fuel and decreases emissions. However, the use of additives may introduce other asphalt interactions that could affect asphalt-aggregate bonding and need to be mitigated. As such, the moisture damage susceptibility of WMA mixtures is a problem that has received much attention in the investigation and development of warm mix technologies.

The National Center for Asphalt Technology (NCAT) has done a significant amount of research with regards to the applicability of warm mix additives to typical paving operations. NCAT in particular has studied the applicability of Sasobit, an organic wax, Aspha-min, a zeolite or water-bearing addtive, and Evotherm, a liquid emulsifier for use in WMA (4, 5, 6). For the purposes of this research effort, the NCAT moisture sensitivity and strength gain findings with respect to Sasobit and Aspha-min will be summarized. Despite the fact that Aspha-min is not evaluated in this study, it is a zeolite, similar to Advera which is used in this study.

The moisture sensitivity evaluation conducted by NCAT utilized the indirect tensile strength testing as per ASTM D 4867 to determine TSRs. The NCAT study evaluated two aggregate sources (granite and limestone) with two binder types (PG 64-22 and PG 58-28). To study the effects of residual moisture, NCAT added moisture to the aggregate at a rate of three percent above the aggregate absorption value before the aggregate was heated. To study the effects of aging on WMA mixtures, NCAT prepared samples that were subjected to short-term aging prior to compaction of two to four hours at 230°F (110°C) and long-term aging of 0 to 5 days at 185°F (85°C) as shown in Table 4. The prepared samples were then tested for strength gain by means of indirect tensile strength testing.

The moisture sensitivity analysis revealed that the Sasobit WMA mixtures could exhibit lowered ITS from control HMA mixtures. The addition of liquid anti-strip (LAS) to the Sasobit WMA mixtures resulted in reduced ITS values and TSR values that were significantly higher than the control HMA mixtures. Despite the increase in TSR values, is it debatable whether the addition of the LAS reduced the potential for moisture damage in the Sasobit mixtures due to the reduction in ITS values.

The aging evaluation revealed that strength varied at different aging times between HMA control and Sasobit WMA mixtures and this variation was aggregate dependent. The Sasobit WMA mixtures showed reduced strengths when compared to the HMA control mixtures. At the long-term aged condition, no significant differences existed between the Sasobit WMA mixtures and the HMA control mixtures (4, 5).

The moisture sensitivity analysis revealed that the Aspha-min WMA mixtures could exhibit lower TSR values as compared to HMA control mixtures. The mixtures with Aspha-min did not meet the minimum TSR criteria for Superpave mixtures of 0.80. The lower TSR values may have been a result of residual moisture so the moisture sensitivity analysis was redone with dry aggregates which also showed that the Aspha-min WMA mixtures did not meet the TSR criteria. The addition of LAS to the Aspha-min WMA mixtures resulted in reduced TSR values. NCAT theorized that the reduced TSR values may have been due to the LAS thinning the binder and reducing the binder viscosity. NCAT also evaluated the moisture sensitivity analysis with hydrated lime. The addition of hydrated lime to the Aspha-min WMA mixtures increased the TSR values but not to the level of the Superpave criteria.

The aging evaluation revealed no significant differences in strength gain between the Aspha-min WMA mixtures and the HMA control mixtures (4, 6).

From the laboratory evaluation of Sasobit and Aspha-min WMA mixtures, NCAT concluded that warm mix additives tended to reduce the ITS and TSR values of asphalt mixtures and thus may decrease the moisture resistance of asphalt mixtures. NCAT also concluded that if the the addition of anti-strip additives (ASA) may mitigate the potential of moisture damage in WMA mixtures (4, 5, 6).

Clemson University conducted a laboratory study regarding the moisture susceptibility of WMA mixtures and the use of ASA (7). Clemson tested three aggregate sources, one water-bearing additive (Aspha-min), one binder (PG 64-22) and three ASA (two LAS and hydrated lime). Mix designs were prepared following Superpave mix design specifications and tested for moisture susceptibility. The moisture susceptibility was evaluated by ITS following South Carolina Test Procedure 70 (SC T 70) and stripping caused by water boiling following ASTM 3625.

Clemson University found that that the addition of Aspha-min lowered the ITS and TSR values of the asphalt mixtures. The LAS increased the moisture-conditioned ITS of the Aspha-min mixtures, but the resulting TSR did not meet the the South Carolina Department of Transportation TSR criteria of 85, except in one of six cases. In general, Aspha-min mixtures with no anti-strip treatment did not meet the TSR criteria. The addition of hydrated lime was effective at increasing ITS values of the Aspha-min mixtures to acceptable levels. The ITS testing indicates that the Aspha-min additive increases the potential for moisture damage, but that the moisture damage potential can be effectively reduced with hydrated lime. The boiling tests confirm a stripping potential in Aspha-min WMA mixtures with and without the LAS additives (7).

As part of the applicability study conducted by NCAT on Aspha-min WMA mixtures, NCAT has conducted a laboratory assessment and is involved with ongoing pavement assessment of a field demonstration project in Orlando, FL constructed in March 2005. The WMA mixture was batched per the HMA mix design with the addition of 0.3% by weight of total mixture of Aspha-min zeolite. The HMA mixture was designed with 20% recycled asphalt pavement (RAP) and crushed granite to meet the requirements of a Florida Department of Transportation fine-graded, Superpave mix compacted to N_{design} = 75 gyrations. Moisture sensitivity testing was conducted per ASTM D4867 with the inclusion of one F-T cycle unlike the previous NCAT laboratory testing.

The results of the moisture sensitivity testing on the field mixture showed that the addition of the Aspha-min decreased the TSR value of the WMA mixture from the TSR value of the HMA control mixture. After one year, a field assessment showed no signs of moisture damage in neither the WMA pavement section nor HMA control section. As part of the pavement assessment, cores were taken from the test sections and tested for ITS. The Aspha-min cores resulted in higher ITS values than the HMA control section cores despite the Aspha-min cores exhibiting slightly higher air voids (6). The field results thus far indicate that the addition of Aspha-min does not increase the potential for moisture damage of WMA pavements.

The Virginia Department of Transportation (VDOT) has conducted studies to evaluate the potential benefits of warm mix additives to pavement construction. VDOT installed three trial sections throughout Virginia between August and November 2006: two Sasobit trial sections and one Evotherm trial section. For the purposes of this research effort, the moisture susceptibility results of the two Sasobit trial sections will be summarized (8, 9, 10). The moisture susceptibility testing was conducted as per a modified AASHTO T 283 and Hamburg wheel track test. The modified AASHTO does not specify the 16 hour curing or 24 hour storage period. Hamburg wheel track testing was evaluated at 122°F and a wheel load of 158 lbs for samples with seven percent air voids.

The first Sasobit test section was constructed on Route 211 in Rappahannock County, Virginia. The project called for the placement of a Sasobit WMA and HMA control section. The mixture utilized had a 9.5 mm nominal maximum aggregate size (NMAS) gradation with 20% RAP. The mixture was produced with PG 64-22 binder treated with 0.5% liquid anti-strip Morelife 3300 by weight of binder. The WMA mixture was produced per HMA mix design proportions with Sasobit added at a rate of 1.5% by weight of binder. The TSR testing conducted on plant samples showed that the Sasobit WMA mixture did not meet the minimum TSR of 0.80. The ITS values of the Sasobit WMA mixture were significantly lower than the HMA control mixture. Due to concerns over residual moisture, laboratory WMA samples were reheated and compacted. The subsequent TSR values increased but still did not meet the minimum TSR criteria. The ITS values of the laboratory WMA mixture were significantly greater than the HMA control mixture. The Hamburg wheel track test showed that all mixtures would be resistant to stripping.

The second Sasobit test section was constructed on Route 220 in Highland County, Virginia. The project called for the placement of a Sasobit WMA and HMA control section. The mixture utilized had a 12.5 mm nominal maximum aggregate size (NMAS) gradation with 10% RAP. The mixture was produced with PG 64-22 binder and aggregates treated with hydrated lime. The WMA mixture was produced per HMA mix design proportions with Sasobit added at rate of 1.5% by weight of binder. The TSR testing conducted on plant samples showed that the Sasobit WMA mixture and the HMA control sample met the minimum TSR value of 0.80. The TSR value of the Sasobit WMA mixture was slightly higher than the HMA control mixture. The ITS values of the Sasobit WMA mixture were lower than the HMA control mixture. The Hamburg wheel track test showed that all mixtures would be resistant to stripping.

Overall, the Virginia test sections resulted in conflicting moisture susceptibility data with respect to the use of the warm mix additive Sasobit. To evaluate occurrence of initial distresses, visual surveys of the test sections were conducted over a two-year period. The surveys indicated that there was no moisture damage in any of the test sections and that the WMA test sections were performing as well as the HMA test sections.

Many pavement professionals, including the researchers of the NCAT and Virginia studies, have theorized that residual moisture influences the moisture susceptibility of the WMA mixtures. In response to this concern, Clemson University conducted a laboratory research effort to evaluate the influence of WMA additives and aggregate moisture on the resistance of asphalt mixtures to moisture damage (2). Moisture damage resistance was evaluated by means of ITS, TSR and toughness which were determined by SC T 70. Toughness is defined as the area under the ITS-deformation curve from initial tensile loading stress to twice the maximum tensile stress.

The research was conducted on a 12.5 mm mixture that met South Carolina Department of Transportation specifications with a combination of three aggregate sources, two warm mix additives, two moisture contents and three lime contents. The aggregates utilized in this research effort were two types: granite and schist. The warm mix additives evaluated were Aspha-min and Sasobit, the moisture contents evaluated were 0% and 0.5% by total weight of mixture and the lime contents evaluated were 0%, 1% and 2% by weight of dry aggregate. The mixtures with residual moisture were prepared as follows:

- Hot water is added to superheated dry aggregate at a rate of 3% by dry weight of aggreate. The aggregates are superheated such that the addition of hot water to the aggregate results in the mixture meeting the target mixing temperature.
- The aggregate-water mixture is mixed by hand for 30 seconds before mixing with binder until a retained moisture content of about 0.5% is achieved.
- Binder heated to mixing temperature is then mixed with the aggregate-water mixture.

The Clemson study found that the presence of aggregate moisture did lower the unconditioned ITS, but did not influence the TSR of the asphalt mixtures. The presence of warm mix additives did not significantly affect the ITS values of the mixtures; however, the Aspha-min may negatively affect the unconditioned ITS of the asphalt mixture. The asphalt mixtures with no lime did not meet the TSR criteria of 0.85. The study concluded that lime can be used to significantly improve the unconditioned ITS with moist aggregate and to increase the TSR of the mixtures to an acceptable level. The toughness values of the WMA mixtures under identical conditions showed no significant differences.

CHAPTER 2 MATERIALS AND MIX DESIGNS

An experimental program was carried out to evaluate the effect of the warm mix additives on the resistance of the asphalt mixture to moisture damage. This chapter describes the materials used in this research effort as well as the developed mix designs.

2.1. Materials

A total of three HMA mixtures and six WMA mixtures were evaluated in this research effort. One aggregate source, two warm mix additives, three binder types, and two anti-strip treatments commonly used in both Nevada and California were evaluated. Table 5 summarizes the asphalt mixtures that were evaluated in this study.

2.1.1. Aggregate

The aggregate source for this research effort is from a hard rock quarry in Lockwood, Nevada that supplies hot mix aggregates to Nevada and California. The aggregate blend selected for the laboratory evaluation met the NDOT Type 2C specifications and Caltrans Type A specifications for dense graded asphalt mixtures as prescribed by the NDOT Standard Specifications for Road and Bridge Construction (4) and Caltrans Standard Specifications (12). Table 6 shows the gradation of the aggregate blend developed for this research effort.

The aggregate gradation was achieved by blending aggregate stockpiles as shown in Table 7. The gradations of the individual stockpiles are shown in Table 8. The following properties were measured on the aggregate blend for the mixtures following the NDOT Standard Specifications (4) and Caltrans Standard Specifications (12):

- Specific gravity and absorption of coarse aggregate (AASHTO T 85)

- Specific gravity and absorption of fine aggregate (AASHTO T 84)

In addition, the following consensus properties were evaluated:

- Coarse Aggregate Angularity (Nev. T230 & CTM 205)
- Fine Aggregate Angularity (AASHTO T 304 (A))
- Sand Equivalent Test (CTM 217)
- Plasticity Index (Nev. T212)
- Liquid Limit (Nev. T210)
- Flat and Elongated Particles (by wt @ 5:1) (AASHTO D 4791)
- Los Angeles Rattler (AASHTO T 96 & CTM 211)
- Soundness (AASHTO T 104)

Table 9 summarizes the aggregate properties for the selected aggregate gradations.

2.1.2. Asphalt Binder

Three binder types were used in this research effort: PG 64-22, PG 64-28 NV/PM, and PG 64-28 NVTR/TR, which are binders commonly used in Nevada and California. The PG 64-22 is a neat binder that meets Caltrans specifications for PG 64-16. PG 64-22 binder is not specified for use by NDOT, but it is used by municipal agencies in Nevada and is the base binder for the polymer-modified and the terminal blend rubberized asphalt binder. The PG 64-28 NV/PM is a polymer-modified asphalt binder that meets both the NDOT and Caltrans specifications for polymer-modified asphalt binders. The PG 64-28 NVTR/TR is a terminal blend rubberized asphalt binder that meets Caltrans specifications for polymer-modified asphalt binders, but that does not quite meet the NDOT specifications for polymer-modified asphalt binders. The properties of each of the asphalt binders can be found in Tables 10 – 12. All binders for this research effort were supplied by Paramount Petroleum Company.

2.1.3. WMA Admixtures

A total of two warm mix additives were evaluated in this portion of Phase I of this research effort: Advera, a powered zeolite, and Sasobit, an organic wax additive.

Advera is an aluminosilicate or hydrated free flowing powdered zeolite that is white to grey in color. When heated, Advera releases steam which foams the asphalt binder and thereby, temporarily reducing the viscosity of the binder. The reduction in binder viscosity improves workability and enhances aggregate coating at reduced mixing temperatures. Advera may be added directly into a batch plant or metered into a drum plant using a recycled asphalt pavement (RAP) collar. Advera is normally added at a rate of 0.2-0.3% by total weight of mixture. In the United States, Advera is produced by the PQ Corporation.

Sasobit is the most commonly used organic additive used in the United States. It is a synthetic paraffin wax that is manufactured by Sasol Wax North America (formerly Schumann Sasol) using the Fischer-Tropsch process that involves treating hot coal or natural gas (methane) with steam in the presence of a catalyst. The synthetic paraffin wax consists of long chemical chains that allow the wax to remain in solution, reduce the melting point of an asphalt binder, and reduce the viscosity of an asphalt binder at mixing and compaction temperatures. Sasobit may be blended with the asphalt binder at the asphalt terminal or in the contractor's tank, added directly to batch plant, or blown into a drum plant. The recommended addition rate is 1.5 to 3.0% by weight of binder. In the United States, Sasobit is supplied by Sasol Wax North America, Inc.

2.1.4. Anti-Strip Additives

Two anti-strip additives (ASA) were evaluated for use in this research effort for the mitigation of moisture damage: hydrated lime and liquid anti-strip (Morlife 5000). While NDOT mandates the use of lime in all its dense graded asphalt mixtures, Caltrans specifies the use of lime or liquid anti-strip to address moisture susceptibility.

Hydrated lime improves the resistance of asphalt mixtures to moisture damage by improving the bond between aggregate and asphalt binder and altering clay particles in the asphalt mixture to increase adhesion and to improve the moisture stability of an asphalt mixture. Dry lime on damp aggregate was added at a rate of 1.0% by dry weight of aggregate.

Morlife 5000 improves the resistance of asphalt mixtures to moisture damage by improving the bond between aggregate and asphalt binder to increase adhesion. Morlife 5000 was added at a rate of 0.5% by weight of asphalt binder. Liquid anti-strips are traditionally added directly to a heated asphalt binder in the laboratory, at the asphalt terminal or in the contractor's asphalt plant metering system. Morlife 5000 is produced and supplied by the Dow Chemical Company.

2.2. Mix Designs

A total of six HMA mixtures and twelve WMA mixtures were prepared and evaluated in this study and are summarized in Table 5. Mixtures with no anti-strip additives are called un-treated mixtures, while mixtures with lime or liquid anti-strip are called lime-treated and liquid-treated mixtures, respectively. All mixtures were designed to meet the NDOT and Caltrans specifications for Hveem mix design methods for heavy traffic. NDOT utilizes the Type 2C mixture specification and Caltrans specifies the QC/QA, Type A mixture specification for heavy traffic applications. Both of these specifications include testing for the resistance to deformation and resistance to moisture damage. An acceptable deformation resistance requires a minimum Hveem Stability (Nev. T303 / CTM 366) of 37 and an acceptable moisture damage resistance requires a minimum Unconditioned Indirect Tensile Strength (Nev. 341) of 65 psi and a Retained Indirect Tensile Strength Ratio (Nev. 341 CTM 371) of 70% (4, 12).

Both NDOT and Caltrans use the Hveem mix design method. The NDOT mix design procedure involves performing Nevada Test Method T760 (13) to determine the optimum binder content (OBC) of a proposed aggregate and binder combination and to verify its compliance to NDOT standard specifications. Similarly, the Caltrans mix design procedure involves performing Caltrans Test Method (CTM) 367 (14) on a proposed aggregate and binder combination to determine the optimum binder content (OBC) and additional HMA mixture qualities to verify its compliance to Caltrans standard specifications.

As per the current Hveem mix design method employed by NDOT and Caltrans, HMA samples were mixed at mixing temperatures determined by utilizing a temperature-viscosity chart as described in AASHTO T 312 (3), cured for 16±1 hours at 140°F (60°C) before compaction at 230°F (110°C). The current mix design procedure for determining mixing temperature is valid for HMA mix designs, but is not valid for WMA mix designs. The optimum binder contents were determined for the HMA mixtures and verified for the WMA.

The WMA mix designs were verified following the mix design procedure proposed by NCHRP 9-43 (1) for warm mix asphalts but using the Hveem mix design method. The mixing and compaction temperatures of the WMA mixtures were determined per NCHRP 9-43. The addition of the Sasobit and Advera to the laboratory prepared mixtures was accomplished by adding heated aggregate to a bowl, creating a crater in the aggregate, adding binder to the aggregate crater and adding the additive to the pool of binder before mixing. The mixture conditioning period was amended to two hours at compaction temperature as suggested by the draft WMA mix design procedure. For the WMA mix designs, the compaction temperature was unchanged from 230°F (110°C).

Figures 2 - 29 present summaries of the HMA and WMA mix designs developed as part of this research effort and Table 13 presents a summary of the optimum binder contents used in this study.

CHAPTER 3 DESCRIPTION OF LABORATORY TESTING

This chapter describes the laboratory tests that were used in this study to evaluate the impact of warm mix additives on the production temperatures and the resistance to moisture damage of modified asphalt mixtures. In order to evaluate the WMA mix designs, first the optimum bitumen contents (OBC) for the WMA mixtures are determined and then the production temperatures for the WMA mixtures are determined using the draft Proposed Standard Practice for Design of WMA (1). Once the WMA mix designs are completed, all mixtures were evaluated in terms of the effects of the warm mix additives on their resistance to moisture damage.

In practice, a WMA mix design consists of running the corresponding HMA mix design with no warm mix additives to determine the OBC. The WMA production temperatures are usually dictated by the warm mix additive supplier recommendations and hot mix plant constraints. The draft Proposed Standard Practice for Design of WMA contains a method for designing WMA mixtures and production temperatures directly; however, its process requires the use of a Superpave Gyratory Compactor (SGC). Since this research effort evaluates asphalt mixtures intended for use in Nevada and California, which are Hveem mix design states that utilize the kneading compactor, the WMA mixtures were based on the HMA mix designs as done in practice.

In order to better evaluate the impacts of the warm mix additives on modified mixtures, the WMA production temperature were evaluated utilizing the procedure prescribed in the draft Proposed Standard Practice for Design of WMA. In the draft standard practice, the WMA mixing and compaction temperatures are determined by evaluating the asphalt binder aging index, the aggregate coating, and the compactability of the WMA mixture at the proposed production temperatures.

3.1. Aging Index of Asphalt Binders

The aging index of an asphalt binder is used to determine the minimum mixing temperature that a WMA mixture can be subjected to before the reduction in mixing temperature impacts the resulting asphalt binder grade as shown in Table 14. The aging index of an asphalt binder is a ratio that indicates the aging susceptibility of a binder. The aging susceptibility of an asphalt binder is the rate of change of the short-term aged high grade temperature of the binder.

The aging susceptibility of an asphalt binder has been found to be correlated to an aging index determined using a relation of $G^*/\sin\delta$ values obtained in the grading of a binder. The aging index of an asphalt binder is defined as the ratio of the $G^*/\sin\delta$ of the binder after short-term aging in the Rolling Thin Film Oven (RTFO) over the $G^*/\sin\delta$ of the unaged binder. A WMA mixture to be produced at mixing temperature lower than indicated by the aging index in Table 14 requires an increase in the high grade temperature of its asphalt binder.

During the grading of an asphalt binder, the $G^*/\sin\delta$ values are obtained using a dynamic shear rheometer (DSR) per AASHTO T 325 (3). The dynamic shear modulus, G^*, and phase angle, δ, in radians are measured by the DSR apparatus at various high grade temperatures at the unaged and short-term aged conditions of the binder at a frequency of 10 Hz. Using these measurements, the high temperature grade of the binder is determined. Once the high temperature grade of the binder is determined, the unaged and RTFO-aged G*/sinδ values at the high temperature grade of the binder are used for the calculation of the aging index.

3.2. Degree of Aggregate Coating of Asphalt Mixtures

The degree of aggregate coating of an asphalt mixture is evaluated using the Standard Test Method for Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures, AASHTO T 195 (3). To determine the degree of coating of an asphalt mixture, a sample is mixed and separated into fine and coarse fractions over a No. 4 sieve. The coarse fraction is then evaluated visually for aggregate coating particle by particle. The degree of coating of an asphalt mixture is the percentage of aggregate particles that are completely coated of the total aggregate particles evaluated. A WMA mixing temperature that results in 100% aggregate coating is deemed acceptable for WMA production.

3.3. Compactability of Asphalt Mixtures

The compactability of a WMA mixture is represented by the number of gyrations to eight percent air voids by means of the Superpave gyratory compactor. Compactability samples are mixed at the proposed mixing temperature, cured for two hours at the proposed compaction temperature and compacted to 92% of their maximum theoretical specific gravity (G_{mm}). This sample preparation procedure is then repeated for samples that are cured at the compaction temperature and allowed to cool to 55^{o}F (30^{o}C) below the proposed compaction temperature before compaction to N_{design} gyrations. The aggregate coating and compactability criteria for the determination of mixture mixing and compaction temperatures are shown in Table 16.

For the purposes of this research effort, the compaction temperature for the WMA mixtures is defined as the mixing temperature reduced by 25°F (14°C) and the design traffic was chosen to be greater than 30 million ESALs. The Superpave mix design method adjusts the compaction effort based on the level of anticipated traffic. Table 15 shows the pavement traffic level versus the Superpave compaction effort required. A traffic level greater than 30 million ESALs corresponds to a compaction effort of 125 gyrations by means of the SGC.

HMA compactability samples were also prepared for comparison purposes. The HMA mixtures were short-term aged at their compaction temperatures for two hours prior to compaction as per AASHTO M 323 (3).

3.4. Resistance of Asphalt Mixtures to Moisture Damage – Tensile Strength Ratio

The resistances of the various HMA mixtures to moisture damage were evaluated by means of indirect tensile strength of the mixtures unconditioned and after one F-T cycle. The F-T cycling followed the procedure outlined in Nev. T341 and CTM 371. Nev. T341 requires samples to contain 7.0-8.0% air voids, while CTM 371 requires samples to contain 6.5-7.5% air voids; therefore, samples were made to contain 7.0% to 7.5% air voids. A total of 12 samples from each mixture were evaluated following the procedure outlined below:

- Measure the unconditioned tensile strength of 6 samples (i.e., 0 F-T cycles).
- Subject 6 samples to 70-80% saturation.

- Subject the saturated samples to one F-T cycle: freezing 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).
- Conduct tensile strength testing after 1 cycle.

Since the determination of tensile strength ratio is part of the mix design evaluation, the HMA and WMA mixtures were prepared as described in Section 2.2.

3.5. Resistance of Asphalt Mixtures to Moisture Damage – Dynamic Modulus Ratio

The resistances of the various HMA mixtures to moisture damage were additionally evaluated by measuring the dynamic modulus of the mixtures after multiple F-T cycles. The multiple F-T cycling followed the procedure outlined in AASHTO T 283 (3) at multiple stages. A total of three samples from each mixture were evaluated following the procedure outlined below:

- Measure the unconditioned |E*| master curve (i.e., 0 F-T cycles).
- Subject the samples to 70-80% saturation.
- Subject the saturated samples to F-T cycling wherein one F-T cycle consists of freezing 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 the prescribed number of F-T cycles.
- Conduct |E*| testing after the number of cycles indicated in the experimental plan.

The AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) uses the dynamic modulus (|E*|) master curve to evaluate the structural response of the flexible pavement under various combinations of traffic loads, speed, and environmental conditions. The |E*| property of the various mixtures is evaluated under multiple combinations of 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 TP 62 (3). Using the viscoelastic behavior of asphalt mixtures (i.e. interchangeability of the effect of loading rate and temperature) the master curve can be developed as specified by AASHTO PP 61 (3). The master curve can be used to identify the appropriate |E*| for any combination of pavement temperature and traffic speed. Figure 30 shows the components and testing conditions of the complex modulus test along with a typical master curve for an asphalt mixture.

The |E*| property provides an indication of the general quality of asphalt mixtures. The relationship between |E*| and the number of F-T cycles gives an excellent indication of the moisture resistance of a mixture in the form of the |E*| ratio. 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. The |E*| master curve can also be used in the mechanistic analyses of various pavement sections.

Please note that for the dynamic modulus performance testing, the HMA mixtures were short-term conditioned by curing the loose mixture at 275°F (135°C) for 4 hours prior to compaction per AASHTO R 30 (3) and the WMA mixtures were short-term conditioned by curing the loose mixture at the determined compaction temperature for two hours prior to compaction per NCHRP 9-43 (1).

3.5.1. Impact of Residual Moisture on Un-treated Mixtures

For each short-term aged, un-treated mixture, the |E*| master curve was determined after 0, 1 and 6 F-T cycles. The short-term aged, un-treated mixtures included mixtures that were subjected to combinations of three binders (PG 64-22, PG 64-28 NV and PG 64-28 NVTR), two warm mix additives (Sasobit and Advera), two aggregate residual moisture conditions (none and moist), and two ASA (LAS and hydrated lime) as shown in Table 1.

In order to determine the amount of residual moisture in aggregates, the blended aggregates were treated for 15 to 18 hours with moisture at two percent above the combined aggregate absorption. The moisture conditioned aggregate was then dried for a calibrated time period in an oven set to the WMA mixing temperature before mixing. The calibrated time period is the period of time for a similarly moisture conditioned aggregate sample to reach constant dry mass in an oven set to the corresponding HMA mixing temperature. The aggregates with the appropriate amounts of residual moisture were then used to produce WMA moist mixtures that were used to fabricate dynamic modulus samples as per AASHTO PP 60 (3).

The impact of residual moisture on un-treated mixtures was then evaluated by comparing the |E*| values and |E*| ratios at 70°F (21.2°C) and 10 Hz of mixtures with no residual moisture with the |E*| values and |E*| ratios at 70°F (21.2°C) and 10 Hz of mixtures with residual moisture.

3.5.2. Impact of Anti-strip Additives

For each short-term aged, treated mixture, the |E*| master curve was determined after 0 and 6 F-T cycles. The short-term aged, treated mixtures included mixtures that were subjected to combinations of three binders (PG 64-22, PG 64-28 NV and PG 64-28 NVTR), two warm mix additives (Sasobit and Advera), one aggregate residual moisture condition (moist), and two ASA (LAS and hydrated lime) as shown in Table 2.

The impact of anti-strip additives on treated mixtures was then evaluated by comparing the |E*| values and |E*| ratios at 70°F (21.2°C) and 10 Hz of mixtures without anti-strip treatment with the |E*| values and |E*| ratios at 70°F (21.2°C) and 10 Hz of mixtures with anti-strip treatment.

3.5.3. Impact of Long-term Aging on Moisture Resistance

For each long-term aged mixture, the dynamic modulus was measured at the unconditioned stage, at various stages of aging and after 6 F-T cycles. The dynamic modulus testing for the aging protocol was limited to 70°F (21.2°C) to reduce the incidence of permanent deformation during various stages of the aging and testing protocol. Samples were prepared with residual aggregate moisture and aged per the aging protocol shown in Figure 2. The |E*| values for the aged samples were then determined at 70°F (21.2°C) and the loading frequencies of 25, 10, 5, 0.5, and 0.1 Hz.

The impact of long-term aging on moisture resistance was then evaluated by comparing the |E*| values and |E*| ratios at 70°F (21.2°C) and 10 Hz of long-term aged mixtures with F-T cycling with the |E*| values and |E*| ratios at 70°F (21.2°C) and 10 Hz of long-term aged mixtures without F-T cycling.

CHAPTER 4 ANALYSIS OF LABORATORY DATA

The section of the study presents the analysis of the data that was generated from the laboratory evaluation of the various HMA mixtures.

4.1. Statistical Analysis Techniques

Statistical analysis was employed to objectively determine the impacts of the warm mix additives on the performance of the modified mixtures. To accomplish this, a statistical procedure called the analysis of variance, ANOVA, was used to determine if observed variances in test data were due to the applied treatment. If variances in test data were due to the applied treatment, t-test analysis was performed to determine which applied treatments were causing variances. A significance level of 0.05 was used to establish the significance of variation in the test data.

4.2. Aging Index of Asphalt Binders

The aging index of an asphalt binder was used to determine the minimum mixing temperature that the WMA mixtures can be subjected to before the reduction in mixing temperature impacts the resulting asphalt binder grade as shown in Table 14. Using the $G^*/\sin\delta$ values obtained during the grading of the asphalt binders, the aging indices for the asphalt binders used in this research effort were determined to be 3.4 for PG 64-22, 2.2 for PG 64-28 NV/PM and 1.7 for PG 64-28 NVTR/TR. The aging indices of the asphalt binders correspond to minimum mixing temperatures of 250°F for PG 64-22, 235°F for PG 64-28 NV/PM, and 220°F for PG 64-28 NVTR/TR.

4.3. Aggregate Coating of Asphalt Mixtures

The aggregate coatings of the mixtures were evaluated using the Standard Method of Test for Determining Degree of Particle Coating of Bituminous-Aggregate Mixtures, AASHTO T 195 (3). The results of the testing to determine the degree of aggregate coating of the mixtures at various mixing temperatures are shown in Table 17. The results show that all of the WMA mixture met the aggregate coating criteria of 100% at mixing temperatures 50°F below the prescribed HMA mixing temperature and most met the aggregate coating criteria at mixing temperatures 70°F below the prescribed HMA mixing temperature. The PG 64-22 with Advera mixture did not meet the criteria at 70°F below the prescribed HMA mixing temperature with an aggregate coating of 99.8% and the PG 64-28 NV/PM with Advera mixture did not meet the criteria at 70°F below the prescribed HMA mixing temperature with an aggregate coating of 99.1%. It should be noted that both values are very close to the 100% aggregate coating requirement.

4.4. Compactability of Asphalt Mixtures

The compactability of the WMA mixtures were evaluated by using the number of gyration to eight percent air voids by means of the Superpave gyratory compactor. The compactability testing was conducted as prescribed in the draft Proposed Standard Practice for Design of WMA (1) to determine the WMA mixing and compaction temperatures. The results of the compactability study are shown in Table 18 and Figure 31.

Evaluation of the compactability tests results show that the use of warm mix additives with unmodified asphalt mixtures can achieve greater reductions in production temperatures than for the modified asphalt mixtures. In this research effort, the unmodified PG 64-22 asphalt mixtures were able to achieve mixing temperature reductions of 48 to 53°F, while the modified PG 64-28 asphalt mixtures were able to achieve mixing temperature reductions of 30 to 45 °F.

Advera was added to the PG64-28NV and PG64-28TR mixes at a rate of 0.3% by weight of the total mix. Sasobit was added to the PG64-28NV and PG64-28TR mixes at a rate of 3.0% and 1.5% by weight of binder, respectively. Based on the laboratory evaluation, a higher rate of Sasobit was needed for the PG64-28NV mixture in order to meet the mixture workability and compactability criteria at a temperature lower than the conventional HMA. As such, it is expected that the production temperature reductions based on compactability will vary by warm mix additive, binder type, aggregate source, and mix design.

4.5. Resistance of Asphalt Mixtures to Moisture Damage – Tensile Strength Ratio

The resistances of the various mixtures to moisture damage were evaluated in terms of the tensile strength of the mixtures unconditioned and after one F-T cycle. For each mixture, the unconditioned and conditioned tensile strengths were measured and the corresponding tensile strength ratios were determined. Figures 32 - 37 show the results of the tensile strength testing on the mixtures that were un-treated, lime-treated, and liquid-treated.

Figure 32 shows the un-treated HMA mixtures met the moisture resistance requirements as measured by the unconditioned tensile strength and retained tensile strength ratio requirements of 65 psi minimum and 70% minimum, respectively. All the un-treated WMA mixtures met the unconditioned tensile strength requirement; however, the PG 64-22 WMA mixtures did not meet the tensile strength ratio requirement. Treatment of the HMA and WMA mixtures with 1.0% hydrated lime or 0.5% LAS resulted in all the asphalt mixtures passing the unconditioned tensile strength and retained tensile strength ratio requirements as shown in Figure 33 and Figure 34.

According to the ANOVA tables for the unconditioned and moisture-conditioned tensile strengths shown in Table 19 and Table 20, the binder type and the addition of the warm mix additives did impact the tensile strengths of the asphalt mixtures. The ANOVA tables suggest that the addition of ASA only impact the moisture-conditioned tensile strength. A paired mean comparison analysis at a significance level of 0.05 was conducted to determine whether there was any statistically significant difference between the TS values of the various mixtures as shown in Table 21. Based on the data analysis the following conclusions can be made:

- Un-treated mixtures
    - Addition of Advera or Sasobit to the PG 64-22 mixtures did not significantly influence unconditioned TS values. Advera and Sasobit resulted in significantly lower moisture conditioned TS values.
    - Addition of Advera or Sasobit to the PG 64-28 NV mixtures resulted in significantly higher unconditioned TS values. The moisture-conditioned TS were not influenced by the addition of the warm mix additives.
    - Addition of Advera or Sasobit to the PG 64-28 NVTR mixtures did not significantly influence unconditioned TS values. Advera resulted in

significantly lower moisture conditioned TS values and Sasobit did not influence the moisture conditioned TS values.

- LAS-treated mixtures
    - Addition of Advera or Sasobit to the PG 64-22 mixtures did not significantly influence unconditioned TS values. Advera and Sasobit resulted in significantly lower moisture conditioned TS values.
    - Addition of Advera or Sasobit to the PG 64-28 NV mixtures did not significantly influence unconditioned TS values. Advera and Sasobit resulted in significantly lower moisture conditioned TS values.
    - Addition of Advera or Sasobit to the PG 64-28 NVTR mixtures did not significantly influence unconditioned TS values. Advera and Sasobit resulted in significantly lower moisture conditioned TS values.
- Lime-treated mixtures
    - Addition of Advera or Sasobit to the PG 64-22 mixtures did not significantly influence unconditioned TS values. Advera resulted in significantly lower moisture conditioned TS values and Sasobit did not influence the moisture conditioned TS values.
    - Addition of Advera or Sasobit to the PG 64-28 NV mixtures did not significantly influence unconditioned TS values. Advera resulted in significantly lower moisture conditioned TS values and Sasobit resulted in significantly higher moisture conditioned TS values.
    - Addition of Advera or Sasobit to the PG 64-28 NVTR mixtures did not significantly influence unconditioned TS values. Advera did not

influence the moisture conditioned TS values and Sasobit resulted in significantly higher moisture conditioned TS values.

In general, the addition of the warm mix additives reduces the TSR of the asphalt mixtures with no anti-strip treatment, but the addition of ASA can be used to mitigate the reduction of the TSR. The warm mix additives do significantly affect the moisture-conditioned and unconditioned tensile strengths of the asphalt mixtures, but these effects vary by binder grade and anti-strip treatment type.

4.6. Resistance of Asphalt Mixtures to Moisture Damage – Dynamic Modulus Ratio

The resistances of the various mixtures to moisture damage were next evaluated by measuring their dynamic modulus under multiple cycles of F-T conditioning. The impact of residual moisture, anti-strip additives and long-term aging on moisture resistance was evaluated by comparing the |E*| values and |E*| ratios at 70°F (21.2°C) and 10 Hz of the WMA mixtures various cycles of F-T conditioning. The |E*| master curves were developed for the short-term aged samples at 70°F (21.2°C) per AASHTO PP 61 (3) for comparison with the |E*| test data obtained for the long-term aged samples.

4.6.1. Impact of Residual Moisture on Un-treated Mixtures

For each short-term aged, un-treated mixture with and without residual moisture, the |E*| master curve was determined after 0, 1 and 6 F-T cycles. The residual aggregate moisture contents of the short-term aged, un-treated samples can be found in Table 22. Figures 38 - 46 show the |E*| master curves for the short-term aged, un-treated mixtures at 0, 1, and 6 F-T cycles.

Generally, the |E*| master curves show that the modified asphalt mixtures had lower |E*| values than the unmodified mixtures. It is a common characteristic of polymer-modified asphalt mixtures to have lower |E*| values than unmodified asphalt mixtures. This characteristic may contribute to the ability of the polymer-modified asphalt mixtures to experience less permanent deformation at higher traffic load levels.

Figures 47 - 52 show |E*| ratio plots for the short-term aged, un-treated asphalt mixtures after 0, 1 and 6 F-T cycles. |E*| ratio plots were generated for the dynamic modulus values at 70°F (21.1°C) and 10 Hz. From the |E*| ratio plots, the following trends can be observed:

- Moisture conditioning may reduce the |E*| ratio of the WMA mixtures after 1 and 6 F-T cycles and the effect varies by binder type.
- The HMA mixtures had higher |E*| ratios than the WMA mixtures after 6 F-T cycles.
- No clear |E*| ratio trend was apparent for the HMA mixture versus WMA mixtures after 1 F-T cycles.
- The modified asphalt mixtures without residual moisture generally had higher |E*| ratios than the unmodified asphalt mixture without residual moisture after 6 F-T cycles.

The |E*| ratios alone may not enough to determine the effect of the warm mix additives on the resistance of the asphalt mixtures to moisture damage; therefore, further plots were created to compare the dynamic modulus |E*| value to the resulting |E*| ratio at 70°F (21.1°C) and 10 Hz as shown in Figures 53 - 55. When comparing the |E*| values of the HMA versus WMA mixtures, it should be noted that the HMA dynamic modulus samples were subjected to more short-term mixture aging as described in Section 3.5. From the dynamic modulus |E*| versus |E*| ratio plots, the following trends can be observed:

- The WMA mixtures with Advera may have lower |E*| values than the corresponding HMA mixtures after 6 F-T cycles.
- The effect of Advera on |E*| value at 0 F-T varies by binder type.
- The WMA mixtures with Sasobit had equivalent or higher |E*| values than the corresponding HMA mixtures after 6 F-T cycles.
- The WMA mixtures with Sasobit had equivalent or higher |E*| values than the corresponding HMA mixtures at 0 F-T cycles.

4.6.2. Impact of Anti-strip Additives

For each short-term aged, treated mixture with residual moisture, the |E*| master curve was determined after 0 and 6 F-T cycles. Figures 56 - 64 show the |E*| master curves for the short-term aged, treated mixtures after 0 and 6 F-T cycles.

Figures 65 - 70 show |E*| ratio plots for the short-term aged, treated asphalt mixtures after 0 and 6 F-T cycles. From the |E*| ratio plots, the following trends can be observed:

- Lime-treated WMA asphalt mixtures had |E*| ratio equivalent to the HMA mixtures after 6 F-T cycles irrespective of binder or warm mix additive type.
- LAS was effective in increasing the |E*| ratio of the WMA mixtures treated with Sasobit to the |E*| ratio level of the HMA mixtures for all binder types after 6 F-T cycles.

- LAS was not as effective in increasing the |E*| ratio of the WMA mixtures treated with Advera to the |E*| ratio level of the HMA mixtures for the PG 64-22 and PG 64-28 NVTR/TR binders after 6 F-T cycles.
- The modified WMA mixtures treated with anti-strip additives had equivalent or higher |E*| ratios than the unmodified WMA mixtures treated with anti-strip additives.

The |E*| ratios alone may not enough to determine the effect of the warm mix additives n the resistance of the asphalt mixtures to moisture damage; therefore, further plots were created to compare the dynamic modulus |E*| value to the resulting |E*| ratio at 70°F (21.1°C) and 10 Hz as shown in Figures 71 - 76. When comparing the |E*| values of the HMA versus WMA mixtures, it should be noted that the HMA dynamic modulus samples were subjected to more short-term mixture aging as described in Section 3.5. From the dynamic modulus |E*| versus |E*| ratio plots, the following trends can be observed:

- Lime was effective in generating WMA mixtures having |E*| values equivalent to or greater than their corresponding HMA mixtures, except for the PG 64-22 mixture at 0 F-T.
- LAS may not be effective in generating WMA mixtures having |E*| values equivalent to their corresponding HMA mixtures for the PG 64-22 mixtures with Advera and the PG 64-28NVTR/TR mixtures with Advera.
- Lime was effective in increasing the |E*| ratio after 6 F-T cycles of all mixtures, except for the HMA mixture with PG 62-22.

- The effectiveness of the LAS in increasing the |E*| ratio after 6 F-T cycles of mixtures varied by binder type and warm mix additive type.

4.6.3. Impact of Long-term Aging on Moisture Resistance

For each long-term aged mixture with residual moisture, the dynamic modulus was measured on samples at various stages of aging with no F-T conditioning and on the same samples after long-term aging and 6 F-T cycles of conditioning. The results of the dynamic modulus testing on the aged samples can be found in Figures 77 - 79.

Figures 77 - 79 show that the |E*| values of the asphalt mixtures did not significantly increase during the first two weeks of aging at room temperature, but the |E*| values of the asphalt mixtures did significantly increase during the five days at 185°F (85°C). The five days of mixture aging in an oven at 185°F (85°C) corresponds to five to seven years of long-term mixture aging in the field (15).

The rate of |E*| value gain of the WMA mixtures tended to be equal or greater than the rate of |E*| value gain of their corresponding HMA mixtures. However, the WMA mixture |E*| values did not necessarily achieve |E*| values equivalent to the HMA mixtures. After simulated long-term aging, the WMA mixtures treated with Sasobit had equivalent or better dynamic modulus values than their corresponding HMA mixtures at 10 Hz. When comparing the |E*| values of the HMA versus WMA mixtures, it should be noted that the HMA dynamic modulus samples were subjected to a more short-term mixture aging as described in Section 3.5.

To evaluate the effects of long-term aging effects on the resistance of mixtures to moisture damage, the |E*| ratios for the aged asphalt mixtures were determined at 70°F

(21.1°C) and 10 Hz. The |E*| values and the |E*| ratios for the short-term aged asphalt mixtures at 70°F (21.1°C) and 10 Hz were then compared with the |E*| values and the |E*| ratios for the long-term aged asphalt mixtures at 70°F (21.1°C) and 10 Hz as shown in Figures 80 - 83. From the dynamic modulus |E*| versus |E*| ratio plots, the following trends can be observed:

- The |E*| values of the long-term aged WMA mixtures treated with Sasobit are equivalent to or greater than the |E*| values of their corresponding long-term aged HMA mixtures after 0 and 6 F-T cycles.
- The |E*| values of the long-term aged WMA mixtures treated with Advera may have lower |E*| values than their corresponding long-term aged HMA mixtures after 6 F-T cycles.
- The unmodified and modified HMA mixtures had equivalent |E*| ratios after long-term aging.
- The |E*| ratios did not increase with long-term aging for any of the asphalt mixtures.

CHAPTER 5 SUMMARY AND CONCLUSIONS

5.1. Conclusions

The laboratory research effort documented in this thesis studied the impact of WMA additives on the performance of unmodified and modified asphalt mixtures for use in Nevada and California resulted in: a) the identification of materials acceptable for use in the respective transportation agencies, b) the determination of asphalt mixture designs appropriate for use by both transportation agencies, and c) the determination of the impact of moisture damage resistance. Previous research efforts have shown that the addition of warm mix additives reduces the tensile strengths and tensile strength ratio of asphalt mixtures, but these reductions could be mitigated by anti-strip treatment. The tensile strength testing conducted in this research effort as part of the moisture damage investigation verified this conclusion. The impact of moisture damage was further evaluated for modified and unmodified mixtures to determine the impacts of residual moisture, anti-strip treatment, and long-term aging.

For short-term aged, laboratory prepared asphalt mixtures without anti-strip treatment subjected to 0, 1 and 6 F-T cycles, the following conclusions can be made regarding the their resistance to moisture damage:

- PG 64-22 mixtures
    - WMA mixtures experienced larger drop in dynamic modulus than HMA mixtures.

    - The presence of residual moisture reduced the dynamic modulus for Advera WMA mixtures but minimally impacted the dynamic modulus for Sasobit WMA mixtures.
- PG 64-28 NV & PG 64-28 NVTR mixtures
    - Advera WMA mixtures performed similar to HMA mixtures.
    - Sasobit WMA mixtures performed better than HMA mixtures.
    - Impact of residual moisture on dynamic modulus is minimal.

For short-term aged, laboratory prepared asphalt mixtures treated with ASA and subjected to 0 and 6 F-T cycles, the following conclusions can be made regarding the their resistance to moisture damage:

- Untreated mixtures
    - Sasobit WMA mixtures performed similar to HMA mixtures.
    - Advera WMA mixtures performed worse than HMA mixtures.
- Lime-treated mixtures
    - WMA mixtures performed similar to HMA mixtures.
- Liquid-treated mixtures
    - Sasobit WMA mixtures performed similar to HMA mixtures.
    - Advera WMA mixtures performed worse than HMA mixtures.

Overall, lime-treated mixtures performed the best with respect to resistance to moisture damage. The lime-treated WMA mixtures performed similar to lime-treated HMA mixtures. The terminal blend rubber-modified mixtures performed similar to the polymer-modified mixtures in both HMA and WMA mixtures. Lime-treated terminal blend rubber-modified mixtures performed slightly better than lime-treated polymer modified mixtures.

For long-term aged, laboratory prepared asphalt mixtures with no ASA subjected to 0 and 6 F-T cycles, the following conclusions can be made regarding their resistance to moisture damage:

- Advera WMA mixtures performed worst.
- Sasobit WMA mixtures performed similar to HMA mixtures.
- Advera WMA mixtures with terminal blend rubber-modified asphalt performed better than Advera WMA mixtures with polymer-modified asphalt binder.

5.2. Summary of Contributions

The findings of this research effort led to recommendations on the applications of the AMPT apparatus to moisture damage testing and the understanding of the use of warm mix additives in asphalt mixtures with respect to moisture damage.

This research effort proved that dynamic modulus testing by means of the AMPT apparatus can be used to detect differences in moisture damage resistance among various asphalt mixtures. Analysis of the tensile strength ratio test results show that the TSR is not as sensitive to changes in resistance to moisture damage as the dynamic modulus. The 6 F-T cycles were shown to be an adequate F-T level for laboratory moisture damage differentiation with respect to dynamic modulus testing. At 6 F-T cycles, complex modulus testing detected more potential moisture resistance issues than the tensile strength ratio testing.

With respect to the research objective of this study, it was found that warm mix additives impact the moisture damage resistance of unmodified and modified asphalt mixtures. The unmodified asphalt mixtures are more sensitive to moisture damage than the modified asphalt mixtures regardless of the presence of the warm mix additives. Furthermore, residual moisture was found to be more detrimental to the moisture damage resistance of unmodified asphalt mixtures than the modified asphalt mixtures. However, anti-strip mitigation by means of lime treatment is shown to be effective by increasing the resistance to moisture damage of WMA mixtures to levels of the HMA mixtures. Additionally, long-term aging was not shown to increase the moisture damage resistance of HMA or WMA mixtures.

5.3. Future Research

The overall objective of this research effort is to evaluate the impact of warm mix additives on the pavement performance properties of modified asphalt mixtures. Phase I of this research effort concentrated on identifying materials, conducting mix designs, and evaluating the impacts of the warm mix additives on the moisture damage resistance of modified asphalt mixtures. This portion of Phase I evaluated impact of Advera and Sasobit on the moisture damage resistance of modified asphalt mixtures; however, ongoing research efforts are evaluating the impact of Evotherm and lab-foaming on the moisture damage resistance of modified asphalt mixtures. Phase II of this research effort will focus on the laboratory evaluation of the impacts of warm mix additives on the mechanical performance properties of modified asphalt mixtures.

Further mechanical property analysis is required as part of this research effort to evaluate the impacts of warm mix additives on the ability of a WMA pavement to resist permanent deformation, fatigue cracking, and thermal cracking in the field. Phase III of this research effort will use the results of mechanical property testing to conduct a mechanistic analysis to evaluate impacts of warm mix additives on the design life of pavements constructed with modified asphalt mixtures. Ultimately, the goal is to conduct a cost-benefit assessment of WMA pavements with respect to traditional HMA pavements constructed with modified asphalt mixtures.

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TABLES

Table 1 Experimental Program to Evaluate the Impact of Residual Moisture in Aggregates

Asphalt Binder Type	**Mixture Type**	**WMA Additives/ Techniques**	**Residual Moisture**	**Dynamic Modulus, $\lvert E^* \rvert$, Master Curve**		
				$\lvert E^* \rvert_{dry}$ After 0 F-T*	**$\lvert E^* \rvert_{Moist}$ after 1 F-T**	**$\lvert E^* \rvert_{Moist}$ 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”

Table 2 Experimental Program to Evaluate the Impact of Anti-strip Additives

Asphalt Binder Type	**Mixture Type**	**WMA Additives/ Techniques**	**Residual Moisture**	**$\lvert E^*\rvert_{dry}$ Master Curve after 0 F-T***	**$\lvert E^*\rvert_{Moist}$ 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

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 Strength Gain Experiment Aging Periods (Hurley & Prowell, 2005)

Set	Short Term Aging (hours) at 110°C (prior to compaction)	Long Term Aging (days) of Compacted Samples at 85°C
1	2	0
2	4	0
3	2	1
4	2	3
5	2	2

Table 5 Summary of the Mixtures to be Evaluated in the Experimental Program

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 6 Lockwood Aggregate Blend Gradation

Sieve		Blend Gradation	NDOT Type 2C	CT 3/4" Max, Type A
US	(mm)			
1"	25.0	100	100	100
3/4"	19.0	94	88-95	90-100
1/2"	12.5	85	70-85	70-90
3/8"	9.5	74	60-78	-
No. 4	4.75	47	43-60	45-55
No. 8	2.36	32	-	32-40
No. 10	2.00	30	30-44	-
No. 16	1.28	24	-	
No. 30	0.600	17	-	12-21
No. 40	0.425	14	12-22	-
No. 50	0.300	10	-	-
No. 100	0.150	6.2	-	-
No. 200	0.075	4.3	3-8	2-7

Table 7 Lockwood Stockpile Blend

Aggregate Stockpile	1" Crushed Rock	1/2" Crushed Rock	3/8" Crushed Rock	Crushed Fines	Wade Sand
Percentage (%)	16	16	30	28	10

Table 8 Lockwood Stockpile Gradations

Sieve		1" Crushed Rock	1/2" Crushed Rock	3/8" Crushed Rock	Crushed Fines	Wade Sand
US	(mm)					
1"	25.0	100.0	100	100	100	100
3/4"	19.0	60.4	100	100	100	100
1/2"	12.5	6.8	99.3	100	100	100
3/8"	9.5	0.6	39.9	99.5	100	100
No. 4	4.75	0.3	0.6	32.0	97.3	99.7
No. 8	2.36	0.3	0.4	1.3	77.2	98.1
No. 10	2.00	0.3	0.4	0.8	69.5	97.4
No. 16	1.28	0.3	0.4	0.6	50.5	94.2
No. 30	0.600	0.3	0.3	0.5	34.1	75.3
No. 40	0.425	0.3	0.3	0.5	28.3	53.5
No. 50	0.300	0.3	0.3	0.5	24.3	32.8
No. 100	0.150	0.3	0.3	0.5	18.6	7.9
No. 200	0.075	0.3	0.3	0.4	14.0	1.9

Table 9 Lockwood Aggregate Properties

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	46	--	--	45% Min	AASHTO T304 (A)
Sand Equivalent	73	--	--	47 Min	CTM 217
Plasticity Index	4 CF; NP Sand	10 Max (Ind. Bins)	Nev. T212	--	--
Liquid Limit	23 CR; 23 Sand	35 Max (Ind. Bins)	Nev. T210	--	--
Flat and Elongated Particles (by wt @ 5:1)	0.9	--	--	10% Min	ASTM D4791
Absorption of Coarse Aggregate	2.1	4% Max	AASHTO T85	--	--
Aggregate Source Tests					
Los Angeles Rattler (100 Rev.)	Not Available	--	--	12% Max	CTM 211
Los Angeles Rattler (500 Rev.)	13.5	37% Max	AASHTO T96	45% Max	CTM 211
Soundness (Coarse Agg.) (5 Cycles, Sodium Sulfate)	2	12% Max Loss	AASHTO T104	--	--
Soundness (Fine Agg.) (5 Cycles, Sodium Sulfate)	4 CF; 3 Sand	15% Max Loss	AASHTO T104	--	--
Absorption of Coarse Aggregate	2.1	4% Max	AASHTO T85	--	--
Specific Gravity of Fine Aggregate	2.51	2.85 Max	AASHTO T84	--	--
Specific Gravity of Coarse Aggregate	2.60	2.85 Max	AASHTO T84	--	--

Table 10 CT PG 64-16 Specifications and Test Results for PG 64-22

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	0.4	--	--	3.0 Max	AASHTO T316
Dynamic shear, G*/sinδ at 64^{0}C (10 rad/s), kPa	1.43	--	--	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*/sinδ at 64^{0}C (10 rad/s), kPa	4.91	--	--	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*sinδ at 28^{0}C (10 rad/s), kPa	1830	--	--	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"

Table 11 NDOT PG 64-28 NV and CT PG 64-28 PM Specifications and Test Results for PG 64-28 NV/PM

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	0.8	3.0 Max	AASHTO T316	3.0 Max	AASHTO T316
Dynamic shear, G*/sinδ at 64^{0}C (10 rad/s), kPa	1.86	1.0 Min	AASHTO T315	1.00 Min	AASHTO T315
Ductility at 4^{0}C (5 cm/min), cm	65	50 min.	Nev. T746	--	--
Sieve particulates retained	NT	0	Nev. T730	--	--
Toughness at 25^{0}C, in-lbs	130	110 Min	Nev. T745	--	--
Tenacity at 25^{0}C, in-lbs	114	75 Min	Nev. T745	--	--
Tests on Residue from RTFO, Nev. T728 (NDOT) / AASHTO T240 (CT)					
Mass loss, %	0.34	1.0% Max	Nev. T728	1.00% Max	AASHTO T240
Dynamic shear, G*/sinδ at 64^{0}C (10 rad/s), kPa	4.16	2.20 Min	AASHTO T315	2.20 Min	AASHTO T315
Dynamic shear, δ at 64^{0}C (10 rad/s), kPa	61	--	--	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	83	--	--	75% Min	AASHTO T301
Tests on Residue from Pressure Aging Vessel, AASHTO R28 @ 100^{0}C					
Dynamic shear, G*sinδ at 22^{0}C (10 rad/s), kPa	1586	5000 Max	AASHTO T315	5000 Max	AASHTO T315
Creep Stiffness at -18^{0}C S-value, MPa m-value	 159 0.307	 300 Max 0.300 Min	AASHTO T313	 300 Max 0.300 Min	AASHTO T313

* NT denotes "Not Tested"

Table 12 NDOT PG 64-28 NV and CT PG 64-28 PM Specifications and Test Results for PG 64-28 NVTR/TR

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	97.5% Min	AASHTO T44	97.5% Min	AASHTO T44
Rotational viscosity at 135^{0}C, Pa·s	1.1	3.0 Max	AASHTO T316	3.0 Max	AASHTO T316
Dynamic shear, $G^*/\sin\delta$ at 64^{0}C (10 rad/s), kPa	1.68	1.0 Min	AASHTO T315	1.00 Min	AASHTO T315
Ductility at 4^{0}C (5 cm/min), cm	55	40 min.	Nev. T746	--	--
Sieve particulates retained	NT	0	Nev. T730	--	--
Toughness at 25^{0}C, in-lbs	**97**	110 Min	Nev. T745	--	--
Tenacity at 25^{0}C, in-lbs	83	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, $G^*/\sin\delta$ at 64^{0}C (10 rad/s), kPa	2.93	2.20 Min	AASHTO T315	2.20 Min	AASHTO T315
Dynamic shear, δ at 64^{0}C (10 rad/s), kPa	66	--	--	80% Max	AASHTO T315
Ductility at 4^{0}C (5 cm/min), cm	NT	20 Min	Nev. T746	--	--
Elastic Recovery at 25^{0}C, cm	80	--	--	75% Min	AASHTO T301
Tests on Residue from Pressure Aging Vessel, AASHTO R28 @ 100^{0}C					
Dynamic shear, $G^*\sin\delta$ at 22^{0}C (10 rad/s), kPa	1607	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"

Table 13 Summary of Mixture Optimum Binder Contents

Mix Type	**Treatment**	**Asphalt Binder Type**		
		PG 64-22	**PG 64-28 NV/PM**	**PG64-28 NVTR/TR**
HMA	Un-treated	5.7	5.8	5.7
	Lime-Treated	5.6	5.6	5.6
	Liquid-Treated	5.7	5.8	5.7
WMA-Advera (0.3% by TWM)	Un-treated	5.7	5.8	5.7
	Lime-Treated	5.6	5.6	5.6
	Liquid-Treated	5.7	5.8	5.7
WMA-Sasobit (1.5% by WB)*	Un-treated	5.7	5.8	5.7
	Lime-Treated	5.6	5.6	5.6
	Liquid-Treated	5.7	5.8	5.7

* 3.0% Sasobit by WB used for the PG 64-28 NV binder

Table 14 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. $AI = \dfrac{(G^*/\sin\delta)_{RTFOT}}{(G^*/\sin\delta)_{Tank}}$ at the high temperature performance grade temperature.

Table 15 Gyratory Compaction Effort

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 16 Degree of Aggregate Coating and Compactability Requirements

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 17 Degree of Aggregate Coating of Lockwood Asphalt Mixture at Various Mixing Temperatures

Binder Type	Additive Type	Mixing Temp, ^{0}F	% Aggregate Coated
PG 64-22	None	308	100.0%
	Advera	258	100.0%
		250	**99.8%**
	Sasobit	258	100.0%
		250	100.0%
PG 64-28 NV/PM	None	320	100.0%
	Advera	270	100.0%
		250	**99.1%**
	Sasobit	270	100.0%
		250	100.0%
PG 64-28 NVTR/TR	None	320	100.0%
	Advera	270	100.0%
		250	100.0%
	Sasobit	270	100.0%
		250	100.0%

Table 18 Compactability of HMA and WMA Mixtures with PG 64-22, PG 64-28 NV/PM, and PG 64-28 NVTR/TR binder

Binder Type	**Additive Type**	**Mixing Temp, °F**	**Compaction Temp, °F**	**N92**	**1.25*N92 @ Compact. Temp**	**N92 < 0.35N_{design} = 0.35*125 = 44**	**N92 @ Compaction Temp. minus 55°F (30°C) < 1.25N92**
PG 64-22	None	308	288	29	36	--	--
		255	230	43	--	--	--
	0.3% Advera by total wt of mix	255	230	36	44	Pass	--
		255	175	37	--	--	Pass
	1.5% Sasobit by wt of binder	260	235	37	46	Pass	--
		260	180	37	--	--	Pass
PG 64-28 NV/PM	None	320	280	36	44	--	--
		290	265	37	--	--	--
	0.3% Advera by total wt of mix	290	265	36	44	Pass	--
		290	210	42	--	--	Pass
	3.0% Sasobit by wt of binder	285	260	37	46	Pass	--
		285	205	44	--	--	Pass
PG 64-28 NVTR/TR	None	320	280	40	49	--	--
		275	250	36	--	--	--
	0.3% Advera by total wt of mix	275	250	41	51	Pass	--
		275	195	41	--	--	Pass
	1.5% Sasobit by wt of binder	280	255	42	53	Pass	--
		280	200	41	--	--	Pass

Table 19 ANOVA Table for Unconditioned Tensile Strengths

Source	DF	SS	MS	F	P-Value
BinderType	2	3363.873	1681.936	41.63	<.0001
WMATrt	2	513.518	256.759	6.36	0.0023
ASATrt	2	281.755	140.878	3.49	0.0334
BinderType*WMATrt	4	362.884	90.721	2.25	0.0675
BinderType*ASATrt	4	194.502	48.625	1.20	0.3123
WMATrt*ASATrt	4	173.355	43.339	1.07	0.3726
BinderType*WMATrt*ASATrt	8	357.784	44.723	1.11	0.3625
Model	26	5247.671	201.833	5.00	<.0001
Error	133	5372.875	40.398		
Total	159	10620.545	66.796		

Table 20 ANOVA Table for Moisture-conditioned Tensile Strengths

Source	DF	SS	MS	F	P-Value
BinderType	2	673.030	336.515	21.94	<.0001
WMATrt	2	1551.888	775.944	50.60	<.0001
ASATrt	2	2292.533	1146.266	74.74	<.0001
BinderType*WMATrt	4	544.805	136.201	8.88	<.0001
BinderType*ASATrt	4	1132.774	283.194	18.47	<.0001
WMATrt*ASATrt	4	263.185	65.796	4.29	0.0027
BinderType*WMATrt*ASATrt	8	169.194	21.149	1.38	0.2112
Model	26	6627.410	254.900	16.62	<.0001
Error	134	2055.035	15.336		
Total	160	8682.445	54.265		

Table 21 Summary of t-Test Analysis of Tensile Strength Data

Binder	Anti-Strip Treatment	Treatment	Unconditioned Tensile Strength		Moisture-conditioned Tensile Strength	
			Pr > |t|	Significance*	Pr > |t|	Significance*
PG 64-22	None	HMA vs Advera	0.785	NS	0.001	SH
		HMA vs Sasobit	0.773	NS	0.009	SH
		Advera vs Sasobit	0.576	NS	0.057	NS
	0.5% LAS	HMA vs Advera	0.801	NS	<.001	SH
		HMA vs Sasobit	0.270	NS	0.004	SH
		Advera vs Sasobit	0.181	NS	0.087	NS
	1.0% Lime	HMA vs Advera	0.425	NS	0.009	SH
		HMA vs Sasobit	0.330	NS	0.595	NS
		Advera vs Sasobit	0.088	NS	0.003	SL
PG 64-28 NV	None	HMA vs Advera	0.012	SL	0.674	NS
		HMA vs Sasobit	0.049	SL	0.281	NS
		Advera vs Sasobit	0.557	NS	0.143	NS
	0.5% LAS	HMA vs Advera	0.883	NS	0.102	NS
		HMA vs Sasobit	0.124	NS	0.551	NS
		Advera vs Sasobit	0.181	NS	0.035	SL
	1.0% Lime	HMA vs Advera	0.549	NS	0.004	SH
		HMA vs Sasobit	0.046	SL	<.001	SL
		Advera vs Sasobit	0.139	NS	<.001	SL
PG 64-28 NVTR	None	HMA vs Advera	0.361	NS	0.018	SH
		HMA vs Sasobit	0.093	NS	0.618	NS
		Advera vs Sasobit	0.015	SL	0.006	SL
	0.5% LAS	HMA vs Advera	0.924	NS	0.089	NS
		HMA vs Sasobit	0.145	NS	0.668	NS
		Advera vs Sasobit	0.170	NS	0.039	SL
	1.0% Lime	HMA vs Advera	0.169	NS	0.123	NS
		HMA vs Sasobit	0.174	NS	0.002	SL
		Advera vs Sasobit	0.012	SL	<.001	SL

* NS - Not Significant SL - Significantly Lower SH-Significantly Higher

Table 22 Measured Residual Moisture Content of Dynamic Modulus Samples

Mix Type	Treatment	PG64-22	PG64-28NV	PG64-28TR
HMA	Un-treated	0.00%	0.00%	0.00%
WMA-Advera (0.3% by TWM)	Un-treated	0.77%	0.13%	0.25%
WMA-Sasobit (1.5% by WB)*	Un-treated	0.68%	0.20%	0.15%

FIGURES

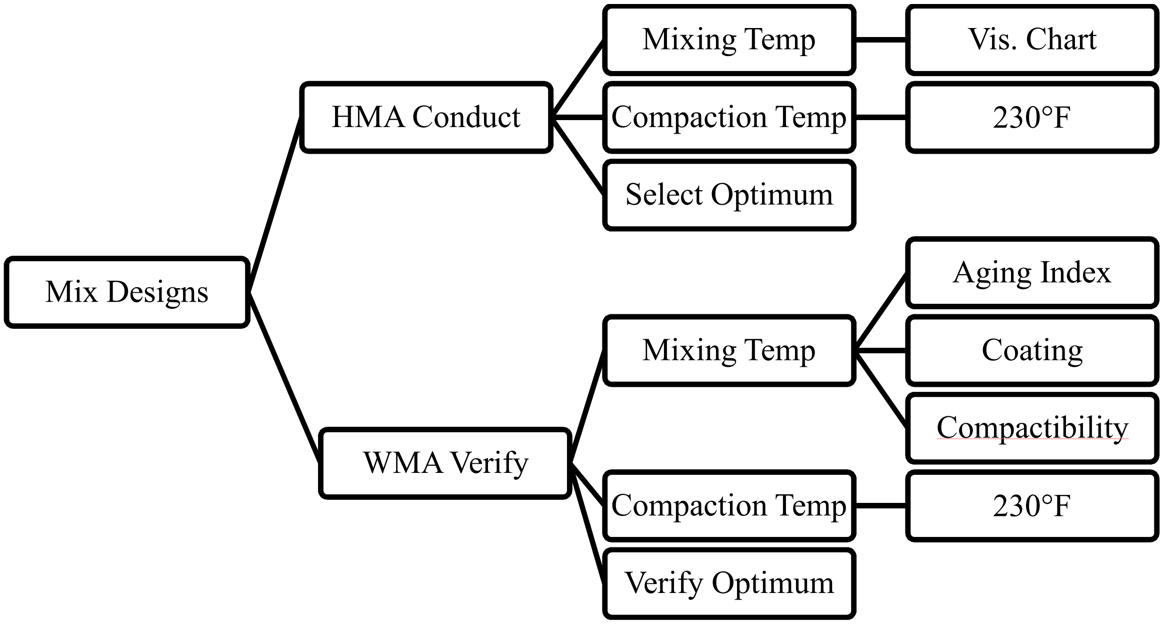


Figure 1 Mix Design Protocol

Stage 0 – No Dynamic Modulus Testing

- Samples Prepared, Cooled to Room Temperature and Cut
- 0 Days Conditioning

Stage 1 – Initial Dynamic Modulus Testing

- Samples Dried for 2 Days
- 0 Days Conditioning

Stage 2 – Dynamic Modulus Testing

- Condition Samples at Room Temperature for 2 Weeks
- 14 Days Conditioning

Stage 3 – Dynamic Modulus Testing

- Condition Samples at 185^{0}F (85^{0}C) for 2 Days and Cool Overnight
- 16 Days Conditioning

Stage 4 – Dynamic Modulus Testing

- Condition Samples at 185^{0}F (85^{0}C) for 3 Days and Cool Overnight
- 19 Days Conditioning

Stage 5 – Final Dynamic Modulus Testing

- Conduct 6 FT Cycles
- 31 Days Conditioning

Figure 2 Mixture Age Conditioning Protocol

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
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}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.0	4-7 / 4.0
VMA, % (NDOT / CT)	15.6 / 13.2	12-22 / 13 Min.
VFA, % (NDOT / CT)	75.0 / 69.6	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.1	8 Min.
Hveem Stability, lbs	39	37 Min.
Max. specific gravity at OBC, G_{mm}	2.440	--
Unconditioned Tensile Strength, psi	80	65 Min.
Tensile Strength Ratio, %	78	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

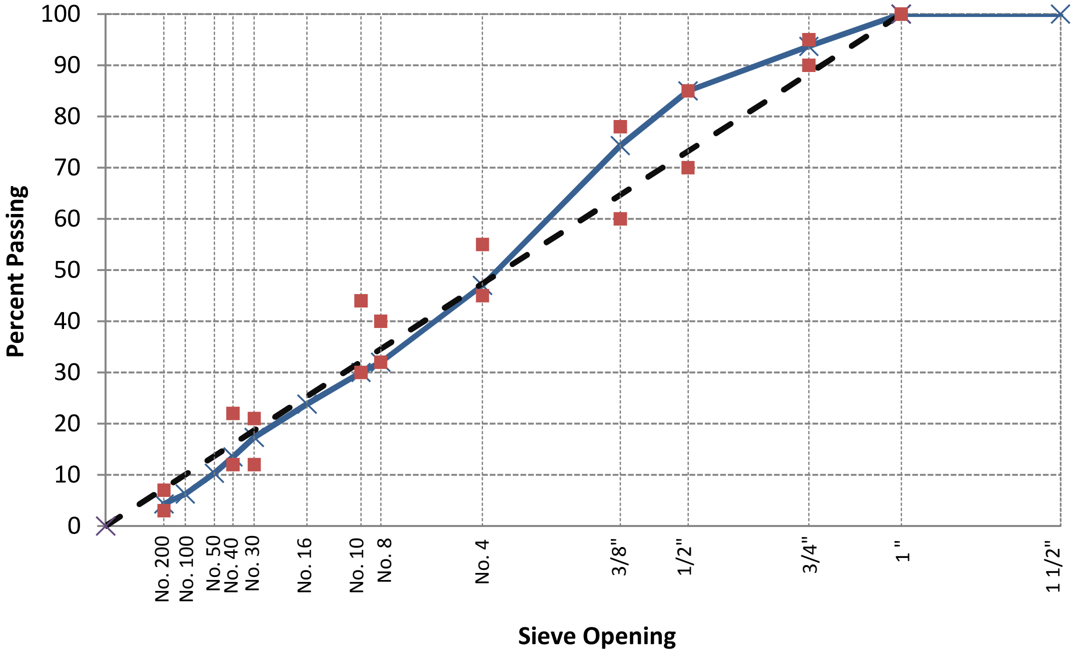


Figure 3 Lockwood un-treated mix design and aggregate properties w/Paramount PG 64-22

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	255	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.4	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.9 / 13.5	12-22 / 13 Min.
VFA, % (NDOT / CT)	73.8 / 67.3	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.0	8 Min.
Hveem Stability, lbs	36	37 Min.
Max. specific gravity at OBC, G_{mm}	2.442	--
Unconditioned Tensile Strength, psi	78	65 Min.
Tensile Strength Ratio, %	59	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

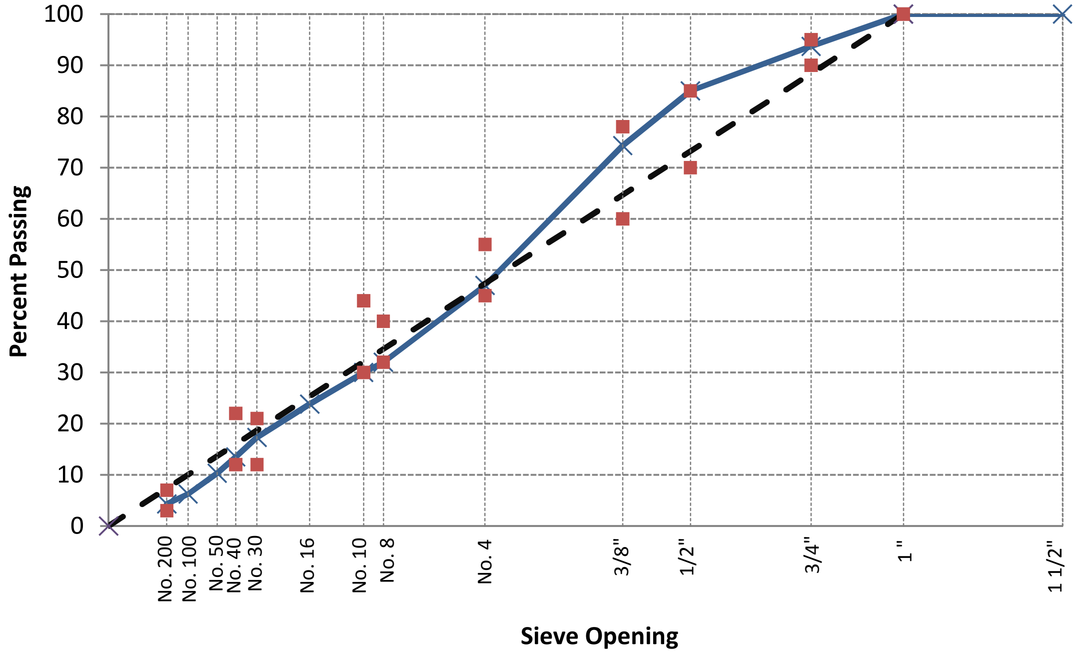


Figure 4 Lockwood un-treated mix design verification and aggregate properties w/Paramount PG 64-22 & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	260	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	**4.9**	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.6 / 14.2	12-22 / 13 Min.
VFA, % (NDOT / CT)	71.7 / 65.9	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.4	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.433	--
Unconditioned Tensile Strength, psi	81	65 Min.
Tensile Strength Ratio, %	**65**	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

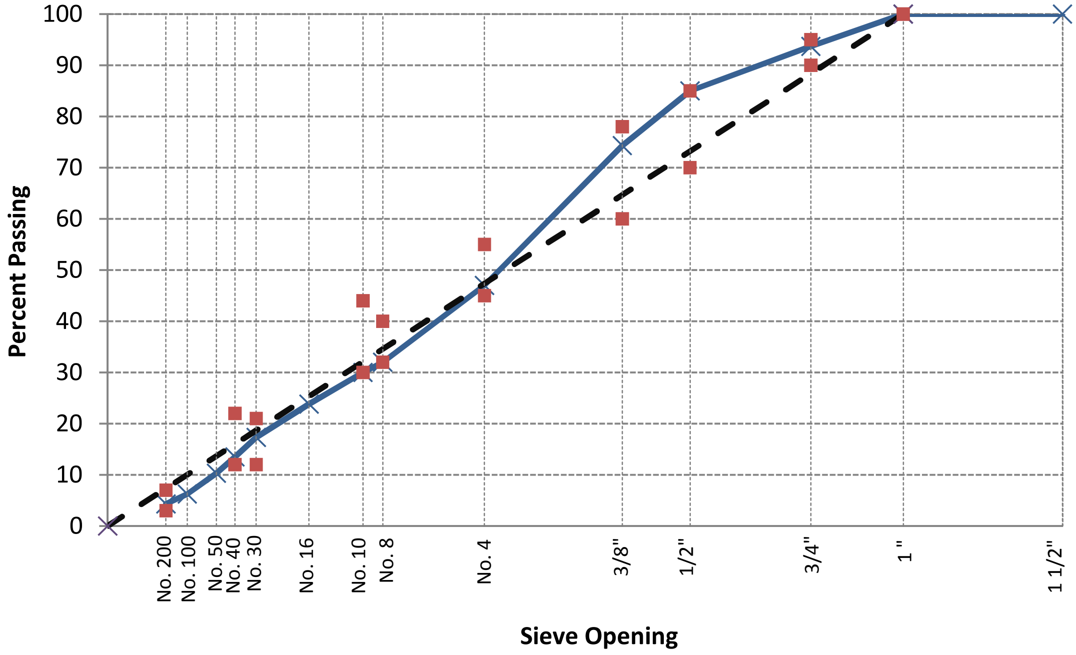


Figure 5 Lockwood un-treated mix design verification and aggregate properties w/Paramount PG 64-22 & 1.5% Sasobit by wt of binder

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	4.0	4-7 / 4.0
VMA, % (NDOT / CT)	15.9 / 13.5	12-22 / 13 Min.
VFA, % (NDOT / CT)	75.4 / 70.6	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.4	8 Min.
Hveem Stability, lbs	42	37 Min.
Max. specific gravity at OBC, G_{mm}	2.433	--
Unconditioned Tensile Strength, psi	70	65 Min.
Tensile Strength Ratio, %	87	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

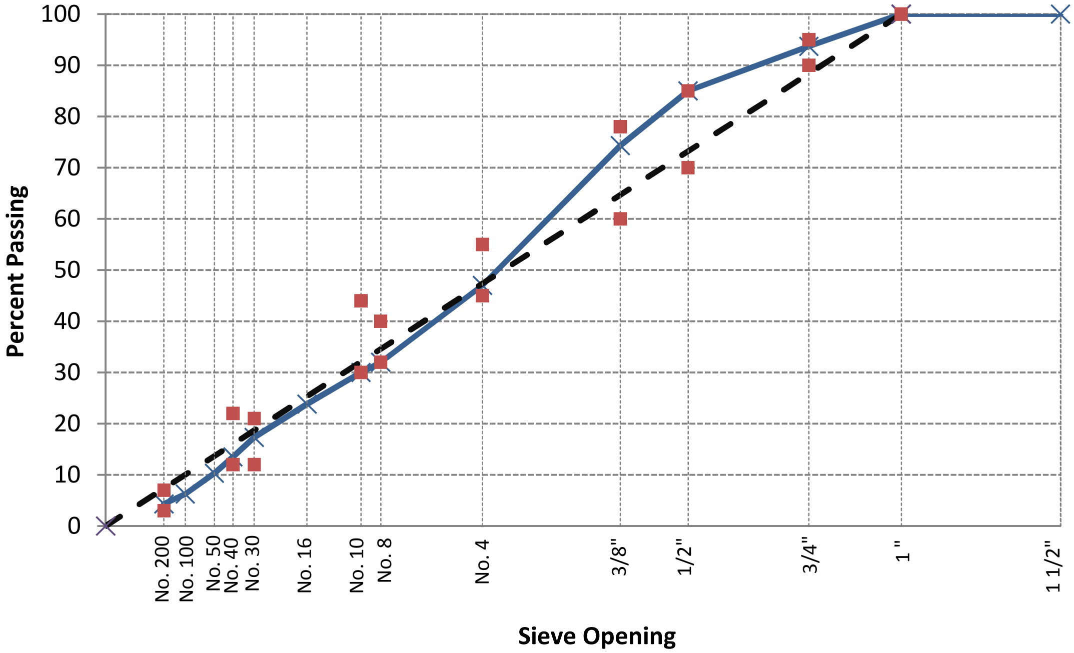


Figure 6 Lockwood un-treated mix design and aggregate properties w/Paramount PG 64-28 NV/PM

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	290	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	4.6	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.2 / 13.8	12-22 / 13 Min.
VFA, % (NDOT / CT)	73.0 / 66.6	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, μm	9.1	8 Min.
Hveem Stability, lbs	41	37 Min.
Max. specific gravity at OBC, G_{mm}	2.441	--
Unconditioned Tensile Strength, psi	79	65 Min.
Tensile Strength Ratio, %	75	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

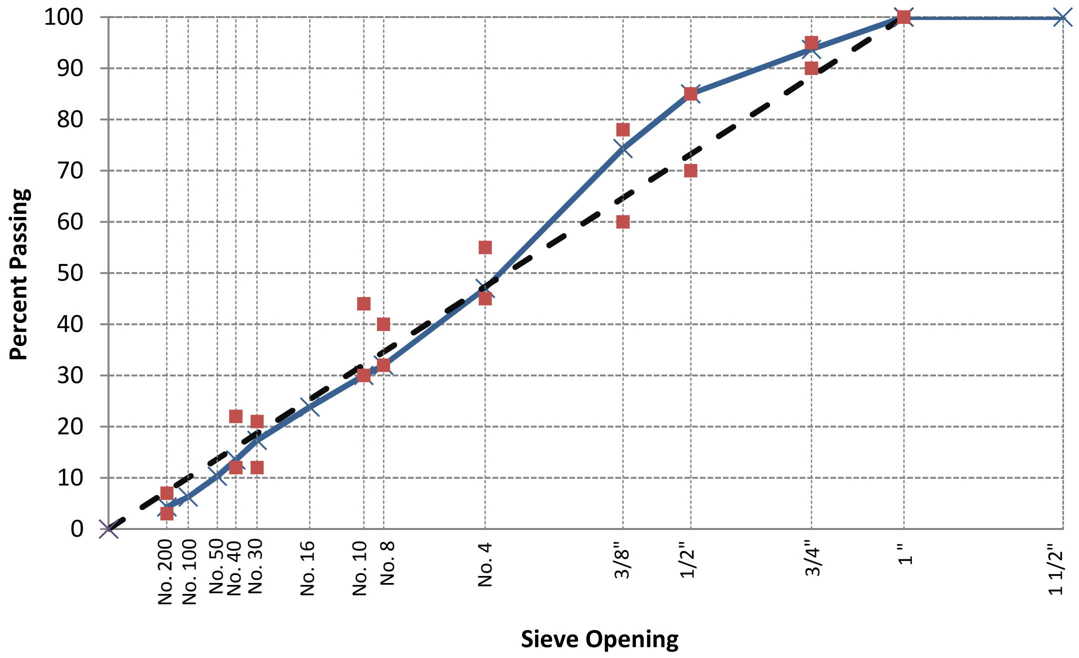


Figure 7 Lockwood un-treated mix design verification and aggregate properties w/Paramount PG 64-28 NV/PM & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	285	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	**4.8**	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.4 / 14.0	12-22 / 13 Min.
VFA, % (NDOT / CT)	72.2 / 66.0	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.2	8 Min.
Hveem Stability, lbs	41	37 Min.
Max. specific gravity at OBC, G_{mm}	2.439	--
Unconditioned Tensile Strength, psi	77	65 Min.
Tensile Strength Ratio, %	81	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

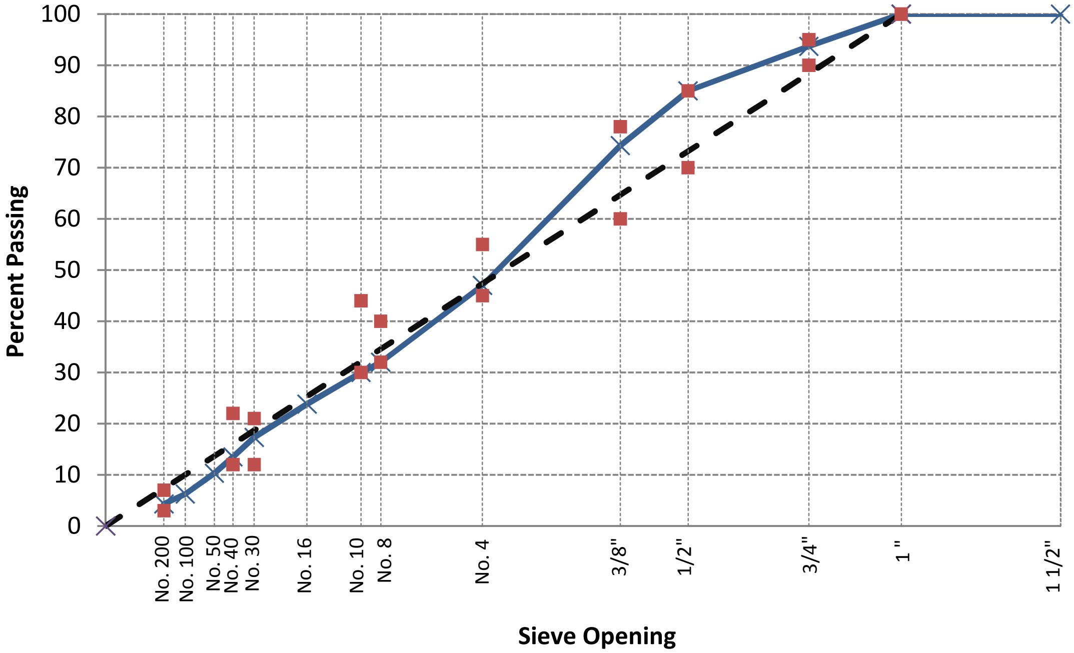


Figure 8 Lockwood un-treated mix design verification and aggregate properties w/Paramount PG 64-28 NV/PM & 3.0% Sasobit by wt of binder

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.0	4-7 / 4.0
VMA, % (NDOT / CT)	16.1 / 13.7	12-22 / 13 Min.
VFA, % (NDOT / CT)	75.1 / 70.6	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.7	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.425	--
Unconditioned Tensile Strength, psi	70	65 Min.
Tensile Strength Ratio, %	83	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

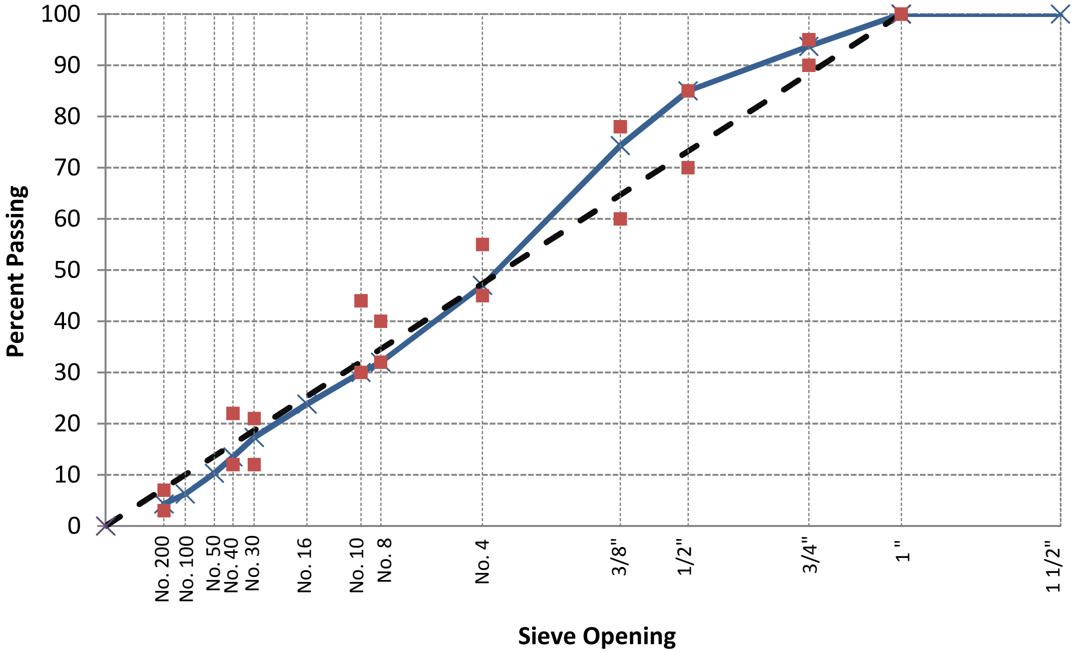


Figure 9 Lockwood un-treated mix design and aggregate properties w/Paramount PG 64-28 NVTR/TR

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.2	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.8 / 13.4	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.4 / 68.5	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.1	8 Min.
Hveem Stability, lbs	36	37 Min.
Max. specific gravity at OBC, G_{mm}	2.439	--
Unconditioned Tensile Strength, psi	67	65 Min.
Tensile Strength Ratio, %	75	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

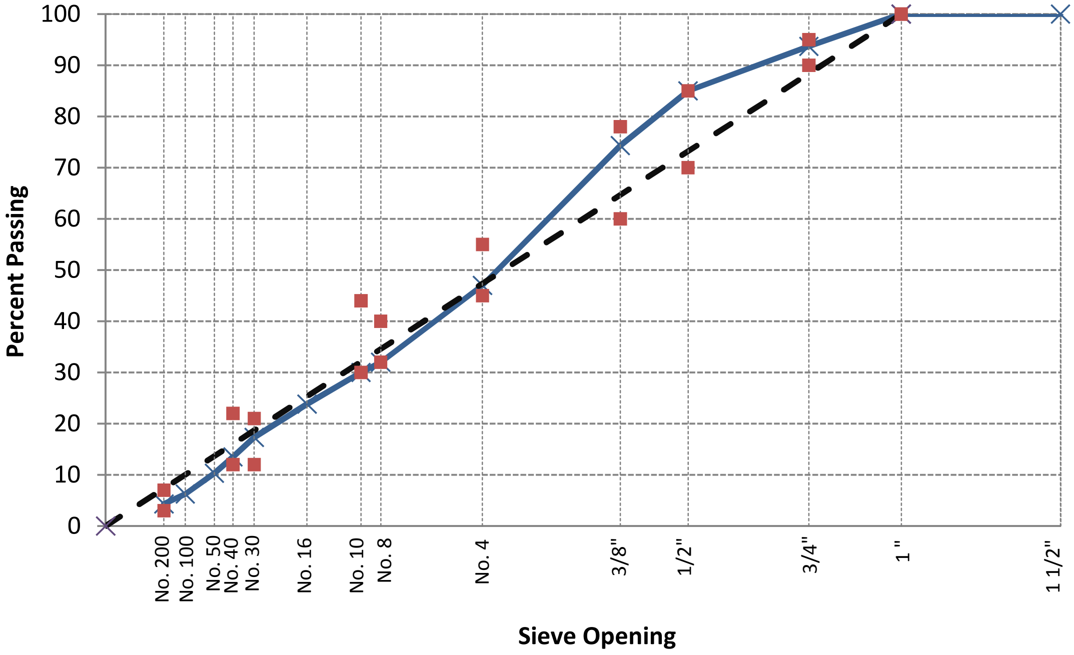


Figure 10 Lockwood un-treated mix design verification and aggregate properties w/Paramount PG 64-28 NVTR/TR & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**None**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	280	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	**5.8**	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	17.2 / 14.9	12-22 / 13 Min.
VFA, % (NDOT / CT)	**67.6 / 61.1**	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.1	8 Min.
Hveem Stability, lbs	**36**	37 Min.
Max. specific gravity at OBC, G_{mm}	2.439	--
Unconditioned Tensile Strength, psi	76	65 Min.
Tensile Strength Ratio, %	79	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

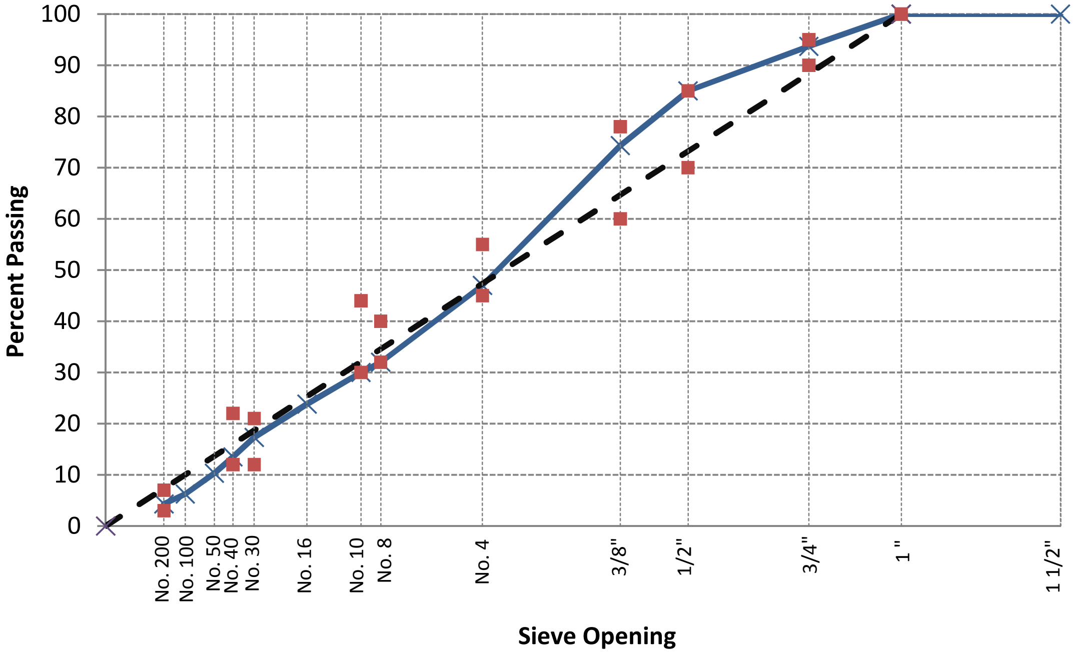


Figure 11 Lockwood un-treated mix design verification and aggregate properties w/Paramount PG 64-28 NVTR/TR & 1.5% Sasobit by wt of binder

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	308	303-313
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	3.9	4-7 / 4.0
VMA, % (NDOT / CT)	15.5 / 13.1	12-22 / 13 Min.
VFA, % (NDOT / CT)	75.5 / 70.4	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.3	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.437	--
Unconditioned Tensile Strength, psi	81	65 Min.
Tensile Strength Ratio, %	90	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

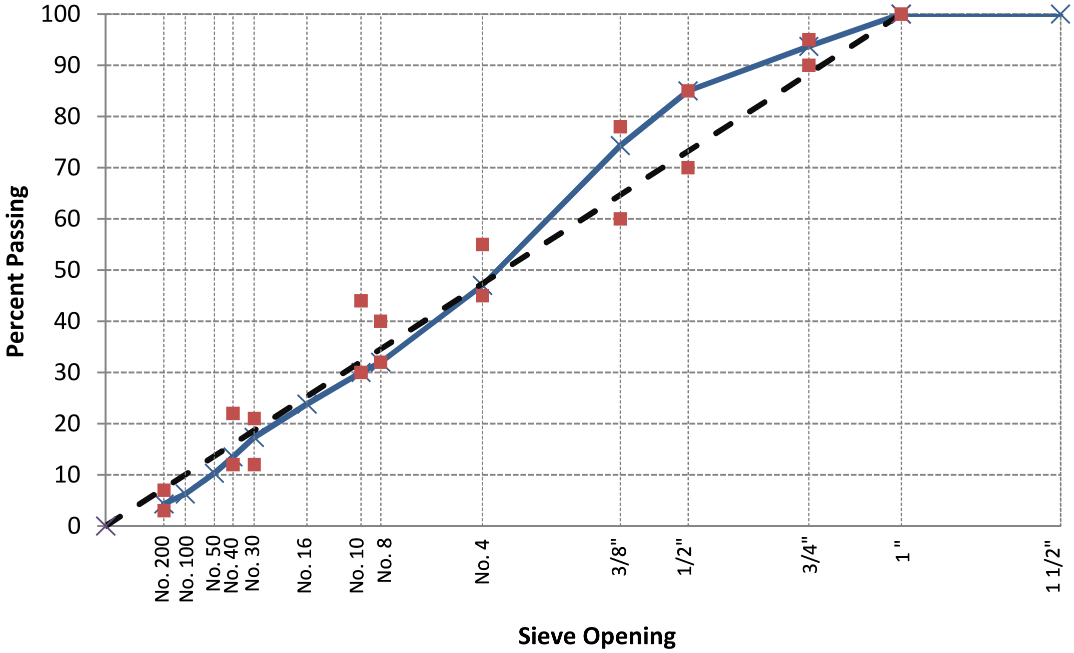


Figure 12 Lockwood lime-treated mix design and aggregate properties w/Paramount PG 64-22

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	255	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	4.0	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.6 / 13.2	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.9 / 69.8	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.3	8 Min.
Hveem Stability, lbs	40	37 Min.
Max. specific gravity at OBC, G_{mm}	2.436	--
Unconditioned Tensile Strength, psi	78	65 Min.
Tensile Strength Ratio, %	85	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

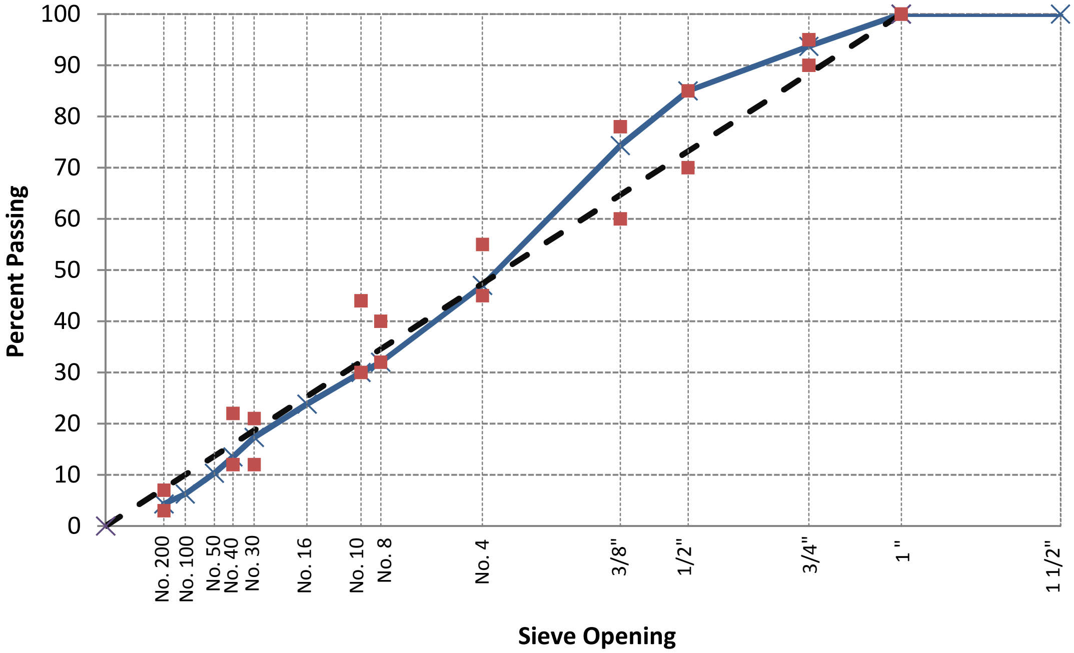


Figure 13 Lockwood lime-treated mix design verification and aggregate properties w/Paramount PG 64-22 & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	260	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	4.3	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	14.4 / 13.5	12-22 / 13 Min.
VFA, % (NDOT / CT)	73.4 / 68.1	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.3	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.429	--
Unconditioned Tensile Strength, psi	86	65 Min.
Tensile Strength Ratio, %	86	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

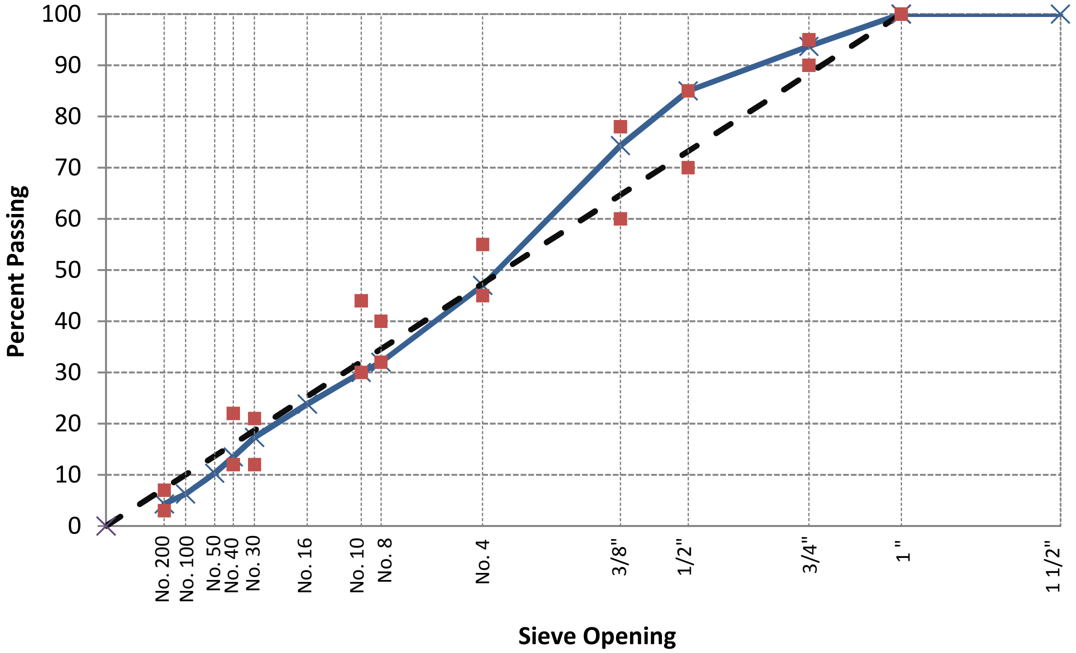


Figure 14 Lockwood lime-treated mix design verification and aggregate properties w/Paramount PG 64-22 & & 1.5% Sasobit by wt of binder

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	3.9	4-7 / 4.0
VMA, % (NDOT / CT)	15.4 / 13.0	12-22 / 13 Min.
VFA, % (NDOT / CT)	75.4 / 70.1	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.2	8 Min.
Hveem Stability, lbs	40	37 Min.
Max. specific gravity at OBC, G_{mm}	2.440	--
Unconditioned Tensile Strength, psi	71	65 Min.
Tensile Strength Ratio, %	91	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

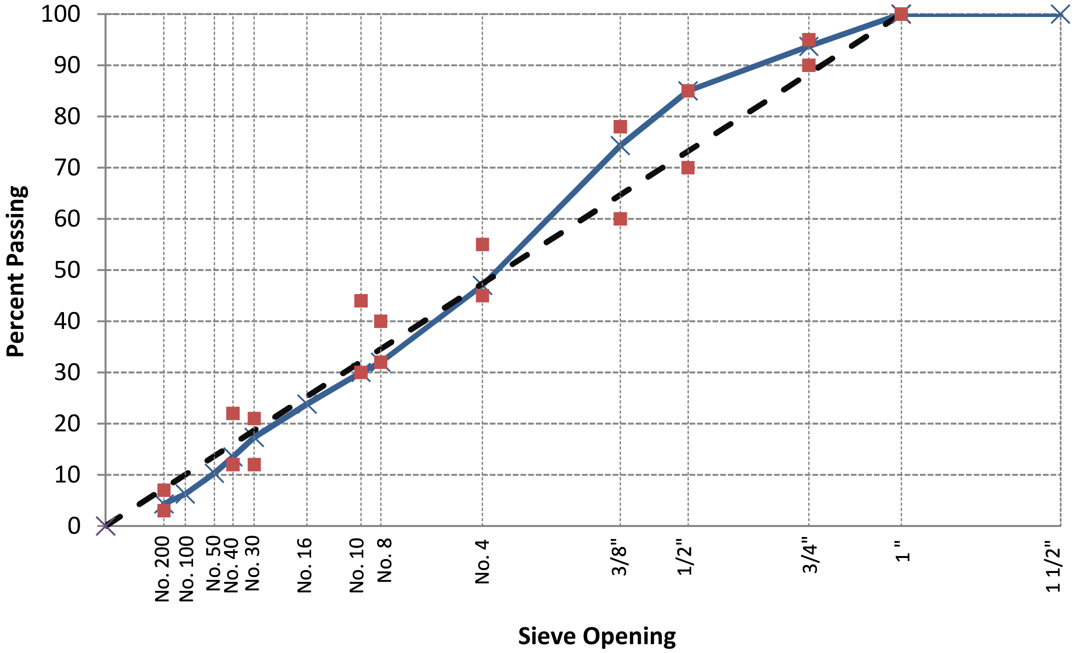


Figure 15 Lockwood lime-treated mix design and aggregate properties w/Paramount PG 64-28 NV/PM

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	290	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	4.0	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.6 / 13.2	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.9 / 70.0	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.3	8 Min.
Hveem Stability, lbs	39	37 Min.
Max. specific gravity at OBC, G_{mm}	2.436	--
Unconditioned Tensile Strength, psi	78	65 Min.
Tensile Strength Ratio, %	85	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

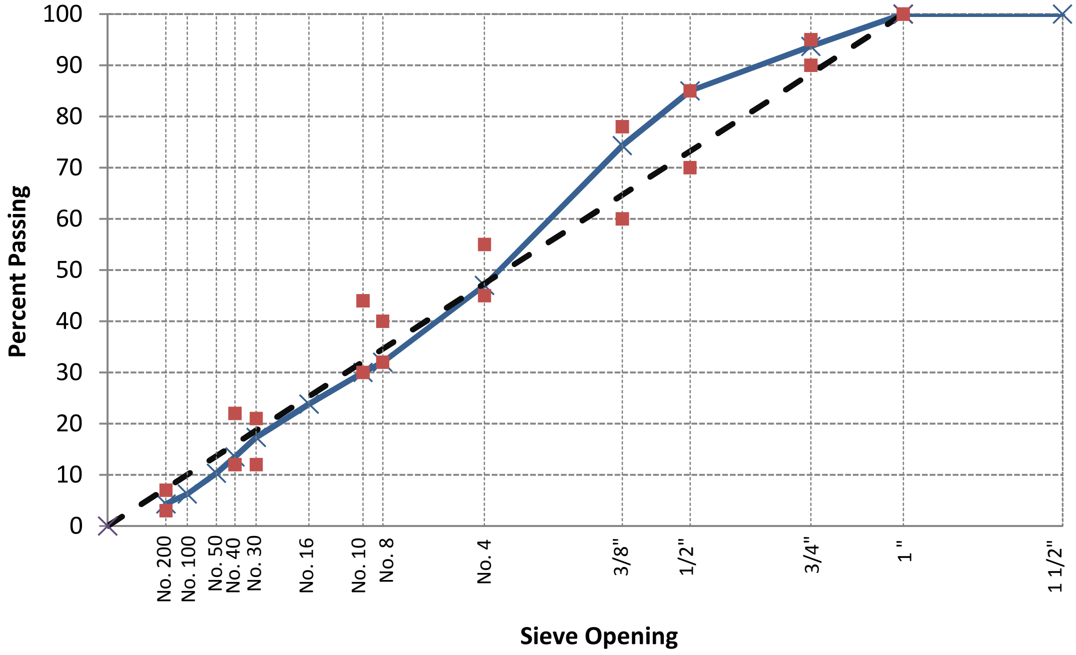


Figure 16 Lockwood lime-treated mix design verification and aggregate properties w/Paramount PG 64-28 NV/PM & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	285	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	**4.7**	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.3 / 14.0	12-22 / 13 Min.
VFA, % (NDOT / CT)	71.6 / 66.5	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.4	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.433	--
Unconditioned Tensile Strength, psi	76	65 Min.
Tensile Strength Ratio, %	92	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

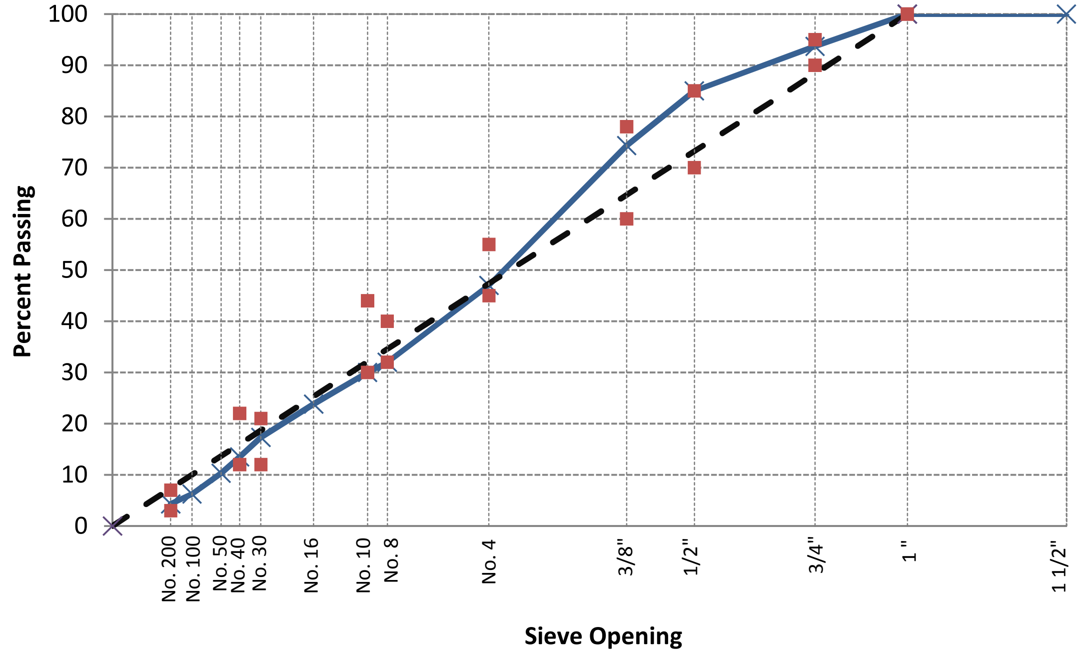


Figure 17 Lockwood lime-treated mix design verification and aggregate properties w/Paramount PG 64-28 NV/PM & 3.0% Sasobit by wt of binder

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	3.4	4-7 / 4.0
VMA, % (NDOT / CT)	15.4 / 13.0	12-22 / 13 Min.
VFA, % (NDOT / CT)	78.0 / 73.7	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.6	8 Min.
Hveem Stability, lbs	43	37 Min.
Max. specific gravity at OBC, G_{mm}	2.429	--
Unconditioned Tensile Strength, psi	71	65 Min.
Tensile Strength Ratio, %	91	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

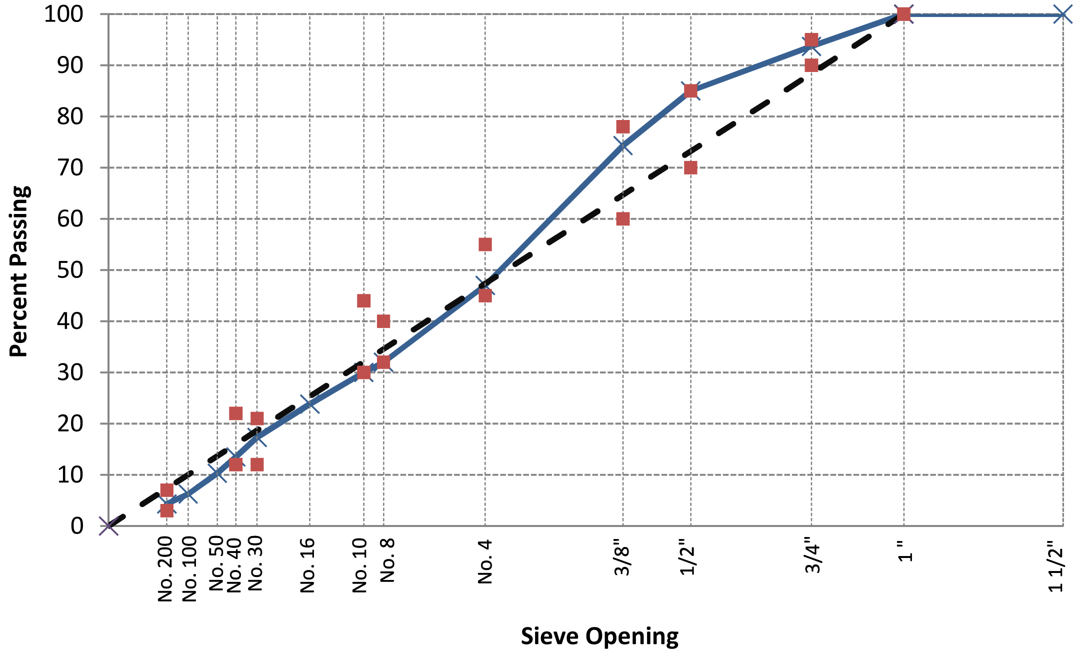


Figure 18 Lockwood lime-treated mix design and aggregate properties w/Paramount PG 64-28 NVTR/TR

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	3.6	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.2 / 12.8	12-22 / 13 Min.
VFA, % (NDOT / CT)	77.0 / 72.2	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.3	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.438	--
Unconditioned Tensile Strength, psi	78	65 Min.
Tensile Strength Ratio, %	85	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

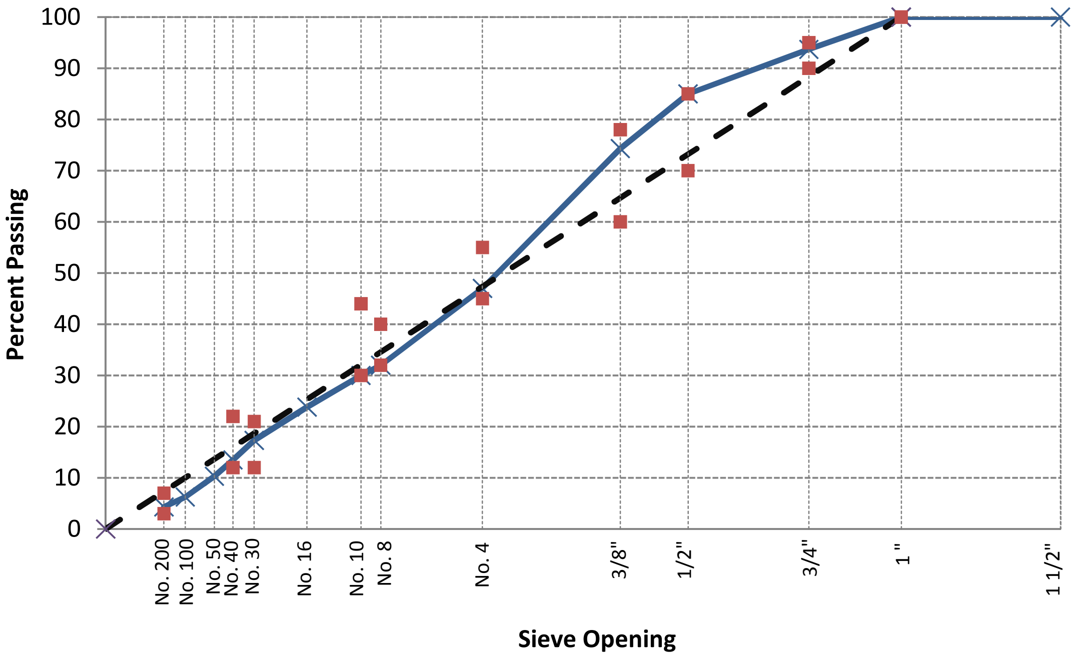


Figure 19 Lockwood lime-treated mix design verification and aggregate properties w/Paramount PG 64-28 NVTR/TR & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**1.0% Hydrated Lime**	
Property	**Value**	**Requirement**
Hydrated Lime, %	1.0	1.5
Mixing Temperature, °F	280	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.60	--
Air Voids, % TMW (NDOT / CT)	4.2	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.7 / 13.4	12-22 / 13 Min.
VFA, % (NDOT / CT)	73.9 / 68.8	70-80 / 65-75
Dust Proportion	1.2	0.6-1.3
Film Thickness, µm	8.3	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.437	--
Unconditioned Tensile Strength, psi	76	65 Min.
Tensile Strength Ratio, %	92	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.1	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	24.3		
0.6 mm (No. 30)	18.0	12	21
0.425 mm (No. 40)	14.3	12	22
0.3 mm (No. 50)	11.1		
0.15 mm (No. 100)	7.04		
0.075 mm (No. 200)	5.17	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	Hyd. Lime
Bin Proportions	16%	16%	30%	27%	10%	1%

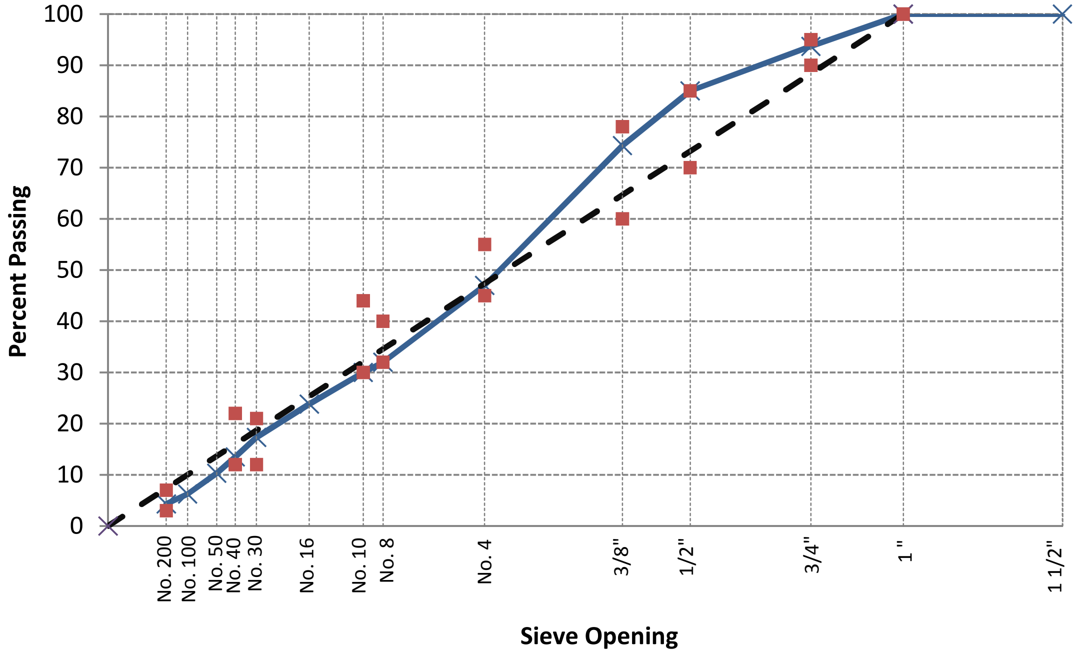


Figure 20 Lockwood lime-treated mix design verification and aggregate properties w/Paramount PG 64-28 NVTR/TR & 1.5% Sasobit by wt of binder

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
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}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.3	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.8 / 13.5	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.2 / 68.1	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.1	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.440	--
Unconditioned Tensile Strength, psi	87	65 Min.
Tensile Strength Ratio, %	86	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

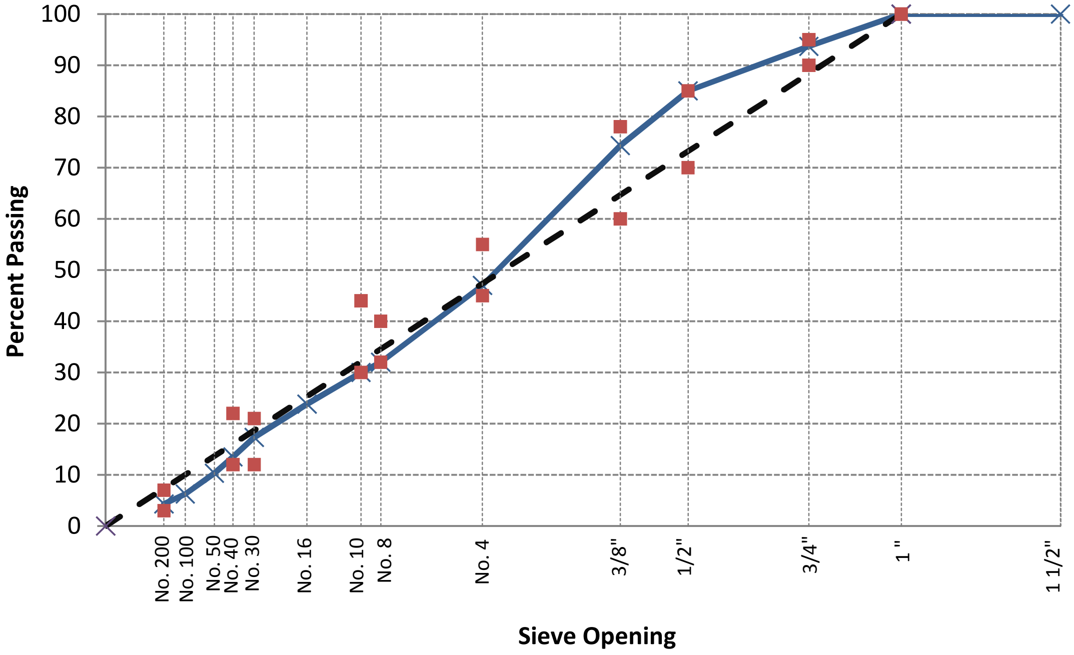


Figure 21 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-22

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	255	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.65	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.4	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.8 / 13.5	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.0 / 67.6	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, μm	9.0	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.442	--
Unconditioned Tensile Strength, psi	88	65 Min.
Tensile Strength Ratio, %	72	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

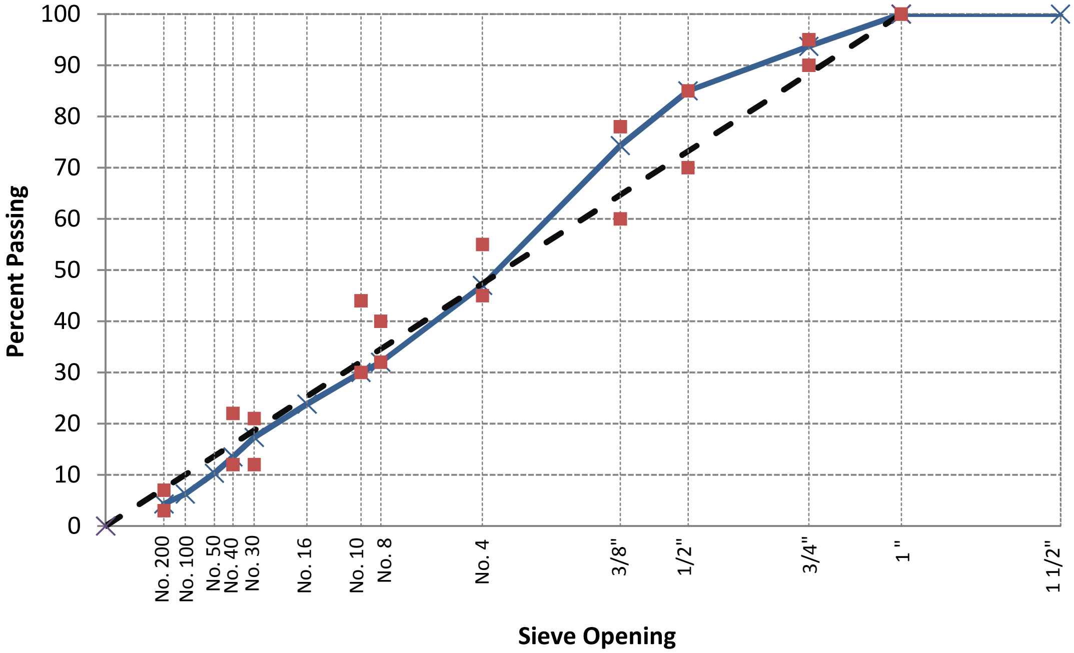


Figure 22 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-22 & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	260	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.4	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.2 / 13.8	12-22 / 13 Min.
VFA, % (NDOT / CT)	73.6 / 68.0	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.4	8 Min.
Hveem Stability, lbs	37	37 Min.
Max. specific gravity at OBC, G_{mm}	2.433	--
Unconditioned Tensile Strength, psi	82	65 Min.
Tensile Strength Ratio, %	81	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

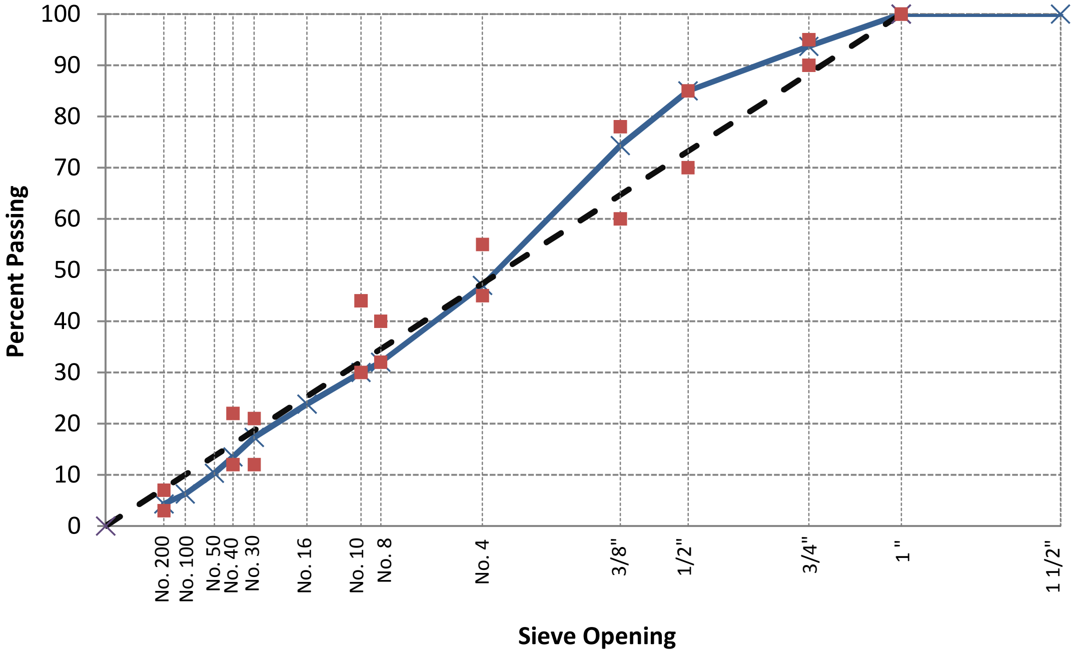


Figure 23 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-22 & 1.5% Sasobit by wt of binder

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	4.2	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.1 / 13.7	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.7 / 69.3	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.4	8 Min.
Hveem Stability, lbs	42	37 Min.
Max. specific gravity at OBC, G_{mm}	2.433	--
Unconditioned Tensile Strength, psi	73	65 Min.
Tensile Strength Ratio, %	89	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

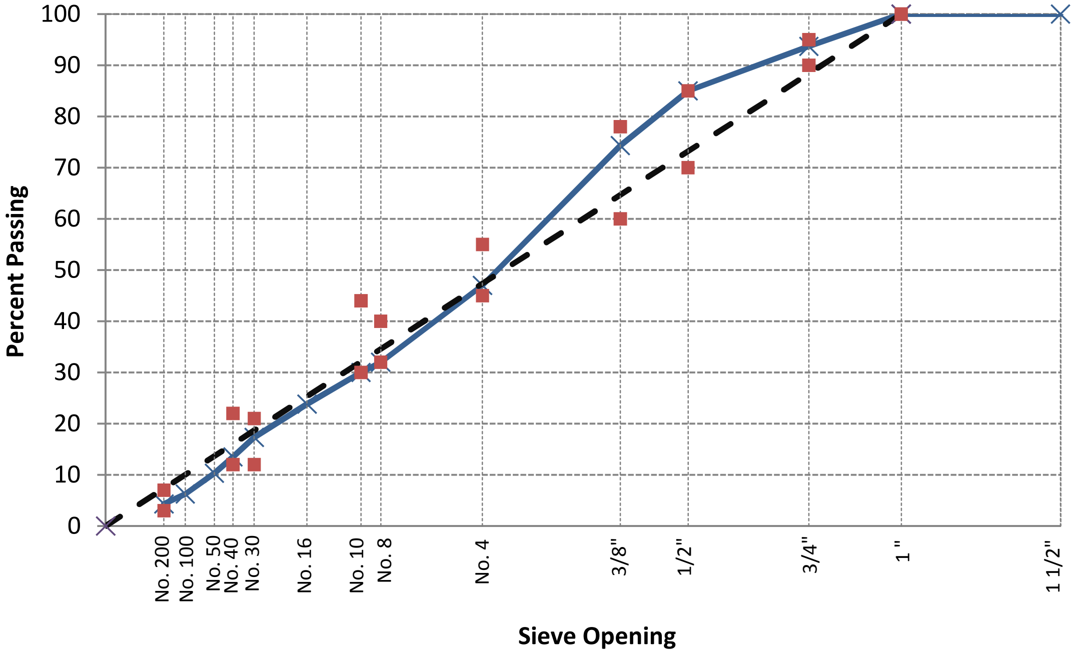


Figure 24 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-28 NV/PM

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	290	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	4.6	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.2 / 13.8	12-22 / 13 Min.
VFA, % (NDOT / CT)	72.9 / 66.5	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.1	8 Min.
Hveem Stability, lbs	39	37 Min.
Max. specific gravity at OBC, G_{mm}	2.441	--
Unconditioned Tensile Strength, psi	74	65 Min.
Tensile Strength Ratio, %	83	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

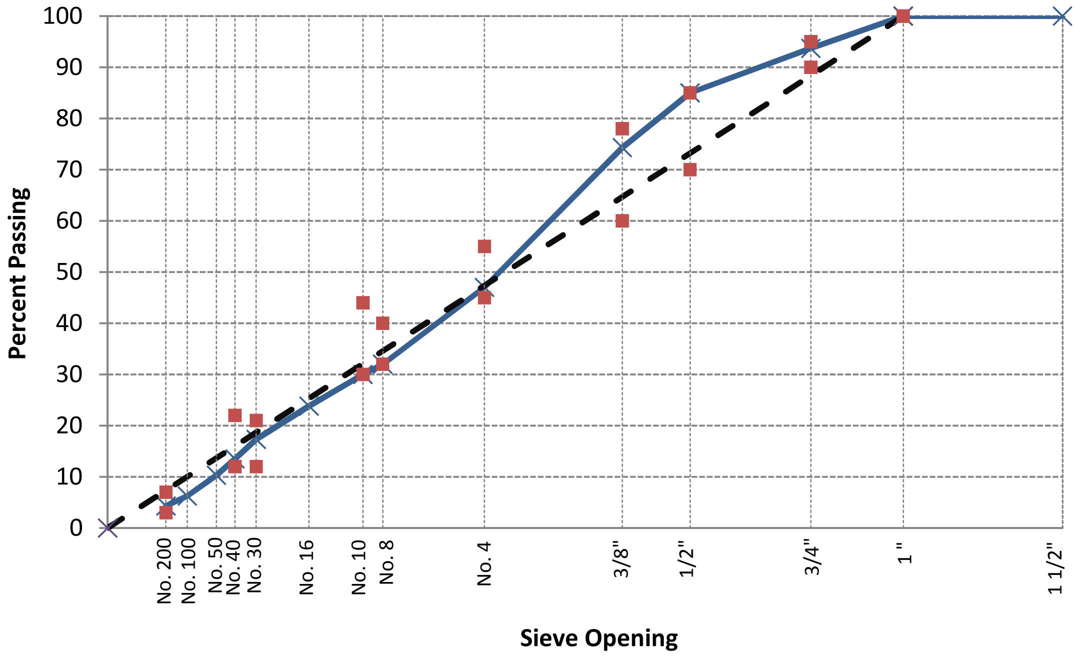


Figure 25 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-28 NV/PM & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	285	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.80	--
Air Voids, % TMW (NDOT / CT)	4.3	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	15.9 / 13.6	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.5 / 68.5	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.2	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.439	--
Unconditioned Tensile Strength, psi	79	65 Min.
Tensile Strength Ratio, %	84	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

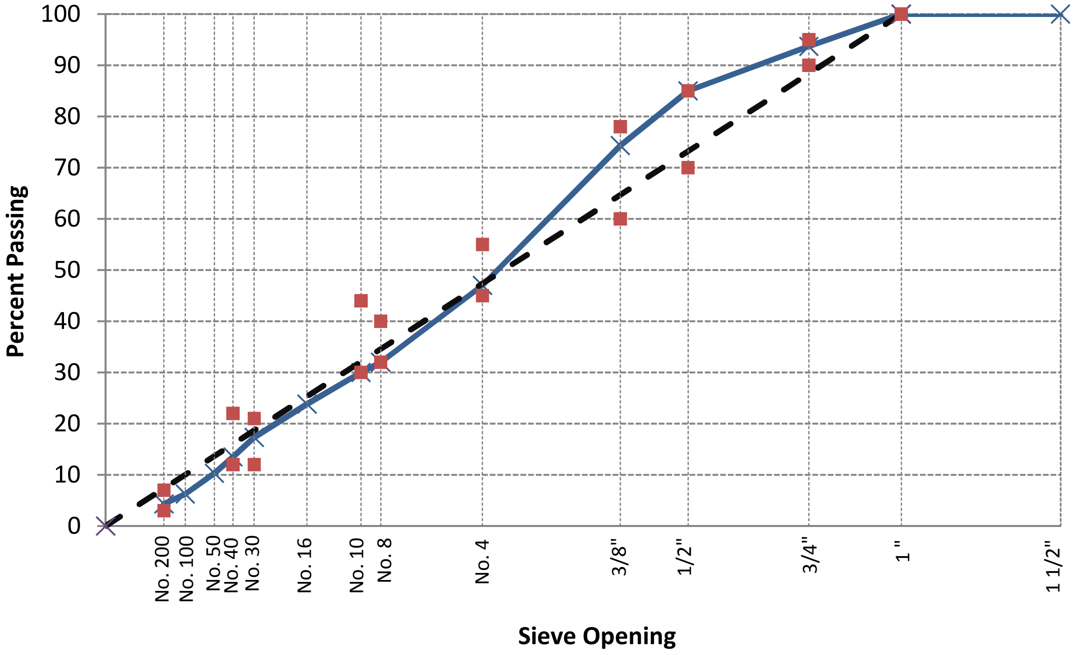


Figure 26 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-28 NV/PM & 3.0% Sasobit by wt of binder

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	320	320
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.2	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.3 / 13.9	12-22 / 13 Min.
VFA, % (NDOT / CT)	74.3 / 69.6	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.7	8 Min.
Hveem Stability, lbs	39	37 Min.
Max. specific gravity at OBC, G_{mm}	2.425	--
Unconditioned Tensile Strength, psi	71	65 Min.
Tensile Strength Ratio, %	86	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

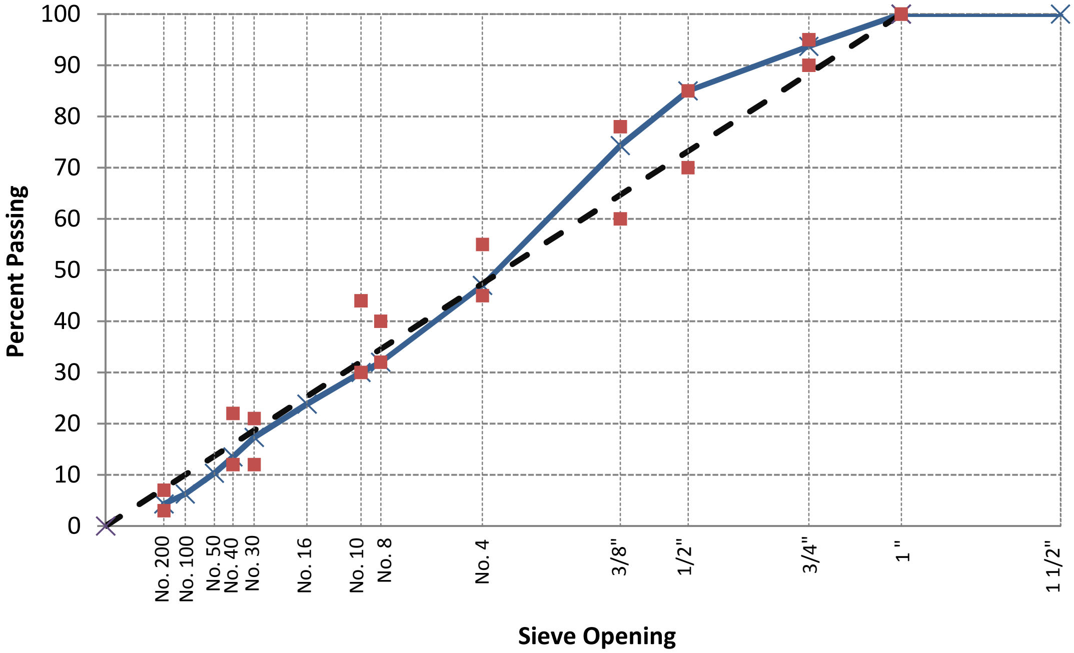


Figure 27 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-28 NVTR/TR

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	275	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	**4.8**	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.3 / 14.0	12-22 / 13 Min.
VFA, % (NDOT / CT)	71.6 / 65.4	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.1	8 Min.
Hveem Stability, lbs	38	37 Min.
Max. specific gravity at OBC, G_{mm}	2.439	--
Unconditioned Tensile Strength, psi	71	65 Min.
Tensile Strength Ratio, %	81	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

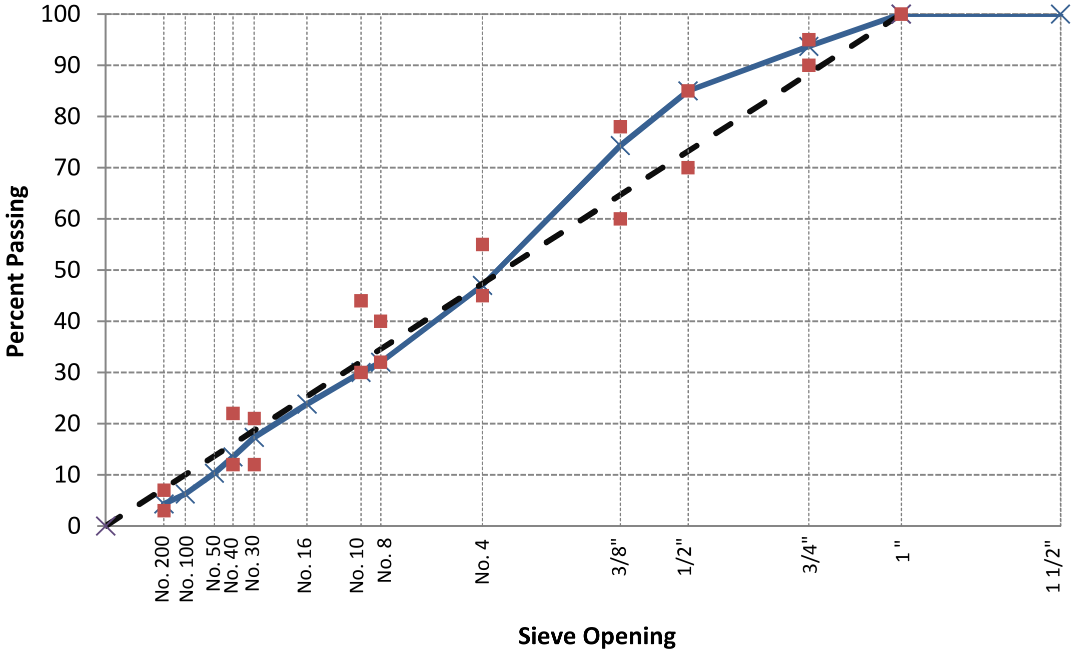


Figure 28 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-28 NVTR/TR & 0.3% Advera by total wt of mixture

Mix Design (NDOT T2C & CT Type A)		
Anti-Strip Treatment	**0.5% Morlife 5000 LAS**	
Property	**Value**	**Requirement**
Hydrated Lime, %	None	1.5
Mixing Temperature, °F	280	--
Compaction Temperature, °F	230	230
Coarse Aggregate Bulk Gravity, G_{sb}	2.60	--
Fine Aggr. Apparent Gravity, G_{sa}	2.66	--
Aggregate Effective Gravity, G_{se}	2.63	--
Optimum Binder (OBC), % DWA	5.70	--
Air Voids, % TMW (NDOT / CT)	4.6	4-7 / 3.5-4.5
VMA, % (NDOT / CT)	16.2 / 13.8	12-22 / 13 Min.
VFA, % (NDOT / CT)	72.6 / 66.6	70-80 / 65-75
Dust Proportion	1.0	0.6-1.3
Film Thickness, µm	9.1	8 Min.
Hveem Stability, lbs	40	37 Min.
Max. specific gravity at OBC, G_{mm}	2.439	--
Unconditioned Tensile Strength, psi	76	65 Min.
Tensile Strength Ratio, %	81	70 Min.

Aggregate Gradation			
Nominal Maximum Aggregate Size, mm			**19.0**
Sieve Size	**% Passing**	**Control Pts**	
		Min	**Max**
37.5 mm (1 1/2")	100.0		
25.0 mm (1")	100.0	100	100
19.0 mm (3/4")	93.7	90	95
12.5 mm (1/2")	85.0	70	85
9.5 mm (3/8")	74.3	60	78
4.75 mm (No. 4)	47.0	45	55
2.36 mm (No. 8)	32.0	32	40
2.00 mm (No. 10)	30.0	30	44
1.18 mm (No. 16)	23.8		
0.6 mm (No. 30)	17.3	12	21
0.425 mm (No. 40)	13.5	12	22
0.3 mm (No. 50)	10.3		
0.15 mm (No. 100)	6.23		
0.075 mm (No. 200)	4.32	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	16%	16%	30%	28%	10%	

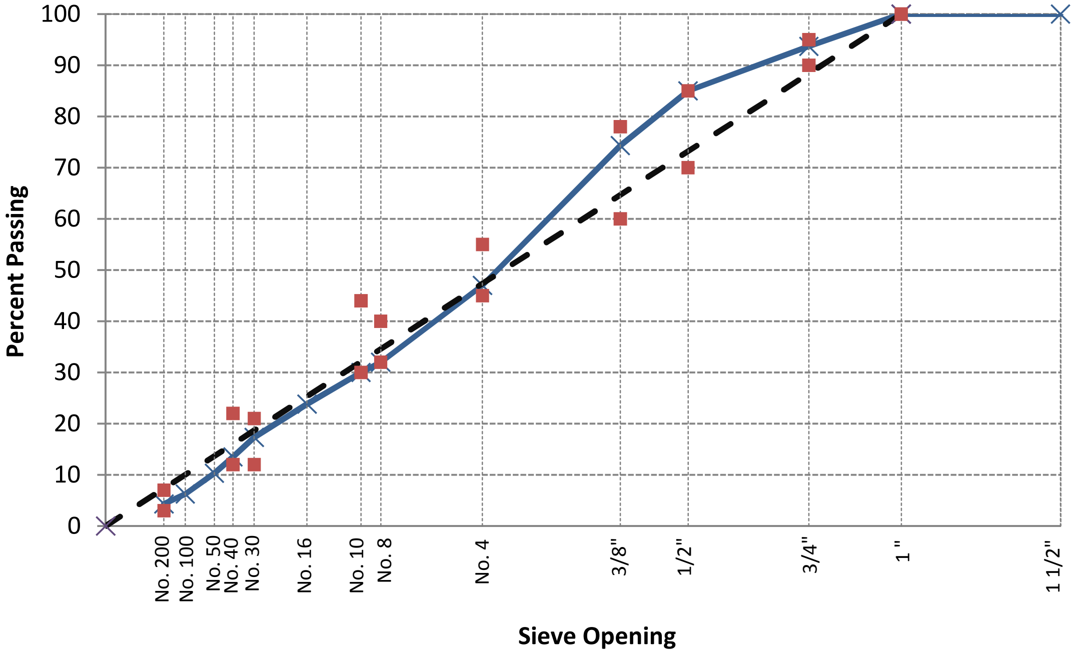
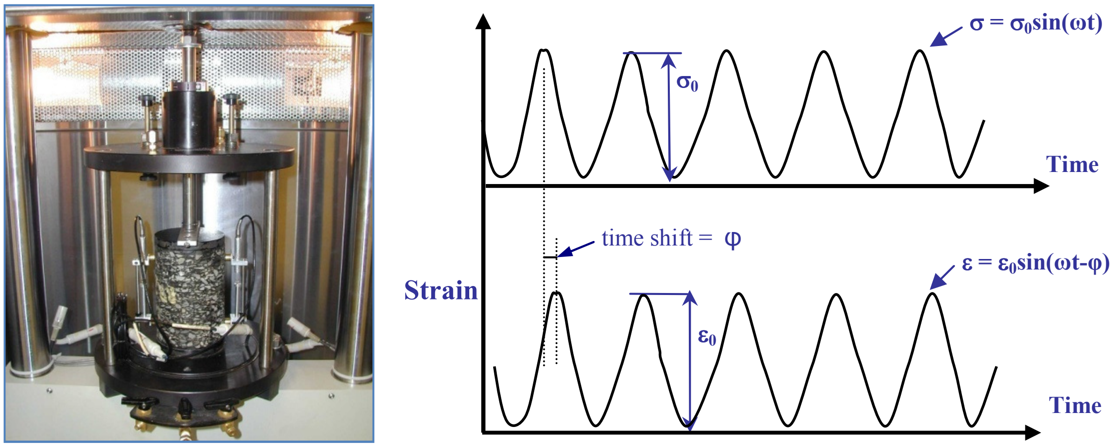


Figure 29 Lockwood liquid-treated mix design verification and aggregate properties w/Paramount PG 64-28 NVTR/TR & 1.5% Sasobit by wt of binder



Dynamic Modulus: $|E^*| = \sigma_0/\varepsilon_0$

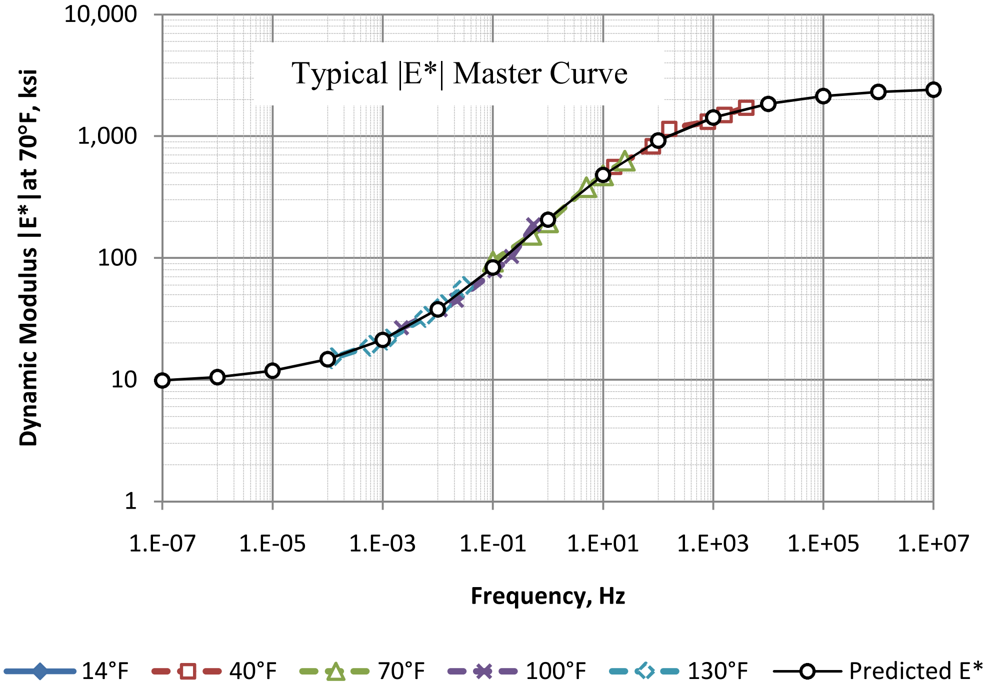
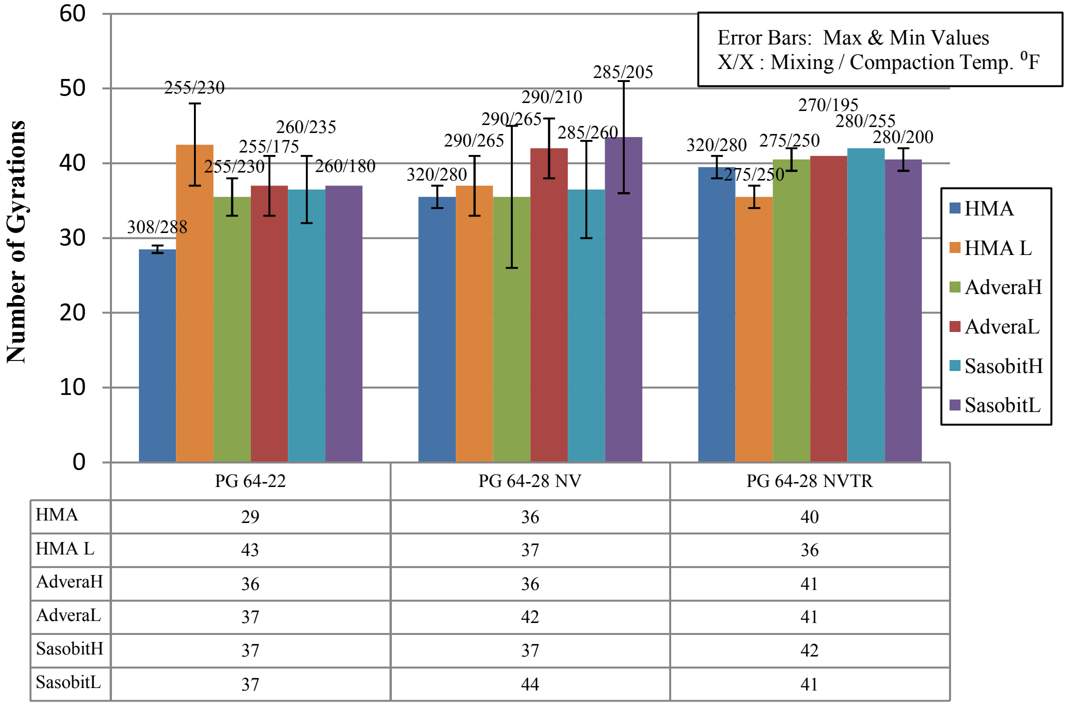


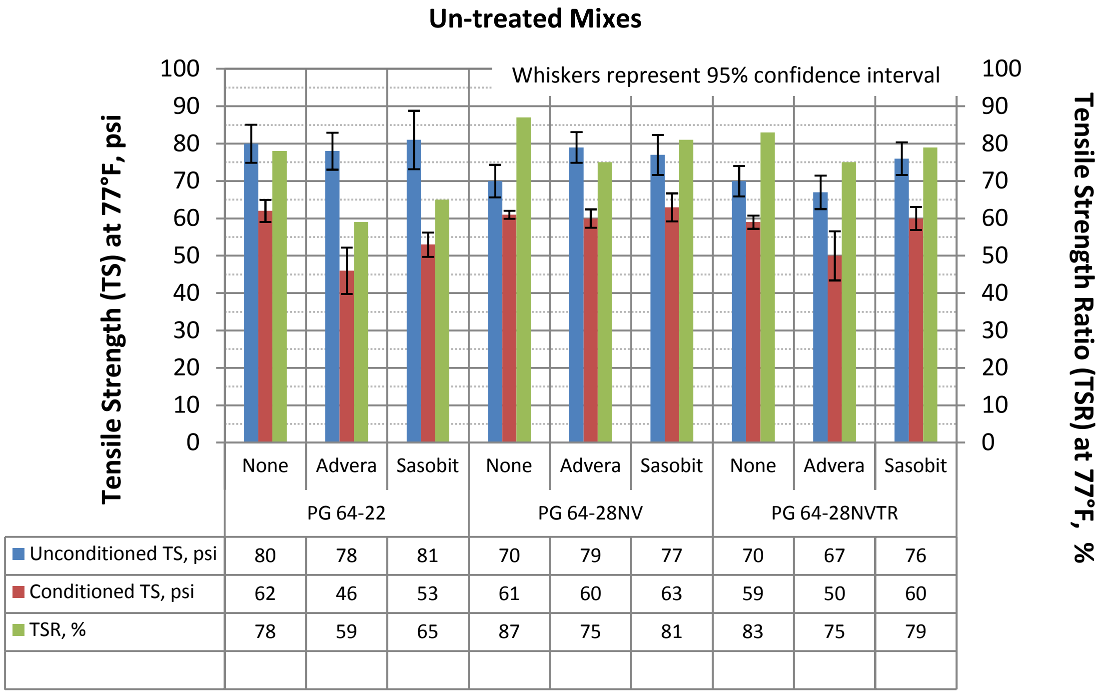
Figure 30 Components of the dynamic modulus test and a typical |E*| master curve



Error Bars: Max & Min Values
X/X : Mixing / Compaction Temp. ^{0}F

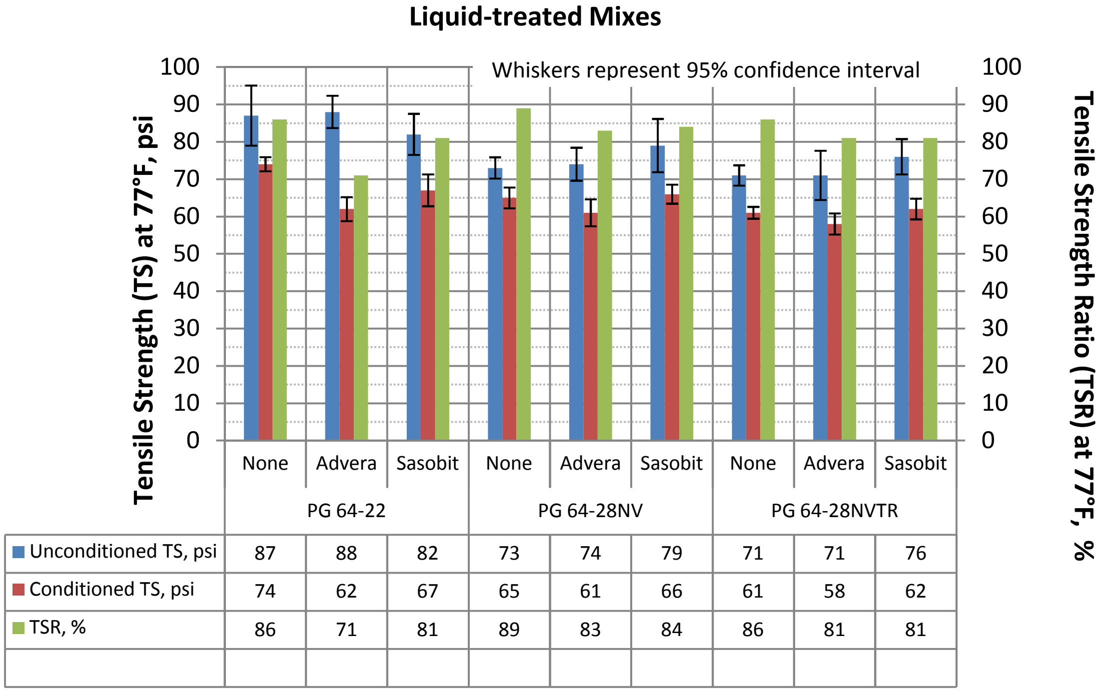
	PG 64-22	PG 64-28 NV	PG 64-28 NVTR
HMA	29	36	40
HMA L	43	37	36
AdveraH	36	36	41
AdveraL	37	42	41
SasobitH	37	37	42
SasobitL	37	44	41

Figure 31 Compactability of HMA and WMA mixtures with PG 64-22, PG 64-28 NV/PM and PG 64-28 NVTR/TR binder



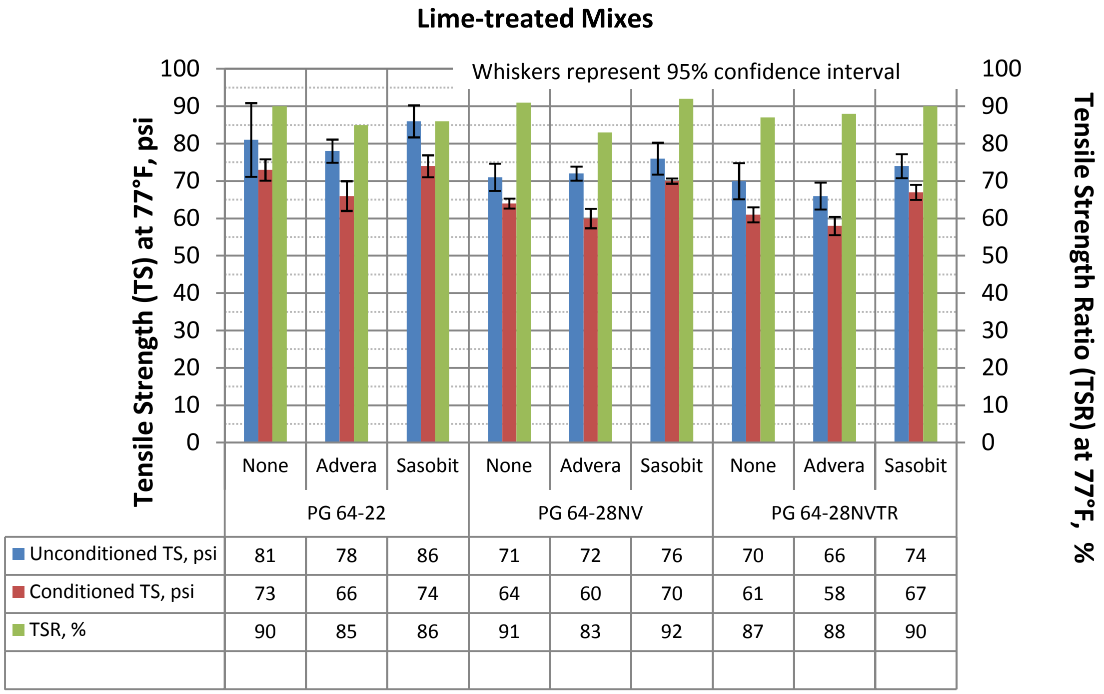
	PG 64-22 None	PG 64-22 Advera	PG 64-22 Sasobit	PG 64-28NV None	PG 64-28NV Advera	PG 64-28NV Sasobit	PG 64-28NVTR None	PG 64-28NVTR Advera	PG 64-28NVTR Sasobit
🟦 Unconditioned TS, psi	80	78	81	70	79	77	70	67	76
🟥 Conditioned TS, psi	62	46	53	61	60	63	59	50	60
🟩 TSR, %	78	59	65	87	75	81	83	75	79

Figure 32 Tensile strength ratio test data of un-treated asphalt mixtures



	PG 64-22 None	PG 64-22 Advera	PG 64-22 Sasobit	PG 64-28NV None	PG 64-28NV Advera	PG 64-28NV Sasobit	PG 64-28NVTR None	PG 64-28NVTR Advera	PG 64-28NVTR Sasobit
🟦 Unconditioned TS, psi	87	88	82	73	74	79	71	71	76
🟥 Conditioned TS, psi	74	62	67	65	61	66	61	58	62
🟩 TSR, %	86	71	81	89	83	84	86	81	81

Figure 33 Tensile strength ratio test data of lime-treated asphalt mixtures



	PG 64-22			PG 64-28NV			PG 64-28NVTR		
	None	Advera	Sasobit	None	Advera	Sasobit	None	Advera	Sasobit
🟦 Unconditioned TS, psi	81	78	86	71	72	76	70	66	74
🟥 Conditioned TS, psi	73	66	74	64	60	70	61	58	67
🟩 TSR, %	90	85	86	91	83	92	87	88	90

Figure 34 Tensile strength ratio test data of liquid-treated asphalt mixtures

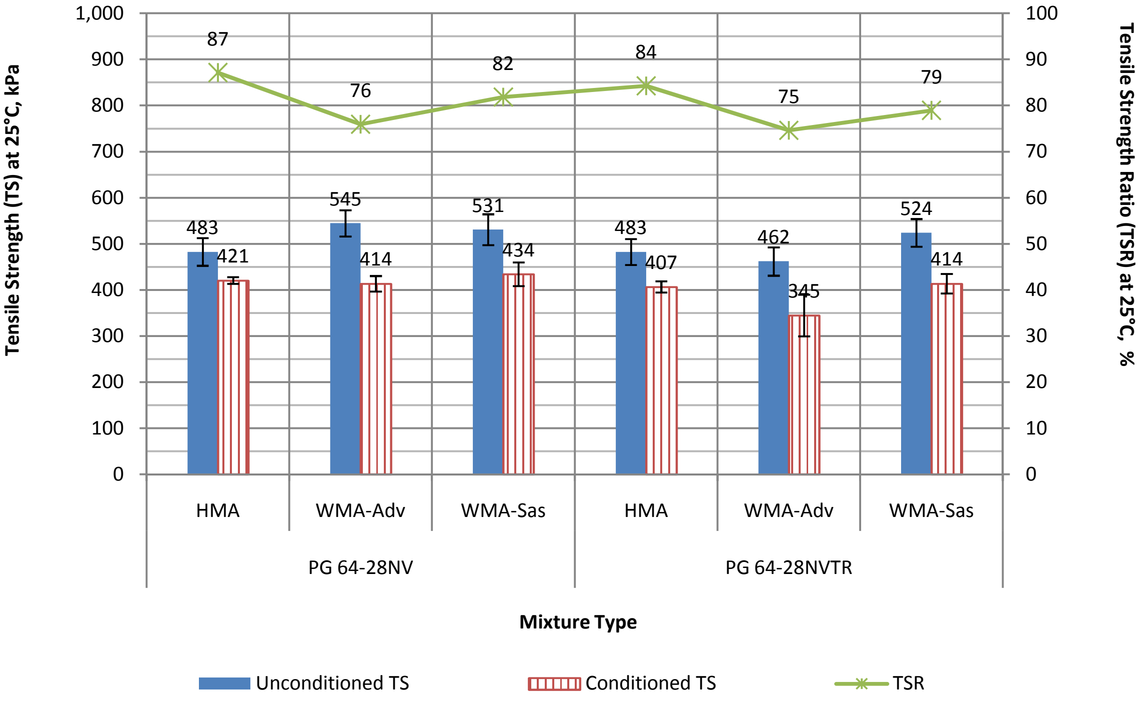


Figure 35 Tensile strength ratio plot of un-treated modified asphalt mixtures

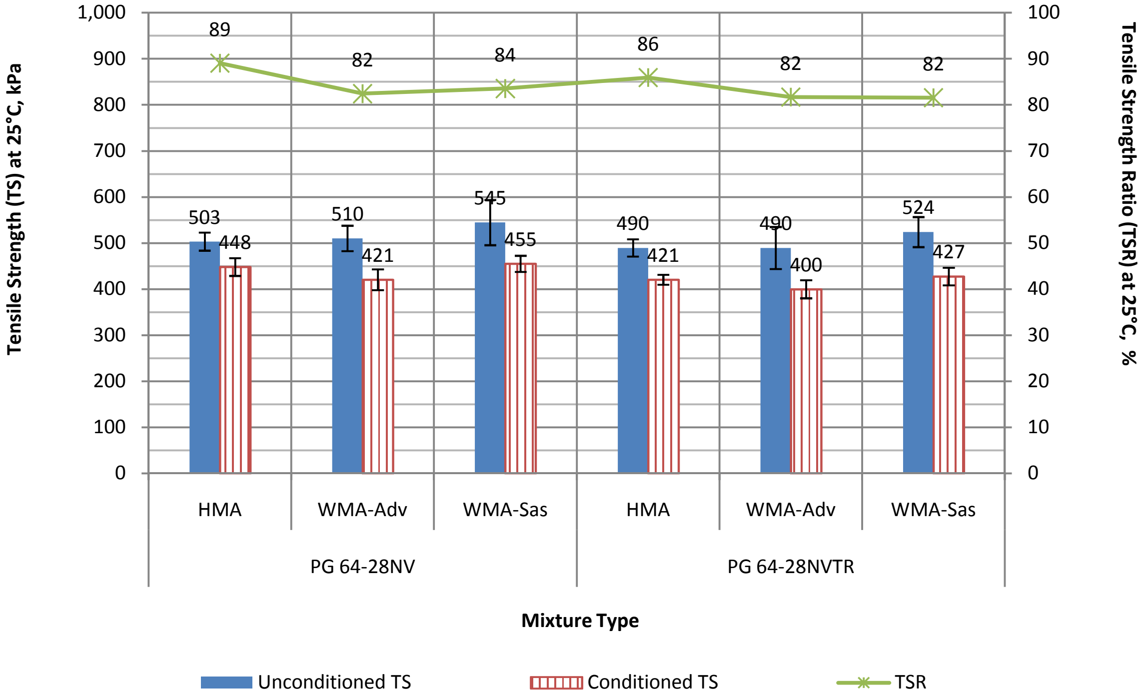


Figure 36 Tensile strength ratio plot of lime-treated modified asphalt mixtures

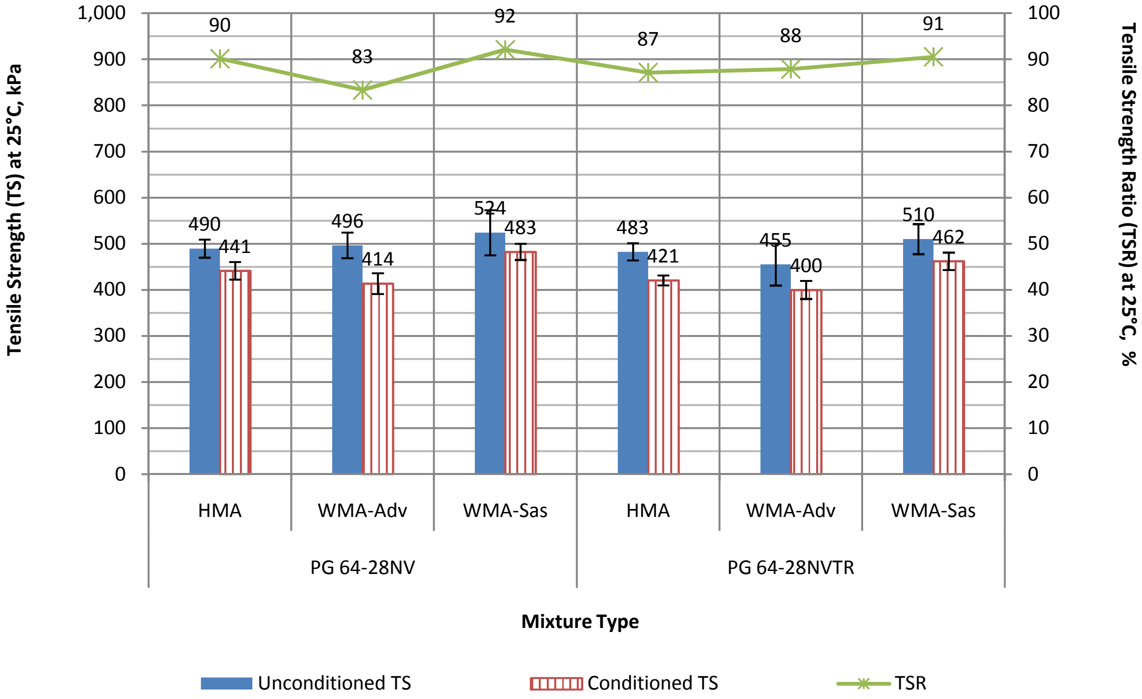


Figure 37 Tensile strength ratio plot of liquid-treated modified asphalt mixtures

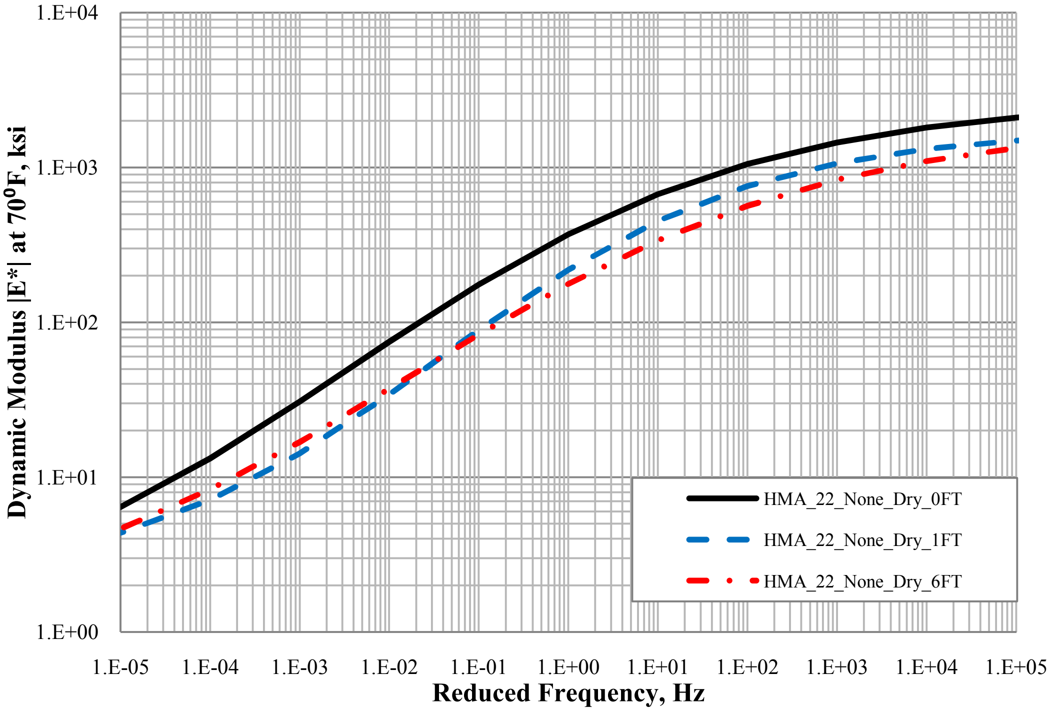
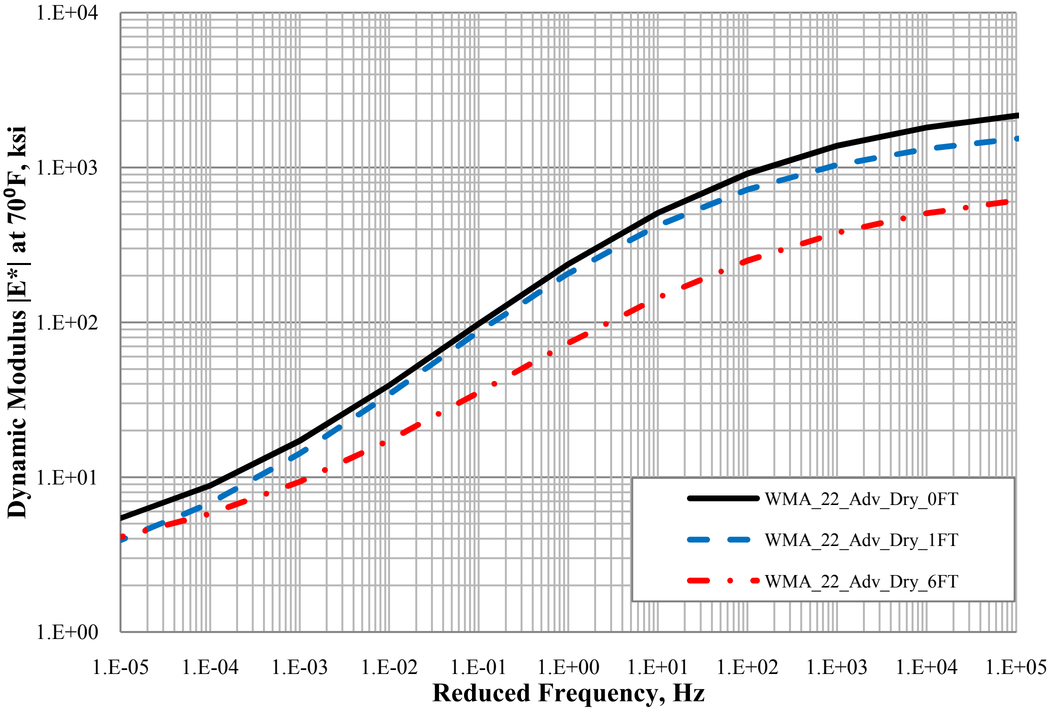


Figure 38 Dynamic modulus (|E*|) master curves for un-treated HMA mixtures with PG 64-22



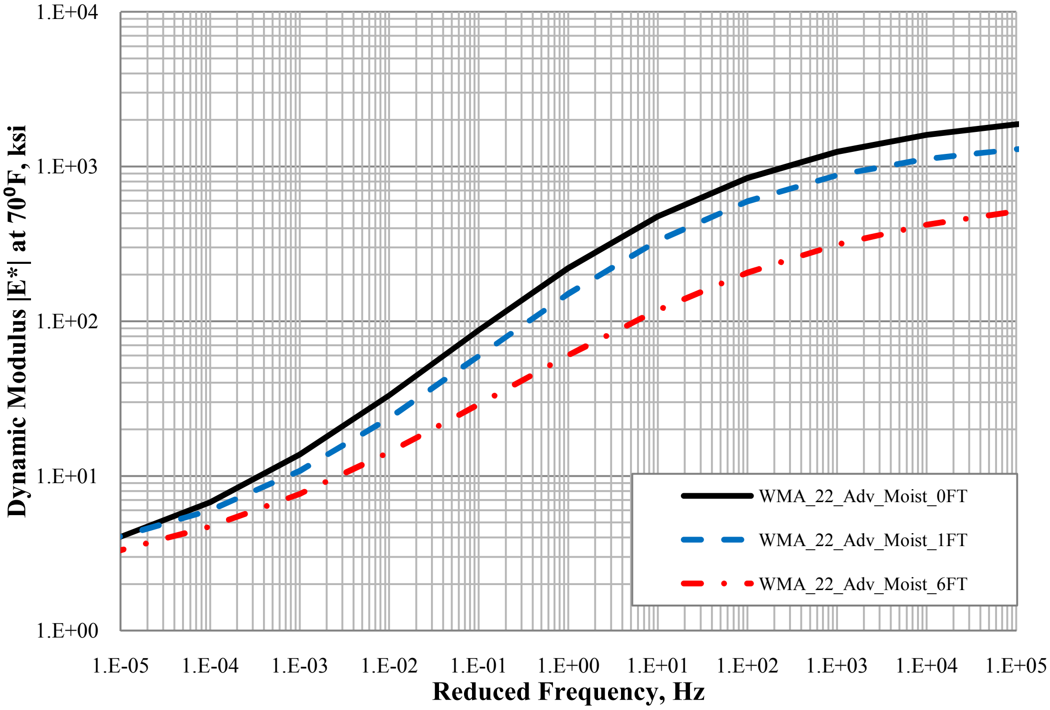


Figure 39 Dynamic modulus (|E*|) master curves for un-treated HMA mixtures with PG 64-22 & 0.3% Advera by total wt of mixture

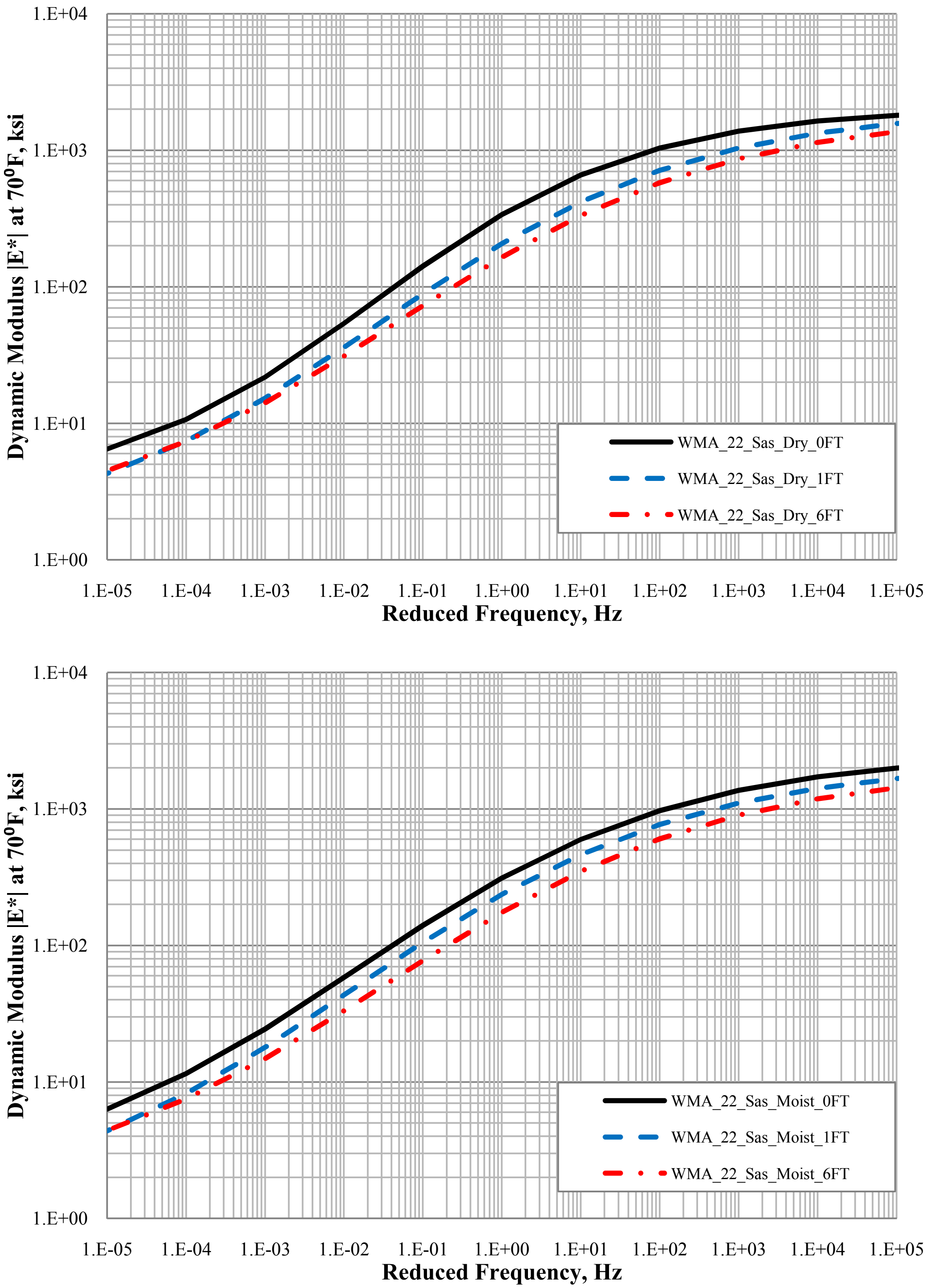


Figure 40 Dynamic modulus (|E*|) master curves for un-treated HMA mixtures with PG 64-22 & 1.5% Sasobit by wt of binder

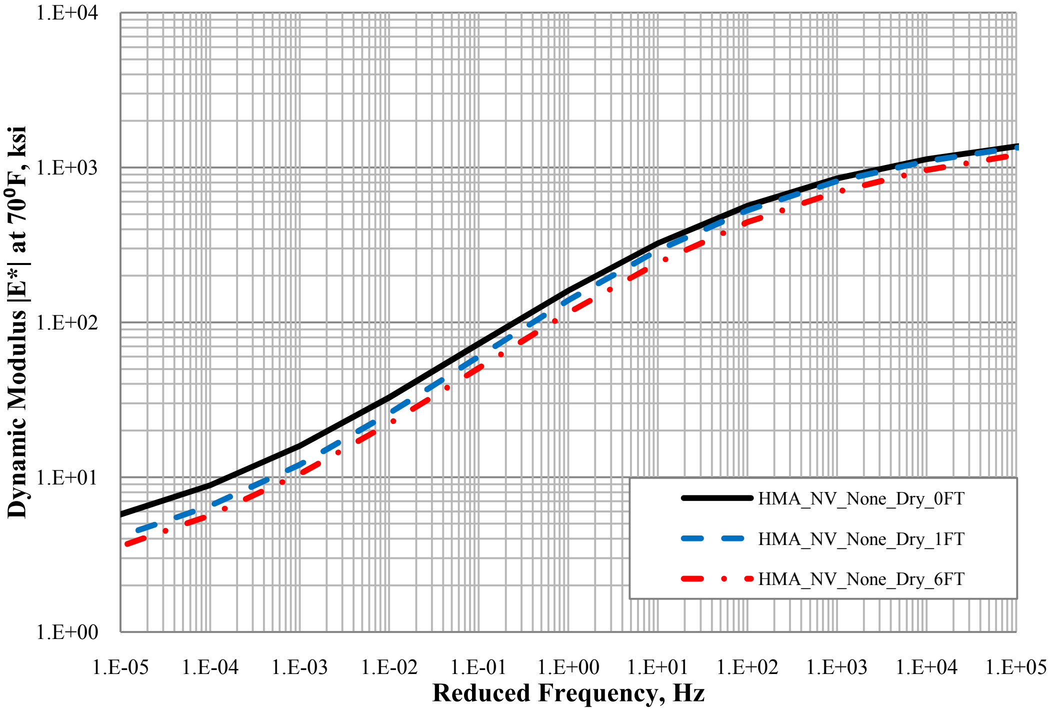


Figure 41 Dynamic modulus (|E*|) master curves for un-treated mixtures with PG 64-28 NV/PM

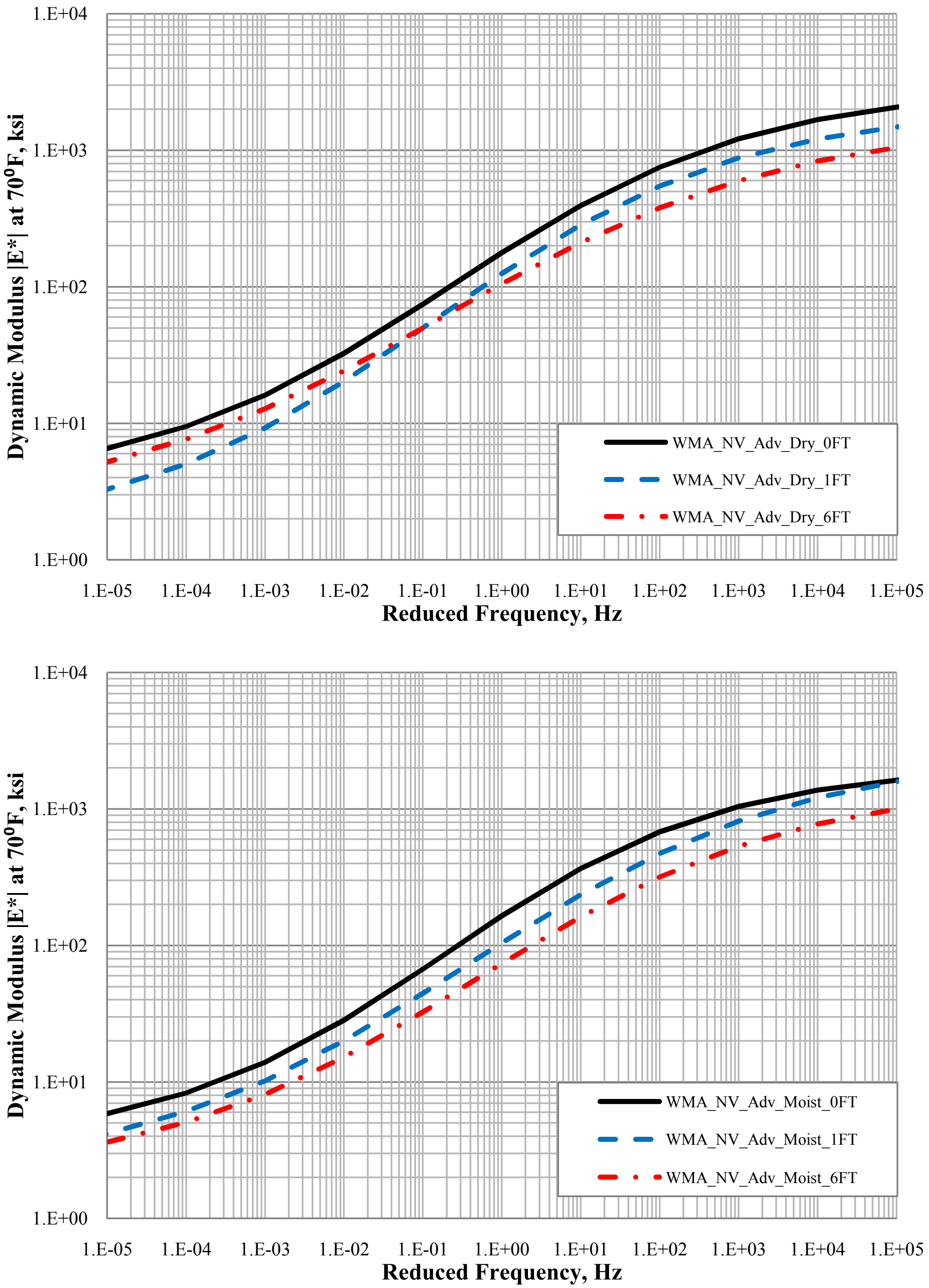
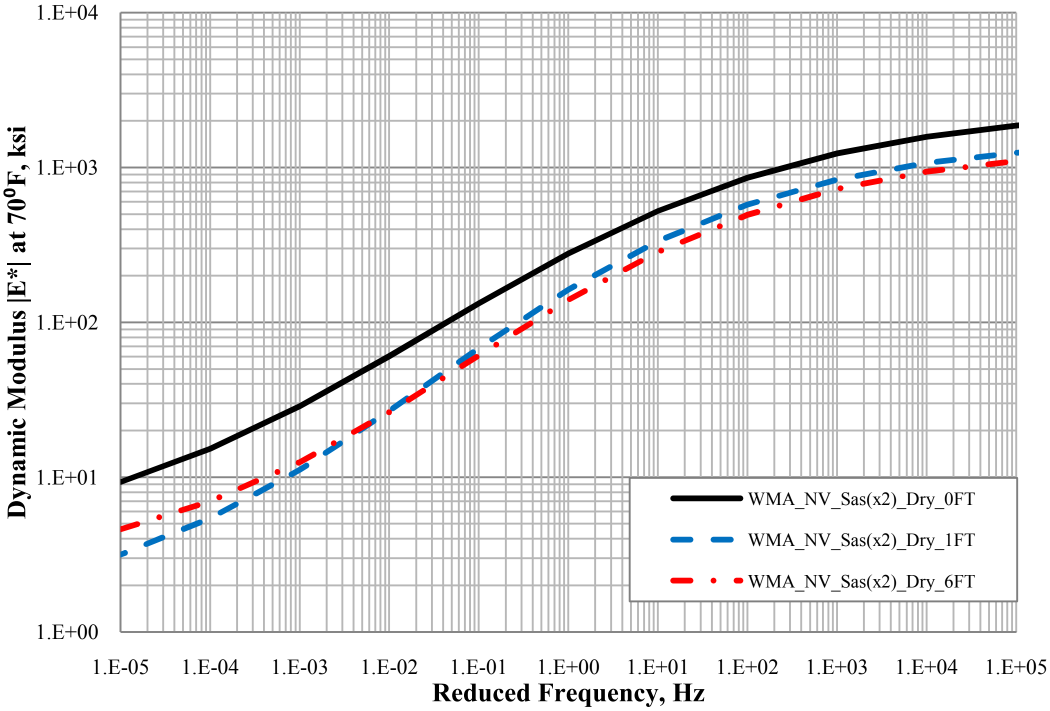


Figure 42 Dynamic modulus (|E*|) master curves for un-treated mixtures with PG 64-28 NV/PM & 0.3% Advera by total wt of mixture



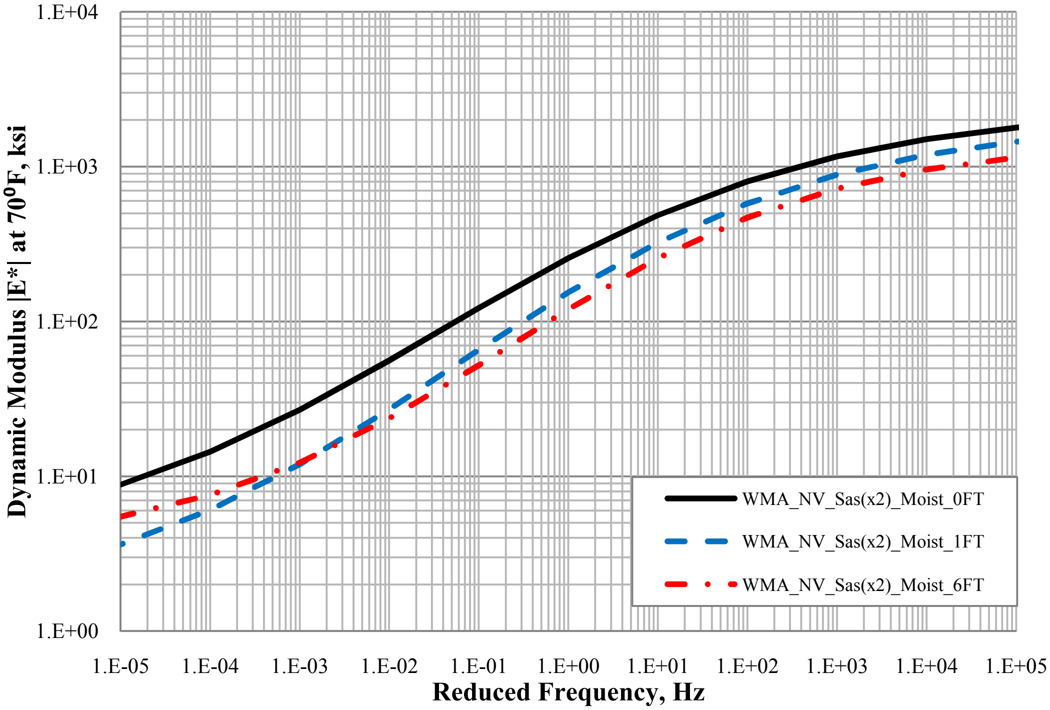


Figure 43 Dynamic modulus (|E*|) master curves for un-treated mixtures with PG 64-28 NV/PM & 3.0% Sasobit by wt of binder

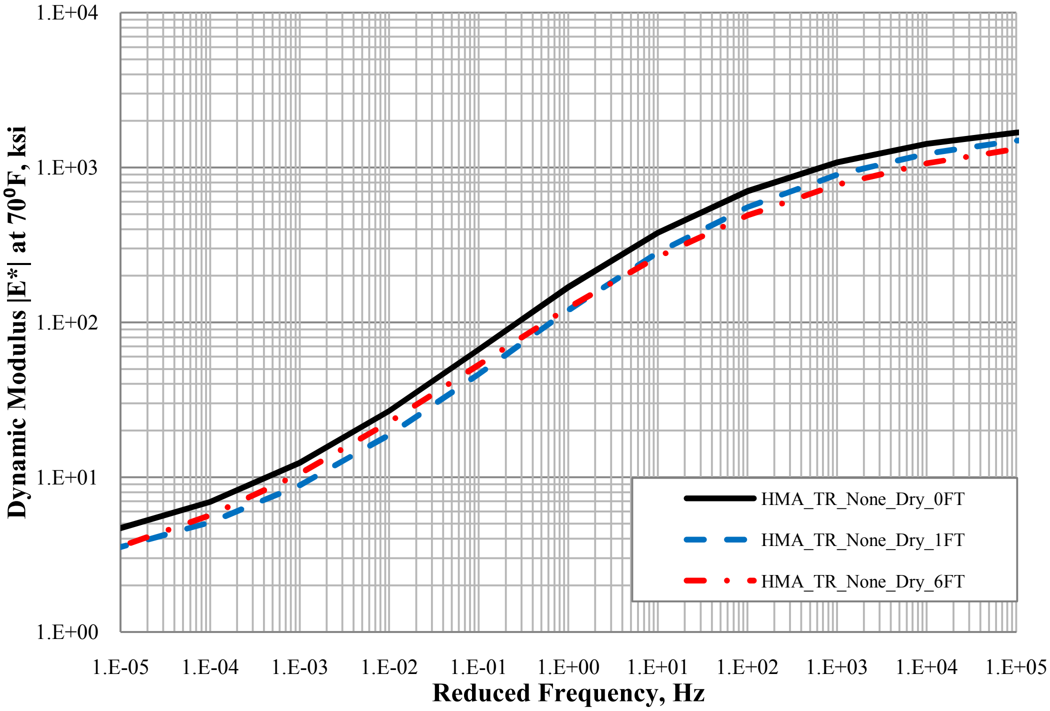
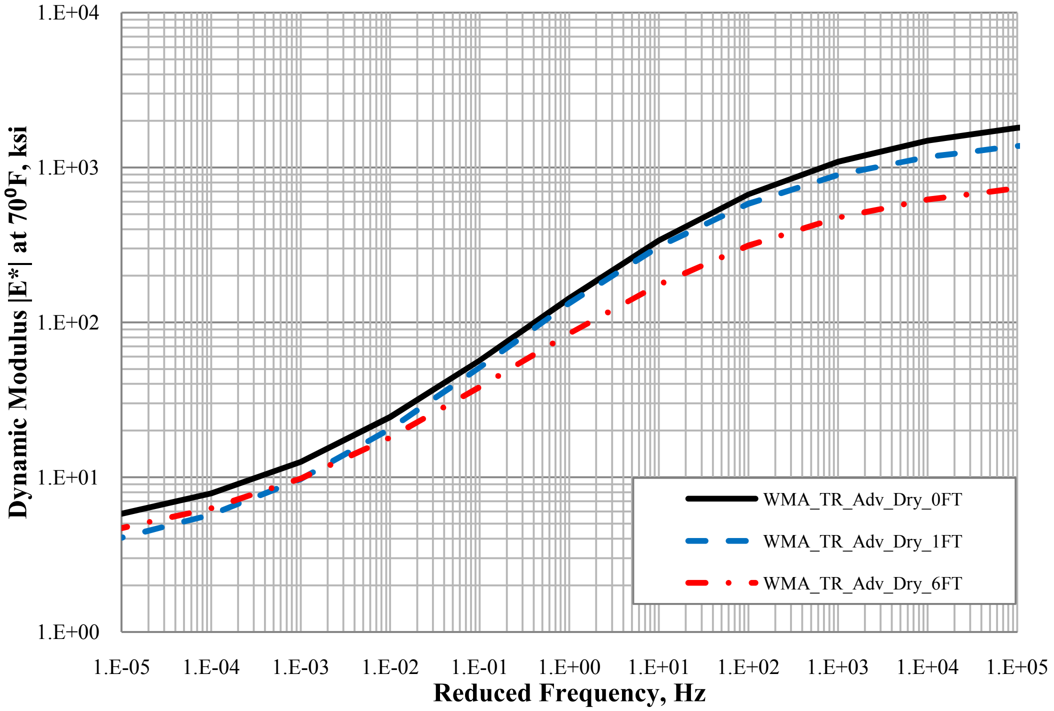


Figure 44 Dynamic modulus (|E*|) master curves for un-treated mixtures with PG 64-28 NVTR/TR



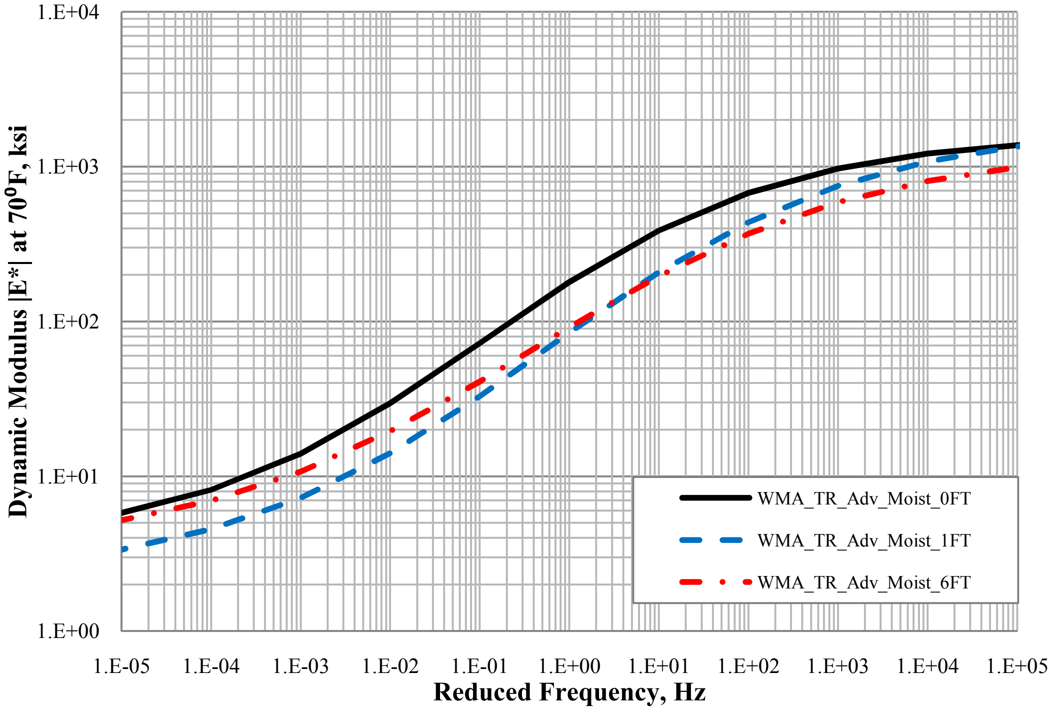


Figure 45 Dynamic modulus (|E*|) master curves for un-treated mixtures with PG 64-28 NVTR/TR & 0.3% Advera by total wt of mixture

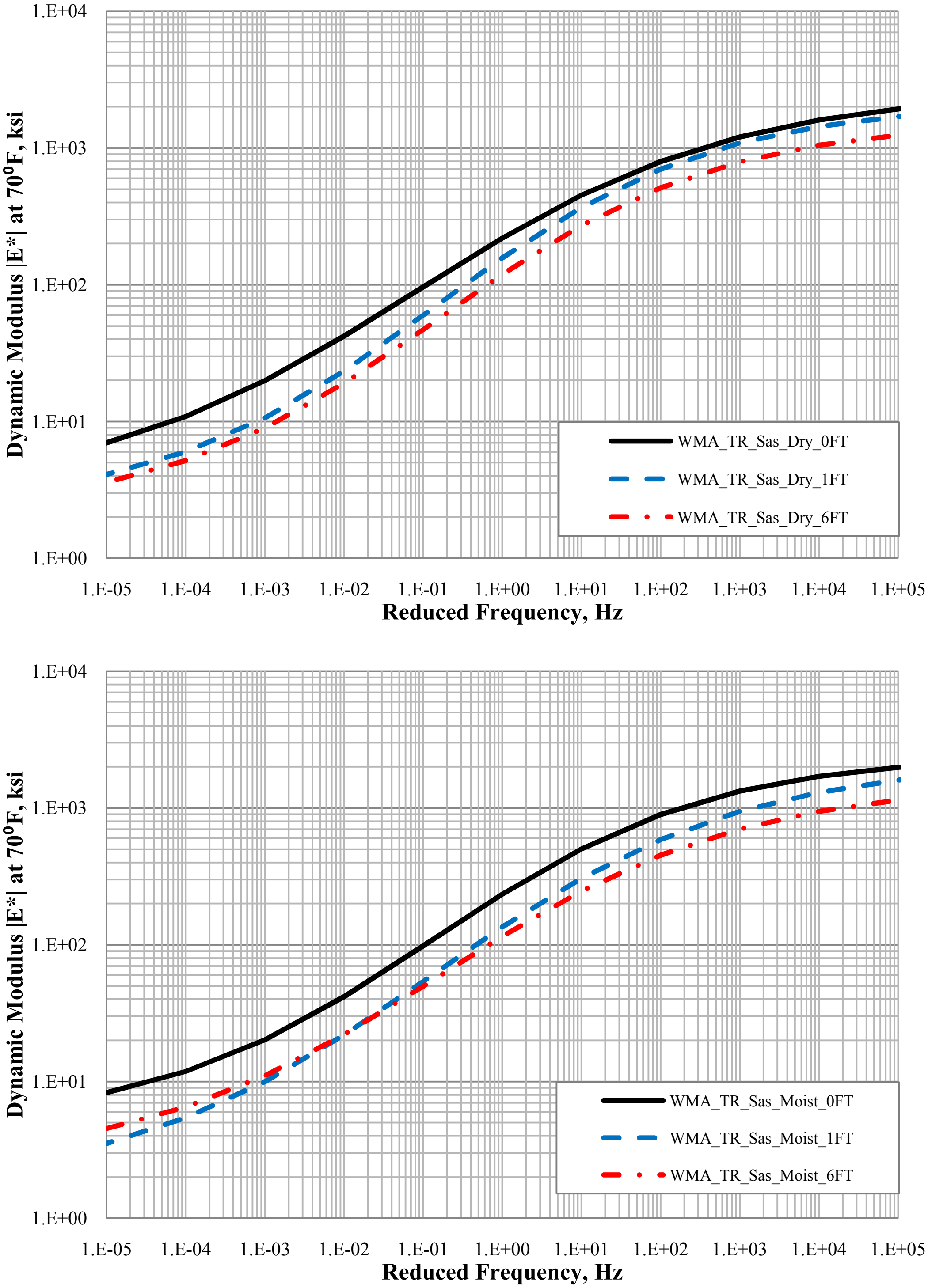


Figure 46 Dynamic modulus (|E*|) master curves for un-treated mixtures with PG 64-28 NVTR/TR & 1.5% Sasobit by wt of binder

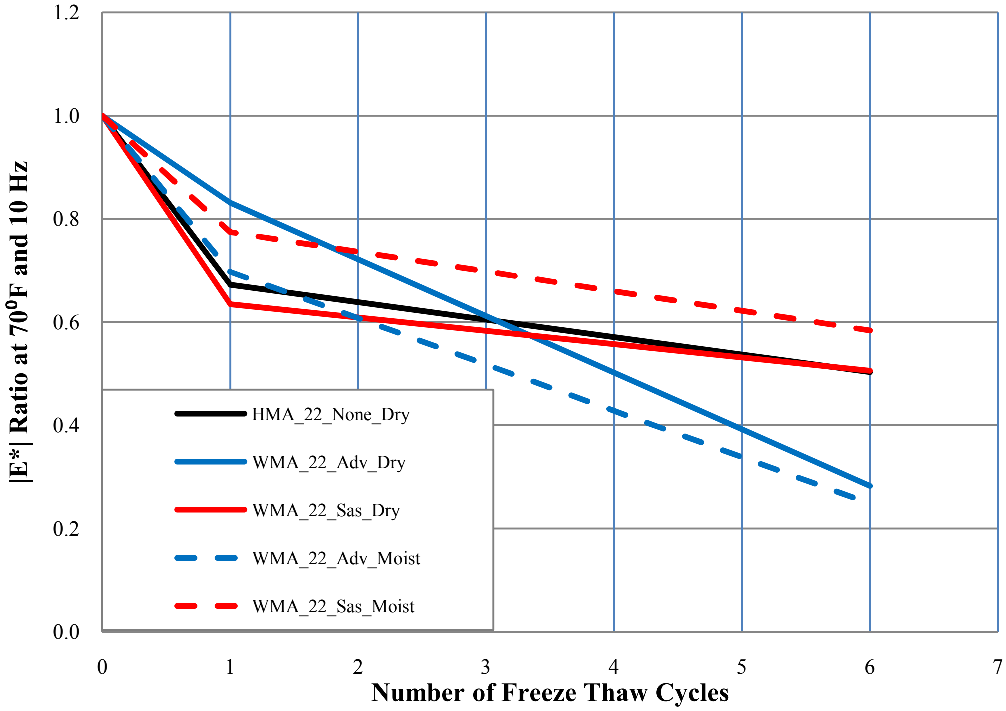


Figure 47 Dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for un-treated asphalt mixtures with PG64-22

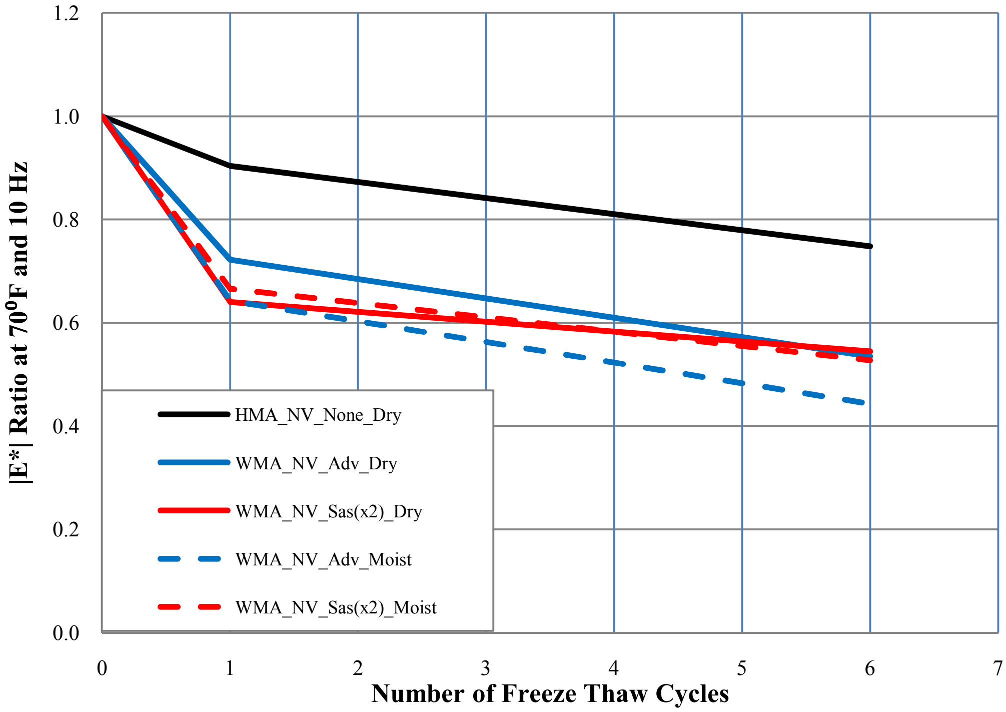


Figure 48 Dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for un-treated asphalt mixtures with PG64-28 NV/PM

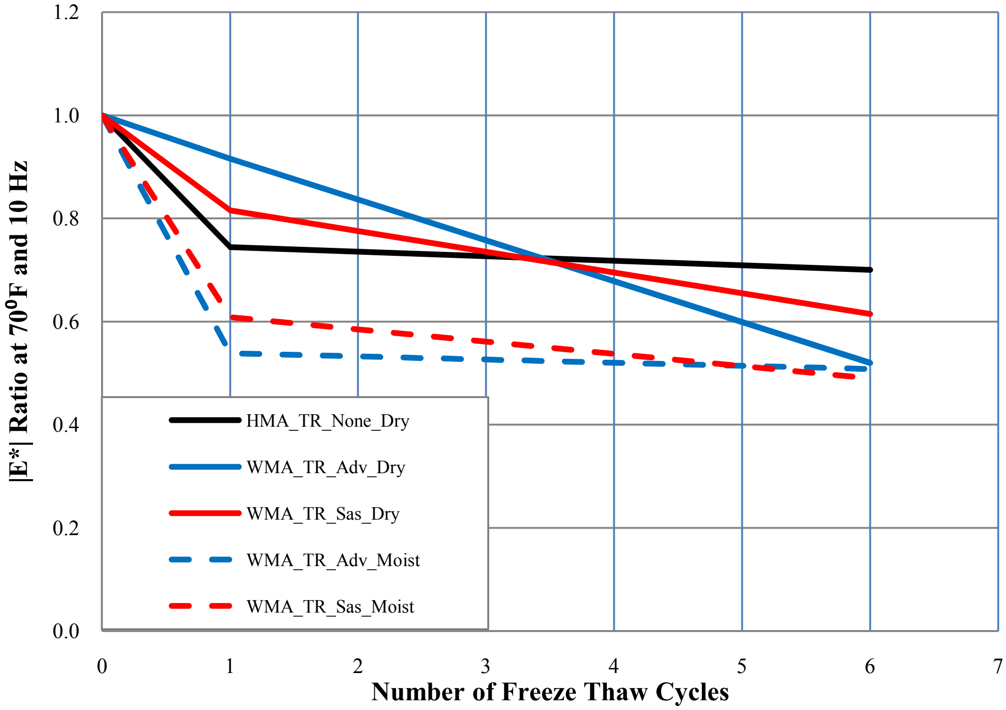


Figure 49 Dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for un-treated asphalt mixtures with PG64-28 NVTR/TR

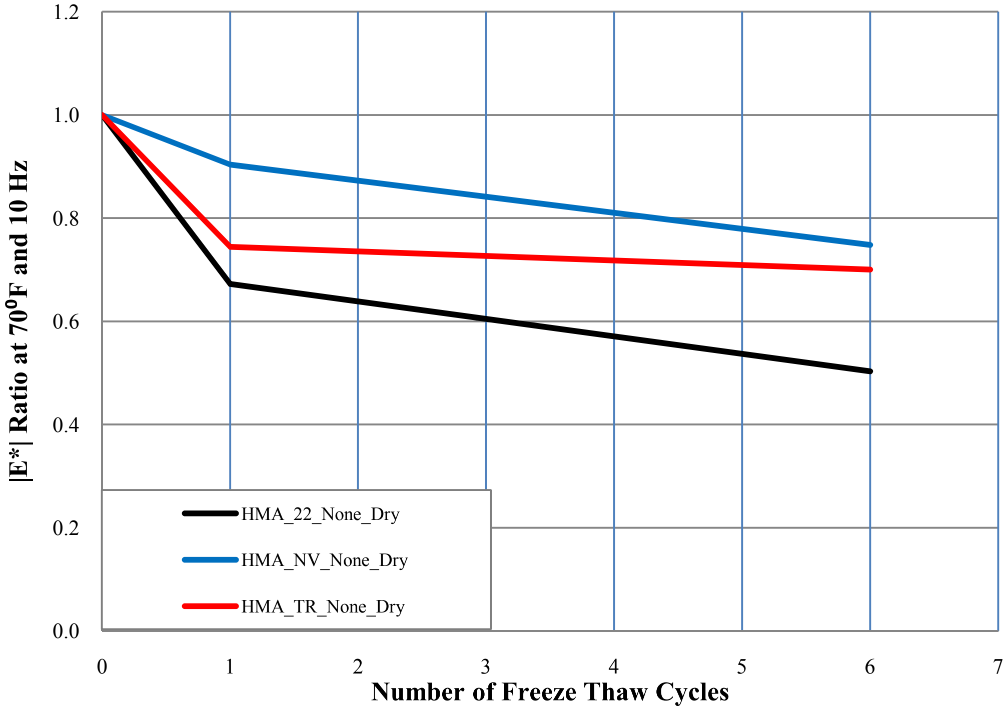


Figure 50 Dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for un-treated asphalt mixtures with no warm mix additive

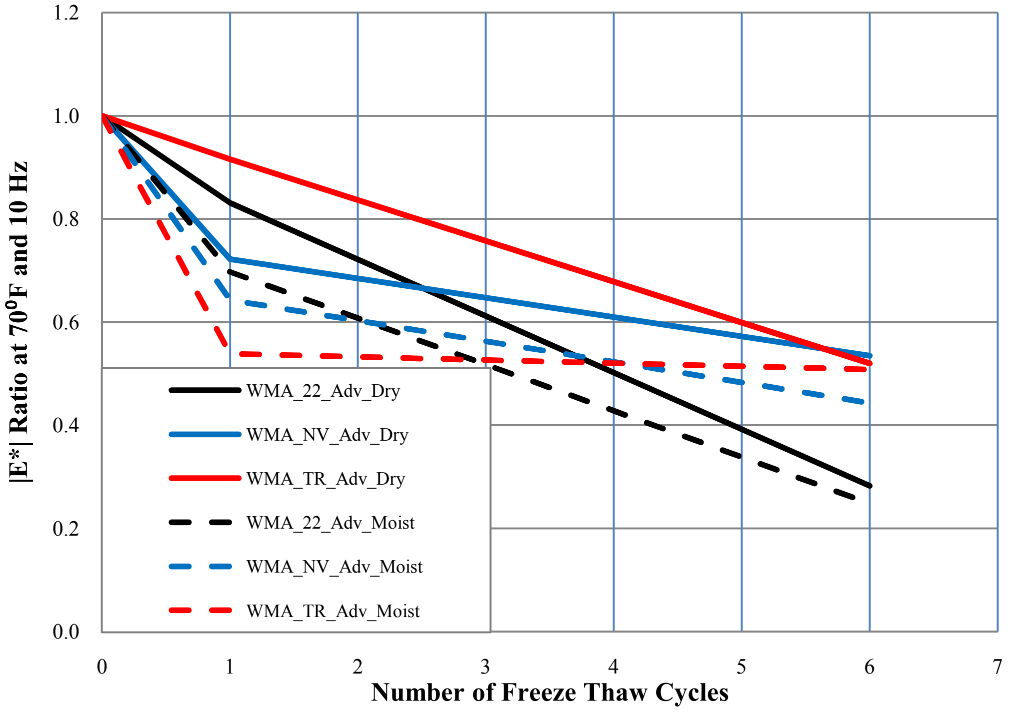


Figure 51 Dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for un-treated asphalt mixtures with Advera

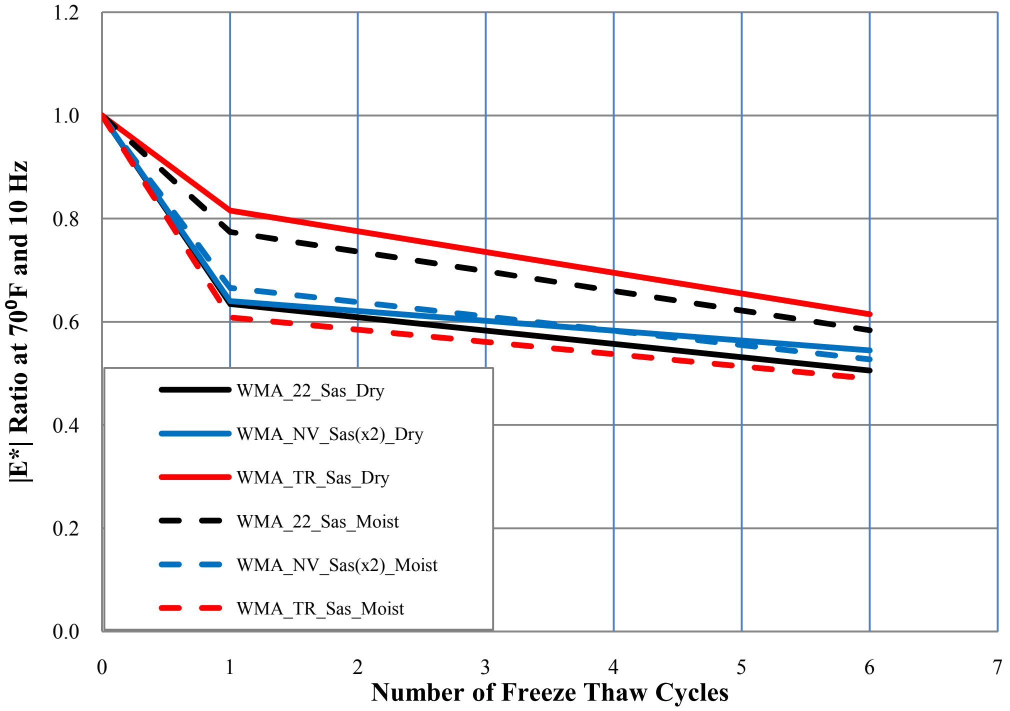


Figure 52 Dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for un-treated asphalt mixtures with Sasobit

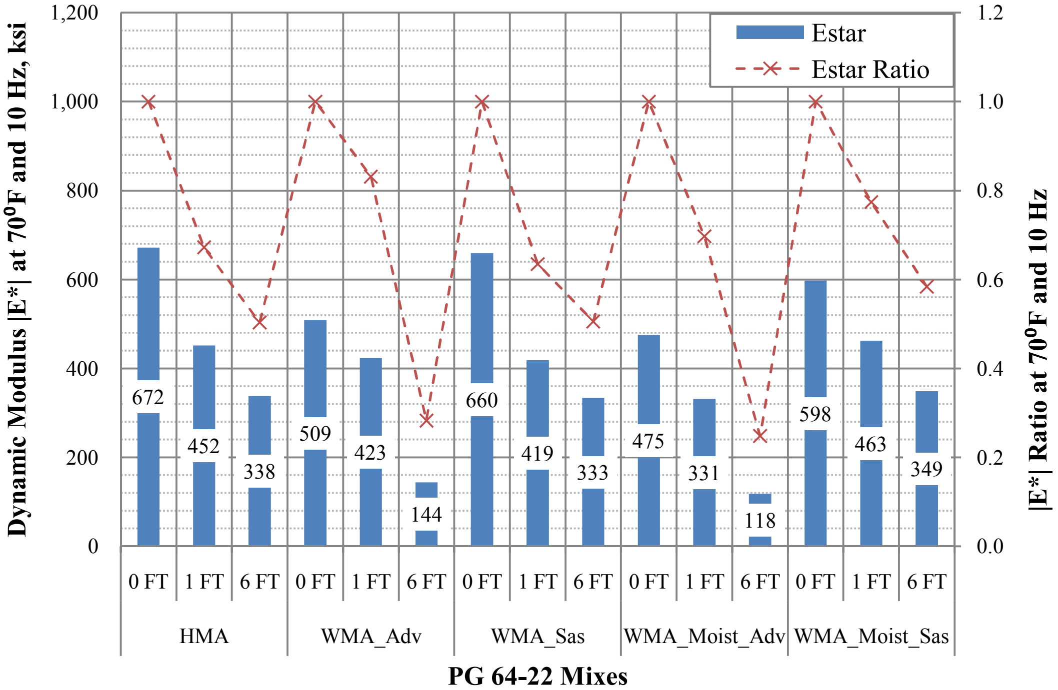


Figure 53 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for asphalt mixtures with PG64-22 without anti-strip treatment

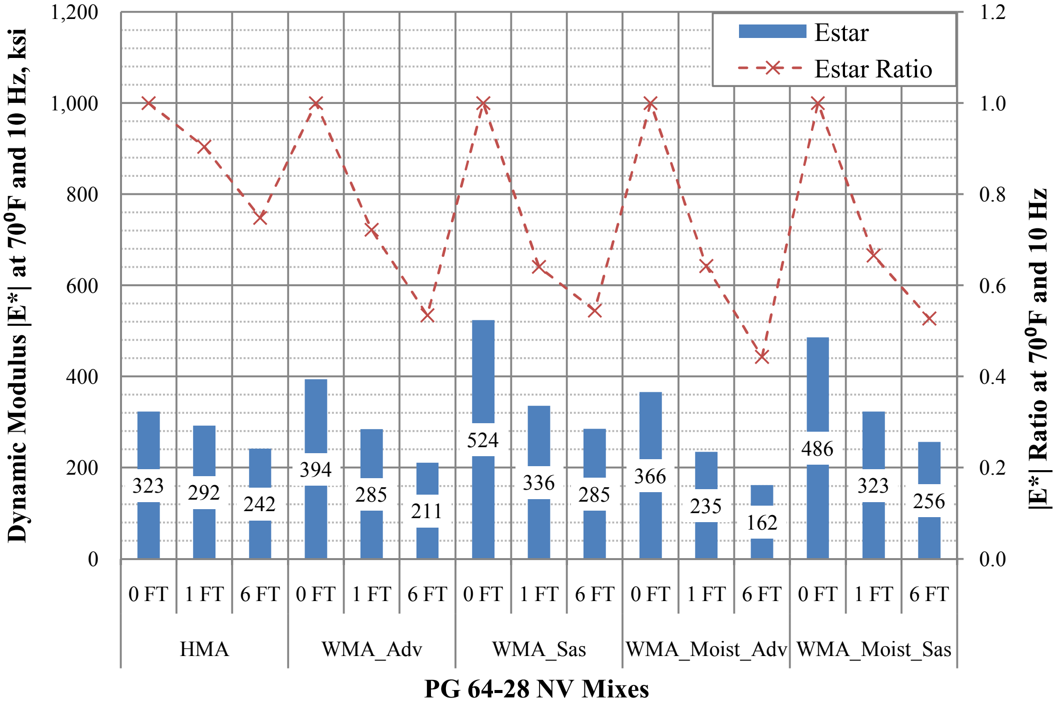


Figure 54 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for asphalt mixtures with PG64-28 NV/PM without anti-strip treatment

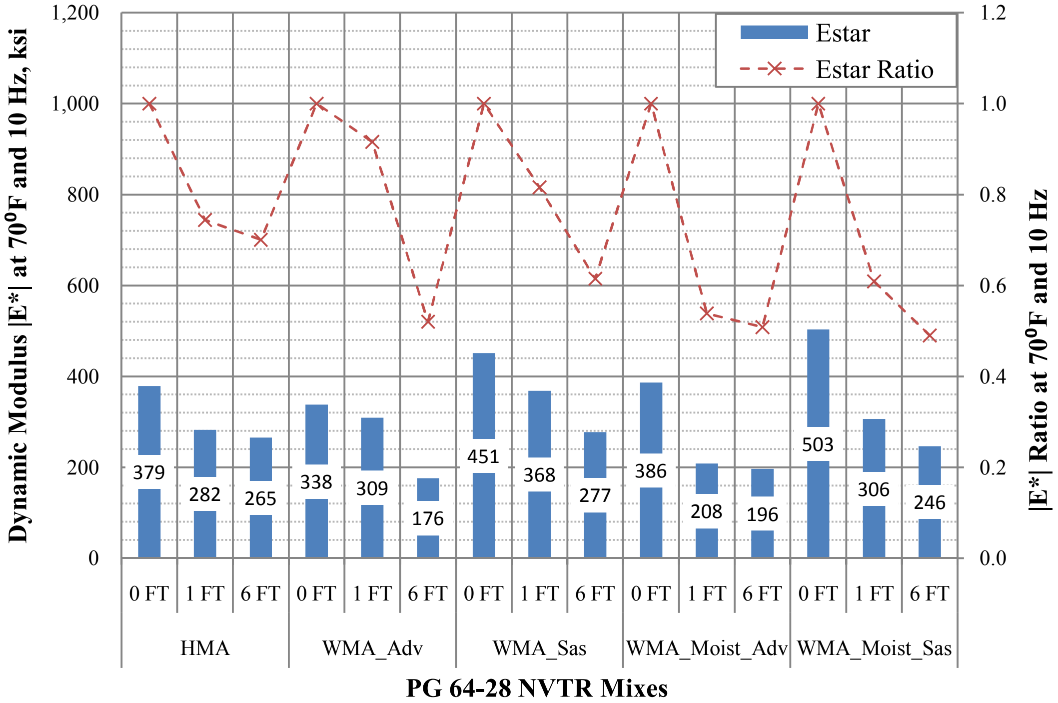
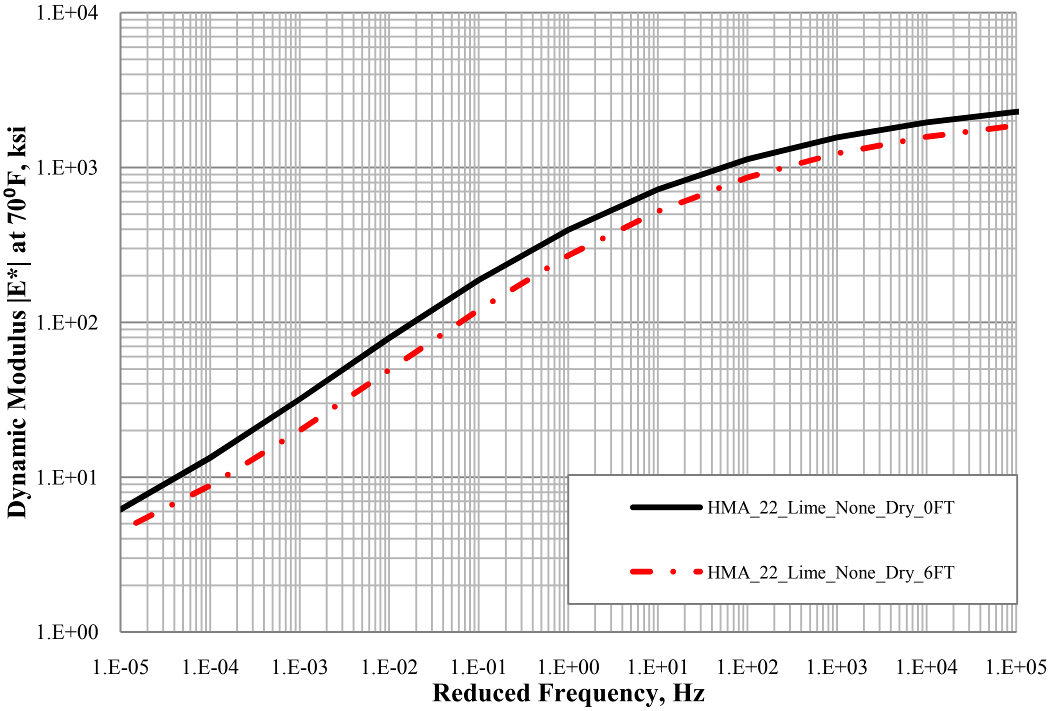


Figure 55 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for asphalt mixtures with PG64-28 NVTR/TR without anti-strip treatment



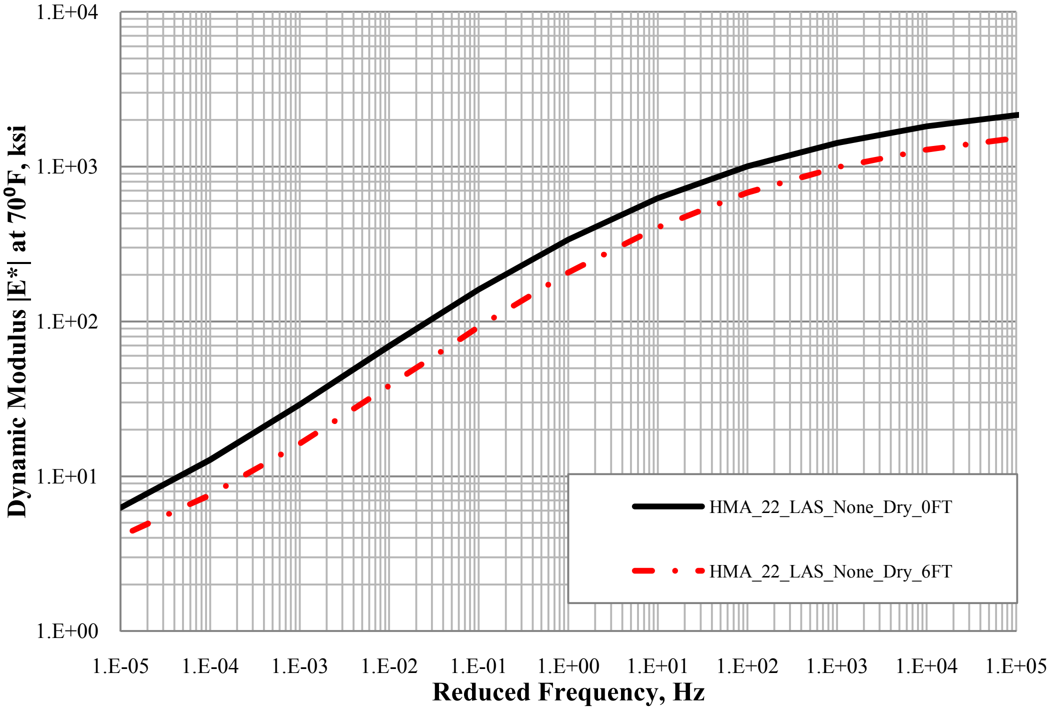
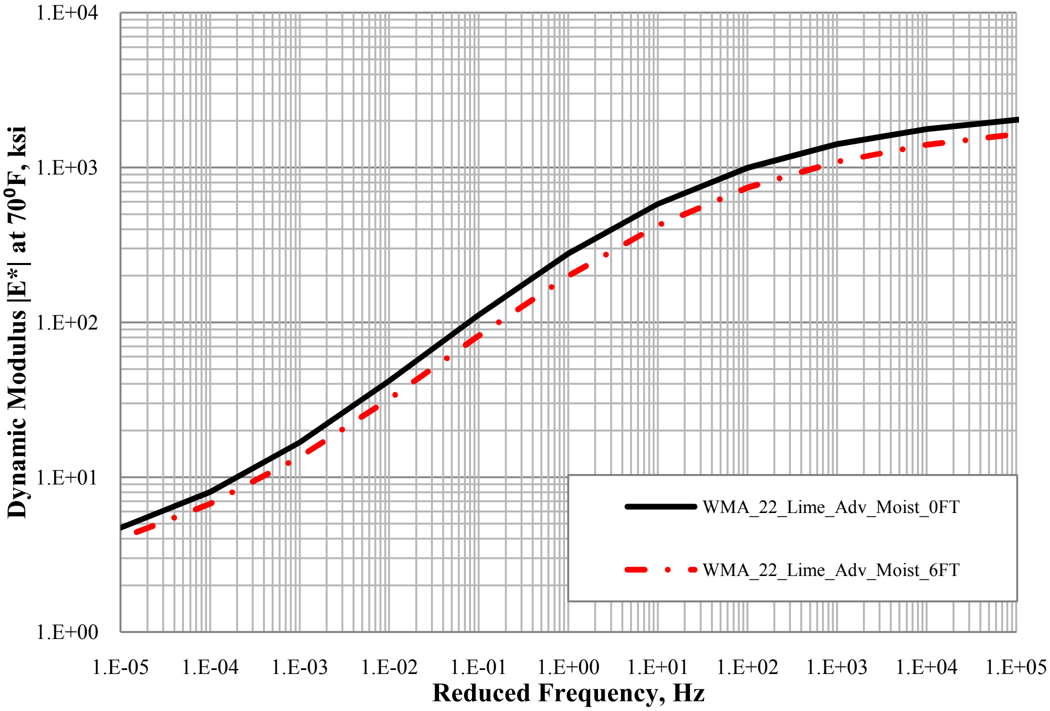


Figure 56 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-22



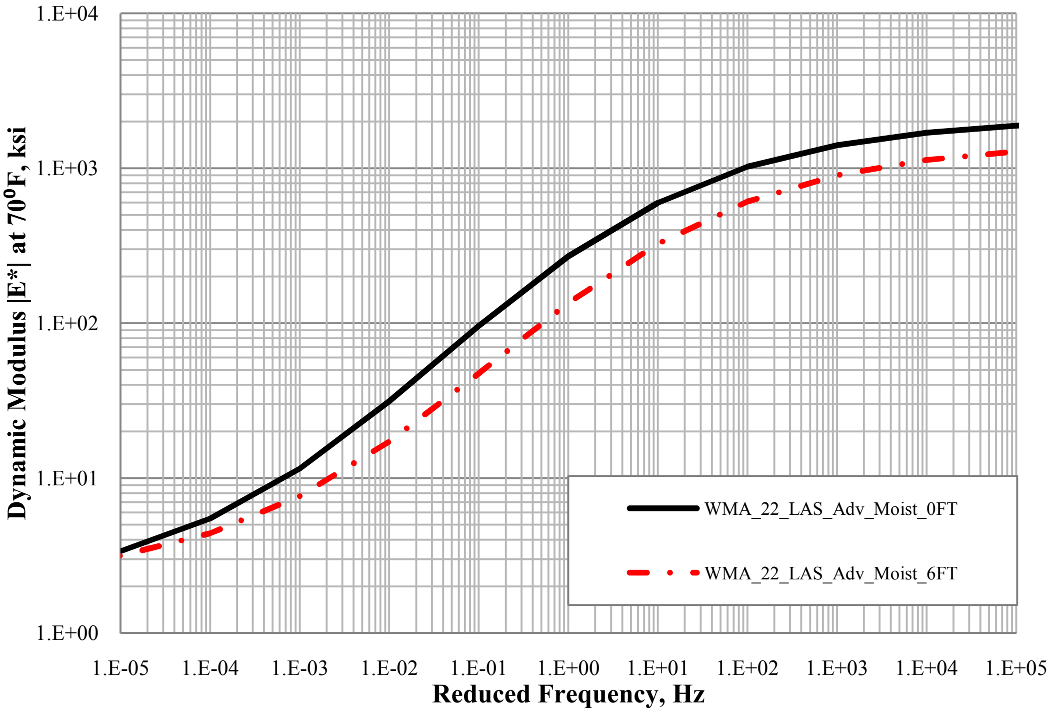


Figure 57 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-22 & 0.3% Advera by total wt of mixture

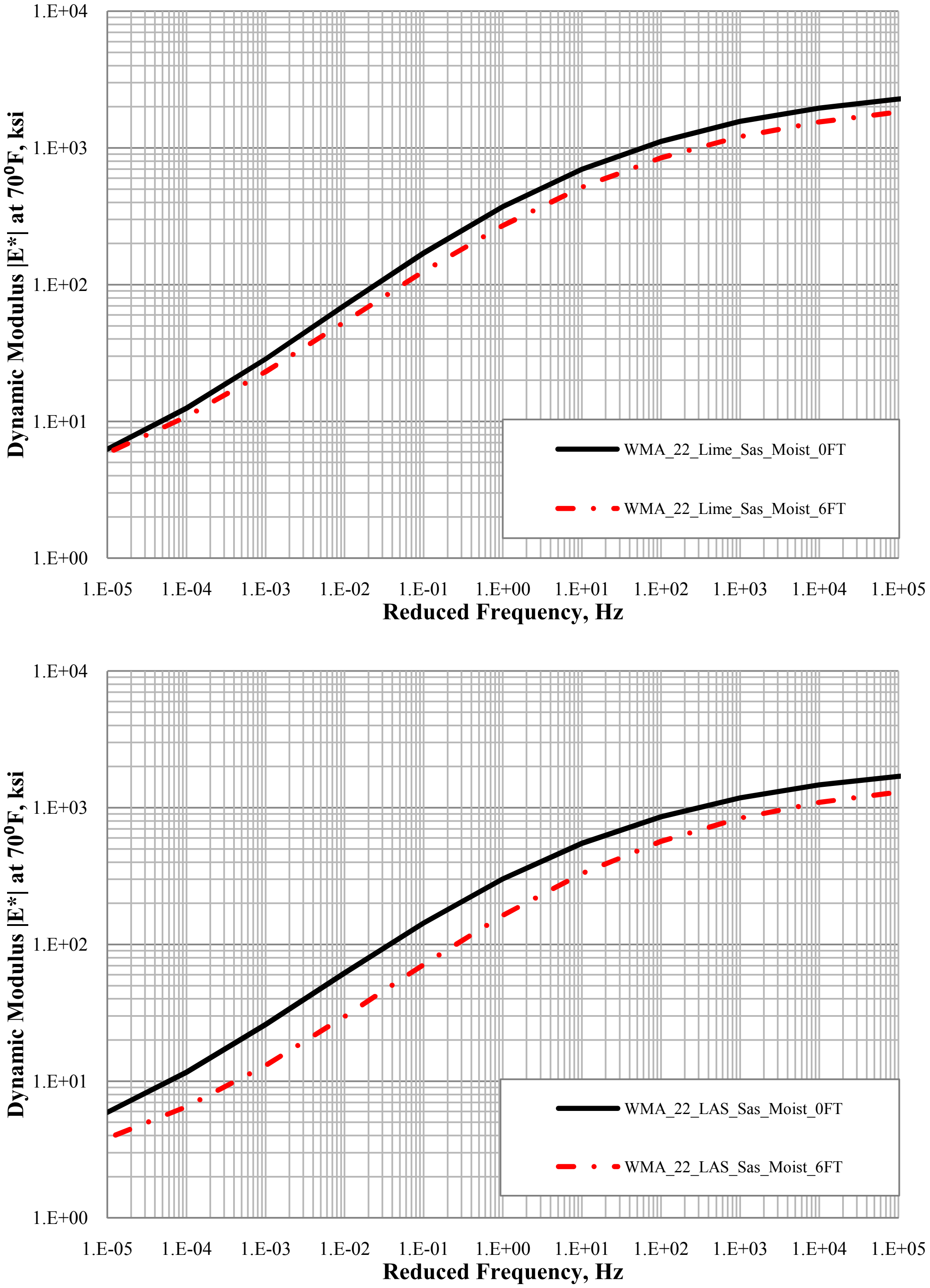
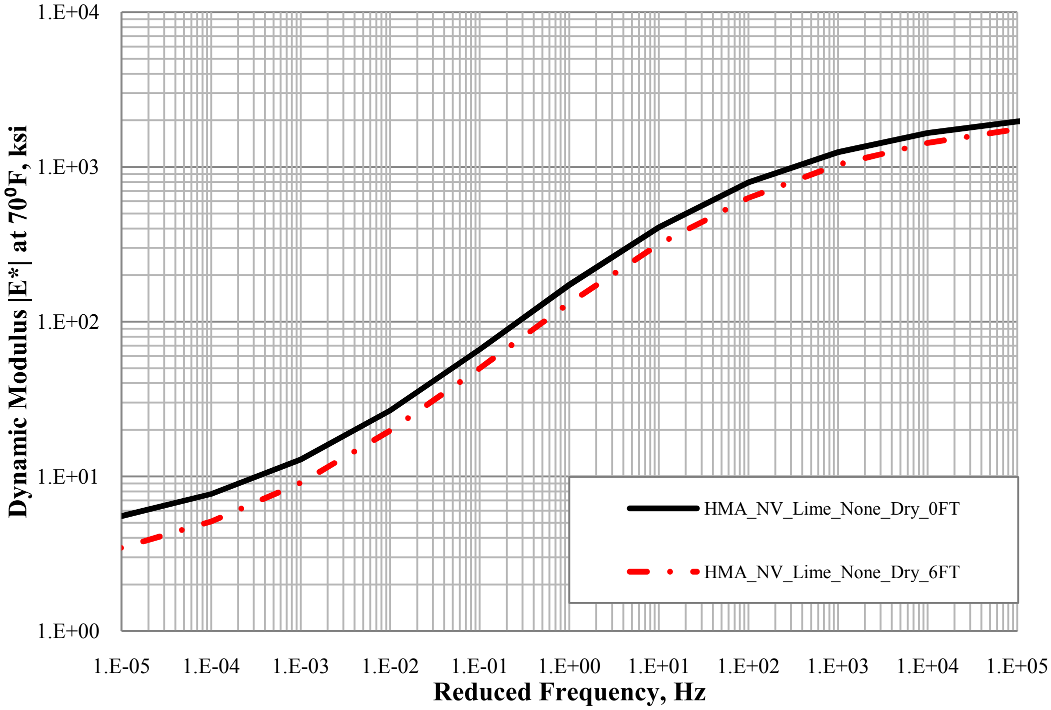


Figure 58 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-22 & 1.5% Sasobit by wt of binder



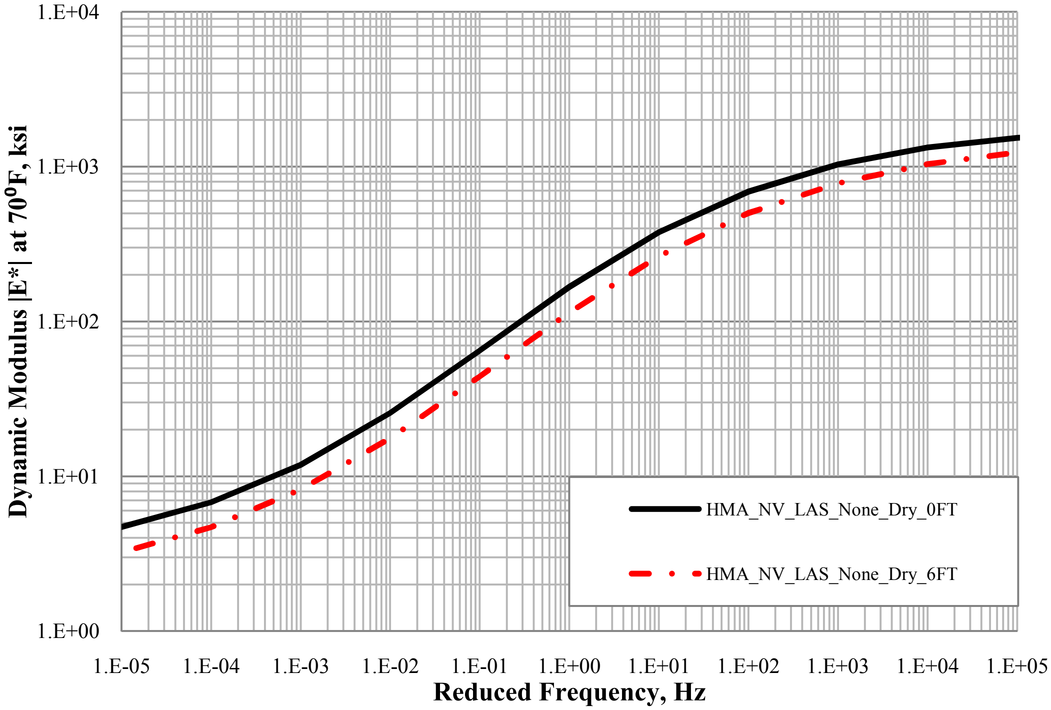
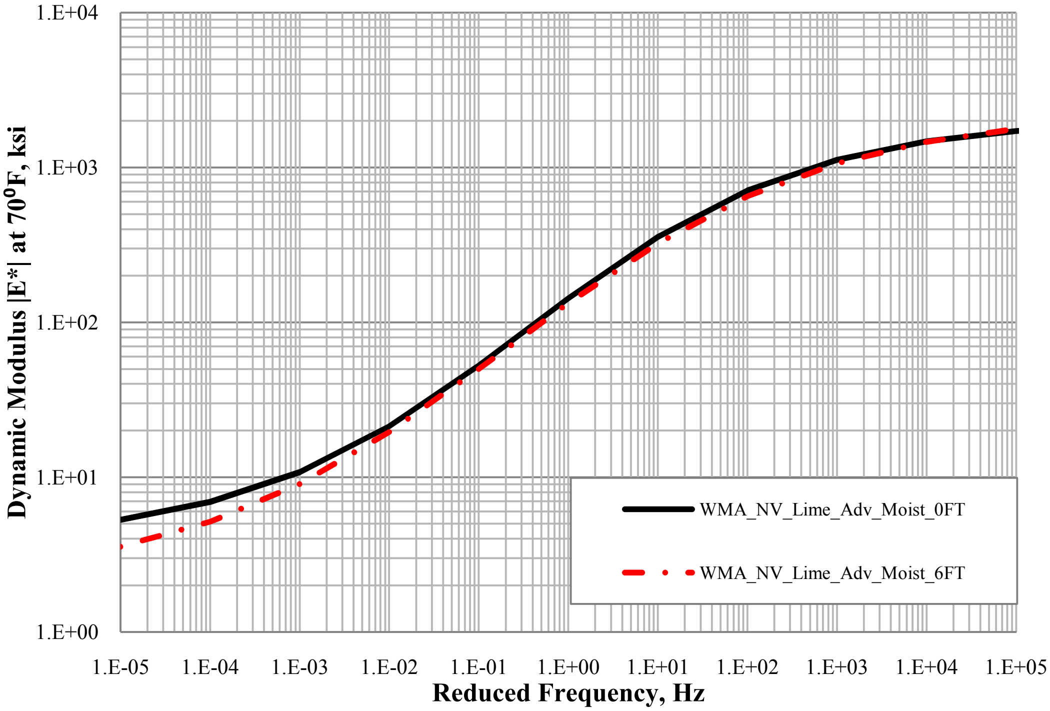


Figure 59 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-28 NV/PM



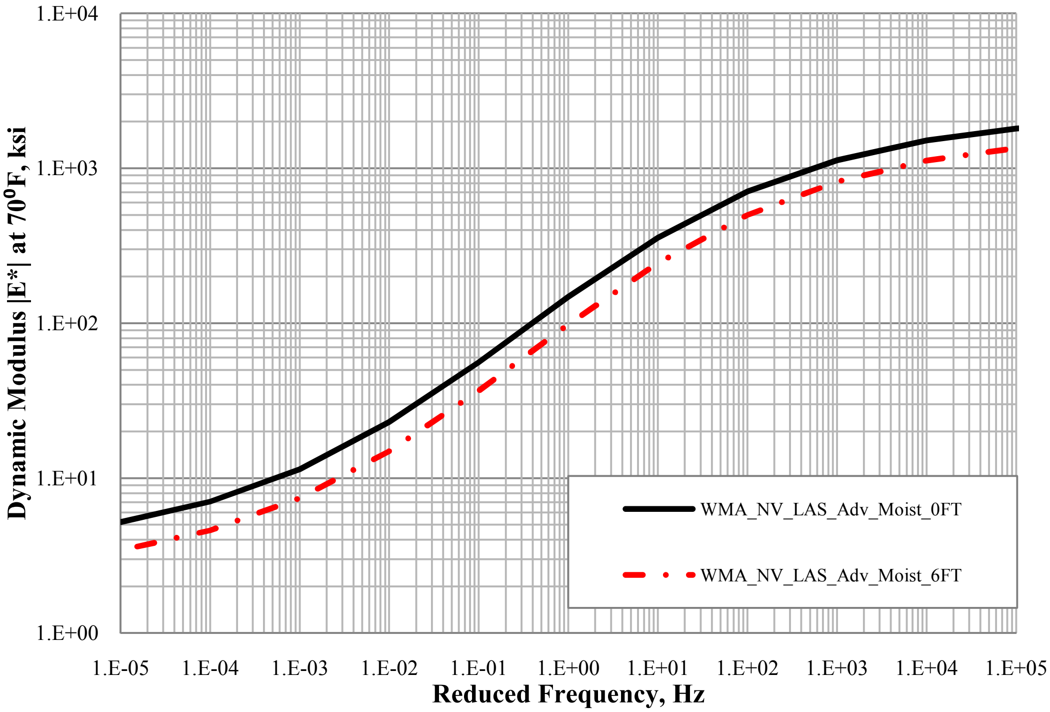
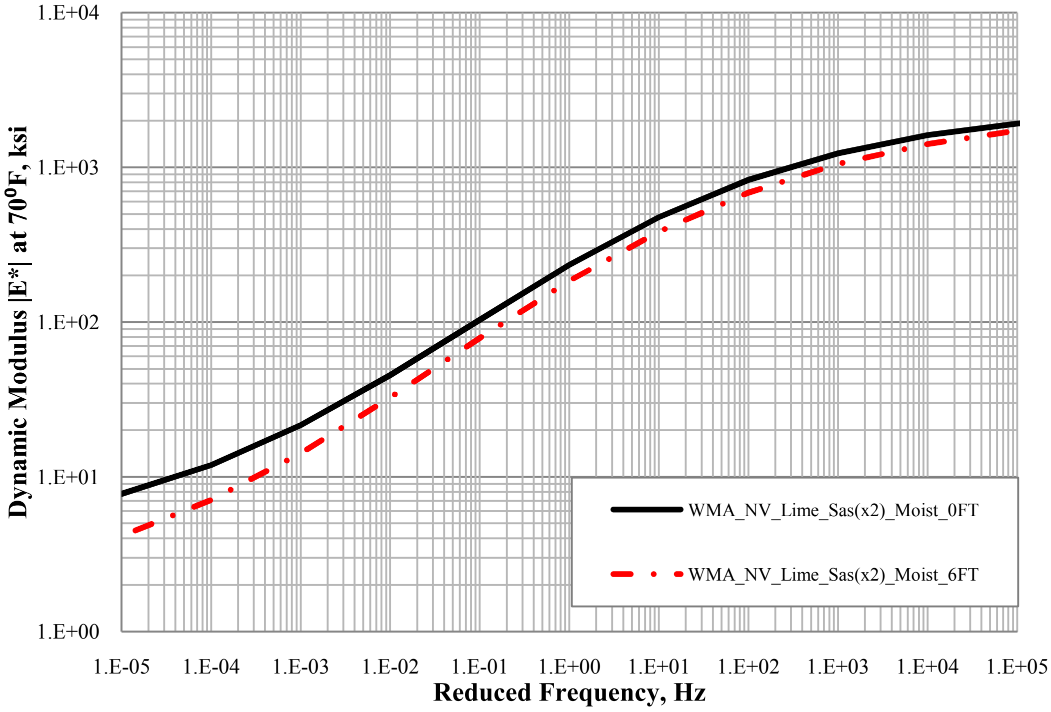


Figure 60 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-28 NV/PM & 0.3% Advera by total wt of mixture



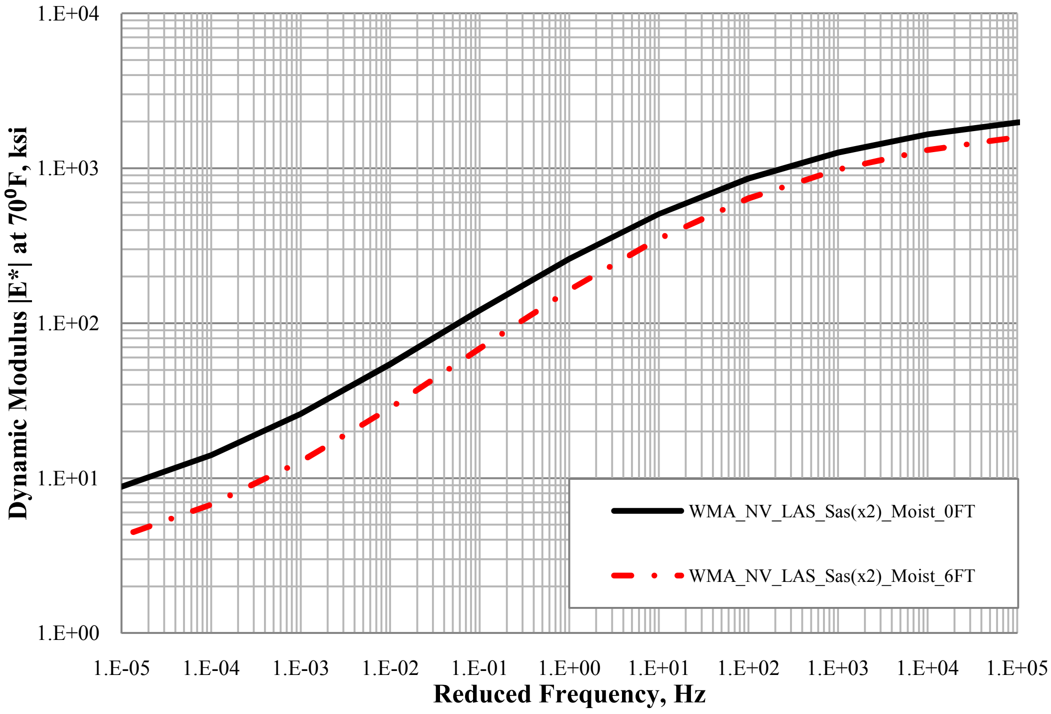
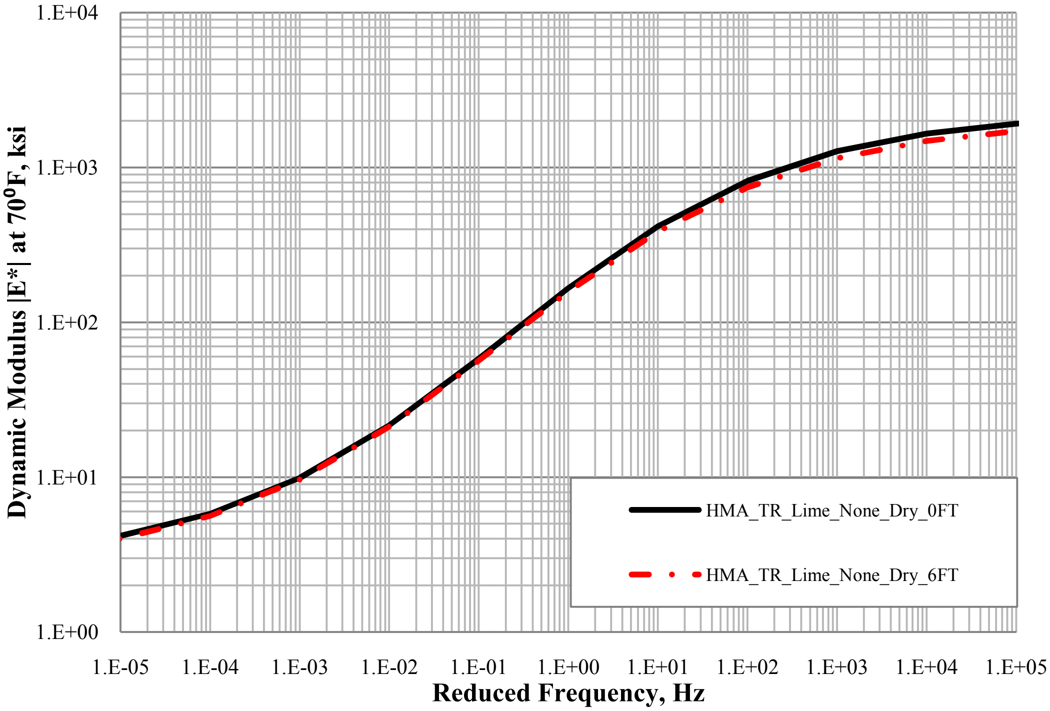


Figure 61 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-28 NV/PM & 3.0% Sasobit by wt of binder



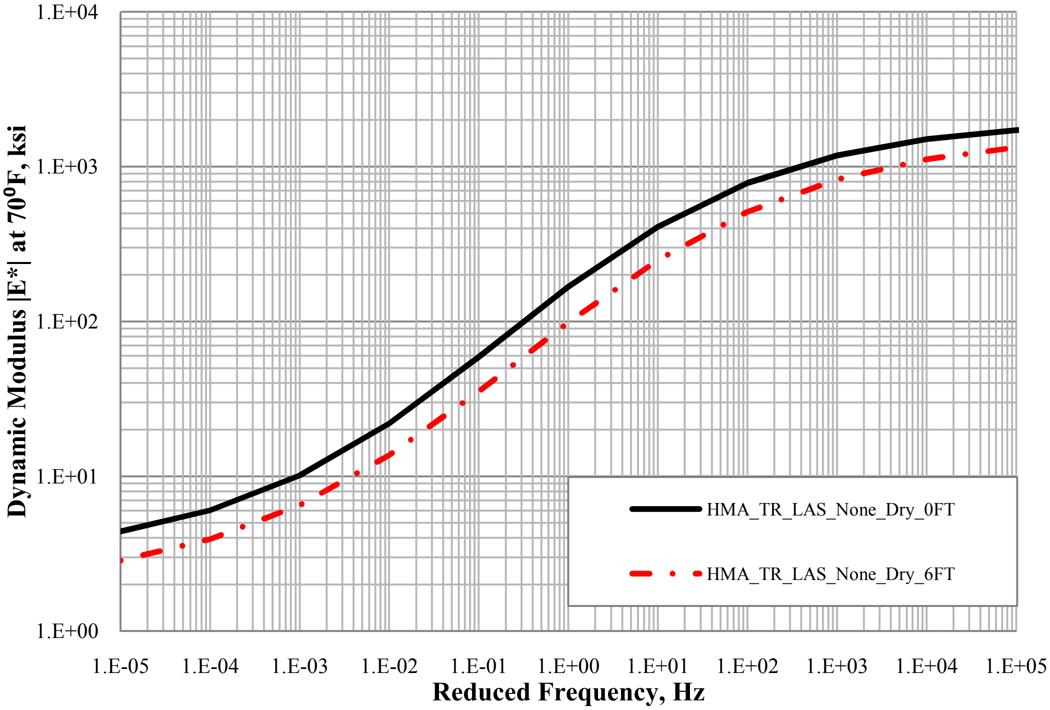


Figure 62 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-28 NVTR/TR

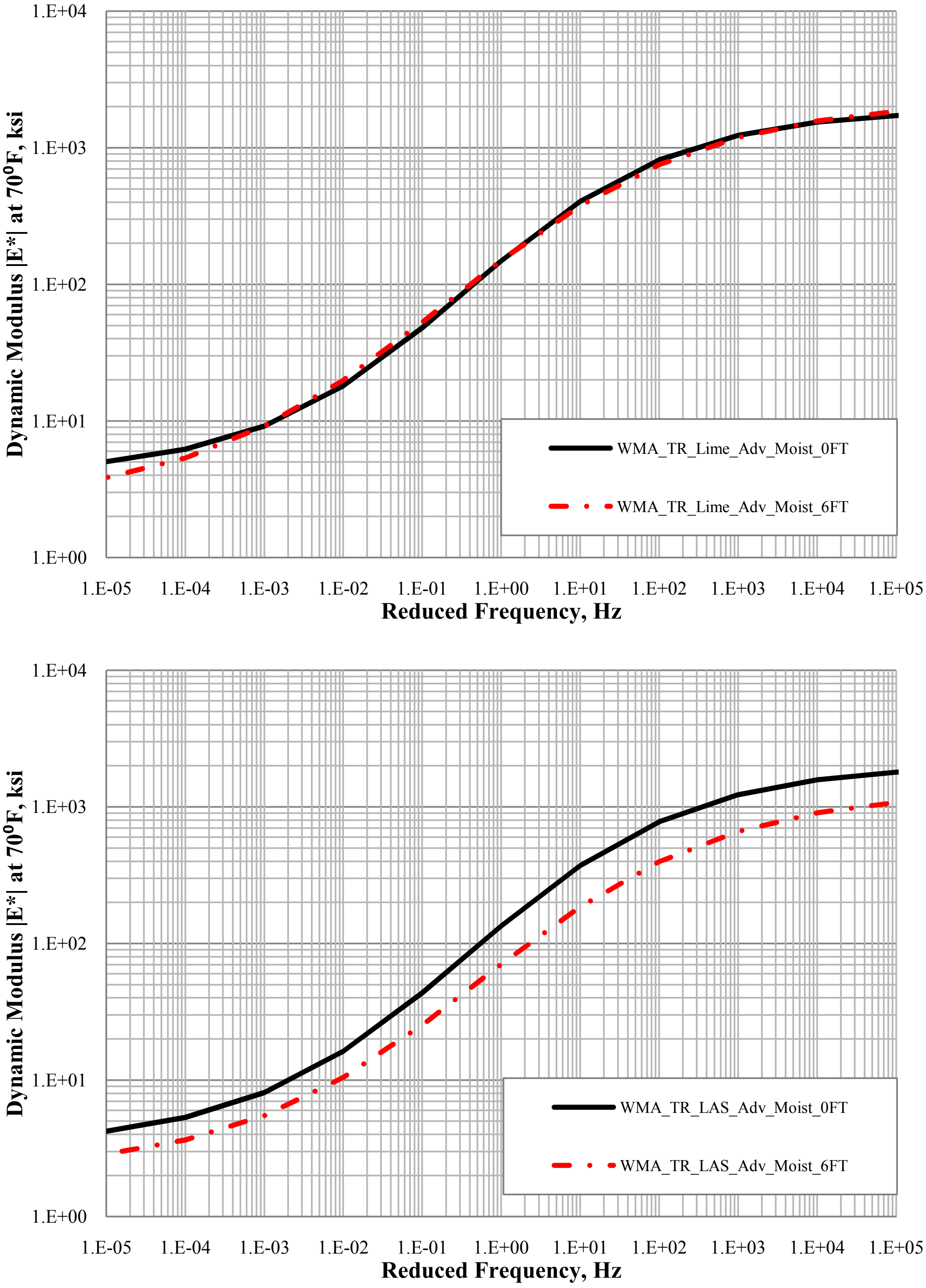
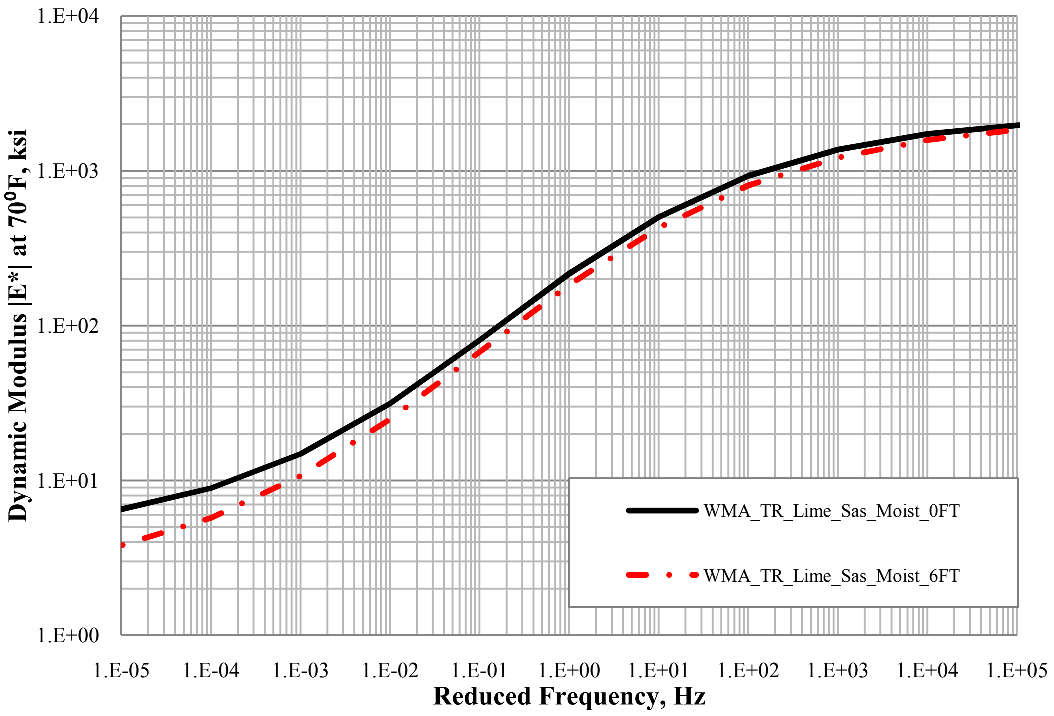


Figure 63 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-28 NVTR/TR & 0.3% Advera by total wt of mixture



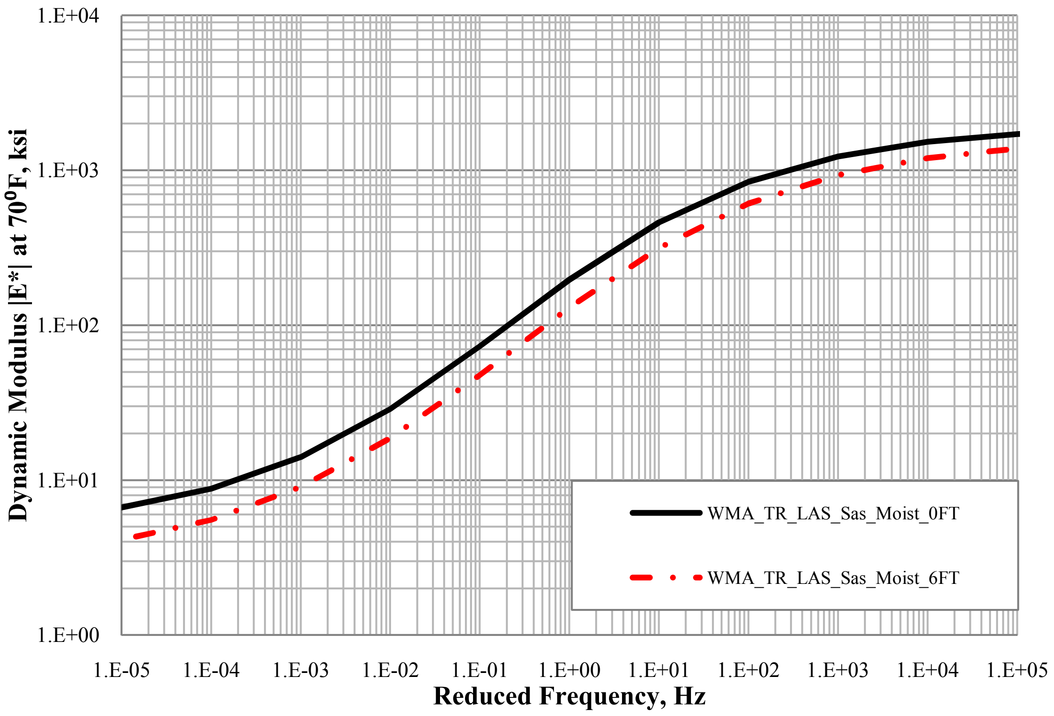
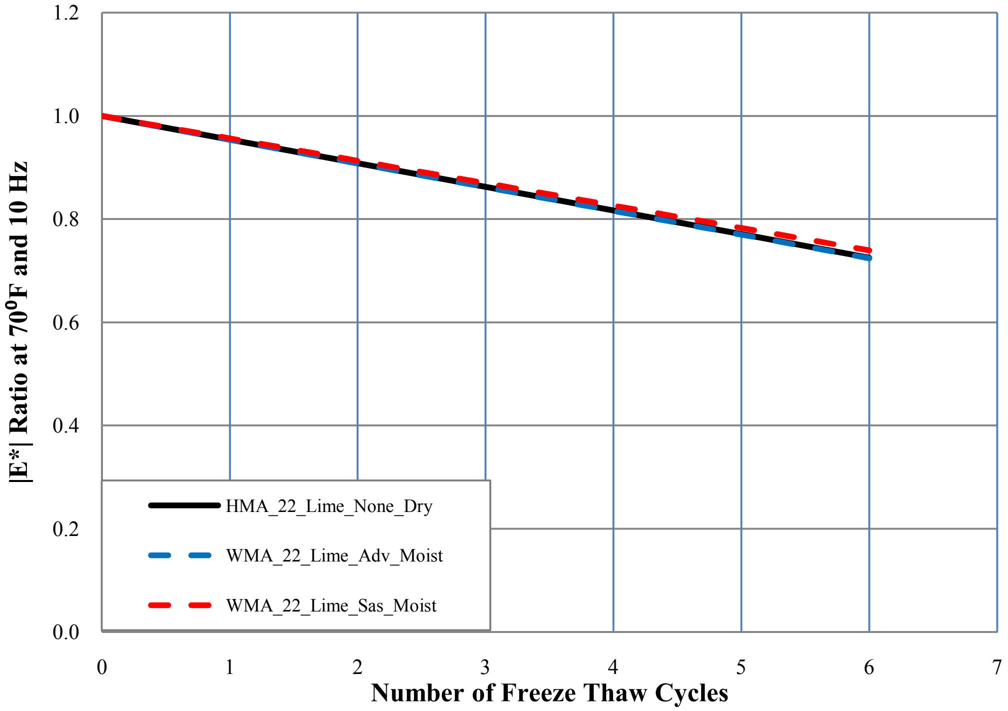


Figure 64 Dynamic modulus (|E*|) master curves for antistrip-treated mixtures with PG 64-28 NVTR/TR & 1.5% Sasobit by wt of binder



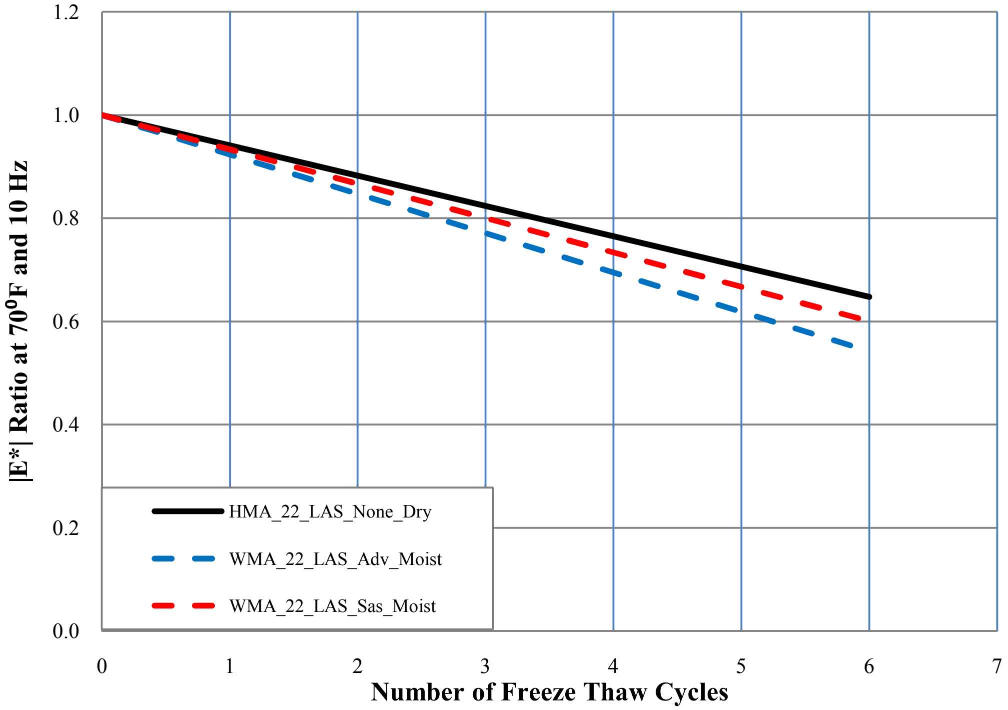


Figure 65 Dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for antistrip-treated asphalt mixtures with PG64-22

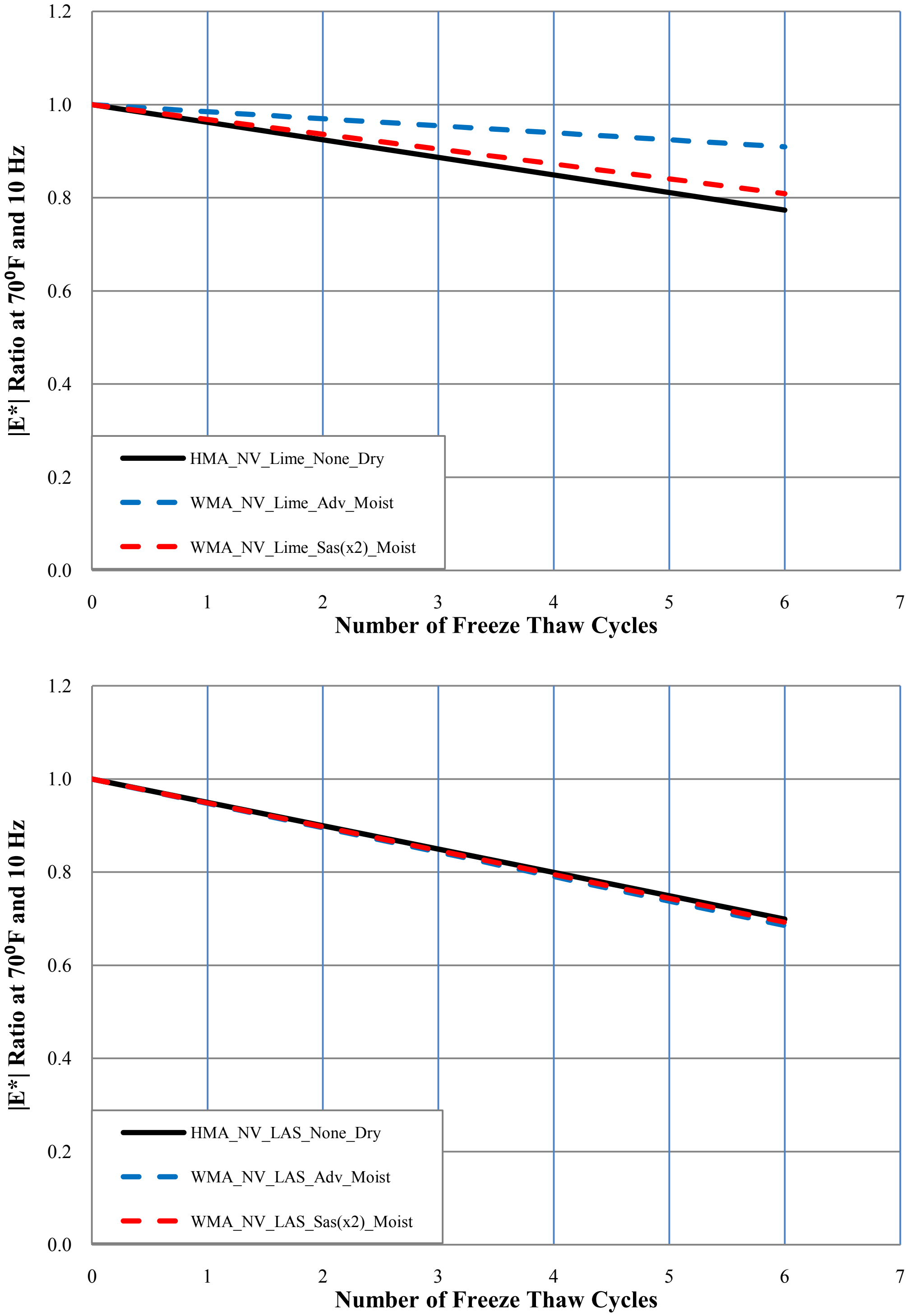


Figure 66 Dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for antistrip-treated asphalt mixtures with PG64-28 NV/PM

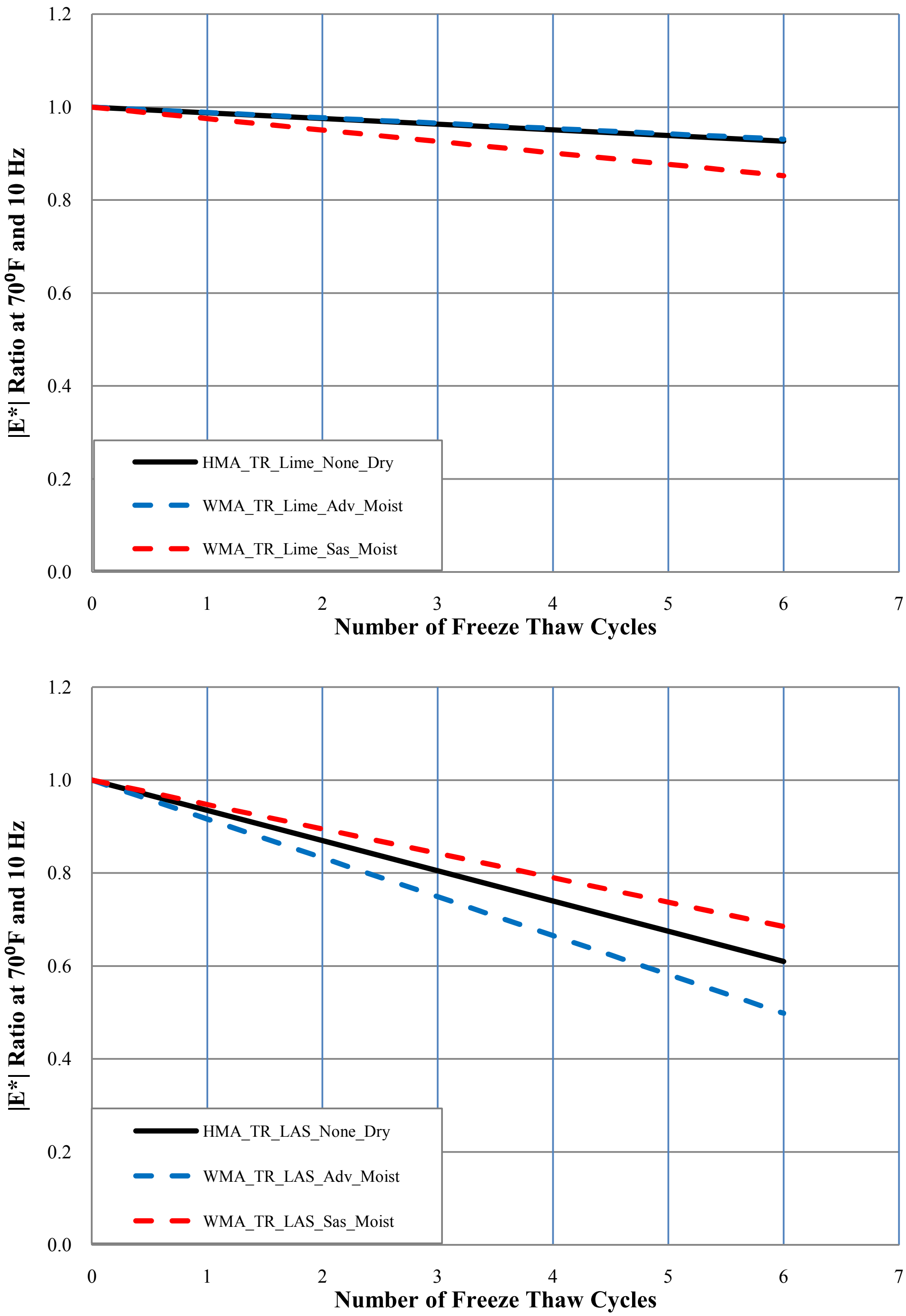


Figure 67 Dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for antistrip-treated asphalt mixtures with PG64-28 NVTR/TR

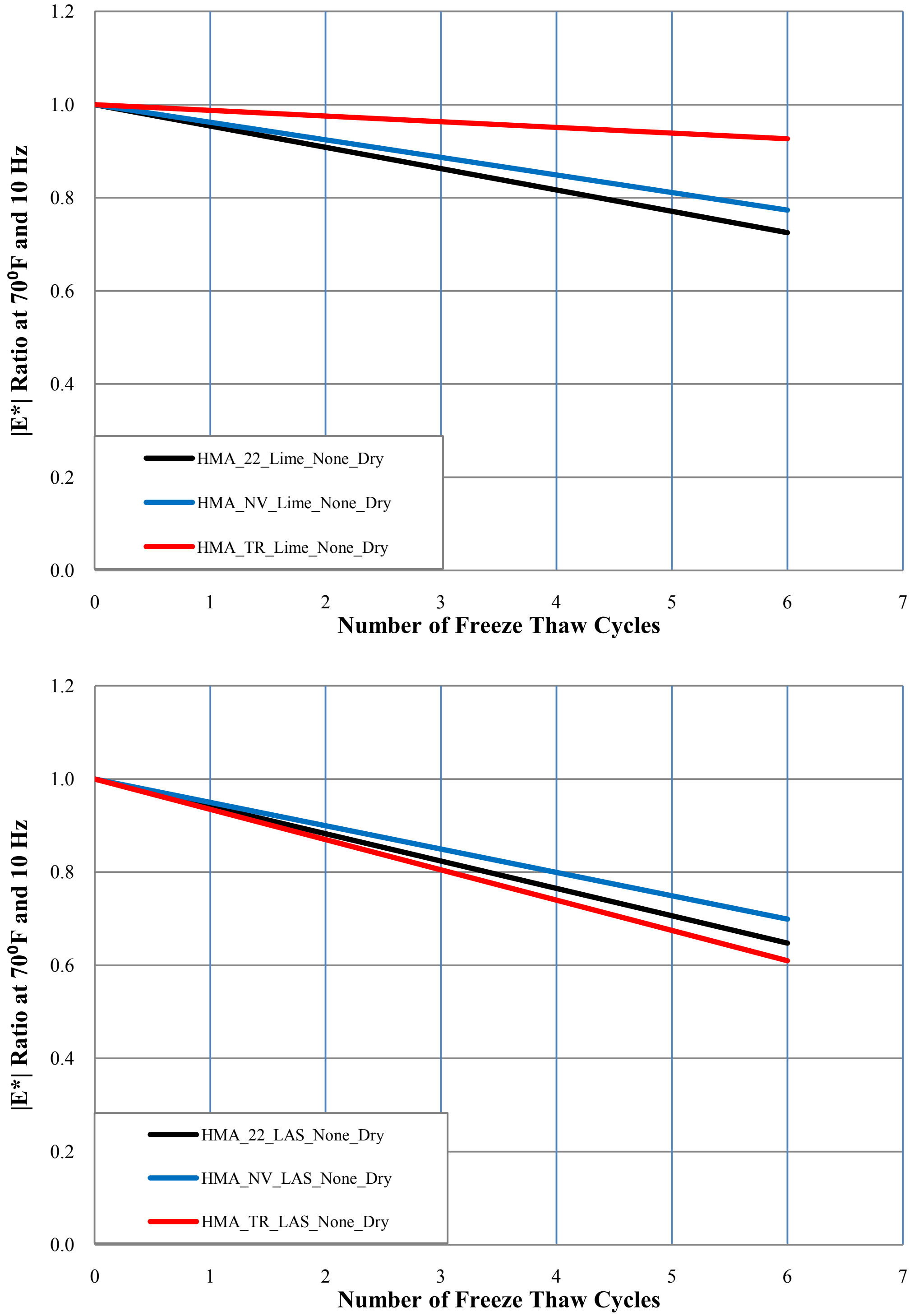
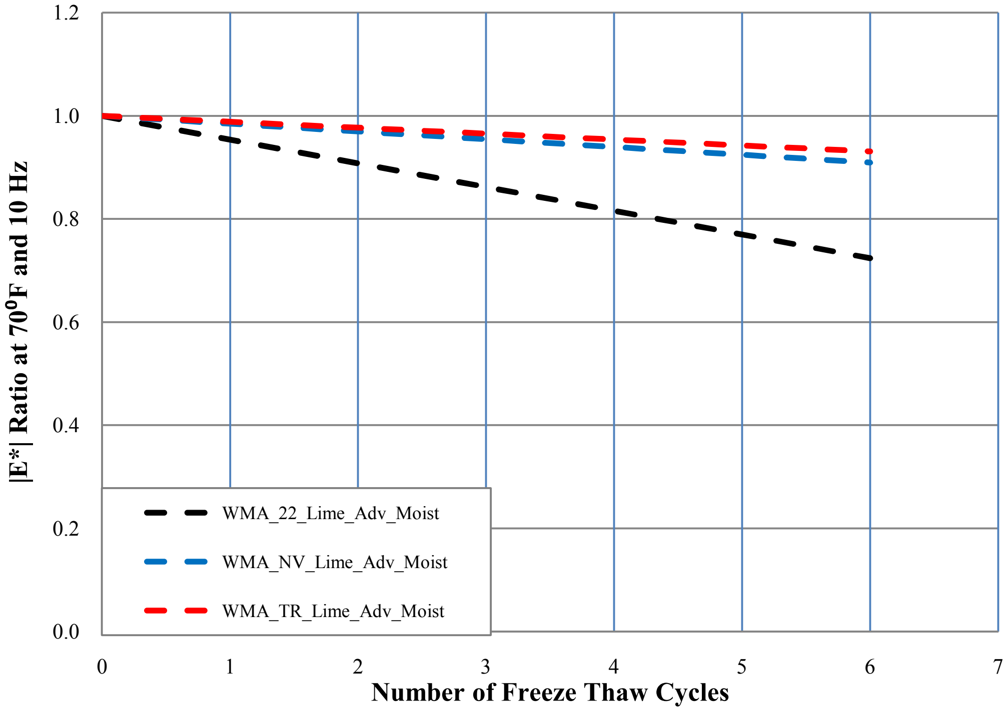


Figure 68 Dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for antistrip-treated asphalt mixtures with no warm mix additive



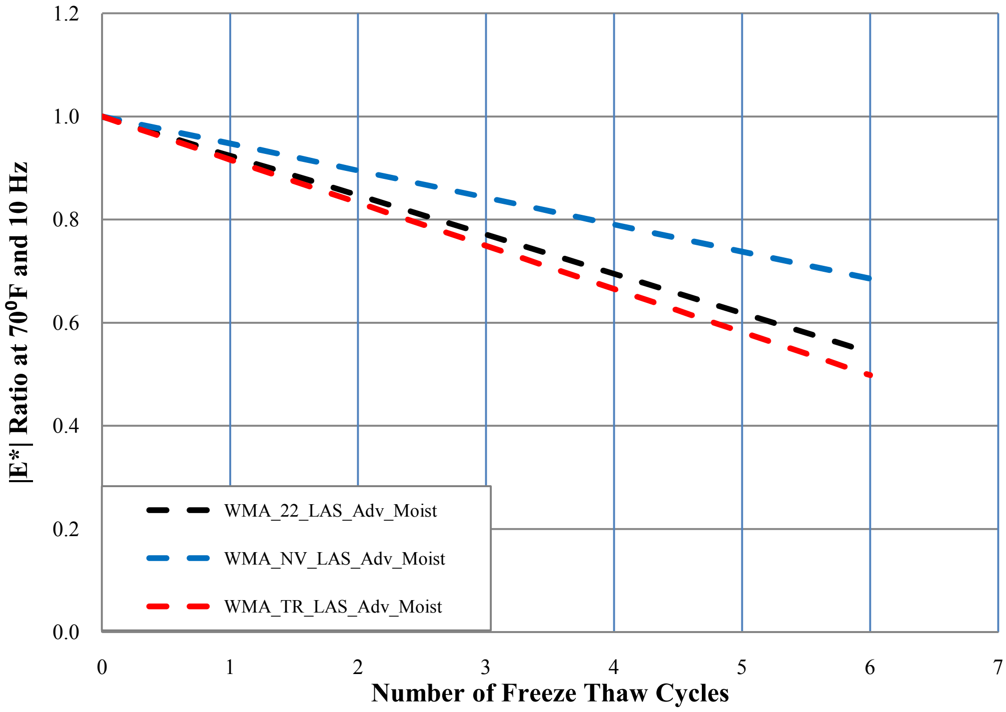


Figure 69 Dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for antistrip-treated asphalt mixtures with Advera

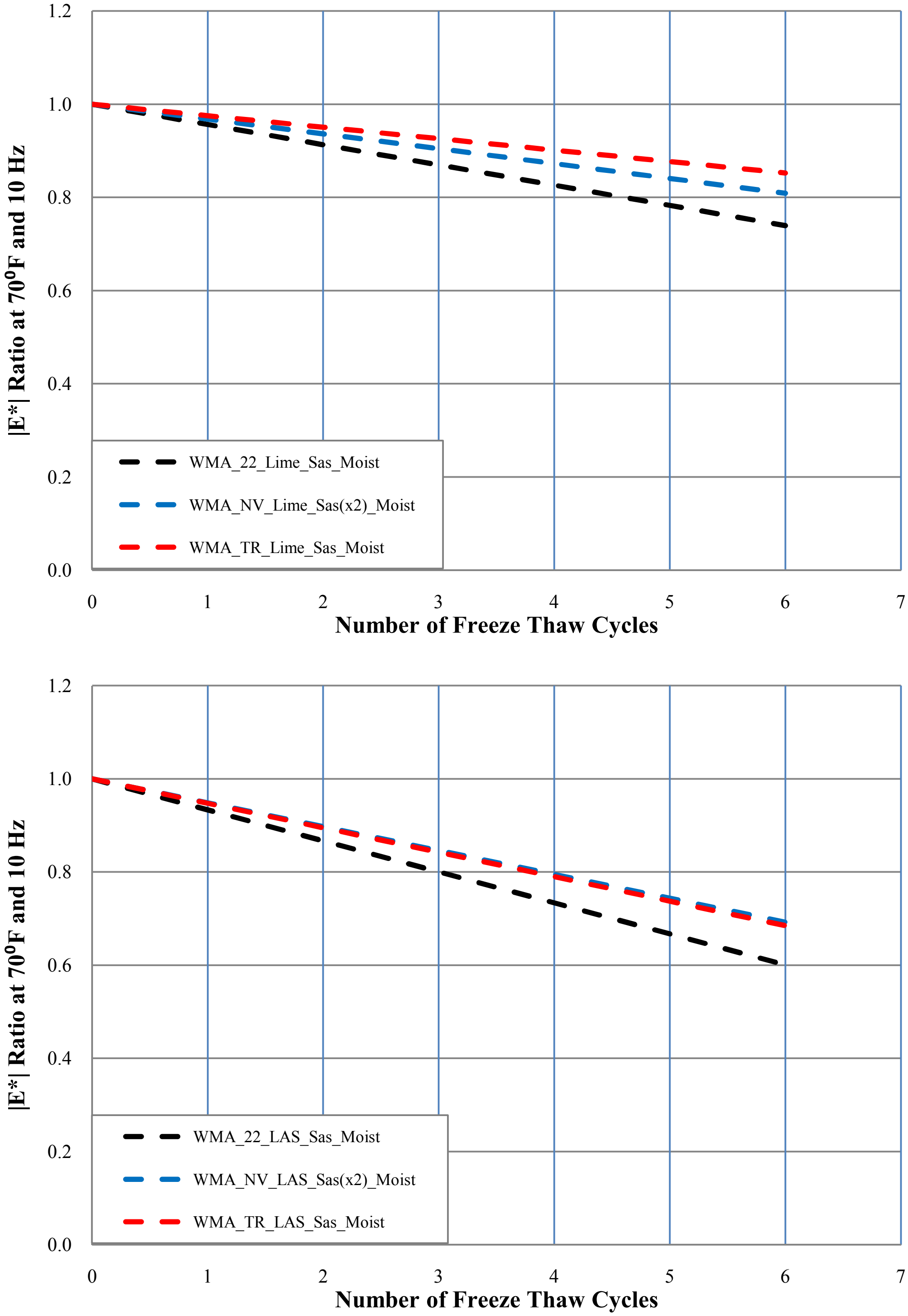


Figure 70 Dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for antistrip-treated asphalt mixtures with Sasobit

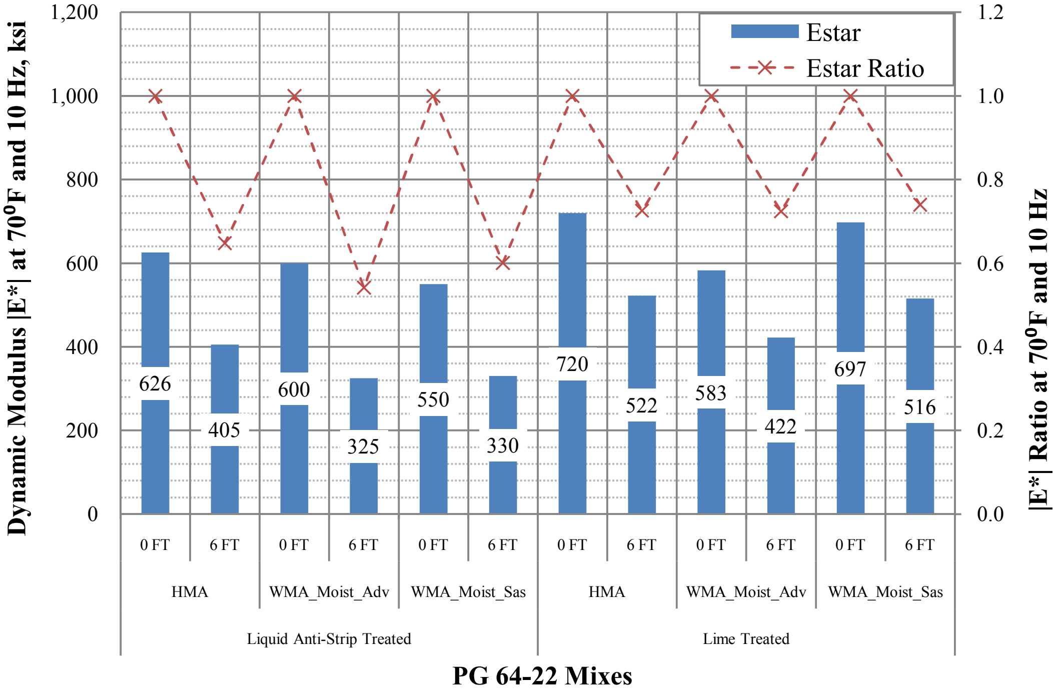


Figure 71 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for asphalt mixtures with PG64-22 with anti-strip treatment

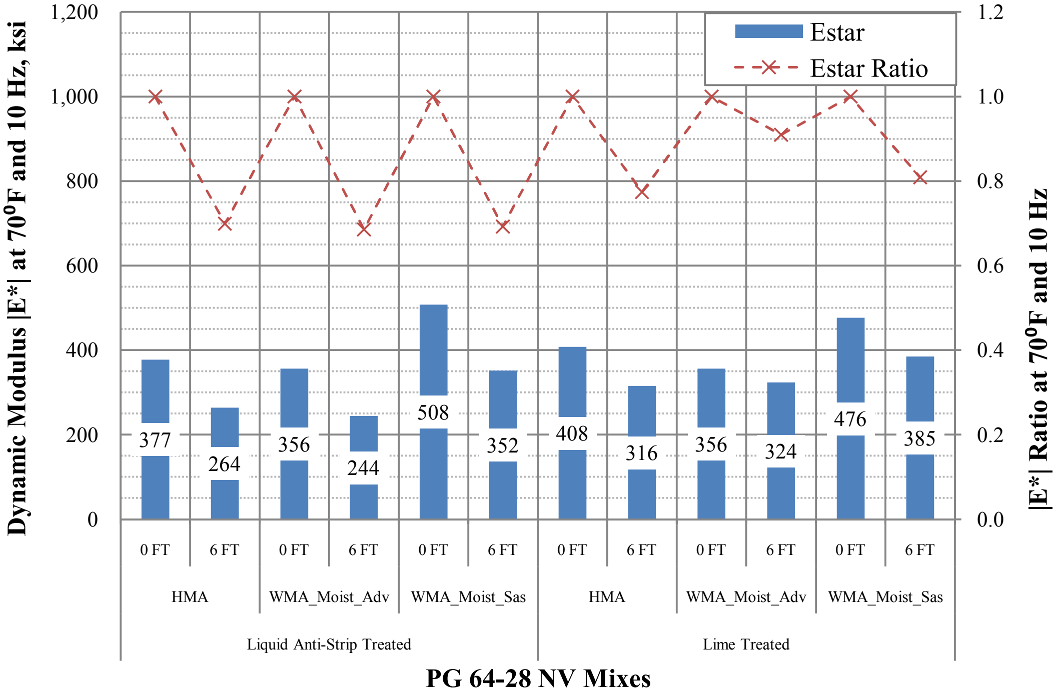


Figure 72 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for asphalt mixtures with PG64-28 NV/PM with anti-strip treatment

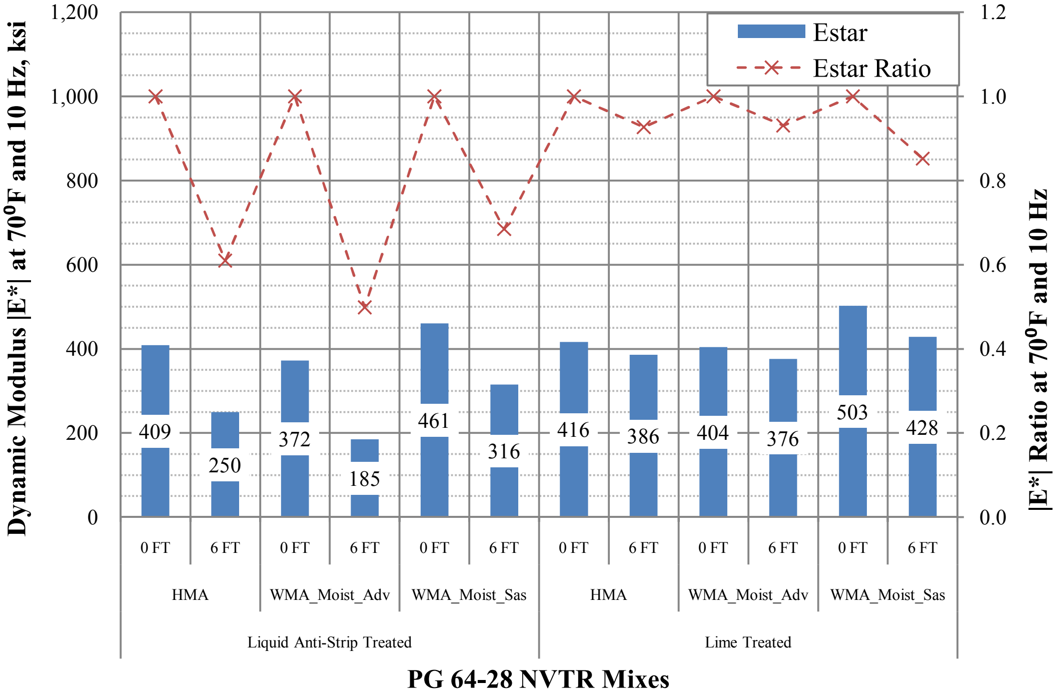


Figure 73 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for asphalt mixtures with PG64-28 NVTR/TR with anti-strip treatment

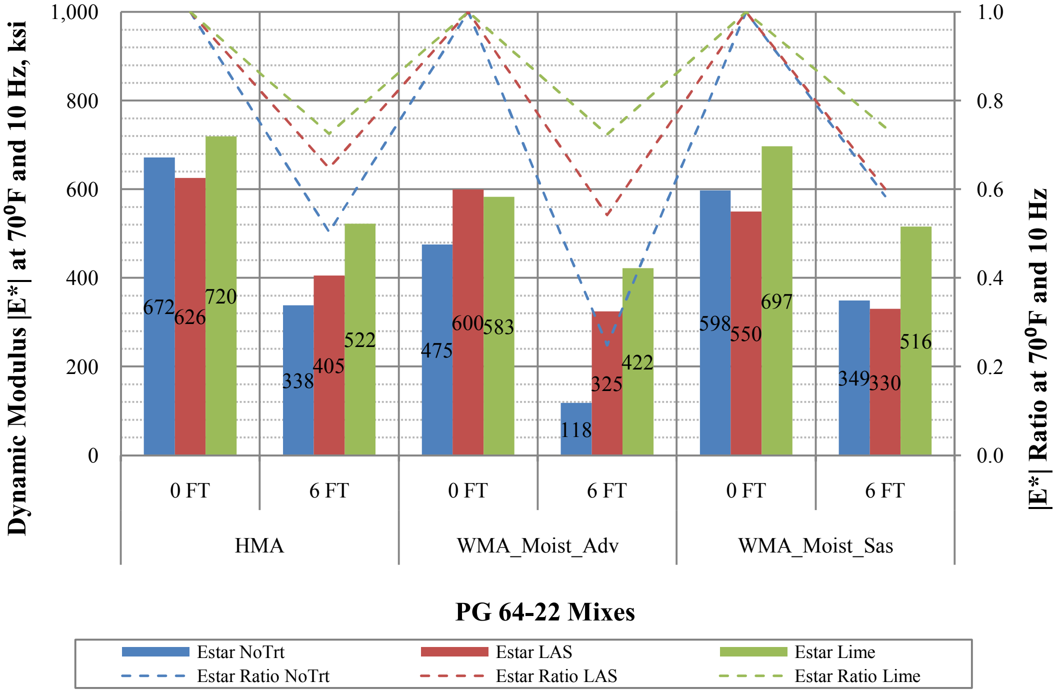


Figure 74 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for asphalt mixtures with PG64-22 with and without anti-strip treatment

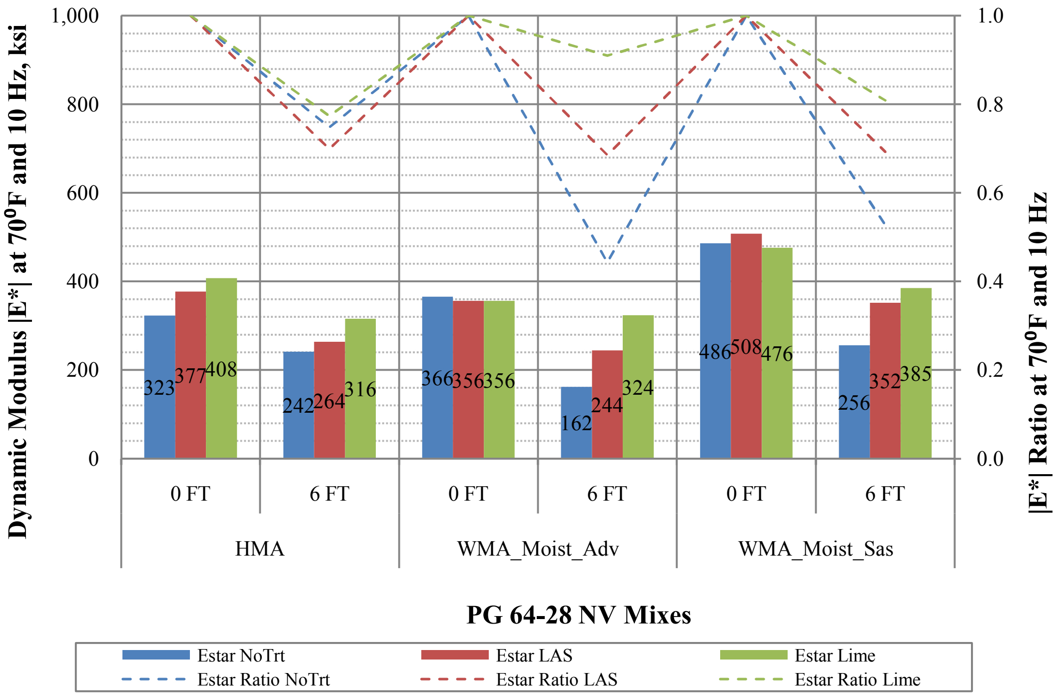
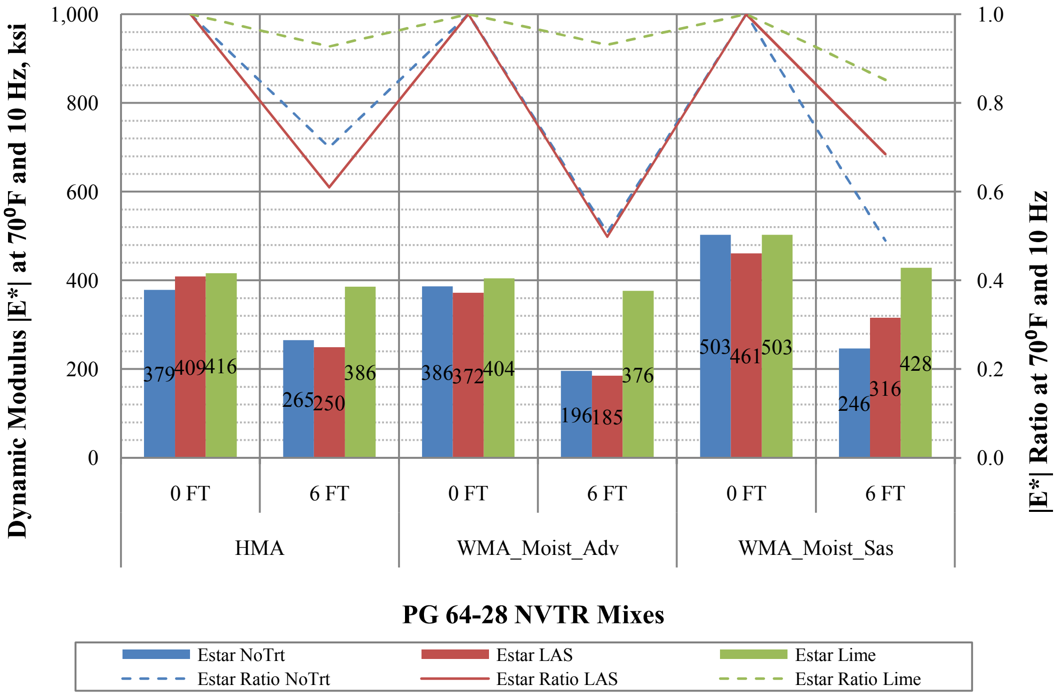


Figure 75 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70⁰F and 10 Hz for asphalt mixtures with PG64-28 NV/PM with and without anti-strip treatment



z

Figure 76 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70⁰F and 10 Hz for asphalt mixtures with PG64-28 NVTR/TR with and without anti-strip treatment

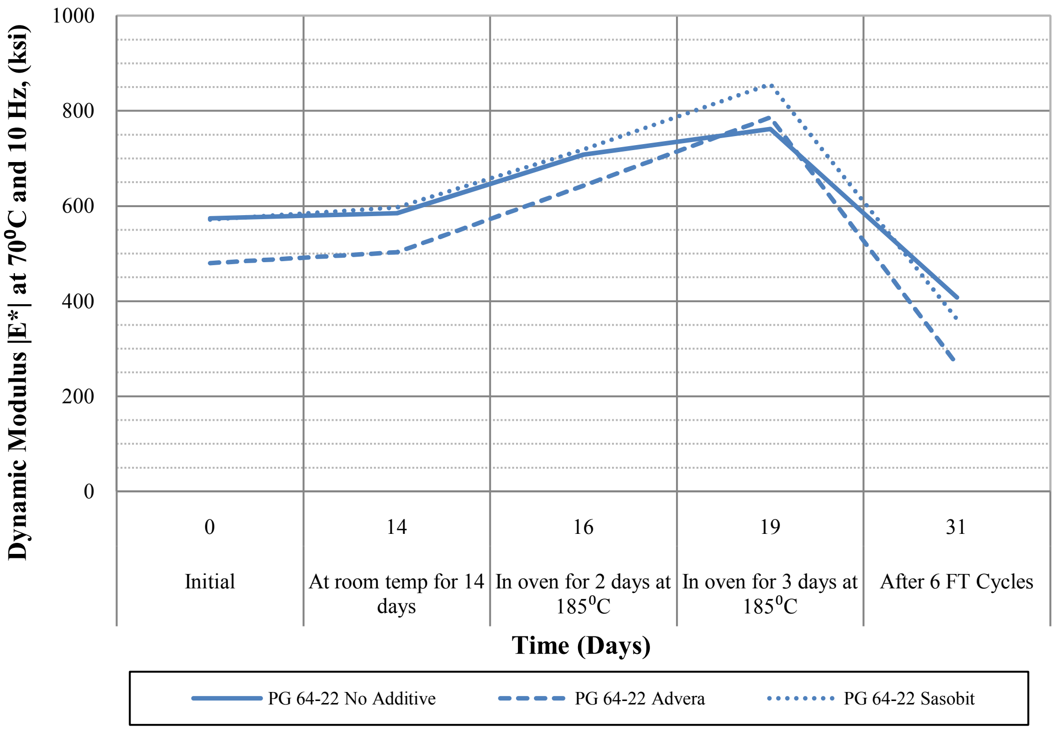


Figure 77 Dynamic modulus |E*| value at 70⁰F and 10 Hz versus aging protocol for PG 64-22 mixtures without anti-strip treatment

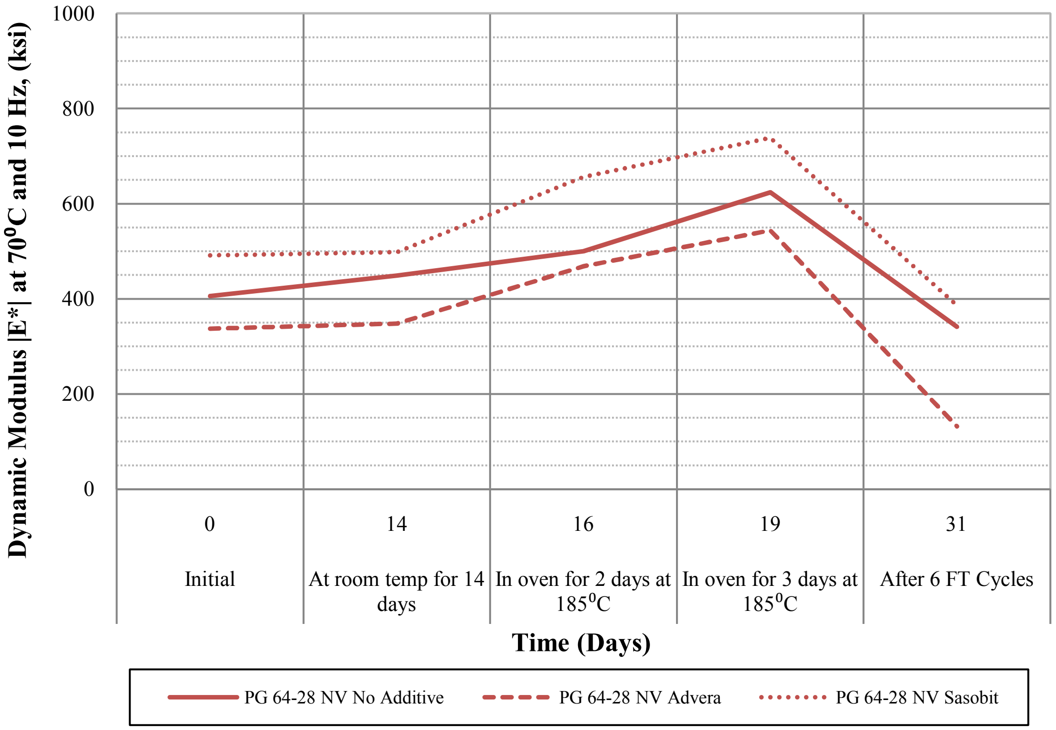


Figure 78 Dynamic modulus |E*| value at 70⁰F and 10 Hz versus aging protocol for PG 64-22 mixtures without anti-strip treatment

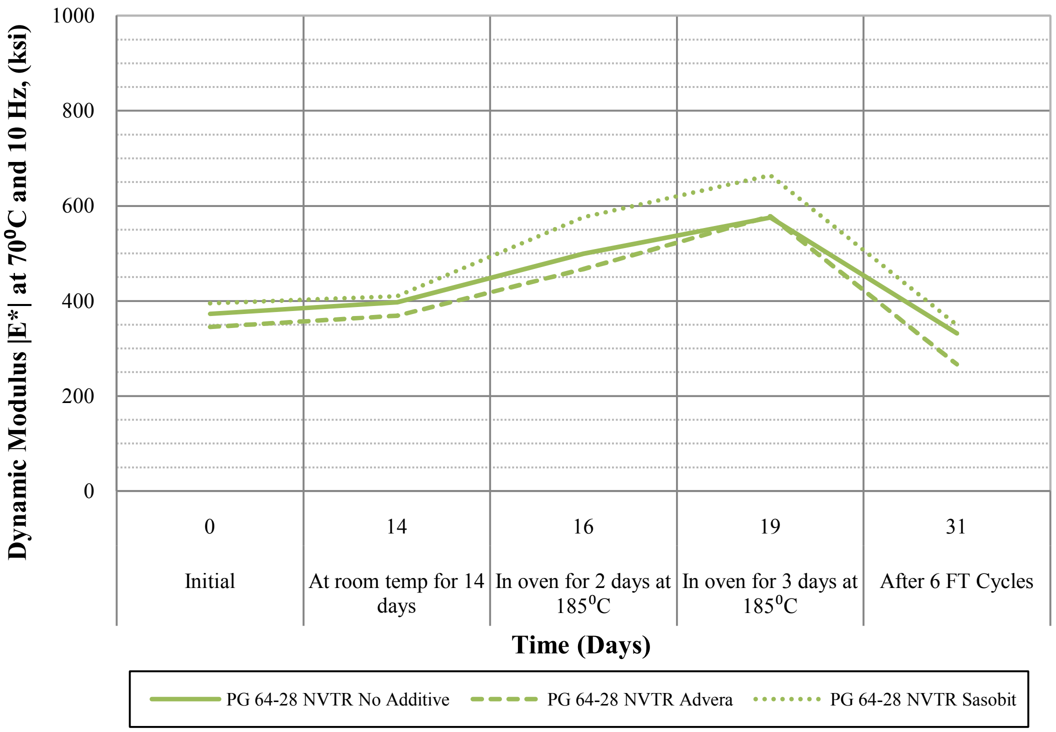


Figure 79 Dynamic modulus |E*| value at 70°F and 10 Hz versus aging protocol for PG 64-22 mixtures without anti-strip treatment

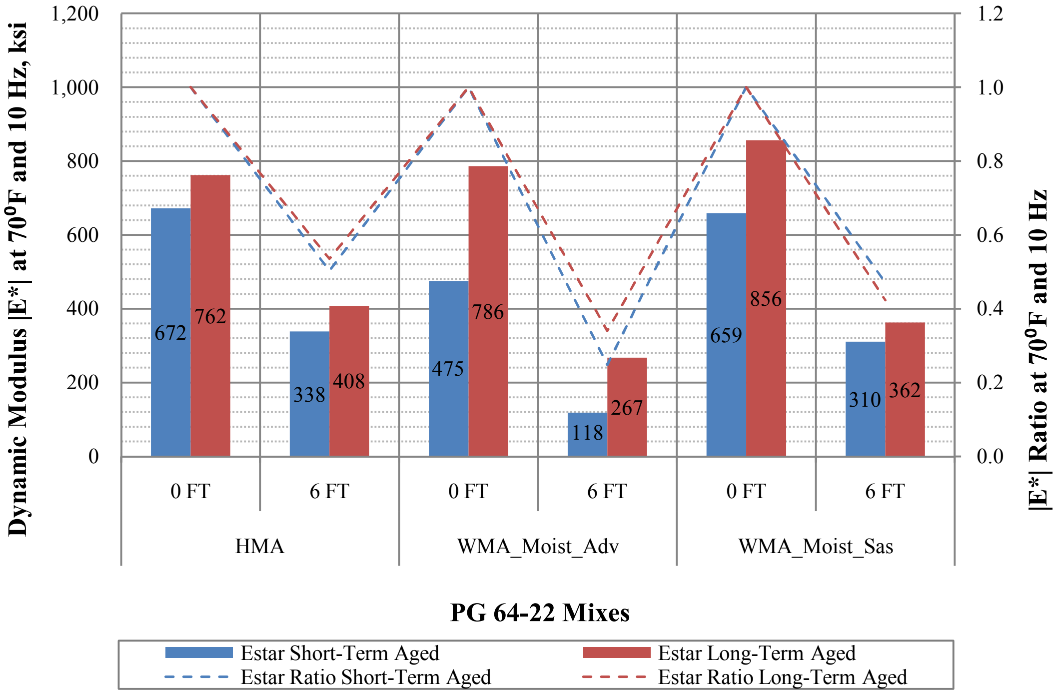


Figure 80 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for asphalt mixtures with PG64-22 short-term and long-term aged

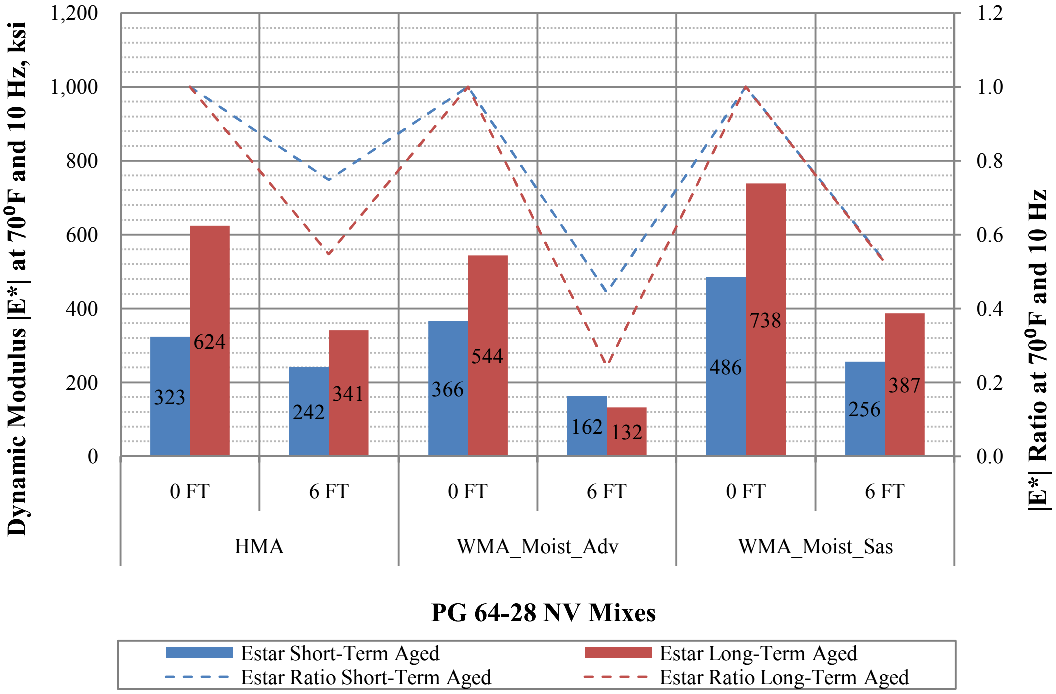


Figure 81 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for asphalt mixtures with PG64-28 NV/PM short-term and long-term aged

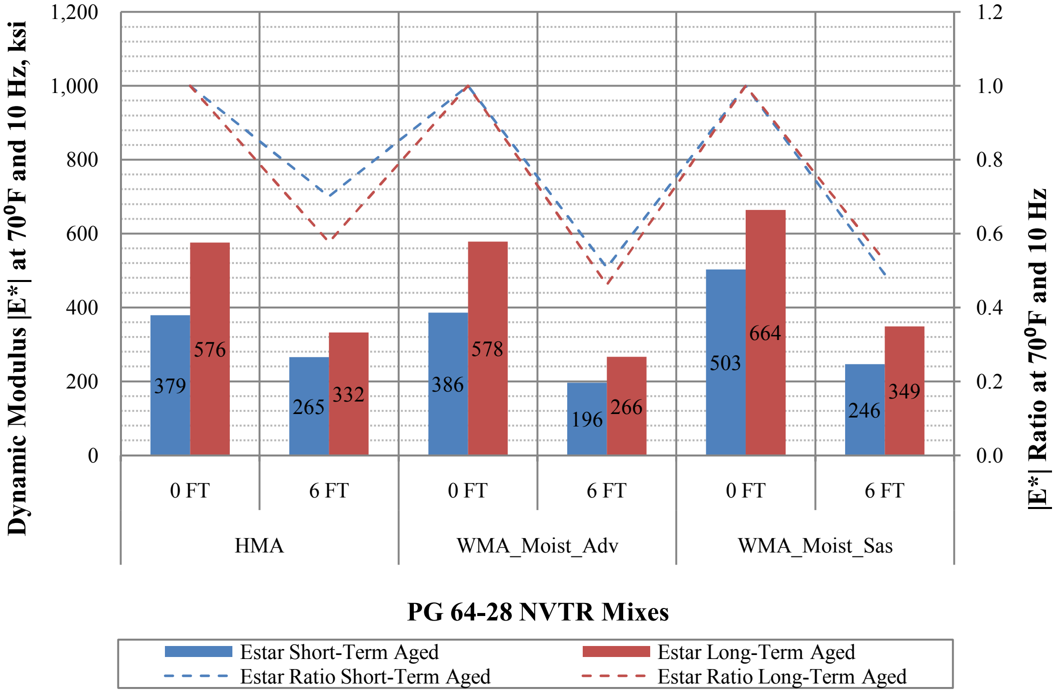


Figure 82 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70^{o}F and 10 Hz for asphalt mixtures with PG64-28 NVTR/TR short-term and long-term aged

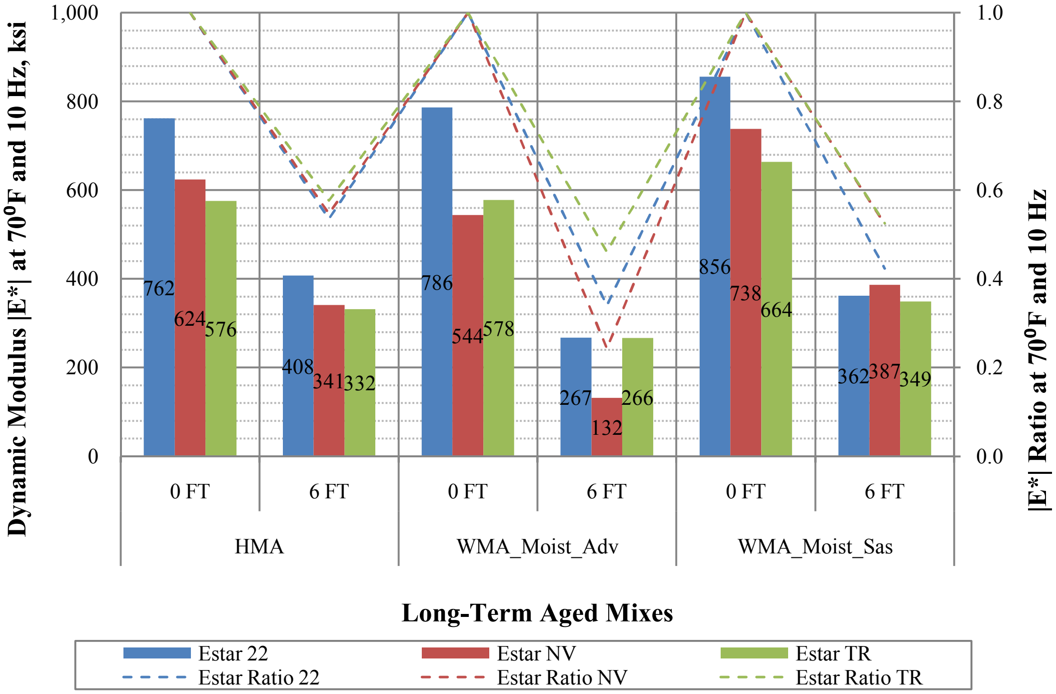


Figure 83 Dynamic modulus |E*| vs dynamic modulus (|E*|) ratio plots at 70°F and 10 Hz for long-term aged asphalt mixtures